#### Photonic Generation of Millimetre Waves for Radio over Fibre Distribution Systems

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A Dissertation submitted in fulfilment of the requirements for the award of Doctor of Philosophy (Ph.D.)

to the



Dublin City University

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May 2015

### Declaration

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### Acknowledgements

Firstly, I would like to acknowledge the constant support of my parents, Patrick and Anne, and my sisters throughout my entire education. Without their encouragement and guidance I most definitely would not be in a position to complete a Ph.D.

I would like to thank my supervisor Prof. Liam Barry both for the faith he showed in me by accepting me as his student and for the continual support and encouragement he provided throughout my time in DCU.

I would also like to acknowledge the enormous help I received from my colleagues at DCU; Colm, Vidak, Josue, Kai, Prince, Tong, Regan, Arsalan and Anthony. These people not only helped me in times of need for my studies but also helped me to relax after work hours.

A special thanks goes to my friends in Dundalk and in Dublin who helped to balance my research life with my social life.

Lastly, I would like to thank Shauna for helping me to keep a perspective on things and who made life so much easier during my studies.

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## **List of Acronyms**

- 1G First Generation
- 2G Second Generation
- **3G** Third Generation
- **3GPP** Third Generation Partnership Product
- 4G Fourth Generation
- ABC Automatic Bias Control
- ADSL Asymmetric Digital Subscriber Loop
- AM Amplitude Modulation
- **ASE** Amplified Spontaneous Emission
- ASK Amplitude Shift Keying
- ATM Asynchronous Transfer Mode
- AWG Arrayed Waveguide Grating
- AWG Arbitrary Waveform Generator
- BER Bit-Error Rate

- **BERT** Bit-Error Rate Tester
- **BL** Bit Rate-Distance Product
- BMRx Burst Mode Receiver
- BPSK Binary Phase Shift Keying
- **BS** Base Station
- BTB Back to Back
- CAGR Compound Annual Growth Rate
- **CAPEX** Capital Expenditure
- Ch. 1 Channel 1
- Ch. 2 Channel 2
- **CO** Central Office
- coax Coaxial
- **CP** Cyclic Prefix
- **CS** Carrier Suppressed
- CS Central Station
- CW Continuous Wave
- DAS Distributed Antenna System
- DBA Dynamic Bandwidth Allocation
- DC Direct Current
- DCF Dispersion Compensating Fibre

#### **DCM** Dispersion Compensating Module

- DDMZM Dual-Drive Mach Zehnder Modulator
- demux Demultiplexer
- **DFB** Distributed Feedback
- DPSK Differential Phase Shift Keying
- DSB Double Sideband
- **DSF** Dispersion Shifted Fibre
- DSL Digital Subscriber Loop
- DSLAM Digital Subscriber Line Access Multiplexer
- **DSP** Digital Signal Processing
- DWDM Dense Wavelength Division Multiplexing
- E/O Electro-Optic
- EBPF Electrical Band Pass Filter
- ECL External Cavity Laser
- EDFA Erbium Doped Fibre Amplifier
- ELPF Electrical Low Pass Filter
- EOM Electro-Optic Modulator
- **EPON** Ethernet Passive Optical Network
- ESA Electrical Spectrum Analyser
- FBC Feedback Control

- FCC Federal Communications Commission
- FDM Frequency Division Multiplexing
- FEC Forward Error Correction
- FFT Fast Fourier Transform
- FM Frequency Modulation
- FP Fabry-Pérot
- FSR Free Spectral Range
- **FTTB** Fibre to the Block
- FTTC Fibre to the Curb
- **FTTH** Fibre to the Home
- **FTTN** Fibre to the Node
- **FTTx** Fibre to the x
- FWHM Full-Width Half Maximum
- FWM Four-Wave Mixing
- GPON Gigabit Passive Optical Network
- GPRS General Packet Radio Service
- GSL Gain-Switched Laser
- GSM Global Standard for Mobile
- **GUI** Graphical User Interface
- GVD Group Velocity Dispersion

- HD High Definition
- HDTV High Definition Television
- HFC Hybrid Fibre-Coaxial
- HSDPA High-Speed Downlink Packet Access
- I In-phase
- **IF** Intermediate Frequency
- IFFT Inverse Fast Fourier Transform
- IM/DD Intensity Modulation with Direct Detection
- IMT-ad International Mobile Telecommunications-Advanced
- IQ In-phase Quadrature
- ISP Internet Service Provider
- ITU International Telecommunication Union
- LAN Local Area Network
- LMPN Laser Mode Partition Noise
- LO Local Oscillator
- LOS Line of Sight
- LPF Low Pass Filter
- LTE Long Term Evolution
- MAN Metropolitan (metro) Area Network
- MCM Multi-Carrier Modulation

- MDU Multi Dwelling Unit
- MLL Mode Locked Laser
- **mm-wave** Millimetre Wave
- MMF Multi-Mode Fibre
- mux Multiplexer
- MZM Mach-Zehnder Modulator
- NRZ NonReturn-to-Zero
- **O-E-O** Optical Electrical Optical
- O/E Optic-Electro
- OADM Optical Add/Drop Multiplexer
- **OBPF** Optical Band Pass Filter
- **OBSF** Optical Band Stop Filter
- **OCS** Optical Carrier Suppression
- OECD Organisation for Economic Cooperation and Development
- **OFC** Optical Frequency Comb
- **OFCS** Optical Frequency Comb Source
- OFDM Orthogonal Frequency Division Multiplexing
- **OIL** Optical Injection Locking
- **OIPL** Optical Injection Phase Locking
- **OLT** Optical Line Terminal

- **ONU** Optical Network Unit
- **OOK** On-Off Keying
- **OPEX** Operating Expenditure
- **OPLL** Optical Phase Lock Loop
- P2P Point-to-Point
- PC Polarization Controller
- PMD Polarisation Mode Dispersion
- **PON** Passive Optical Network
- **POTS** Plain Old Telephone Service
- PPG Pulse Pattern Generator
- PRBS Pseudo-Random Bit Sequence
- **PSD** Power Spectral Density
- **PSK** Phase Shift Keying
- **Q** Quadrature
- **QAM** Quadrature Amplitude Modulation
- QDash Quantum Dash Semiconductor
- QPSK Quadrature Phase-Shift Keying
- RAU Remote Antenna Unit
- **RF** Radio Frequency
- **RIN** Relative Intensity Noise

#### ROADM Reconfigurable Optical Add/Drop Multiplexer

- RoF Radio-over-Fibre
- **RTS** Real-Time Scope
- SCM Sub Carrier Multiplexed
- **SDH** Synchronous Digital Hierarchy
- SMF Single Mode Fibre
- SMSR Side Mode Suppression Ratio
- SNR Signal-to-Noise Ratio
- SOA Semiconductor Optical Amplifier
- **SONET** Synchronous Optical Networking
- **SSB** Single Sideband
- SSMF Standard Single Mode Fibre
- **TDM** Time Division Multiplexing
- TDMA Time Division Multiple Access
- **TS** Training Sequence
- **UDWDM** Ultra Dense Wavelength Division Multiplexing
- **UHDTV** Ultra High Definition Television
- **UMTS** Universal Mobile Telecommunication System
- UWB Ultrawideband
- VDSL Very-high-bit-rate Digital Subscriber Loop

- **VOA** Variable Optical Attenuator
- **VOD** Video on Demand
- WCDMA Wideband Code Division Multiple Access
- WDM Wavelength Division Multiplexing
- WDMA Wavelength Division Multiple Access
- WiMax Worldwide Interoperability for Microwave Access
- WLAN Wireless Local Access Network
- WPAN Wireless Personal Access Network
- WSS Wavelength Selective Switch

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### Abstract

### Photonic Generation of Millimetre Waves for Radio over Fibre Distribution Eamonn Martin

In the Millimeter Wave (mm-wave) range there is a large amount of available bandwidth, however, such systems are limited to short-range wireless communications (<50 m). Radio-over-Fibre (RoF) can be used to extend the transmission distances of the mm-waves in order to benefit from the large available bandwidth and low transmission loss of fibre in Fibre to the Home (FTTH) Passive Optical Network (PON) architectures.

In this research, generation of mm-waves is demonstrated using Optical Frequency Combs (OFCs). Using a Gain Switched Laser (GSL), this research works towards a RoF system capable of transmitting an Orthogonal Frequency Division Multiplexing (OFDM) mm-wave signal. This thesis also examines the coherence of a Quantum Dash Semiconductor (QDash) laser and discusses its potential for the generation of mm-wave and THz radiation.

The work presented in this thesis demonstrates mm-wave generation and RoF transmission systems using GSLs to generate a mm-wave RoF system capable of data rates of up to 25 Gb/s over 50 km of fibre. The QDash laser is demonstrated to have high coherence, in particular when actively mode-locked. Along with it's low power requirements, mm-scale device footprint and monolithic manufacturability, the QDash is advocated as a promising fit to generate mm-wave and THz radiation. The systems and devices presented possess the potential to be implemented in future access networks integrating both wired and wireless networks.

### Introduction

The demand for higher internet speeds is ever-increasing and being driven by media-rich online services such as online video, online gaming and high-speed data transfer. As a result, Internet Service Providers (ISPs) will be required to upgrade existing communication networks to satisfy the needs of the end-user, whether residential or commercial. While the core networks and Metropolitan (metro) Area Networks (MANs) are capable of employing expensive optical networks, it is important that future access networks developed for wide deployment are cost sensitive. Current access networks consist primarily of electrical cables (telephone or Coaxial (coax)) which are cheap but limited in terms of data through-put and transmission distance. A solution is to open up the "last-mile bottleneck" through the use of optical fibre and its inherent advantages of low loss and un-limited bandwidth. Utilising optical fibre in the access network can create an all-optical communication network. This type of all optical access network is termed as Fibre to the Home (FTTH) and has been put forward as a long term solution to meet growing bandwidth demands.

Of utmost importance for future access networks is the capability to seamlessly connect between the wired and wireless networks. The use of portable and mobile devices over wired devices is becoming ever more prevalent in modern society. An increasing number of users are utilising portable and mobile devices to access High Definition (HD) online video and to bulk transfer files at ultra high speeds. This creates a major driving force for the development of extremely high-speed wireless access infrastructure. Current wireless networks operate in lower frequency bands, such as 2.4 or 5 GHz, where there is a lot of congestion and a lack of available bandwidth. At much higher carrier frequencies in the Millimetre Wave (mm-wave) range there is a large amount of available bandwidth. In particular, at 60 GHz there is a minimum of 5 GHz available in most countries. However, mm-waves suffer high attenuation due to atmospheric oxygen, as such mm-wave systems are used primarily for short-range indoor wireless communications (<50 m). Therefore, a system which utilises a Radio-over-Fibre (RoF) architecture can take advantage of the large available bandwidth and low transmission losses of fibre in a FTTH Passive Optical Network (PON) architecture while providing a high-speed wireless access network using mm-waves.

A RoF system can provide a cost-effective architecture to successfully integrate the wired and wireless access networks. A RoF system allows for the centralisation of the data modulation and system control in a shared location while optical fibre is used to distribute the mm-wave signals to the Remote Antenna Unit (RAU). The RAU can subsequently transmit the wireless signal to the end-user's device. The installation of the expensive generation components at a shared location reduces both the Capital Expenditure (CAPEX) and Operating Expenditure (OPEX).

#### **Main Contributions**

This thesis is concerned with the photonic generation of mm-wave signals that can be employed in RoF networks, and specifically the main contributions of this work are:

• Demonstration of an Optical Frequency Comb (OFC), generated by a Gain-

Switched Laser (GSL), used to create a highly stable 60 GHz optical mm-wave and transmit a 2.5 Gb/s On-Off Keying (OOK) mm-wave signal over fibre. Analysing the suppression of the unwanted comb lines of the OFC shows that suppression of <15 dB causes a major detrimental effect on system performance. This emphasises the importance of the optical filtering technique used. Pre-compensation for chromatic dispersion is demonstrated using a single multi-functional programmable optical filter to filter unwanted comb lines and to pre-compensate for 12 km of dispersion.

- Demonstration of a 60 GHz RoF system, based on the GSL, utilising low cost electronics to implement a baud rate/modulation format scalable Single Sideband (SSB) Sub Carrier Multiplexed (SCM) Quadrature Phase-Shift Keying (QPSK) system. Error-free transmission of a 1.25 GBaud/s QPSK signal over 25 km of fibre is achieved.
- Simplification of the GSL RoF based on a Wavelength Division Multiplexing (WDM) technique. Two high-speed 60 GHz Orthogonal Frequency Division Multiplexing (OFDM) RoF systems are realised using this transmitter. The initial system utilises a low complexity gain switched Distributed Feedback (DFB) laser with a large linewidth per comb line, however, it requires a precompensation technique for optical phase decorrelation between the optical comb lines due to chromatic dispersion. The second system does not require this pre-compensation and utilises an externally injected DFB laser to generate a low linewidth coherent comb source. Both systems are capable of transmitting a 25 Gb/s OFDM signal over fibre.
- Investigation of the evolution of the spectral mode coherence for a passively and actively mode-locked Quantum Dash Semiconductor (QDash) laser. Excellent coherence of the spectral modes is inferred from the results, in par-

ticular, when the QDash laser is actively mode-locked. The QDash laser is put forward as a promising fit for the generation of mm-wave and THz radiation owing to its high coherence, low power requirements, mm-scale device footprint and monolithic manufacturability.

#### **Thesis Structure**

This thesis is structured as follows:

- Chapter 1 describes the evolution of optical communication networks while examining the catalysts behind their continued growth in capacity. The optical network topology is introduced with a description of each network layer. Particular focus is placed on the optical access network with an overview of past, current and future networks given.
- Chapter 2 provides a detailed introduction to RoF systems. This chapter illustrates the growing trend of subscribers moving towards using portable and mobile devices to wirelessly access online services such as internet video. While highlighting the increasing data rates required to deliver high quality online services, the current and future wireless access networks are examined. The use of mm-wave frequency bands and the utilisation of RoF architectures are advocated as a means to overcome congestion and a lack of available bandwidth in the lower frequency bands. An overview of RoF architectures and optical methods of generating mm-waves is given before some key components of RoF optical communications are presented.
- Chapter 3 introduces a method of generating a stable mm-wave signal for use in a RoF system based on generating an OFC using a GSL. An explanation of the gain switching technique is given. In this chapter, four experimental works are carried out to evaluate the effectiveness of the GSL and

its suitability for a low cost 60 GHz RoF architecture. Initially, the GSL is used to transmit a 2.5 Gb/s OOK signal over 25 km of fibre. The setup is also used to evaluate the merits of the optical filtering techniques used thus demonstrating the quality of optical filtering required, an important factor in the implementation of a practical mm-wave RoF system. A dispersion pre-compensation technique is illustrated utilising a single multi-functional device which also carries out the optical filtering. Lastly, the GSL setup is used to demonstrate a baud rate/modulation format scalable SSB SCM QPSK 60 GHz RoF system using low cost analog components.

- Chapter 4 simplifies the GSL RoF transmitter using a WDM technique and allows for a single optical tone of the OFC generated by the GSL to be modulated individually. Modulation of a single tone overcomes the effects of bit-walk off and enables the use of OFDM to increase the spectral efficiency of the RoF systems and in turn, the achievable data rate. An overview of the OFDM technique is given before two experimental works are demonstrated transmitting a 25 Gb/s OFDM mm-wave over fibre. In the initial system, a pre-compensation technique is used to overcome the dispersion induced phase decorrelation between the optical tones allowing for the transmission of the signal over 50 km of fibre. To eradicate the requirement of the pre-compensation, the GSL is externally injected using an External Cavity Laser (ECL) to generate a low linewidth OFC. Using this highly coherent OFC demonstrates a robust mm-wave RoF system with negligible phase noise penalties without the need for complex phase noise suppression or a pre-compensation technique.
- Chapter 5 introduces the technique of using Mode Locked Lasers (MLLs) to generate OFCs which can be used for the generation of mm-wave and THz radiation. Passive and active mode-locking techniques are discussed. In this

chapter a QDash laser is used to generate an OFC with a Free Spectral Range (FSR) of 42.7 GHz . Utilising this laser, coherence measurements are carried out for adjacent and non-adjacent tones of the OFC out to a frequency separation of 1.1 THz. Coherence measurements of adjacent tones can be inferred from the Radio Frequency (RF) beat tone linewidth measured using a photodetector and an Electrical Spectrum Analyser (ESA). While for the non-adjacent tones where the frequency separation is >80 GHz, an optical down-conversion technique based on Four-Wave Mixing (FWM) must be implemented to measure the RF beat tone linewidth. Coherence measurements are carried out when the laser is passively, electrically and optically modelocked. The results are used to infer the suitability of the QDash laser as a source for the generation of mm-wave and THz radiation.

• Chapter 6 provides a brief summary of conclusions which can be drawn from the results presented in this thesis. The potential for future work in the areas discussed throughout the thesis is also outlined.

#### Chapter 1

### **Optical Networks**

Communication is an imperative part of our life and development. Cultural and technological evolution would not be feasible without efficient information exchange. The requirement for higher speeds of information transfer is the major driving force for technological development.

This chapter presents an introduction to optical communications and how it has evolved from original research to current technologies to provide for the growth of internet traffic.

#### 1.1 Introduction

The Bit Rate-Distance Product (BL) has increased to an enormous extent over a 150 year period extending from 1850 to 2000 and is shown in Figure 1.1 with the emergence of technological advances being illustrated also. The BL, where B is the bit rate and L is the repeater spacing, is a commonly used figure of merit for communication systems. It was realised during the second half of the twentieth century that optical waves could be used as a carrier and increase the BL product

by several orders of magnitude [1]. However, during the 1950s, neither a coherent optical source nor suitable transmission medium was available. In 1960, the first functional laser was demonstrated [2] and in 1966, it was proposed to use optical fibres as the transmission medium [3]. These two events marked the beginning of modern optical communications.



Figure 1.1: Increase of the bit-rate distance product, BL, from 1850-2000. The emergence of new technologies is denoted by a solid circle [4].

The first demonstration of a semiconductor laser operating at room temperature was in 1969 [5]. During the 1960s, optical fibres suffered extremely high losses of ~1000 dB/km and it wasn't until 1970 that a breakthrough occurred and fibre losses were reduced to 20 dB/km in the wavelength region ~1  $\mu$ m [6]. Such advancements lead to widespread research in optical communications systems. In 1980, the first commercial optical network became available operating at a bit rate of 45 Mb/s with repeater spacings of up to 10 km [1]. This was the First Generation optical network and is depicted by a black square in Figure 1.2. The archi-

tecture and functionality of optical networks evolved accordingly to accommodate the traffic growth requirement up until 1985. For the subsequent five years the BL product remained reasonably constant as demonstrated in Figure 1.2.



Figure 1.2: Increase in the BL from 1975 through to 2000 spanning several generations of lightwave systems. Different symbols are used for successive generations [4].

In 1990, commercially available optical fibre amplifiers led to increased transmission distances which were previously limited by the requirement to use electrical regeneration at repeater spacings of 70-80 km [1]. In 1992, along with the advent of Wavelength Division Multiplexing (WDM) technology, it is evident from Figure 1.2 that the Fourth Generation of lightwave systems, illustrated by a green diamond, revolutionised optical communications and resulted in a doubling of system capacity every ~6 months [1]. The timing of the Fourth Generation of lightwave systems was significant as it coincided with the commercial deployment of the internet.



Figure 1.3: Estimated internet traffic in North America between 1990 and 2008 along with forecasted internet traffic for the periods between 2008 and 2018.<sup>1</sup>

The internet traffic in North America between 1990 and 2008 estimated by the University of Minnesota [7], along with the internet traffic for the periods between 2008 and 2018 forecasted by Cisco Systems is illustrated in Figure 1.3 [8, 9]. Between 1990 and 1994, internet traffic has increased rapidly coinciding with the introduction of optical fibre amplifiers with a huge Compound Annual Growth Rate (CAGR) of ~270%. This rapid growth continued in 1994 with the large-scale deployment of WDM technology coinciding with the release of Microsoft's Windows 95 producing a demand from the end user for internet access causing a steep in-

<sup>&</sup>lt;sup>1</sup>The University of Minnesota (MINTS) provide a high and low estimate for the internet traffic growth between 1990 and 2008. In Figure 1.3, the median of these two estimates is calculated and plotted.

crease in internet traffic from 1994 until 1996, as can be seen in Figure 1.3 [1]. The internet traffic continued to double every year from 1996 to 2003 [1]. The combination of both technologies saw a CAGR in internet traffic of ~130% from 1990 to 2003. From Figure 1.3, it is evident that the growth of the internet traffic has begun to slow in North America with a CAGR of ~32% from 2003 until 2018. Despite the apparent slow down in the growth of internet traffic in North America, annual global internet traffic has increased fivefold in the past 5 years and it will increase threefold over the next 5 years expecting to reach over a zettabyte ( $10^{21}$  bytes) by the end of 2016 [10]. The forecasted growth poses many significant technological challenges for the telecommunications industry, thus research and development of optical solutions in order to solve such challenges are extremely important.

#### 1.2 Wavelength Division Multiplexing

WDM is one of the main reasons as to why optical networks experienced rapid growth in the early 1990s in tandem with the widespread commercial deployment of the internet, as discussed in Section 1.1. WDM is a multiplexing technique currently employed in the core and metro networks in order to increase system capacity. WDM provides a technique for the efficient utilisation of the large available bandwidth of optical fibre by splitting the total available bandwidth of the fibre into a defined set of independent channels. The available bandwidth is largely dependent on the wavelength regions which experience low losses in fibre [11]. As can be seen from Figure 1.4, the region with the lowest losses is ~1530-1612 nm [1]. These cover the C- and L-bands as shown in Table 1.1 and is where WDM operates. As Erbium Doped Fibre Amplifiers (EDFAs) are the most commonly used amplifiers in optical communications, they are a critical component of WDM systems. EDFAs provide a way to amplify all wavelengths in the WDM system regardless of
their individual bit rate, modulation scheme, or power level. The advent of EDFAs enabled long-haul transmission of a large quantity of channels ensuring sufficient power for each channel in WDM systems [11]. As the EDFAs operate in the C- and L-bands this gives rise to another constraint to the wavelengths within which WDM must operate.



Figure 1.4: Loss in optical fibre [12].

WDM is conceptually similar to Frequency Division Multiplexing (FDM) in radio communications in that WDM divides the optical spectrum into a certain number of channels allowing each optical carrier to be modulated independently [13]. The individual channels are then multiplexed, transmitted over fibre and subsequently demultiplexed back to the individual channels for distribution to the intended destination. The demultiplexing is carried out using an Arrayed Waveguide Grating (AWG) which uses precise phase shifts and free space propagation to direct each WDM channel to an individual fibre and vice versa for multiplexing. A typical WDM configuration is shown in Figure 1.5.



Figure 1.5: Typical WDM system configuration.

The frequency separation between two adjacent WDM optical carriers is known as the channel spacing. To avoid crosstalk and maintain the integrity of the signal for subsequent retrieval at the receiver it is important to choose the channel spacing carefully. The ultimate capacity of WDM systems is dependant on how closely the channels can be placed together without jeopardising the integrity of the received signal. Channel spacings of 100 GHz or 50 GHz are typically used in current core and metro networks as specified by the International Telecommunication Union (ITU). WDM with these channel spacings are known as Dense Wavelength Division Multiplexing (DWDM) systems and operate in the C- and L-bands [14]. For such channel spacings, each individual optical carrier can be used to transmit data rates of up to 40 Gb/s using On-Off Keying (OOK) or Differential Phase Shift Keying (DPSK) modulation formats for direct detection, discussed in greater detail in Section 2.5.1 [1]. Standardisations have already been published in ITU G.694.1 for the use of grid spacings as low as 25 GHz and 12.5 GHz as the use of advanced modulation formats improve spectral efficiencies (Bit Rate/Channel Spacing measured in b/s/Hz [1]) [15]. These systems are known as Ultra Dense Wavelength Division Multiplexing (UDWDM). The decrease in grid spacing also enables the realisation of WDM systems for access networks which demands the capability to reach a higher number of users i.e. smaller grid spacing within the usable bandwidth [16].

Band	Name	Range (nm)	
0	Original	1260-1360	
Е	Extended	1350-1460	
S	Short Wavelength	1460-1530	
С	Conventional	1530-1565	
L	Long Wavelength	1565-1625	
U	Ultra Wavelength	1625-1675	

Table 1.1: Spectral-band classification scheme.

It is clear that WDM has played a major role in the advancement of optical communications. WDM will be extremely important to service the growing bandwidth demand of future network topologies.

## **1.3** Network Topology

The optical network topology consists of a number of interconnected sub-networks; the core, metro and access networks, illustrated in Figure 1.6. Each architecture is designed to perform specific functions within the network. The core and metro networks are considered the backbone of the topology. However, both the core and metro networks along with the access networks must become more reconfigurable and adaptable. Internet traffic growth will continue to soar, putting increasing pressure on the networks for greater bandwidth, as demonstrated in Figure 1.3. The requirement for greater bandwidth is driven by on-demand services such as Video on Demand (VOD), online gaming and internet teleconferencing and the next generation optical networks must be reconfigurable in order to adapt to increasing internet traffic growth and to cater for such on-demand services [17]. The



three layers of the optical network topology are discussed below.

Figure 1.6: Network topology consisting of the core, metro and access networks.

### 1.3.1 Core Networks

The core network connects to the long haul networks to extend the global connectivity between nations [18]. The core network also consists of many nodes, typically at major cities, interconnecting regional networks by an amplified fibre link, shown in Figure 1.7 [19]. The core network transports amalgamated user data from one node to another over hundreds and thousands of kilometres. The nodes pass the data from the core network to the metro network and vice versa by using either electrical or optical switching. Core networks employ Point-to-Point (P2P) WDM between nodes, a typical P2P WDM configuration is shown in Figure 1.5.

Early core networks, circa 1996, had a capacity of 40 Gb/s comprising of WDM systems with 16 channels at 2.5 Gb/s each or 4 channels at 10 Gb/s each [20]. By 1998, this capacity was increased to 160 Gb/s with 10 Gb/s on 16 channels [1]. Since then the number of channels and the bit rate per channel has increased, but the essential



Figure 1.7: Core network model based on the United States.

architecture has remained the same. The main limitation of these legacy core networks is the Optical Electrical Optical (O-E-O) switching technique used. With this technique all data passing through the node is converted into an electrical signal, switched by an electrical switching module and subsequently regenerated in the optical domain [20]. This approach limits the optical fibre core networks to utilise the bandwidth compatible with the electronics required for the O-E-O conversion. Along with the limitations on the bandwidth, the regeneration and amplification during the process is costly. Such networks are termed "opaque" networks as they require O-E-O conversion and neither the bit rate nor the modulation format can be changed without changing the electronic switching equipment [11]. Upgrade and maintenance of such static networks is expensive and time consuming. Legacy networks exclusively use EDFA amplification and have an optical reach of ~500 km [17].

Recently deployed core networks represent a major departure from the legacy architecture and utilise all-optical networking where the switching at each node is carried out in the optical domain. A significant step towards all optical routing was the development of the Optical Add/Drop Multiplexer (OADM) making optical bypass switches possible. Optical bypass switches allow traffic at a particular node destined for a different node to be passed through without undergoing the O-E-O conversion. Optical bypassing is a result of these all-optical switching nodes and the technological advances which allow for greater optical reach. The optical reach is defined as the distance the optical signal can travel before it degrades to a level which requires regeneration. The optical reach of recently deployed core networks is in the order of 1500-4000 km [17]. This has been made possible through the use of Raman amplification (allowing for the C-band and L-bands to be used), advanced modulation formats, Dispersion Compensating Fibre (DCF) and Forward Error Correction (FEC). All-optical networks are known as "transparent" optical networks as O-E-O conversion is not required and not limited to the bandwidth of the electronic equipment used. These factors may help mitigate the cost of installing, upgrading and maintaining the network.

Current core networks being deployed can operate at 40 Gb/s per channel over 80 channels, resulting in an aggregate bit rate of 3.2 Tb/s per fibre [1]. Future networks will work towards employing 100 Gb/s and have already been provisioned for by the IEEE standard 802.3ba.

### 1.3.2 Metropolitan Area Networks

Metropolitan (metro) Area Networks (MANs) networks connect several Central Offices (COs) within a metropolitan area and provide the optical link between the core and access networks. Like the core networks, metro networks must evolve to support the increasing growth in internet traffic stemming from the ever-increasing demand for online video services. Legacy metro networks typically employed

WDM with a bit rate of 2.5 Gb/s on each channel and a grid spacing of 200 GHz. These networks were primarily deployed to enable high speed Synchronous Optical Networking (SONET) and Synchronous Digital Hierarchy (SDH) services. As with the core networks, the metro networks also benefited from transparent optical networking and the alleviation of the requirement of the O-E-O conversion. Nowadays, the metro networks have evolved to support higher bit rates and are capable of supporting a large range of technologies such as DWDM, Asynchronous Transfer Mode (ATM), and Ethernet, all of which can be operating using different modulation formats and different bit rates [11]. The introduction of advanced modulation formats and Reconfigurable Optical Add/Drop Multiplexers (ROADMs) into the metro networks allow for higher spectral efficiencies and the potential for future deployment of 40 and 100 Gb/s channels with grid spacings of 50 GHz and less, thus facilitating integration with current core network standards [21].

### 1.3.3 Access Networks

Access networks are considered the "first/last" mile of the optical network connecting the end user to the first node on the metro network, typically a distance of up to 20 km. Currently, there are very few optical access networks. The main impediment associated with deploying all optical access networks is the Capital Expenditure (CAPEX) involved. Current architecture consists of copper wire connecting each individual customer directly to the network. Therefore, the cost of migrating to an all optical network solution would be very high.

Current service providers have managed the growing internet traffic demand by employing more spectrally efficient modulation formats and in turn, increasing the bit rates on the existing copper cables. Future access networks will be required to evolve and move towards an all optical solution like the core and metro networks. As access networks are of particular interest to the work in this thesis, they will be discussed in more detail in the following section, Section 1.4.

## 1.4 Optical Access Networks

Unlike the core and metro networks, where the BL makes it feasible to employ expensive optical techniques, it is imperative that access networks be extremely cost effective due to their high market volume. Emerging technologies must not only demonstrate the benefits of increased spectral efficiency and higher data rates but also their cost effectiveness. While the CAPEX expenditure of deploying fibre may be costly, it can be offset by the cheaper Operating Expenditure (OPEX) compared to other technologies [14].



Percentage of Fibre Connections in Total Broadband Subscriptions (%)

Figure 1.8: Broadband connections as a percentage of total broadband subscriptions, OECD, January, 2013 [22].\*<sup>2</sup>

In recent years, Fibre to the Home (FTTH) has experienced large growth. The total number of FTTH subscribers increased by 29% in 2013, a substantial increase from 2012 where the growth was ~15% [24]. According to the analyst firm Heavy Reading, a country only reaches "fibre maturity" when 20% of households are FTTH subscribers. This is reinforced by Figure 1.8 showing the percentage of fibre broadband connections as a percentage of total broadband connections for Organisation for Economic Cooperation and Development (OECD) countries and the USA as of January 2013 [22] where only a small number of countries have reached fibre maturity.

### 1.4.1 Current State of Access Networks - Legacy Networks

Currently, Plain Old Telephone Service (POTS) is the most common broadband communication connection service to the end user in place. POTS technologies use a pair of twisted copper wires originally designed for transmission of 4 kHz voice data. Through the use of the latest Digital Subscriber Loop (DSL) technology, the telephone wire can carry very high bit rates and supply the end user with broadband services [25]. The telephone and broadband services are initially assigned a specific frequency sub-band from the bandwidth available and subsequently separated by filtering at the subscriber end. Upstream data is transmitted through the telephone wire to a Digital Subscriber Line Access Multiplexer (DSLAM) which is located at the CO. The DSLAM multiplexes multiple lower data rate signals from the end users into one higher speed data signal for further transmission. DSL techniques such as Asymmetric Digital Subscriber Loop (ADSL) offer speeds of up to 8 Mb/s [26]. While newer DSL techniques, such as Veryhigh-bit-rate Digital Subscriber Loop (VDSL), can increase the data rate to above

<sup>&</sup>lt;sup>2</sup>OECD do not provide the percentage of total broadband subscriptions for the USA, this data was sourced independently from the Fibre to the Home Council Europe's website [23]

50 Mb/s, DSL is considered a declining technology as service providers move towards FTTH [26] [27].

The second most deployed broadband connection is Coaxial (coax) copper cable used for the transmission of TV signals. As analog TV requires 8 MHz of bandwidth, it would be almost impossible to transmit a TV signal over twisted pair copper cables for a worthwhile distance. For this reason, TV service providers opted to make use of coax cable due to the larger bandwidth available. Despite the larger bandwidth, transmission distances are limited and regeneration with electrical amplifiers is required every 100-200 m, increasing cost and decreasing energy efficiency.

To overcome the distance/regeneration problem, a combination of fibre and coax cables can be used to form a Hybrid Fibre-Coaxial (HFC) network [28]. In this architecture, fibre is the backbone while coax is the distribution network. Each subscriber transmits data to a remote node via a coax cable. At the remote node, the electrical signal is multiplexed into a higher data rate signal, converted to the optical domain and transmitted to the CO. This system alleviates the need for electrical regeneration by placing the remote node as close as possible to the end-user. There are many forms of network configurations for HFC systems; Fibre to the Node (FTTN) brings the fibre to a remote node within 1.5 km of the subscriber, Fibre to the Curb (FTTC) which runs the fibre to a cabinet within 150 m of the subscriber which may be located at the top of a street to service many buildings or Fibre to the Block (FTTB) which brings the fibre to a large commercial premise or Multi Dwelling Unit (MDU), FTTH brings the fibre directly to the subscriber's household. As there are many acronyms describing various configurations of HFC, Fibre to the x (FTTx) can be used as an all encompassing acronym to describe the technologies collectively. Using current HFC access networks, 100 Mb/s downstream per subscriber is possible [29].

Currently, it is commercially advantageous to make use of legacy networks such as POTS, coax and HFC to satisfy current network requirements. As more advanced technologies, such as higher order modulation formats, are required to satisfy the continued internet traffic growth, the financial incentives of utilising legacy networks will diminish. Corning Incorporated forecast that the deployment of Passive Optical Networks (PONs) becomes more financially attractive than the alternatives as time progresses due to a reduction in the OPEX, this forecast is shown in Figure 1.9 [30]. The subsequent sections will discuss PONs and the role they play in continuing the evolution of access networks.



Figure 1.9: PON, HFC and VDSL economic comparison based on net income [30].

### **1.4.2** Passive Optical Networks

FTTH networks can be configured as P2P systems or PONs. P2P have the advantage of supplying each subscriber with a dedicated fibre and therefore providing unrivalled security and bandwith. However, P2P systems require active electronics in the field. In contrast, as early as the 1980s, the potential of PONs for future optical networks was recognised due to the simplicity of splitting and combining optical signals using passive optical splitters located at remote nodes [31]. The active components are located at the CO and at the Optical Network Unit (ONU). This reduces both the CAPEX and the OPEX in comparison to a P2P system [31] and indeed other access network architectures. As a result, PONs are considered the future of next generation network architectures [32].

In a typical PON configuration, a single feeder fibre is used to connect the CO to the remote node. At the remote node, an Optical Line Terminal (OLT) manages the transmission with multiple drop fibres running to each subscriber. The end user's requested downstream data is received by an ONU which converts the optical signal into the electrical domain. The ONU can also transmit the upstream data back to the OLT at the CO. A single ONU can serve as a point of access for one (FTTH) or multiple (FTTB or FTTC) subscribers. The ONU can be located either at the customer's premises (FTTH or FTTB) or a cabinet on the street for multiples premises (FTTC). In the following sections, a number of candidate PON technologies will be discussed [33].

### 1.4.3 Time Division Multiplexing Access Networks

A typical Time Division Multiple Access (TDMA) PON architecture consists of a single transmission channel where each subscriber is allocated a time slot in which they can access the full bandwidth of the optical link for the duration of their allotted time slot as shown in Figure 1.10. A passive optical splitter is used to couple and transmit the subscriber's upstream data back into the feeder fibre and back to the OLT. This is a difficult task as the OLT requires precise time-delay information from a probe signal [34]. Another major challenge of employing TDMA PONs is that packets of data can arrive at any given time from various subscribers located at different lengths from the OLT. This requires precise clock synchronisation

and receiver gain equalisation for each individual packet received from the ONU. Therefore, a Burst Mode Receiver (BMRx) must be used. As the time delay and optical losses of each ONU varies, the burst-mode receiver needs to quickly adjust the clock synchronisation and receiver gain for each data packet from the different subscribers [35]. Thus, increasing the level of complexity of the PON system while also increasing the expenditure.



Figure 1.10: Typical TDM PON system configuration.

For the downstream direction, transmission is much simpler. Burst-mode transmitters/receivers are not required as the OLT transmits at constant data rate and signal strength. One main advantage of TDMA PON is the ability to allow subscribers to utilise bandwidth which other subscribers are not using, known as Dynamic Bandwidth Allocation (DBA). For the downstream direction, transmission is much simpler. The ONUs simply select their destined packets and discard the packets belonging to the other subscriber based on their predetermined time slot. TDMA is currently used in PON standards Ethernet Passive Optical Network (EPON) IEEE 802.3ah and Gigabit Passive Optical Network (GPON) ITU-T G.984 [36] [37].

### 1.4.4 Wavelength Division Multiplexing Access Networks

In a Wavelength Division Multiple Access (WDMA) scheme, each subscriber is allocated a particular wavelength. This means that each subscriber can use their wavelength for upstream/downstream data independent of other subscribers, this is in contrast to TDMA. To do this, an AWG is used as a passive wavelength Multiplexer (mux) to couple each individual wavelength. An AWG Demultiplexer (demux), located at the CO, separates the multi-wavelength signals to be distributed to the ONUs. A basic WDMA PON is illustrated in Figure 1.11. Utilising the AWG is more efficient than using a power splitter as in the TDMA scheme [34]. Also there is no need for burst mode receivers/transmitters or to manage the timing of the transmissions. This makes WDMA a less complex system, however it is not without its technical challenges. Despite these advantages, WDM requires independent laser sources at the OLT for each individual subscriber. The wavelengths of the laser sources must match the optical passband of the mux/demux. This is added cost, and the implementation of cost effective WDM is difficult.



Figure 1.11: Basic WDM PON system configuration.

WDM systems are popular with network operators because they allow them to

expand the network without laying additional fibre or increasing the complexity of the system. Capacity of the network can be upgraded by simply upgrading the multiplexers and demultiplexers at each end. Furthermore, as WDM is the primary technology for the core and metro networks, its adoption in access networks would facilitate simpler integration with the higher layer systems. This ability to accommodate several generations of technology development without the need to overhaul the backbone network has led to WDM becoming the primary network layer for current and future access networks.

### 1.4.5 Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) PON transmits an OFDM signal from the CO to the ONU where it is converted from the optical domain to the electrical domain. A specific portion of the signal, a single subcarrier, holds the information determining which subcarriers at a particular Radio Frequency (RF) are designated for a particular subscriber. At the ONU the data is processed accordingly. Upstream data is modulated onto an optical carrier at the ONU using the same designated RF subcarrier as the downstream data. At the remote node, the various ONU's upstream subcarriers are combined and subsequently transmitted to the OLT through a feeder fibre. A basic OFDM PON architecture is illustrated in Figure 1.12. One of the main advantages of using OFDM PON is that it offers network reconfigurability with dynamic bandwidth. Dynamic bandwidth allows a user to be allocated a number of subcarriers, depending on their subscription, to increase their specific data rate [38]. A key advantage of OFDM itself is the ability to overcome chromatic dispersion utilising the OFDM cyclic prefix. OFDM will be discussed in further detail in Section 4.2.



Figure 1.12: Basic OFDM PON system configuration.

## 1.5 Conclusion

The technological advancement of future optical communications networks is driven by the increasing internet traffic growth fuelled by on-demand and interactive internet services such as High Definition Television (HDTV), VOD and internet teleconferencing. The core network holds a relatively small volume of the market while having large throughput and therefore the deployment of costly new technologies to meet future demands is justifiable. However, the next generation of metro and access networks, in particular, must be extremely cost sensitive in their planning and deployment.

Current access networks, such as legacy copper, coax and HFC are capable of dealing with the current internet traffic demand but are not future proof. FTTH has been presented as a potential solution to the inevitable bottleneck problem of access networks. PON networks utilising Time Division Multiplexing (TDM) have already been deployed to satisfy the internet traffic demand. Next generation access networks are required to transmit higher downstream data rates to deal with future data heavy services, such as 4K Ultra High Definition Television (UHDTV) (a resolution of 3840 x 2160 pixels, a horizontal resolution of almost 4,000 which is approximately 4 times the resolution of Full High Definition (HD) [39]). Future access networks will also be required to remain cost effective while offering greater reconfigurability. One promising technology for use in the next generation access networks is OFDM which offers spectral efficiency and reconfigurability using low cost electronics while being able to deal with optical impairments such as dispersion. Another important trend which must be considered for future access networks is the growing wireless devices market. Next generation access networks should possess the ability to provide seamless broadband connectivity to end users for both wired and wireless devices.

This thesis explores how the integration of wired and wireless can be achieved utilising photonic generation of Millimetre Waves (mm-waves) for use in Radio-over-Fibre (RoF) systems. The thesis also works towards using the OFDM modulation format for greater data rates and reconfigurability which will be essential for the next generation of access networks.

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## **Chapter 2**

# **Radio over Fibre Systems**

This chapter discusses the future trends in wireless access networks and how the Millimetre Wave (mm-wave) spectrum can be used to provide for the increasing bandwidth required for wireless services and applications which demand high data rates. Utilising mm-waves in conjunction with Radio-over-Fibre (RoF) architectures is proposed as a solution to increase the bandwidth availability of current wireless access networks. Photonic methods of generating mm-waves are discussed before various important techniques, parameters and considerations for optical systems and RoF systems are presented.

## 2.1 Introduction

An increasingly large portion of internet traffic is delivered to, or originates from, portable and mobile devices. Therefore, access networks must work towards developing seamless connectivity between the wired and wireless devices. Currently, wired devices account for the majority of internet traffic at 56%. In comparison, by 2016, Cisco Systems forecasts that wireless and mobile devices will account for the

majority of internet traffic with 54% of all internet traffic. Between the period 2013 and 2018, it is expected that mobile data will experience the largest increase in internet traffic growth with a Compound Annual Growth Rate (CAGR) of 61% over the five year period [1]. Wireless will also see a large growth in internet traffic with 25% CAGR in the same period while fixed networks will see the least amount of growth with a 12% CAGR [1]. This demonstrates the subscriber trend towards using more portable devices. It is also important to note that the number of devices per household and per user is also expected to rise from 6.1 billion mobile devices and connections in 2013 to 8.9 billion by 2018 [2]. The need for higher speed wireless access networks increases year on year as new portable and wireless devices in various forms such as smartphones, tablet devices, smart TVs, become available with increased capabilities and intelligence.

While the trend towards portable and wireless devices in the access networks increases, it is important to examine the range of services being used by the subscribers. Overall, internet video dominates internet traffic with a forecasted 60.04% of all internet traffic originating from internet video (including video-conferencing) and will continue to grow to account for 75.6% of all internet traffic [3]. Analysing this further shows that by 2018, 1.912 billion of the expected 2.5 billion residential users will use online video services [3]. Figure 2.1 demonstrates that online video is the fastest growing service in the near future. The increased internet traffic for online video puts strain on the current wireless access networks as the bit rate for increasingly popular 4K TV or Ultra High Definition Television (UHDTV) is 18 Mb/s when compressed [4].

The move towards using more portable and wireless devices coupled with increased data rates required for the higher quality video signals, as 4K is expected to become a prominent technology, makes it important to analyse the current wireless access networks capabilities. Researching how the future access networks



Figure 2.1: Forecast residential services adoption for 2018. The number of millions of subscribers is denoted in parenthesis.

can provide high speed seamless connectivity between the wired and wireless networks is also of great importance.

## 2.2 Wireless Access Networks

The first cellular mobile services were initially intended for simple voice transmission with the main difference between the two generations being that First Generation (1G) used analogue signals while Second Generation (2G) used digital signals. Global Standard for Mobile (GSM) is the most popular digital cellular network standard and is allocated the frequency bands around 900 MHz and 1800 MHz. Initially the GSM standard catered for 13 kb/s for voice transmission and 9.6 kb/s for data transmission [5]. This was evolved to use General Packet Radio Service (GPRS) offering data transmission speeds of up to 160 kb/s [6]. The Third Generation (3G) of wireless cellular phone communications is known as Universal Mobile Telecommunication System (UMTS). UMTS allows for voice transmission and for applications to send text messages, multimedia and browse the internet and can be considered more data-centric [7] [8]. The third generation of wireless mobile services originally used Wideband Code Division Multiple Access (WCDMA) to boost the data rate up to 2 Mb/s [7]. High-Speed Downlink Packet Access (HSDPA) specification, released by the Third Generation Partnership Product (3GPP), increases the data-rate further to 8-10 Mb/s [7]. The Fourth Generation (4G) offers higher data rates and more mobility with technologies such as Long Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMax). According to the International Mobile Telecommunications-Advanced (IMT-ad) standard speeds will reach a target peak download speed of 100 Mb/s for high mobility communications in a moving vehicle and provide a peak download speed 1 Gb/s for static/low mobility communications (pedestrians and stationary users) [9] [7].

Historically, the first popular standards IEEE 802.11a and 802.11b were the early types of Wireless Local Access Network (WLAN) technologies. These first two generations of wireless access networks were designed primarily for use with a home/office laptop PC and later to allow connectivity in hotels, airports, internet cafes and shopping malls [10]. The main use of the IEEE 802.11a and 802.11b standards was to provide a complement to wired broadband to enable wireless access to web browsing and email. IEEE 802.11b allowed for speeds from 2 to 11 Mb/s comparable to the speeds or earlier Local Area Network (LAN) of 10 Mb/s [2] [10] [7]. 802.11a provided peak download rates of 54 Mb/s with 802.11g in 2003 maintaining the same data rate but consolidating the use to the 2.4 GHz band [7] [2] [10]. The

802.11n amended standard was introduced in 2009 and allowed for data speeds of up to 600 Mb/s [7] [10]. The latest standard IEEE 802.11ac, the fifth generation of Wi-Fi ratified in January 2014, with theoretical speeds of 3.47 Gbps can be considered one of the first true wired complements [11].

A third type of wireless access networks is the Wireless Personal Access Network (WPAN). The WPAN provides short range wireless connectivity and stretches from centimetres to tens of metres. The IEEE standard 802.15.1 for Bluetooth was the first low data rate standard for WPAN networks enabling connectivity between mobiles phones, computers and electronic devices at data rates of up to 3 Mb/s. The IEEE standard 802.15.4 for ZigBee wireless technology allows for data rates of up to 250 kb/s and is used primarily for wireless sensor applications such as wireless light switches and electrical meters with displays [12]. These applications usually require low data rate, low power consumption and low cost wireless networking. Ultrawideband (UWB) wireless technology is designated to the frequency band 3.1 - 10.6 GHz and is required to have low power consumption [13]. UWB is designed for short range wireless communications for fast video and audio data transport.

As discussed in Section 2.1, more and more end users are moving towards portable and mobile devices, and they are using them to stream video content online. The quality of this video content is constantly increasing with the trend towards 4K content and this will inevitably increase to 8K in the future. Therefore, it is important that these wireless access networks are future proof. One technology which is capable of providing a future proof wireless standard is mm-wave technology with a range of unlicensed bands allowing for much higher data rates than current standards. As illustrated in Table 2.1 and Figure 2.2, mm-wave technology will be able to provide for much larger data rates than the current standards.

Technology	Frequency Band	Data Rate	Signal Range	Typical Usage
GSM*	800-960/	9.6 kb/s	35 km	Voice and Data
	1700-1900 MHz			
GPRS*	800-960/	160 kb/s	35 km	Data and WAP
	1700-2500 MHz			
UMTS*	800-960/	10 Mb/s	2 km	Voice, Data and
	1700-2500 MHz			Multimedia
LTE*	700-850/	150 Mb/s	100 km	Voice, Data and
	1700-2600 MHz			Multimedia
802.11b	2.4 GHz	11 Mb/s	100 m	WLAN
802.11a	5 GHz	54 Mb/s	100 m	WLAN
802.11g	2.4 GHz	54 Mb/s	100 m	WLAN
802.11n	2.4/ 5 GHz	600 Mb/s	100 m	WLAN
802.11ac	5 GHz	3.6 Gb/s	100 m	WLAN
Zigbee	2.4 GHz	250 kb/s	10 m	WPAN
Bluetooth	2.4 GHz	2.1 Mb/s	10 m	WPAN
UWB	3.1 - 10.6 GHz	>100 Mb/s	10 m	WPAN
mm-Wave*	57-64 GHz	>7 Gb/s	50 m	WPAN/WLAN
(60 GHz)				

Table 2.1: Wireless access network technologies [2] [10] [14] [13] [15].<sup>1</sup>

#### 2.2.1 Millimetre-Waves in the Wireless Access Network

Due to the scarcity of available bandwidth at the lower frequencies, mm-waves have attracted a large amount of attention. Mm-waves refer to the frequency range between 30 and 300 GHz, corresponding to wavelengths of between 10 and 1 mm respectively. In particular, the 60 GHz band has garnered most of the attention due to the unlicensed bandwidth around 60 GHz with at least 5 GHz of continuous bandwidth available in most countries. The available bands in their respective regions are illustrated in Figure 2.3. While the 60 GHz band can be compared to the unlicensed bandwidth allocated for UWB (3.1 - 10.6 GHz), the 60 GHz band has less restrictions with regards to emitted power. In most countries, the max-

<sup>&</sup>lt;sup>1</sup>Many of the mobile technologies cover a range of different frequency bands depending on the service providers and the regional standards. The bands displayed in Table 2.1 are the designated technology frequency bands for North America where indicated by \*. All other bands can be considered to be the worldwide designated frequency.



Figure 2.2: Wireless access network technologies.

imum transmitted power allowable for 60 GHz is 10 dBm with North America allowing 27 dBm and Europe allowing 13 dBm [9] [16] [17]. The large amount of available bandwidth around 60 GHz makes multi-Gb/s wireless communication feasible without necessarily requiring complex signal modulation with high spectral efficiency that may increase system costs [18]. This will enable the 60 GHz band to deal with many applications along with the emerging trends discussed in Section 2.1 such as [19] [10] [20]:

- Online video streaming and video conferencing using wireless and portable devices utilising better resolution video standards such as Full High Definition (HD) and 4K which require high data rates. The multi-Gb/s transmission rates possible will also help alleviate the need for video compression techniques.
- Wireless docking stations allowing multiple peripheral devices, such as ex-

ternal monitors or projectors in a conference room, to be wirelessly connected.

- Wireless gaming ensuring a high quality gaming experience free from buffering/lag.
- Ultra fast "sync and go" file transfers between devices allowing for the transfer/syncing of large data in seconds e.g transfer of movie content to a mobile device.
- High speed wireless networking for offices.

However, mm-wave signals experience high attenuation due to the atmospheric oxygen, particularly around 60 GHz (12 - 16 dB/km [21]), making it unsuitable for long range transmission (>2 km) [22] [19]. The attenuation due to atmospheric oxygen in the 60 GHz band is considerably greater than at 2.5 GHz and 5 GHz [23]. In addition, free space losses increase quadratically with frequency [19]. This means the 60 GHz band can be used exclusively for short-range communications (<1 km) [19]. When used indoors for small distances of wireless communications (<50 m) the attenuation due to the atmospheric oxygen can be overcome [19]. The 60 GHz band also demonstrates greater wall transmission losses in comparison to lower frequencies [19]. While at first the higher emitted power required to overcome the higher path losses in comparison to lower frequencies may seem a disadvantage, it results in the mm-wave being confined to operate within the boundaries of one room in an indoor environment providing security and increasing the potential for frequency resuse [10] [19].

The US Federal Communications Commission (FCC) first proposed to establish an unlicensed band at 59 - 64 GHz in 1994 and since then radio regulatory organisations across the globe have been legislating frequency allocations and modulation paramaters in similar 60 GHz bands in their respective jurisdictions [10]. North

America, Europe, Japan, South Korea and China among other countries have all approved an unlicensed spectrum allocation in the 60 GHz region. The spectrum allocation is summarised in Figure 2.3.



Figure 2.3: Worldwide 60 GHz band allocation.<sup>2</sup>

## 2.3 Radio over Fibre Systems

While Fibre to the x (FTTx) provides suitable bandwidth to the home/premises, it is when used in conjunction with RoF technology that the full potential of seamless convergence between the wired and wireless access networks can be realised. RoF shows great promise of supporting a plethora of current and future broadband services and applications on the same infrastructure. RoF is the most promising solution to increase bandwidth, coverage and mobility allowing for seamless integration of the optical access network and the transmitting antenna [17]. In this

<sup>&</sup>lt;sup>2</sup>The available band for Europe excludes Austria which operates from 59.4 to 62.9 GHz [24] [17] [25] [16].

section, the general RoF architectures will be discussed and photonic techniques used to generate mm-waves will be presented.

### 2.3.1 Radio over Fibre Architectures

RoF provides for the centralisation of the data modulation and system control process in a shared location, the Central Office (CO) or Central Station (CS). Optical fibres can then be used to distribute the Radio Frequency (RF) signals to the Remote Antenna Unit (RAU). This allows for the simplification of the RAU as only optoelectronic conversion, filtering and amplification may be required. Installation of the expensive components required for the data modulation and system control process in a shared location, the CS, can aid reduction in both Capital Expenditures (CAPEXs) and Operating Expenditures (OPEXs), in particular for distribution of broadband wireless signals where a large number of RAUs are necessary. A typical RoF distribution system from the core/metro network through fibre to the end-user is demonstrated in Figure 2.4.



Figure 2.4: Illustration of a typical RoF distribution network.

RoF systems can also be used to implement a fibre Distributed Antenna System (DAS). DAS is considered as a large mass market for extending the capacity and range of radio signals in a variety of locations such as offices, stadiums, airports and hospitals [26]. A DAS uses a large number of remote sites within a heavily populated building, known as pico cells. Each pico cell is connected to the CS through the fibre infrastructure and is capable of distributing the wireless RF signal throughout the building [27]. A DAS RoF architecture is shown in Figure 2.5. This offers a cost effective solution to wireless distribution of mm-wave RF signals as the up-conversion to the desired mm-wave can be carried out at the CS before transmission through the fibre network and subsequent wireless distribution to the end user.



Figure 2.5: Illustration of a typical DAS RoF architecture.

In a RoF system, the CS initially performs the Electro-Optic (E/O) conversion of a

RF signal and frequency up-conversion to the desired RF frequency. This E/O conversion and frequency up-conversion can be executed using a number of various techniques, which will be discussed in Section 2.4. The modulated optical signal with the required data is subsequently transmitted over fibre to the RAU. In the RAU, the Optic-Electro (O/E) conversion is carried out through photodetection. The generated electrical mm-wave is then wirelessly distributed to the user where the data can be extracted. For the uplink, the RAU down converts the mm-wave to a lower frequency band in order to avoid requiring a high frequency modulator in each RAU and optical receiver in the CS. The down-converted uplink signal can be used to modulate an optical carrier from a Continuous Wave (CW) laser using an Electro-Optic Modulator (EOM) preceding transmission to the CS. At the CS, only a low cost optical receiver is required to recover the uplink signal as the uplink signal is already in a low frequency band. Figure 2.6 is used to illustrate the basic RoF full-duplex configuration.



Figure 2.6: Outline of a simplified full-duplex RoF configuration.

### 2.3.1.1 Bi-Directional Radio Over Fibre Scheme

The bi-directional RoF scheme can be considered one of the most straight forward RoF architectures. In both the downlink and uplinks, the laser source is directly modulated with an RF signal. The RF signal is then transmitted to a photodiode through an optical fibre link. The photodiode used to carry out the O/E conversion is typically a PIN photodiode. Normally, two Single Mode Fibres (SMFs) are used in this configuration, one for the downlink and one for the uplink. Multi-Mode Fibre (MMF) can be used to transmit the downlink and uplink at different wavelengths along the same fibre. Wavelength Division Multiplexing (WDM) can also be used to transmit the downlink and uplink signals at different wavelengths using the same optical fibre link.

Two of the main components in the RoF system are the optical source and the electro-optic modulation technique used. In the following sections, methods to generate mm-wave radiation will be discussed and modulation techniques and formats will be presented along with other considerations for RoF systems.

### 2.4 **Optical Generation of Millimetre-Waves**

In general, the photonic generation of mm-waves is based on the optical heterodyning technique. The mm-wave is generated through the beating of two phase correlated optical tones with a frequency offset equal to the desired mm-wave frequency on a high-speed photodetector to generate a single beat component at the mm-wave frequency. Consider two optical fields [28],:

$$E_1 = E_{01}\cos(\omega_1 t + \phi_1) \tag{2.1}$$

$$E_2 = E_{02}\cos(\omega_2 t + \phi_2)$$
 (2.2)

where,  $E_{01}$ ,  $E_{02}$  are the amplitude terms,  $\phi_{01}$ ,  $\phi_{02}$  and  $\omega_{01}$ ,  $\omega_{02}$  represent the instantaneous phase terms and the angular frequency terms of the individual optical waves, respectively. When the two optical fields beat together on the surface of a photodetector with a limited bandwidth, a photocurrent which is proportional to the square of the sum of the two fields is generated at the output of the photodetector:

$$I_{PD} = A\cos\left[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)\right] + higher \ frequency \ terms \tag{2.3}$$

where, A is a constant dependent on the amplitudes  $E_{01}$ ,  $E_{02}$  and the responsivity of the photodetector. Only the first term is of interest as the higher order terms are higher frequency components which are negligible due to the limited bandwidth of the detector. Equation 2.3 demonstrates that an RF signal of any frequency can be generated by the frequency difference between two optical fields, limited only by the bandwidth of the photodetector.

One of the major considerations for this technique is the purity of the generated RF signal. It is important that the generated RF signal possesses low phase noise. To generate a stable low phase noise mm-wave, several techniques can be used and will be discussed in the following section.
#### 2.4.1 Optical Heterodyning of Two Lasers

The simplest method of generating mm-waves is to use two independent lasers with a frequency separation between the two lasers equal to that of the desired mm-wave frequency. These two lasers can then be optically heterodyned on a photodetector to generate the RF mm-wave. Figure 2.7 demonstrates how two independent laser sources can be used to generate an RF mm-wave.



Figure 2.7: Generation of mm-waves using two free lasers.

As the lasers are independent of each other, the generated optical tones will not be correlated and the phases will be different resulting in an RF signal with high phase noise. To generate an RF signal with low phase noise, the phases of the two lasers must be correlated or locked and the phase noise removed. This is typically carried out using the following methods:

- Optical Phase Lock Loop (OPLL)
- Optical Injection Locking (OIL)

- Optical Injection Phase Locking (OIPL)
- Intensity Modulation with Direct Detection (IM/DD)

#### 2.4.1.1 Optical Phase Lock Loop

The mm-wave is generated through the beating of the two free laser sources on the photodetector. The resulting RF signal is amplified and mixed with a reference signal from a Local Oscillator (LO) by an RF mixer. The resulting phase error between the LO and the RF signal can be used to tune the frequency of one of the lasers, the slave laser, in order to force it to track the master laser with a frequency offset equal to the desired RF frequency. The OPLL will help achieve coherence between the laser sources but still requires two lasers with narrow linewidths limiting the phase fluctuations to low frequencies. Implementation of a OPLL is displayed in Figure 2.8.



Figure 2.8: Generation of mm-waves using two lasers and an OPLL.

#### 2.4.1.2 Optical Injection Locking

OIL can also be used to correlate two free running lasers to produce a high quality RF signal [29]. A master laser is directly modulated with an RF reference signal. This will generate an optical carrier with sidebands with equal frequency separation to that of the RF signal. The output of this master laser is then injected into the two slave lasers. To achieve injection locking the wavelengths of the two slave lasers must be chosen to ensure that they are close to the  $\pm 2^{nd}$  order sidebands. Using this technique correlates the phase of the two lasers and allows for the generation of a mm-wave with low phase noise. The OIL technique is shown in Figure 2.9.



Figure 2.9: Generation of mm-waves using two lasers and OIL.

#### 2.4.1.3 Optical Injection Phase Locking

Signal quality can be further enhanced by using a combination of both OPLL and OIL [30]. As with the OPLL technique, the master laser is directly modulated with an RF reference signal producing an optical carrier with sidebands. The output from the master laser is then split with one channel being injected into a slave laser. The slave laser's wavelength is tuned as before in the OIL technique, to match that

of one of the sidebands of the master laser. In this case, the slave laser is tuned in order that the frequency separation between the optical carrier and the slave laser is equal to the desired mm-wave signal frequency. The other channel contains the master laser alone and is combined with the output of the slave laser and beat on the photodetector. At this point the OPLL is implemented and the RF output is mixed with the original LO reference signal and the slave laser is tuned to track the desired wavelength. The OIPL is illustrated in Figure 2.10.



Figure 2.10: Generation of mm-waves using two lasers, OPLL and OIL.

#### 2.4.1.4 Intensity-Modulated Direct Detection

One of the simplest methods to generate mm-waves is to modulate the intensity of a laser with a mm-wave RF signal followed by direct detection on a photodetector after fibre transmission [31]. The intensity of the laser can be modulated either directly or externally as demonstrated in Figure 2.11.

When generating mm-waves it is important to use a coherent optical source whereby the two tones carry the same optical phase fluctuation in order to minimise the phase noise impact. Direct modulation simply modulates the current driving a CW laser with a RF signal at the desired mm-wave frequency. However, the use of this



Figure 2.11: (a) Direct and (b) External modulation of the optical intensity of a laser to create a mm-wave.

technique is usually limited by the modulation bandwidth of directly modulated laser diodes (~10 GHz).

Due to the limited modulation bandwidth for direct modulation, external modulation is typically used whereby a CW laser is modulated by an EOM at the desired mm-wave frequency. However, modulation of the lasers intensity, directly or externally, results in Double Sideband (DSB) modulation. The output optical field contains two sidebands separated by the desired mm-wave frequency either side of an optical carrier. The external modulation scheme is sensitive to RF power fading induced by fibre chromatic dispersion, limiting the frequency range and the optical transmission distance [32] [33]. A number of schemes have been shown to mitigate the chromatic dispersion effect without the use of dispersion compensation [33].

One method is to use Single Sideband (SSB) modulation to avoid the destructive interference the tones will have on each other caused by chromatic dispersion. SSB can be achieved by filtering one of the sidebands optically [34], or a Dual-Drive Mach Zehnder Modulator (DDMZM) can be used to give SSB operation [32] [33].

Two phase-correlated optical tones can be generated by using Optical Carrier Suppression (OCS) techniques by biasing a Mach-Zehnder Modulator (MZM) at the minimum transmission point [32]. This technique suppresses the optical carrier leaving the two sidebands separated by the desired frequency. The suppression of the optical carrier means that the LO RF frequency required is only half of the desired mm-wave frequency.

Another technique to suppress the optical carrier is to use a notch filter to remove the optical carrier after external modulation is carried out by a MZM as illustrated in Figure 2.12. These techniques are simple but require a large RF drive power to obtain good modulation depth as the modulator is biased in the nonlinear region.



Figure 2.12: External modulation and notch filtering.

Overall, the external modulator techniques suffer from high insertion loss, requires high driving voltages and sometimes instability requiring complex bias control circuitry such as Automatic Bias Control (ABC) or a Feedback Control (FBC) [35]. Thus, using IM/DD techniques can increase the cost and complexity of the mmwave photonic generation process [36].

#### 2.4.2 Optical Frequency Comb Generation

Mm-waves can also be generated by utilising an Optical Frequency Comb Source (OFCS). An Optical Frequency Comb (OFC) produces an optical spectrum with a number of lines spaced equally by a specific frequency, known as the Free Spectral Range (FSR). Two modes of the OFC which are separated by the desired mm-wave frequency can be filtered off, transmitted over the fibre link and subsequently beat on a photodetector to generate the electrical mm-wave. The schematic for a generic mm-wave generation setup using an OFC is illustrated in Figure 2.13. The most conventional method to generate the OFC is to use a Mode Locked Laser (MLL). Generation of an OFC can also be carried out using the gain switching technique. Both of these techniques are investigated in more detail in Section 5.1.1 and Section 3.2 respectively.



Photodetector

Figure 2.13: Filtering an OFC for generation of mm-waves.

# 2.5 Key Components, Techniques and Considerations for Optical Communications and Radio over Fibre Systems

This section presents the modulation formats used within this thesis before the main considerations for RoF systems employing optical techniques for generation and transmission are discussed.

#### 2.5.1 Modulation Formats

#### 2.5.1.1 Non-Return-to-Zero On-Off Keying

NonReturn-to-Zero (NRZ)-On-Off Keying (OOK) is one of the most widely used modulation formats in today's optical networks. NRZ-OOK is an extremely simple modulation format and can be implemented cheaply. The NRZ-OOK information is encoded in the intensity of the optical signal and recovered through direct detection at the receiver. In the simple case of transmitting a logic "1", the light intensity is at a maximum. For logic "0", there is an absence of light. This intensity modulation is illustrated in Figure 2.14. The extinction ratio between the minimum and maximum powers,  $P_0$  and  $P_1$  respectively, determines the modulation efficiency. The modulation efficiency can be expressed, in dB, as follows:

Extinction Ratio(dB) = 
$$10 \times \log \frac{P_1}{P_0}$$
 (2.4)

This format can be generated through direct modulation of the lasers current, as shown in Figure 2.14. It can also be generated by modulating a laser in CW operation with an external modulator such as a MZM biased at the quadrature point with a voltage swing of less than  $V_{\pi}$  to drive from minimum to maximum transmission. The NRZ-OOK constellation diagram of the two signals is also shown in



Figure 2.14: Modulation of a laser with OOK data.

Figure 2.15, which displays the signal as a two-dimensional scatter diagram in the complex plane at symbol sampling instants.

#### 2.5.2 Advanced Modulation Formats

Existing optical networks are mainly based on WDM IM/DD networks and operate at 10 Gb/s per channel [37] [38]. Due to the expenses involved in deploying new fibre optic links, the main focus is to upgrade the existing network. To upgrade the network, it is not feasible to simply increase the bit rate as transmission impairments such as dispersion and nonlinear effects have a greater impact at higher bit



Figure 2.15: OOK constellation.

rates. Therefore, the solution is to use more advanced modulation formats which have a higher tolerance to transmission impairments and are more spectrally efficient, in order to maximise the efficiency of each optical channel [38].

The aim of advanced modulation formats is to increase the number of bits transmitted per symbol from one, which is used in conventional IM/DD OOK systems, to the maximum number of bits per symbol allowable by the Signal-to-Noise Ratio (SNR) of the optical system. Increasing the number of bits per symbol transmitted increases the spectral efficiency for a given bit rate and reduces the baud rate which allows for the use of readily available lower cost electro-optic devices and high speed electronics [39]. The simplest method of transmitting multiple bits per symbol is to use a multilevel amplitude modulation format, known as Amplitude Shift Keying (ASK).

More advanced modulation formats modulate not only the amplitude of the optical signal but the phase also. Multiple phase shifts can be used to represent data symbols assigned by a unique pattern of bits. Modulation of the phase alone is known as Phase Shift Keying (PSK). Using a combination of amplitude and phase modulation increases the symbol modulation space allowing for a greater number of bits to be transmitted [40]. The technique of modulating both the amplitude and phase is known as Quadrature Amplitude Modulation (QAM).

For any modulation format the relationship between the number of symbols, M, and the number of bits transmitted per symbol, m, is given by:

$$m = \log_2(M) \tag{2.5}$$

#### 2.5.2.1 Quadrature Phase Shift Keying

The simplest PSK format is where the phase of the optical carrier is varied between two distinct values, typically 0 and  $\pi$  to represent logic "0" and logic "1" [41]. This format is simply known as PSK or Binary Phase Shift Keying (BPSK). However, coherent detection, through the mixing of the detected optical signal and a local oscillator, is required at the receiver to retrieve the data. The use of PSK formats requires the phase of the optical carrier to remain stable over a duration much longer than the bit duration,  $T_b = \frac{1}{B}$ , at a given bit rate, B. Therefore, the spectral linewidth of the source laser and the local oscillator is extremely important [42].

To alleviate the stringent conditions on the source laser and the local oscillator, Differential Phase Shift Keying (DPSK) can be used. In the case of DPSK, the phase of two neighbouring bits changes to signify the transition from a binary "1" to a binary "0" or vice versa. The advantage of using DPSK is that the received signal can be successfully demodulated if the carrier phase remains reasonably stable over two successive bits.

However, DPSK and BPSK alone do not improve spectral efficiency, compared to



Figure 2.16: QPSK constellation.

OOK, as they only employ two carrier phase values. To improve spectral efficiency, the number of carrier phase values employed can be doubled to four distinct values, typically chosen to be 0,  $\frac{\pi}{2}$ ,  $\pi$  and  $\frac{3\pi}{2}$ . In practice, two binary signals known as the In-phase (I) and the Quadrature (Q) signals are used independently to modulate the optical field and a version of the optical field which is out of phase by  $\frac{\pi}{2}$ , respectively. This allows for the transmission of 2 bits simultaneously. This format is called Quadrature Phase-Shift Keying (QPSK) and its constellation diagram is illustrated in Figure 2.16. As conveyed in the constellation diagram, there are four possible combinations of two bits, 00, 01, 10 and 11, which correspond to the four unique values of carrier phase.

As two bits are assigned to each carrier value, the bit rate is effectively halved. To calculate the total bit rate, B, Equation 2.5 is multiplied by the symbol rate giving:

$$B = m \times B_S \tag{2.6}$$

In the case of QPSK, which uses 4 bits, M = 4, employed at  $B_S = 10$  GBaud/s, the total bit rate will be 20 Gb/s resulting in doubling the spectral efficiency compared to an OOK or BPSK system. The spectral efficiency can be increased further by using more phase levels such as 8 PSK and 16 PSK, which decreases the separation between the constellations points and places more stringent conditions on the SNR required to successfully recover the data signal.

#### 2.5.2.2 Quadrature Amplitude Modulation

To further enhance the spectral efficiency and reduce the symbol rate, multilevel Amplitude Modulation (AM) of two carriers with two bit streams can be carried out. The carriers are out of phase by  $\frac{\pi}{2}$  radians and are said to be in quadrature. The two carriers are subsequently summed and the resultant waveform is modulated in both amplitude and phase. QAM increases the distance between constellation points by utilising multiple amplitude levels which can be used for symbol mapping. An example of this modulation format is the 16 QAM format illustrated by the constellation diagram in Figure 2.17. 16 QAM reduces the symbol rate even further than QPSK at a given rate by increasing the number of symbols to 16, M = 16. Examining Equation 2.6, it is evident that this will double the bit rate compared to QPSK, in turn increasing spectral efficiency. Despite the increase in spectral efficiency, it is important to consider how the increase in QAM constellation size will require an increase in the SNR to ensure symbols are correctly decoded at the receiver. It is also possible to further increase the constellation size to 32 QAM, 64 QAM and above, however, the same trade off between constellation size and achievable SNR must be considered.

Each symbol, or constellation point, has a unique combination of amplitude and phase. The bits assigned to each symbol, as shown in Figure 2.17, are such that



Figure 2.17: 16 QAM constellation.

the assigned bit code of adjacent symbols varies by only a single bit. The coding scheme used is known as Gray coding. If Gray code is not used a symbol incorrectly decoded can produce errors in multiple bits which will result in an increase in the system Bit-Error Rate (BER) [42].

#### 2.5.2.3 Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) is a Multi-Carrier Modulation (MCM) technique which uses many harmonically related subcarriers to transmit data. OFDM is a Frequency Division Multiplexing (FDM) technique but the key difference between the two is that in OFDM schemes the subcarrier spectra overlap but do not interfere due to their harmonic relationship known as orthogonality. This allows for an increased number of subcarriers to be transmitted within a given bandwidth allowing for greater spectral efficiency [43] [15]. A symbolic example of the individual subcarriers for an OFDM system is shown in Figure 2.18 [43]. The key characteristics of a MCM format, such as OFDM, is that a high data rate stream can be split into multiple lower data rate streams [15]. The lower data rate streams are typically modulated with QAM and transmitted in parallel. While concurrently providing high spectral efficiency, OFDM demonstrates an inherent tolerance to chromatic dispersion making it particularly attractive for optical communication systems [44]. OFDM is discussed in more detail in Section 4.2.



Figure 2.18: Symbolic illustration of the individual subcarriers of an OFDM system. Note that each subcarriers peak coincides with a zero for the other subcarriers.

#### 2.5.3 Considerations for Radio over Fibre Systems

This section discusses important aspects of RoF systems focusing on sources of noise and distortions which limit the performance of RoF systems.

#### 2.5.3.1 Fibre Dispersion

Dispersion is the overall name given to all the effects which cause light at different wavelengths to travel through fibre at varying speeds [45]. As a result, the signal

becomes broadened as shown in Figure 2.19. Signals which experience very high dispersion can cause problems at the receiver as the required information cannot be extracted properly [45].

There are three types of dispersion:

- **Modal Dispersion** is the first type of dispersion which is caused by multiple modes travelling at different speeds in MMF. It is the effect which limits the transmission distances achievable in MMF and the reason why SMF is used in Dense Wavelength Division Multiplexing (DWDM) systems [45].
- **Polarisation Mode Dispersion (PMD)** is the second type of dispersion, introduced by fibres having a core with imperfect concentricity. This results in different polarisations of the optical signal having different propagation speeds [45]. PMD effects are small and can be neglected in the transmission link.
- **Chromatic Dispersion** is the third and most important type of dispersion, also known as Group Velocity Dispersion (GVD) [45]. Chromatic dispersion is caused by the wavelength dependent refractive index of the silicon used to produce the fibre and the wavelength dependent power distribution between the core and the cladding [45]. Both components result in different parts of a channels wavelength spectrum to travel at different speeds.

The effect of chromatic dispersion is more prevalent at higher modulation frequencies and severely limits the fibre transmission distance. As discussed in Section 2.4.1.4, in conventional IM/DD RoF systems the information is generated on both sides of the optical carrier and when transmitted over fibre, chromatic dispersion causes different phase fluctuations for each sideband dependant on the wavelength, fibre length, modulation frequency and the chromatic dispersion parameter. When this optical signal arrives at the detector the two RF signals beating with the optical carrier are out of phase and results in a low RF power.

Dispersion is the main limiting factor for long distance transmission and is usually measured in ps/nm.km. It is relatively simple to overcome attenuation through the use of optical amplifiers but dispersion compensation requires more complex mechanisms. One solution is to use Dispersion Shifted Fibre (DSF) which has ~0 ps/nm.km [46] in the 1550 nm window compared with ~17 ps/nm.km [47] for SMF [45]. While zero dispersion is desirable for WDM systems, reducing chromatic dispersion gives rise to an increase in the influence of nonlinear effects, such as Four-Wave Mixing (FWM) [45]. Therefore, it is better to use SMF coupled with dispersion compensation techniques.



Figure 2.19: Dispersion forces the optical pulses to broaden.

#### 2.5.3.2 Noise Sources in Radio over Fibre Systems

The dominant source of noise in a RoF system is laser noise which is predominantly due to random spontaneous emissions [48]. Each spontaneous photon emitted will result in a small field component with a random phase to the coherent field. This results in fluctuations of both the amplitude and phase of the optical source. Relative Intensity Noise (RIN) is the name given to the unwanted intensity variation. The amount of RIN is a function of the modulation frequency and will inevitably degrade the SNR [42]. In typical semiconductor lasers operating at 1550 nm, RIN increases with the modulation frequency until it peaks at the relaxation oscillation frequency. At higher frequencies the laser can not respond to the fluctuations causing the RIN to decrease rapidly. The phase noise of the laser can be converted to intensity noise during transmission over fibre, resulting from fibre dispersion, further reducing the SNR and achievable transmission distance [49].

Laser Mode Partition Noise (LMPN) is a phenomenon which can also increase the RIN effects. Ideally, a single mode semiconductor laser oscillates in a single longitudinal mode. However, in practice, this mode is accompanied by one or more side modes. All of the modes experiences fluctuation in intensity but the total intensity remains relatively constant [50]. In the absence of fibre transmission, LMPN is negligible but when transmitted over fibre, the modes do not arrive at the receiver simultaneously due to fibre dispersion. This causes fluctuations in the amplitude of the optical signal at the receiver which may inhibit the receiver from detecting the correct data required [50]. As a result, LMPN can degrade system performance. LMPN is dependant on what is known as the Side Mode Suppression Ratio (SMSR) which defines the ratio between the peak amplitude of main optical mode and the side modes. Most Distributed Feedback (DFB) lasers exhibit one or more sidebands which are suppressed by approximately 30 dB [42].

#### 2.5.4 Injection locking

Injection locking is a technique used to stablise the spectra of a laser typically with a broader linewidth which will be subjected to high speed modulation [51]. The injection locking technique is based on light injection from a master laser into the cavity of a slave laser. If the wavelength of the injected laser is within a particular detuning range, dependent on the optical power injected, the frequency of the slave laser locks onto that of the master laser [51]. A narrow linewidth laser is required to stablise the slave laser. An isolator is required between the lasers to prevent feedback from the slave laser into the master laser.

## 2.6 Conclusion

This chapter outlines the future trends of internet users moving towards more mobile and wireless devices. One of the main services of future wireless access networks will be online video applications such as online video streaming and internet teleconferencing. Both residential users and commercial users will look towards higher quality online video with 4K video technology expecting to become the dominant video format in the near future. The 4K video format demands a data rate nine times greater than Full HD. These factors put a demand on wireless access networks to be capable of providing higher data rates.

As discussed, this can be carried out by using unlicensed frequency bands in the mm-wave spectrum. In particular, the 60 GHz band has been advocated for applications such as ultra fast data transfer, HD video transmission and wireless docking and display. Worldwide the 60 GHz band offers at least 5 GHz of unallocated spectrum which can be taken advantage of for applications necessitating high data rate.

Subsequently, mm-waves can be used in conjunction with RoF architectures to aid the distribution of the mm-wave RF signal. It is envisaged that the mm-wave generation process can be carried out at one localised site and distributed to multiple RAUs over the fibre optic network. This helps alleviate the issues associated with the distribution of mm-waves due to their high attenuation in atmospheric oxygen. The localisation of the mm-wave generation process also saves on CAPEX as it allows for the centralisation of the expensive mm-wave generation components. This chapter also discusses some of the current techniques used to generate mmwave radiation before briefly introducing OFC generation which is the basis for mm-wave generation in this thesis with the subsequent chapters utilising both the gain switching technique and MLLs to demonstrate the generation of phase coherent mm-waves. These techniques will be investigated in more detail in Chapter 5 and Chapter 3.

Finally, key components, techniques and considerations for optical systems and RoF systems which are of importance in this thesis are presented.

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# **Chapter 3**

# 60 GHz Radio over Fibre Systems Based on a Gain Switched Laser

## 3.1 Introduction

As discussed in Chapter 2, there is a huge demand for greater bandwidth to provide for high-speed wireless connectivity infrastructure. One possible solution is to use Millimetre Wave (mm-wave) frequency bands in a Radio-over-Fibre (RoF) system. In Section 2.4, many methods of generating mm-waves were presented. Remote heterodyning of two independent lasers requires additional components to ensure phase coherence between the two optical tones. Direct modulation of a laser's bias current can produce two coherent optical tones but has limited modulation bandwidth and experiences frequency chirp. External modulation can resolve the frequency chirp but like the direct modulation scheme still suffers from Radio Frequency (RF) power fading induced by chromatic dispersion.

In this chapter, the technique of gain switching a laser diode to produce an Optical Frequency Comb (OFC) is presented and investigated as a method of generating mm-wave signals for use in RoF systems. An OFC which can be used to generate a highly stable mm-wave for use in a RoF system is demonstrated. Transmission of a 2.5 Gb/s On-Off Keying (OOK) signal over 25 km of fibre is achieved and the merits of achieving a good suppression of the unwanted tones is investigated. In addition, a programmable optical filter is used to not only filter but to provide precompensation for chromatic dispersion reducing the effects of bit-walk off which impair the system performance. As internet usage moves towards devices and services requiring higher data rates, it is important to investigate the use of higher order modulation formats. Therefore, the Quadrature Phase-Shift Keying (QPSK) modulation format is implemented in the gain switched laser RoF system using low cost analog electronics, demonstrating a simple and cost-effective QPSK RoF system operating at 60 GHz.

## 3.2 Gain Switching Technique

Gain switching is a technique of producing optical pulses with high repetition rates and high peak power utilising laser diodes of any structure [1]. Gain switching relies upon the switching of the optical gain through modulation of the laser's bias current. One of the main advantages of gain switching over mode locking is the ease of tuning the repetition rate of the optical pulses through varying the driving conditions [2].

A laser can be gain switched when biased below threshold and modulated using a large sinusoidal signal at GHz or sub-GHz frequencies. Gain switching excites the first spike of the relaxation oscillation and terminates the electrical pulse before the onset of the second spike [1]. This requires the electrical pulsewidth to be short and in the pico/nano second range. The electrical pulse causes the carrier density to rise to a maximum, which is maintained during a turn-on delay until there is large

photon density build up and the carriers deplete [2]. The generation of ultrashort light pulses is illustrated in Figure 3.1.

A Direct Current (DC) bias and sinusoidal electrical signal is applied to the laser as presented in Figure 3.1. At t = 0, the current applied to the laser begins to increase. The initial photon density increases at a slow rate as the stimulated emission rate is proportional to the photon density. Lasing occurs when the electric pulse increases the injected carrier density above the threshold density,  $n_{th}$ . Above the threshold, the carrier density reaches the peak inversion density increase is repressed and the carrier density reduces to the transparency density,  $n_t$ . If the sinusoidal electrical signal continues, the described procedure will repeat several times until stationary levels for the carrier and photon densities are reached, as shown in Figure 3.1 [2].

The optical spectrum of a typical gain switched Distributed Feedback (DFB) laser is demonstrated in Figure 3.2 whereby the frequency separation is determined by the repetition rate of the pulses. In this case, an electrical sinusoidal signal at a frequency of 20 GHz was applied to the DFB laser.

## 3.2.1 2.5 Gb/s On-Off Keying Radio over Fibre System utilising a Gain Switched Laser

In this section, the gain switching technique demonstrated in [3] is used to generate a highly stable mm-wave signal. System performance is improved through the use of superior filtering to increase the suppression of the unwanted comb lines in [3] and an external intensity modulator is used to modulate the optical mm-wave with 2.5 Gb/s downstream data. In Section 3.2.2, the signal is transmitted through fibre, detected and Bit-Error Rate (BER) measurements are taken showing error free



Figure 3.1: Gain switching: typical time development of (a) the applied current, (b) the carrier density and (c) the output pulses.



Figure 3.2: Optical spectrum of a gain switched DFB laser.

transmission (a BER of  $10^{-9}$  for OOK transmission systems is considered error-free) over 25 km with a receiver sensitivity of -34 dBm (at a BER of  $10^{-9}$ ).

An integral part of the system setup is the optical filtering used to create the mmwave and in Section 3.2.4, the merits of achieving good suppression of unwanted comb lines are investigated. The unwanted comb lines of the OFC are suppressed to varying levels using a programmable optical filter. BER measurements are taken for the different levels and various transmission lengths measured against received optical power.

Another important aspect of the system is the limited transmission length due to bit-walk off caused by chromatic dispersion as the data is modulated onto the two optical comb lines separated by 60 GHz [4]. As the two optical carriers travel along the fibre with different speeds, the optical carriers are therefore received at the photodetector with a time shift [5]. This is known as "bit-walk off" and the time shift will cause a decrease in the duration of a received single "1" bit [5]. However, in a Back to Back (BTB) system, the two data streams will experience a negligible time shift.

In Section 3.2.5, the programmable optical filter's dispersion compensation capability is used to pre-compensate for 12 km of dispersion thus extending the transmission distance and alleviating the effects of dispersion on the system. BER measurements are carried out demonstrating that when transmitted over 24 km of fibre and using the dispersion compensated technique the receiver sensitivity can be improved by 2 dB. All experimental works are simulated using the VPI TransmissionMaker simulation platform to validate the experimental measurements.

The VPI software package contains an extensive library of photonic modules. The description of the photonic modules/components ranges over several levels of abstraction from detailed physical models to black box devices and data sheet models. All modules, depending on the level of abstraction have a set of variable parameters which define and control their functionality. Modules such as the laser are solved using the laser rate equations. VPI also has an easy to use Graphical User Interface (GUI) to drag and drop the various modules. The signals in VPI are modelled using samples (periodic or aperiodic signals) and block modes (periodic signals). Sample to block conversions were performed when utilising the gainswitched laser as the laser required only supports sample mode signals. Furthermore it also has a tailored Graphical User Interface (GUI) with drag and drop, easy to use modules. All modules (depending on the level of abstraction) have a set of parameters (variable), which define and control their functionality. Signals in VPI are modelled using sample (supports aperiodic signals) and block modes (supports periodic signals). Sample to block conversions had to be performed while working with multi-section lasers since most of such lasers were supported by sample mode signals.

#### 3.2.2 Experimental Setup



Figure 3.3: Experimental setup of a GSL utilising a programmable optical filter to create a 60 GHz mm-wave optical signal for data modulation and transmission over fibre.

The setup for this experiment is presented in Figure 3.3. The front-end transmitter utilises a commercially available DFB laser diode with an emission wavelength of 1541 nm at room temperature and a threshold current of 15 mA. This DFB was biased at 61.72 mA and subsequently gain switched using an amplified 20 GHz RF sinusoidal signal from a local oscillator with an output power from the amplifier of 19.67 dBm. The Gain-Switched Laser (GSL) produces the OFC with a Free Spectral Range (FSR) of 20 GHz, shown in Figure 3.4a (point (a) in Figure 3.3). The linewidth of the individual comb lines are ~60 MHz. The Wavelength Selective Switch (WSS) is used as a programmable optical filter to filter out two comb lines separated by 60 GHz with the resulting optical spectrum being shown in Figure 3.4b (point (b) in Figure 3.3). The suppression is excellent (~45 dB) and there are no unwanted comb

lines present. A Polarization Controller (PC) is used to change the polarization state of the optical signal before the Mach-Zehnder Modulator (MZM), where the optical signal is modulated by a 2.5 Gb/s OOK NonReturn-to-Zero (NRZ) data stream from a Pseudo-Random Bit Sequence (PRBS) generator.



Figure 3.4: Optical spectra: (a) before filtering and (b) the filtered comb spectrum with a frequency separation of 60 GHz between the two comb lines.

In the BTB case, the optical signal is detected by a high-speed photodetector with a 3-dB bandwidth of 70 GHz. The two comb lines beat together to generate a modulated 60 GHz electrical signal. The electrical mm-wave is amplified before being demodulated using a 60 GHz sinusoidal electrical signal and an electrical mixer. A Low Pass Filter (LPF) and an amplifier are used to reduce noise and increase signal level for signal analysis. The data stream is analysed using a Bit-Error Rate Tester (BERT), and a high-speed digital sampling oscilloscope is used to monitor the eye-diagram and to optimise the system during initial setup.

#### 3.2.3 Results and Discussion

The BER measurements were carried out for BTB transmission, and transmissions over 12 km, 25 km, and 37 km of fibre. The BER was plotted against the received

optical power, measured before the Erbium Doped Fibre Amplifier (EDFA) in front of the photodetector. This EDFA is required to ensure an optimum power, before the photodetector, of -1 dBm . These results are presented in Figure 3.6. Evident from Figure 3.6, for a BER of  $10^{-9}$ , the receiver sensitivity for BTB transmission is -39 dBm with inset Figure 3.6(a) showing a clear and open eye diagram. From these results, it is clear that there is an approximate 3 dB drop in receiver sensitivity when the optical signal is transmitted over 12 km of fibre and a further 2 dB drop when transmitted over 25 km of fibre. The system was also tested over 37 km of fibre where the eye was closed due to dispersion and a BER measurement was not possible, shown by inset (b) in Figure 3.6. The power penalties and closure of the eye with increased transmission distance is due to bit-walk off between the two modulated comb lines.

To demonstrate that the system suffers due to dispersion, a Dispersion Compensating Module (DCM) was installed after the 37 km length of fibre. The DCM compensates for 40 km of fibre and was able to bring the sensitivity back to -37 dBm therefore lowering the power penalty to 2 dB, as shown in Figure 3.6 with inset (c) demonstrating the opening of the eye due to the addition of the DCM. It is important to note, 3 km of dispersion will remain present in the system due to the over-compensation of the DCM. Also, as the mm-wave optical signal is attenuated over the 37 km of fibre and the DCM, there will be a decrease in the Signal-to-Noise Ratio (SNR) due to Amplified Spontaneous Emission (ASE) when the signal is amplified by the EDFA before detection.

The system was simulated using the VPI TransmissionMaker simulation platform. The setup for the VPI simulation was similar to that of the experimental setup in Figure 3.3 with simulation parameters chosen to represent the experimental parameters. To replicate the function of the programmable optical filter, it was necessary to use an Optical Band Stop Filter (OBSF) to remove the unwanted comb lines


Figure 3.5: Simulation setup of a GSL utilising a programmable optical filter to create a 60 GHz mm-wave optical signal for data modulation and transmission over fibre.

between the required comb lines separated by 60 GHz. In conjunction with this filter, an Optical Band Pass Filter (OBPF) was used to remove remaining comb lines other than the two selected comb lines separated by 60 GHz. The simulation setup is illustrated in Figure 3.5. The fibre used in the simulation had a Group Velocity Dispersion (GVD) of 16.67 ps/nm.km and an attenuation factor of 0.2 dB/km. The system was tested over 37 km to correlate with the experimental work. After transmission through 37 km of fibre the eye-diagram was fully closed and there was an floor BER well below  $10^{-4}$ . For the dispersion compensation measurement, fibre of length 2 km was added to the system, after the initial transmission distance, with a GVD set to 333.2 ps/nm.km to counter the dispersion in the system and replicate the DCM used in the experimental work. The simulated results shown as the lines in Figure 3.6 are in reasonable agreement to that of the experimental results.



Figure 3.6: Measured (symbols) and simulated (lines) results for  $log_{10}(BER)$  versus received optical power (dBm) for transmission distances of BTB, 12 km, 25 km, and 37 km with a DCM. Measured eye-diagrams inset for transmission distances of: (a) BTB, (b) 37 km and (c) 37 km with a DCM.

## 3.2.4 Merit of Suppressing Unwanted Comb Lines

The system performance as a function of the suppression of the unwanted comb lines was investigated as in a practical system it is likely that the optical filters used will not have the level of performance of the programmable optical filter used in this work. Using the programmable optical filter, the unwanted comb lines of the OFC were suppressed to varying levels and BER measurements were taken. The three cases used to demonstrate the effects of suppressing the unwanted comb lines were for maximum suppression and when the unwanted comb lines are suppressed by 15 dB and 25 dB relative to the two selected comb lines separated by 60 GHz. The OFC with unwanted comb lines suppressed by 15 dB is presented in Figure 3.7. BER measurements were carried out for BTB transmission and transmis-



Figure 3.7: Filtered OFC where the suppression of the unwanted comb lines is set to 15 dB relative the selected comb lines separated by 60 GHz.

sion over 12 km. The resulting BER measurements plotted against received optical power are demonstrated in Figure 3.8a and Figure 3.8b. Evident from the results is that a reduction in the suppression of the unwanted comb lines degrades the system performance. The degradation of the system performance results from interference of additional 60 GHz signals generated due to the unwanted comb lines. These comb lines are not in phase with the 60 GHz signal generated by the main comb lines and therefore cause interference in the down-converted data stream. In the BTB case, there is an approximate power penalty of 3 dB (at a BER of  $10^{-9}$ ) for a suppression of 25 dB and a power penalty of 5 dB when unwanted comb lines are suppressed by 15 dB. However, when transmitted over fibre, as such in the 12 km case, the power penalty is not as severe with a 1 dB power penalty for suppression by 25 dB while only a power penalty of 3 dB for suppression by 15 dB. In the 12 km transmission case, dispersion causes the phase of the unwanted 60 GHz signals to change such that the signals do not cause the same level of interference and system

degradation in comparison to the BTB case. This increase in receiver sensitivity in comparison to the BTB case is random and may increase/decrease depending on the fibre length therefore demonstrating the instability and unpredictability of the system when unwanted modes are present.

The experiment is modelled using the VPI TransmissionMaker simulation platform using the setup demonstrated in Figure 3.5. Changing the suppression variables of the OBSF and OBPF replicates the functionality of the programmable optical filter. Simulated results for BTB transmission and transmission over 12 km of fibre are demonstrated by the lines in Figure 3.8a and Figure 3.8b respectively. The BTB simulation shows reasonable agreement with the experimental results, there is a slight penalty in the experimental results which could be due to additional ASE in the experiment or due to inefficient mixing of the 60 GHz signals by the RF mixer used in the experiment. As there is a number of 60 GHz signals mixing in the RF mixer at the same time, it is possible that the performance of the simulated RF mixer outperforms the experimental RF mixer. The slope of the simulated results over 12 km are not in good agreement with the experimental results. Again, this could be due to the RF mixer and also due to the difficulty in replicating the dispersion slope of the optical fibre used in the experiment which will have major implications on the mixing 60 GHz products. However, as with the experimental case, it is evident that when transmitting through 12 km of fibre the penalty between Max suppression and 15 dB suppression is not as severe as the BTB case. This will not always be the case for various lengths of fibre as the length of fibre changes so will the chromatic dispersion. This will have a major influence on how the 60 GHz signals constructively/destructively interfere with each other with respect to varying fibre lengths.



Figure 3.8: Measured (symbols) and simulated (lines) results for log<sub>10</sub>(BER) versus received optical power (dBm) for analysing the effects of suppressing unwanted comb lines for; maximum, 25 dB and 15 dB suppression over (a) BTB and (b) 12 km transmission distances.

## 3.2.5 Dispersion Pre-Compensation Utilising a Programmable Optical Filter

The third system analysis utilises the programmable optical filter's dispersion compensation capability to compensate for the dispersive effects encountered by the system shown in Figure 3.3. The maximum dispersion which can be compensated for using the programmable optical filter is 200 ps/nm corresponding to ~12 km of Standard Single Mode Fibre (SSMF) with a GVD parameter of 16.67 ps/nm.km. It was not possible to use the programmable optical filter to compensate for dispersion using the initial setup in Figure 3.3 as the dispersion compensation would be before the modulation of the 60 GHz optical mm-wave and would ultimately be ineffective. Therefore, it was necessary to change the front-end transmitter architecture while the receiver architecture remained unchanged.

To implement the necessary changes the initial EDFA and the programmable optical filter were removed and replaced directly after the MZM in Figure 3.3. This



Figure 3.9: Optical spectra demonstrating OFC from GSL modulated with 2.5 Gb/s OOK NRZ data stream; (a) before and (b) after filtering to generate a 60 GHz optical mm-wave signal.

results in the modulation being carried out directly after the laser and over all the comb lines. The modulated comb lines are shown in Figure 3.9a. Subsequently, the filtering is carried out and the two comb lines separated by 60 GHz are shown in Figure 3.9b. BER measurements were conducted for BTB, 12 km and 24 km transmission distances. As evident in the results in Figure 3.10, the receiver sensitivity (at a BER of  $10^{-9}$ ) for the BTB case is -35 dBm, with less than a 1 dB power penalty for 12 km, while there is a significant power penalty of greater than 3 dB for the 24 km case. The subsequent step was to use the programmable optical filter to partially compensate for the dispersive effects experienced by the optical signal travelling over 24 km of fibre. Using the programmable optical filter's group delay capability brought the power penalty back to approximately 1 dB, evident in Figure 3.10. While the programmable optical filter compensates for 12 km of dispersion, it attenuates the optical signal by a small amount when executing the compensation and, in turn, decreases the SNR. The decrease in SNR accounts for the ~1 dB power penalty experienced in the 24 km case using the programmable optical filter's dispersion compensation.



Figure 3.10: Measured results for  $log_{10}(BER)$  versus received optical power (dBm) utilising the programmable optical filter for dispersion compensation.

# 3.3 60 GHz Single Sideband Subcarrier Modulation Quadrature Phase Shift Keying Radio over Fibre System Utilising a Gain Switched Laser

This experiment further researches the 60 GHz RoF system with the aim of employing a simple, energy efficient and cost effective RoF system capable of transmitting advanced modulation formats. The system utilises the GSL to generate an OFC which is modulated with a Single Sideband (SSB) Sub Carrier Multiplexed (SCM) QPSK signal generated by low cost analog electronics.

## 3.3.1 Experimental Setup

The DFB laser used possesses an emission wavelength of 1541 nm at room temperature and a threshold current of 15 mA. The DFB laser is gain switched using a 17.35 GHz sinusoidal RF signal with an amplified RF power of 18 dBm in conjunction with a bias current of ~53 mA for the laser. The individual comb lines possess a linewidth of ~60 MHz. The spectral output of the gain switched DFB laser is an optical frequency comb with an FSR of 17.35 GHz, shown in Figure 3.12a (point (a) in Figure 3.11). A programmable optical filter (WSS) is subsequently used to filter two comb lines separated by 69.4 GHz, Figure 3.12b (point (b) in Figure 3.11). From Figure 3.12b, it can be seen that it was not possible to fully suppress all unwanted comb lines due to the limited bandwidth of the employed filter.



Figure 3.11: Schematic of the experimental setup for 60 GHz SSB SCM QPSK RoF system using a Gain Switched Laser.

The electrical SSB SCM QPSK signal is generated using low cost analog components. A Pulse Pattern Generator (PPG) is used to generate a PRBS at a bit rate of 1.25 Gb/s. The data and the inverse data streams are decorrelated with a 12 bit delay, and bit-aligned using various electrical cable lengths and an RF phase shifter. The two decorrelated data signals are subsequently applied to the In-phase (I) and



Figure 3.12: Optical spectra: (a) OFC; and (b) filtered comb lines separated by 69.4 GHz.

Quadrature (Q) inputs of an electrical In-phase Quadrature (IQ) mixer to generate a 2.5 Gb/s QPSK signal. The QPSK signal is upconverted to a frequency of 10 GHz using a sine wave derived from a signal generator to drive the Local Oscillator (LO) input of the IQ mixer. This results in a 1.25 Gbaud QPSK signal centered at 10 GHz. The QPSK signal is amplified before being passed through a 90° hybrid electrical coupler. The 90° hybrid electrical coupler creates two QPSK signals with a phase offset of 90° which are subsequently applied to individual arms of the Dual-Drive Mach Zehnder Modulator (DDMZM). This modulates the optical comb lines with the 2.5 Gb/s SSB SCM QPSK signal centered at 10 GHz, illustrated in Figure 3.13 (point (c) in Figure 3.11).

After the DDMZM, the optical signal is amplified with an EDFA. An OBPF is subsequently used to suppress the unwanted comb lines and the unwanted QPSK signal, to leave a QPSK signal and a single comb line separated by 59.4 GHz, shown in Figure 3.14 (point (d) in Figure 3.11). Utilising the OBPF allows only the QPSK signal and the optical comb line separated by 59.4 GHz to propagate through the fibre and enhances the beating efficiency on the photodetector. The optical signal is subsequently transmitted BTB and over 25 and 50 km of SSMF. A Variable Optical Attenuator (VOA) is employed to vary the received optical power after fibre transmission for BER measurements. After the VOA, an EDFA in conjunction with a second VOA is used to maintain the received optical power falling on the photodetector at -1 dBm. A 70 GHz photodetector is used to generate a 59.4 GHz electrical QPSK signal from the received optical signal.



Figure 3.13: Optical spectrum of the SSB SCM QPSK signal upconverted to 10 GHz modulated onto the two comb lines separated by 69.4 GHz modulated

The mm-wave signal is then passed through an Electrical Band Pass Filter (EBPF) (56.3 to 62 GHz) before being amplified. The filtered QPSK signal is downconverted using an IQ mixer with a 59.4 GHz sine wave derived from a signal generator applied to the LO input. The downconverted I and Q data signals are amplified and filtered with a 1.25 GHz Electrical Low Pass Filter (ELPF) before being sent to the BERT for BER measurements while a high-speed digital sampling oscilloscope is used to monitor the eye-diagram.



Figure 3.14: Optical spectrum of the filtered comb line and QPSK signal separated by 59.4 GHz.

### 3.3.2 Results and Discussion

The performance of the 60 GHz RoF QPSK system utilising low cost components was analysed over three different transmission configurations: BTB, 25 and 50 km of SSMF. The BER was taken as the averaged BER of the I and Q data streams with the results being illustrated in Figure 3.15. Evident in Figure 3.15, is that for BTB transmission, the receiver sensitivity (at a BER of  $10^{-9}$ ) is -33 dBm. For transmission over 25 km of SSMF there is a 3 dB penalty. When transmitted over 50 km of BER, chromatic dispersion limits the system performance and causes an error floor at a BER of  $10^{-4}$ . When transmitting over fibre, chromatic dispersion induces a time delay between the QPSK signal and the optical tone separated by 59.4 GHz. The induced time delay can partially impair the phase noise on the resultant 59.4 GHz QPSK signal after the photodiode, in turn, limiting the transmission length.

#### 3.3.3 Simulation Setup

The system was simulated using the VPI TransmissionMaker simulation platform to verify the performance. The setup for the VPI simulation was similar to that of the experimental setup in Figure 3.11 with simulation parameters chosen to represent the experimental parameters. To replicate the function of the programmable optical filter, it was necessary to use an OBSF to remove the unwanted comb lines between the required comb lines separated by 69.4 GHz. In conjunction with this filter, an OBPF was used to remove remaining comb lines outside comb lines separated by 69.4 GHz. The 69.4 GHz comb lines are then modulated with the QPSK signal centered at 10 GHz. Another OBPF is used to filter out the required QPSK signal and the optical tone separated by 60 GHz. The fibre used in the simulation had a dispersion of 16.67 ps/nm.km and an attenuation factor of 0.2 dB/km.

#### 3.3.4 Results and Discussion

The system was tested for the same transmission configurations as the experimental work and the results are displayed in Figure 3.15 with constellation plots of the received QPSK signals shown in Figure 3.16 for: (a) BTB and (b) 50 km of SSMF. Upon examination, it is clear that the experimental results and the simulation results are in excellent agreement. To verify that chromatic dispersion is the main limiting factor to the system transmission length, a DCM was added after the 50 km SSMF transmission. The DCM compensates for 833 ps/nm of dispersion. The simulated QPSK measurements with the DCM added are plotted in Figure 3.15 with Figure 3.16b showing the constellation plot. The constellation plot demonstrates that the phase correlation between the QPSK signal and the optical tone separated by 59.4 GHz is partially destroyed due to the time delay induced by chromatic dispersion. Evident from Figure 3.16b and Figure 3.16c, the DCM is capable of recovering the phase correlation that is lost due to fibre dispersion, and improve the system performance. In comparison to the BTB case, 1 dB penalty is still present due to a decrease in the SNR after fibre transmission and amplification by the EDFA.



Figure 3.15:  $-\log_{10}(BER)$  versus received optical power (dBm) for transmission over SSMF of length: BTB (black); 25 km (red); 50 km (green); simulated 50 km with a DCM.



Figure 3.16: Constellation plots for simulated results taken at a received optical power of -33 dBm with transmission lengths of: (a) BTB; (b) 50 km and (c) 50 km with a DCM.

## 3.3.5 Summary and Conclusion

Section 3.2.1 further expands on work carried out in [3] using the generation of modulated optical mm-waves for 2.5 Gb/s downstream data using improved suppression of unwanted comb lines through the use of superior filtering. This method uses a GSL to create an OFC which generates a number of comb lines separated by the frequency of the driving frequency. Subsequent filtering generates a highly stable 60 GHz optical mm-wave signal. The optical mm-wave is modulated using an external intensity modulator with 2.5 Gb/s downstream data. Using this scheme, it is demonstrated that error-free transmission with receiver sensitivities as low as -34 dBm for transmission over 24 km is possible. Analysis of the suppression of the unwanted comb lines has been carried out where unwanted comb lines were not fully suppressed and their effects on the system is analysed for BTB transmission and transmission over 12 km. The analysis found that suppressing the unwanted comb lines by <15 dB had a major detrimental effect on the system causing a reduction in system performance. As bit walk-off caused by chromatic dispersion is a limiting factor to the system, using the programmable optical filter to not only filter but to compensate for disperion was demonstrated to extend the transmission distance of the setup. As per results, pre-compensating for 12 km of dispersion using the multi-functional programmable optical filter was possible.

Overall, the techniques and analysis demonstrate an uncomplicated and cost effective method for generating highly stable 60 GHz mm-waves which requires basic filtering to achieve good performance.

Section 3.3 builds on the gain switched laser RoF system and experimentally demonstrates a 60 GHz RoF system based on the gain switched laser utilising low cost electronics to implement a baud rate/modulation format scalable SSB SCM QPSK system. The system achieves successful error-free transmission of a 1.25 Gbaud/s QPSK signal over 25 km of SSMF. Transmission over longer distances is limited by the loss in correlation between the QPSK signal and the comb line, due to fibre dispersion, which increases the phase noise on the detected 60 GHz QPSK signal. Simulations demonstrate that error-free transmission over 50 km is possible with the implementation of a DCM.

In conclusion, both methods demonstrate a simple and cost-effective RoF system utilising cheap analog electronics which do not require costly low linewidth lasers at the Central Station (CS) or complex Digital Signal Processing (DSP) at the Base Station (BS). The QPSK RoF system illustrates a baud rate/modulation format scalable RoF system. However, both systems are limited due to chromatic dispersion. Therefore, it is important to overcome these limitations in order to increase the transmission length and to implement higher order modulation formats utilising the GSL. Methods implementing a RoF transmitter based on Wavelength Division Multiplexing (WDM) are explored and demonstrated in Chapter 4. The transmitter is used in conjunction with techniques to enhance the tolerance to chromatic dispersion and to increase the achievable data rate allowing for the use of Orthogonal Frequency Division Multiplexing (OFDM).

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## Chapter 4

# Radio over Fibre Orthogonal Frequency Division Multiplexing Systems Based on a Gain Switched Laser

## 4.1 Introduction

In this chapter, a technique based on Wavelength Division Multiplexing (WDM) is used to simplify the Gain-Switched Laser (GSL) Radio-over-Fibre (RoF) transmitter [1] [2] [3] by allowing for the modulation of one optical tone individually. This technique overcomes the issues with bit-walk off and enables the use of Orthogonal Frequency Division Multiplexing (OFDM) to increase the spectral efficiency of the RoF system and in turn, the achievable data rate. However, using this 60 GHz generation technique the performance remains sensitive to the delay between the optical tones as it can lead to significant phase noise on the Millimetre Wave (mmwave) and cause system degradation. The initial system presented demonstrates a pre-compensation technique for the optical delay between the comb lines capable of transmitting a 25 Gb/s OFDM signal. This chapter also demonstrates the use of an externally injected Distributed Feedback (DFB) laser to negate the requirement for the pre-compensation and generate a low phase noise mm-wave for the transmission of a 25 Gb/s OFDM signal.

## 4.2 Orthogonal Frequency Division Multiplexing

OFDM is a type of Multi-Carrier Modulation (MCM) which transmits data on a number of harmonically related subcarriers. The premise behind MCM techniques is that one high data rate stream is split into several lower data rate streams and these streams are transmitted in parallel, giving longer symbol periods than single carrier techniques. In contrast to typical MCM systems, such as Frequency Division Multiplexing (FDM), where there is sufficient frequency guard bands between the subcarriers as shown in Figure 4.1a, OFDM subcarriers overlap as illustrated in Figure 4.1b. The overlapping allows for an increased number of subcarriers to be transmitted in a given bandwidth. In OFDM the parallel streams are typically modulated with Quadrature Amplitude Modulation (QAM). The compact arrangement of the OFDM orthogonal subcarriers ensures high spectral efficiency and is the main reason for OFDM's popularity in current radio standards. However, OFDM's inherent tolerance to chromatic dispersion makes OFDM particularly attractive for use in optical communications [4]. The main attributes of OFDM will be discussed in the following sections.



Figure 4.1: (a) FDM and (b) OFDM subcarriers.

### 4.2.1 Inverse Fast Fourier Transform

While FDM and OFDM are similar as each subcarrier has a different frequency, the key difference is that the individual OFDM subcarriers overlap in the frequency domain. If each subcarrier is made orthogonal to all other subcarriers then parallel transmission without interference is possible. In OFDM, the subcarriers are chosen to be orthogonal to each other in the frequency domain. To do this, an Inverse Fast Fourier Transform (IFFT) is implemented at the transmitter.

Equation 4.1 gives the discrete form of the IFFT:

$$x_m = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k \exp\left(\frac{j2\pi km}{N}\right) \quad \text{for} \quad 0 \le m \le N-1$$
(4.1)

where, *N* is the number of IFFT inputs (resulting in the number of subcarriers), *X* denotes the frequency domain inputs and *x* is the time domain output arising from the IFFT. Each output *x* contains information about all *X* coefficients, *X<sub>k</sub>*, for  $0 \le k \le N - 1$ . Examining equation 4.1, it is evident that the output frequencies vary as  $\frac{k}{N} = \frac{0}{N}, \frac{1}{N}, \dots, \frac{N-1}{N}$ . Each subcarrier frequency is an integer multiple of a fundamental frequency. As is known the area under the product of two sinusoids

with a frequency of an integer number of a fundamental frequency ( $\omega$ ) is 0.

$$\frac{1}{T} \cdot \int_{\frac{-T}{2}}^{\frac{T}{2}} \sin(p\omega t) \cdot \sin(q\omega t) dt = 0 \quad p, q \in \mathbb{Z}, p \neq q$$
(4.2)

As a result, the sinusoids, or the subcarrier frequencies, assigned by the IFFT are said to be orthogonal over one IFFT operation. The subcarriers do not interfere and are therefore capable of being uniquely detected by the inverse function at the receiver, the Fast Fourier Transform (FFT). Examining Figure 4.1b, it is evident that at the peak of an individual subcarrier all other subcarriers pass through 0.

A conceptual diagram of the IFFT where a bank of mixers represent the transform is illustrated in Figure 4.2. The respective sinusoidal inputs, at frequencies  $f_0$  to  $f_{N-1}$ , are orthogonal. The summation of all the orthogonal sinusoids is the output  $x_m$ . Each IFFT operation results in an output,  $x_m$  and this represents an OFDM symbol containing *N* orthogonal subcarriers.



Figure 4.2: Conceptual diagram of the discrete IFFT.

## 4.2.2 Cyclic Prefix

One of the enabling techniques and most important factors for the use of OFDM in optical communications is the insertion of a Cyclic Prefix (CP) to mitigate the chromatic dispersion induced by fibre [5] [6]. As presented in Section 4.2.1, each OFDM symbol contains *N* orthogonal subcarriers. Each subcarrier is at a different frequency, therefore when transmitted through fibre, dispersion will introduce a delay spread across all transmitted subcarriers.

The FFT window size at the receiver is the same size as the transmitted IFFT size. Two subcarriers within an OFDM symbol may be aligned in time at the transmitter as per Figure 4.3a. After transmission through fibre, one of the subcarriers, Subcarrier 1, has been delayed due to dispersion by a time  $t_d$ , as in Figure 4.3b. Evident from Figure 4.3 is that the received Subcarrier 1 is a truncated version of the originally transmitted subcarrier. As a full copy of Subcarrier 1 has not been received, the subcarriers are no longer orthogonal and symbol interference occurs.



Figure 4.3: (a) Transmitted OFDM subcarriers, (b) received OFDM subcarriers.

To solve this problem, a portion of the end of the subcarrier is appended to the beginning of the subcarrier as demonstrated in Figure 4.4. This additional portion of the subcarrier is known as the CP. In order for the CP to enable the reception of the full subcarrier and maintain the orthogonality of the subcarriers, the maximum delay spread due to dispersion,  $t_{max}$ , must be be less than the length of the CP.



## Time

Figure 4.4: Implementation of an OFDM cyclic prefix.

The addition of a CP at the transmitter is shown in Figure 4.5c. The received signal after transmission through fibre is illustrated in Figure 4.5d. As demonstrated in Figure 4.5, the received subcarrier is a time shifted version of the originally transmitted subcarrier. This is essentially the original subcarrier with an additional time delay. As each subcarrier is at a different frequency, the time delay varies and each received subcarrier will have a phase shift relative to the corresponding transmitter subcarrier. The phase shift and other frequency selective effects affect the received data and therefore must be taken into account.



Figure 4.5: (c) Transmitted OFDM subcarriers including a CP, (d) received OFDM subcarriers including a CP.

### 4.2.3 Channel Estimation and Equalisation

Typically, the modulation format used in conjunction with OFDM is QAM. A single QAM symbol is described by a single complex number. The QAM data is modulated onto the OFDM subcarriers using the IFFT. An FFT is carried out at the receiver on the received phase shifted version of the transmitted subcarriers. The output of this FFT is the original QAM data with channel effects. The channel frequency response results in different subcarriers experiencing different channel gains. The different channel gains experienced result in the individual QAM symbols possessing various magnitudes, not corresponding to the original transmitted QAM symbol magnitudes. To correctly retrieve the QAM symbols, the channel effects must be estimated and accounted for by equalising the QAM data accordingly.

The solution is the addition of a Training Sequence (TS) at the OFDM transmitter. The TS is a known sequence of complex numbers which occupies one OFDM symbol as the input to the N dimensional IFFT. It is common that the TS is added more than once throughout the entire OFDM signal. As the TS constitutes one entire OFDM symbol it contains every subcarrier and therefore, information about the channel effects on every OFDM subcarrier can be obtained. The transfer function of a channel is obtained through the comparison of the transmitted and received TS, known as channel estimation. The estimated channel function is given by:

$$H_{est} = \frac{R_{ts}}{T_{ts}} \tag{4.3}$$

where,  $R_{ts}$  is the received TS and  $T_{ts}$  is the transmitted TS. An estimated channel transfer function describes the effect of the channel on each OFDM subcarrier. The channel effects can be compensated through the inversion of the estimated channel transfer function and by applying the resulting equaliser to all the subsequent data.

In optical systems, the addition of the TS can be used to overcome chromatic dispersion which is a linear impairment. Considering a single subcarrier in an OFDM symbol in the range of  $0 \le k \le N - 1$ , the time domain OFDM symbol associated with the  $k^{th}$  subcarrier at the transmitter can be given as:

$$s(k,t) = \frac{1}{\sqrt{N}} X_k \exp\left(\frac{j2\pi kt}{T}\right)$$
(4.4)

where, T is the OFDM symbol duration and  $0 \le t \le T$ . Ignoring noise effects, the received signal will experience channel gain,  $g_k$  and a time shift,  $\tau_k$ , induced by chromatic dispersion. Therefore, the received signal is:

$$r(k,t) = g_k \cdot \frac{1}{\sqrt{N}} X_k \exp\left(\frac{j2\pi k(t-\tau_k)}{T}\right)$$
(4.5)

Rearranging equation 4.5,

$$r(k,t) = \frac{1}{\sqrt{N}} X_k \exp\left(\frac{j2\pi kt}{T}\right) \cdot \left[g_k \cdot \exp\left(\frac{-j2\pi k\tau_k}{T}\right)\right]$$
(4.6)

After demodulation at the receiver using the FFT and accounting for noise effects:

$$R_k = X_k \left[ g_k \cdot \exp\left(\frac{-j2\pi k\tau_k}{T}\right) \right] + W_k \tag{4.7}$$

$$R_k = X_k \cdot H_k + W_k \tag{4.8}$$

Therefore, the transmitted  $X_k$  can be retrieved from the received  $R_k$  using only one complex multiplication to correct for phase shifts, attenuation and chromatic dispersion on the  $k_{th}$  subcarrier after transmission over fibre.

# 4.3 25 Gb/s Radio over Fibre Orthogonal Frequency Division Multiplexing Systems Based on a Gain Switched Laser

## 4.3.1 60 GHz Generation and Modulation Utilising an Arrayed Waveguide Grating

As in [2], two optical tones separated by the desired mm-wave frequency can be split using an optical Arrayed Waveguide Grating (AWG) (Demultiplexer (demux)). This allows for the modulation of one optical tone individually. The tone can then be recombined with the unmodulated tone. An important factor in this system setup is the different optical path lengths experienced by the two tones as it can lead to significant phase noise on the detected mm-wave and cause system degradation. The proposed 60 GHz RoF generation and modulation scheme is presented in Figure 4.6 as demonstrated previously in [3]. Methods to overcome the induced time delay between the optical paths are demonstrated in the following sections.



Figure 4.6: Principle of the 60 GHz RoF system utilising an optical AWG to split the optical channels to allow for modulation of one optical tone.

## 4.3.2 60 GHz Orthogonal Frequency Division Multiplexing Radio over Fibre System Using a Gain Switched Distributed Feedback Laser and Phase Noise Pre-Compensation

In this section, the DFB laser is gain switched, two comb lines separated by 54.3 GHz are filtered off and used to transmit a 25 GB/s OFDM signal on a 59.3 GHz carrier over 50 km of fibre optical using the mm-wave generation technique outlined in the previous section. The impact of the phase noise due to the dispersion induced optical phase decorrelation is evident. Pre-compensation for the time delay induced by chromatic dispersion is implemented in the system in order to reduce the impact of phase noise and extend the transmission distance.

#### 4.3.2.1 Experimental Setup

The experimental setup presented in Figure 4.7 is used to achieve transmission of a 25 Gb/s OFDM signal on a mm-wave. The DFB laser is gain switched by an 18.1 GHz sinusoidal Radio Frequency (RF) signal with an amplified RF power of 24 dBm. The spectral output of the gain switched DFB is an Optical Frequency Comb (OFC) with a Free Spectral Range (FSR) of 18.1 GHz, shown in Figure 4.8a (point (a) in Figure 4.7). The linewidth of the individual comb lines are ~60 MHz.



Figure 4.7: Experimental setup for a 25 Gb/s OFDM 60 GHz RoF system utilising a GSL.

A Wavelength Selective Switch (WSS) is used to filter off two tones separated by 54.3 GHz, the two tones are shown in Figure 4.8b (point (b) in Figure 4.7). The two tones are amplified by an Erbium Doped Fibre Amplifier (EDFA) before being split using a 100-GHz demux. Due to the large bandwidth of the demux, the required channels cannot be selected with perfect rejection of the neighbouring channels. Therefore, tunable Optical Band Pass Filters (OBPFs) are used, in both arms, to further suppress the unwanted channels.

The optical tone in Channel 1 (Ch. 1) is modulated with a 25 Gb/s Double Sideband

(DSB) OFDM signal using a Dual-Drive Mach Zehnder Modulator (DDMZM). The OFDM signal is generated using an Arbitrary Waveform Generator (AWG) and amplifed before being applied to the individual arms of the DDMZM. The 25 Gb/s DSB OFDM signal comprises of 64 subcarriers with the 16 QAM format on each subcarrier and an OFDM symbol rate of 97.656 MHz. The incorporation of the 7% Forward Error Correction (FEC) overhead together with a CP length of 6.25% of the IFFT, which has 256 inputs, gives a net data rate of ~21.69 Gb/s. The total bandwidth of the signal is ~6.36 GHz. These properties are summarised in Table 4.1.

IFFT/FFT Size	256
IFFT Data Inputs	64
Modulation	16 QAM
OFDM Symbol Rate	97.656 MHz
Bandwidth	6.336 GHz
Raw Data Rate	25 Gb/s
Net Data Rate	21.69 Gb/s
СР	6.25%
FEC	7%

Table 4.1: Summary of the OFDM properties.

The DDMZM is biased at the null point to achieve DSB-Carrier Suppressed (CS) modulation. DSB-CS provides a greater beating efficiency on the photodetector between the OFDM data and the free channel separated by 59.1 GHz through the reduction of the unwanted beating of the optical carrier with the unmodulated channel and the two OFDM sidebands. Figure 4.8c (point (c) in Figure 4.7) shows the modulated optical tone with the suppressed optical carrier and the DSB OFDM signal. A Variable Optical Attenuator (VOA) is used to vary the optical power of Channel 2 (Ch. 2) to achieve the most efficient beating of the modulated and unmodulated signals at the photodetector. A polarisation controller optimises and rematches the polarisation of the two split channels. Excellent rejection of the un-

wanted neighbouring channels is achieved with the tunable OBPFs and is conveyed in Figure 4.8d (point (d) in Figure 4.7). A tunable delay line is used in Ch. 2 to compensate for the decorrelation between the optical channels when transmitted over fibre.



Figure 4.8: Optical Spectra: (a) optical frequency comb; (b) filtered comb lines separated by 54.3 GHz; (c) Ch. 1, modulated data channel; and (d) Ch. 2, unmodulated free channel; Electrical spectrum: (e) received OFDM data down-converted from 59.1 GHz to 4.8 GHz, amplified and filtered prior to offline processing.

The two channels are recombined before being amplified by an EDFA with an OBPF employed after to reject Amplified Spontaneous Emission (ASE). The system is analysed for Back to Back (BTB) transmission and transmission over 50 km of Standard Single Mode Fibre (SSMF). The optical power launched into the fibre is maintained at 3 dBm in order to minimise the effects of fibre non-linearity [7]. After fibre transmission, the optical signal is sent to an EDFA via a VOA which is employed to vary the received optical power for Bit-Error Rate (BER) measurements. The output power of the EDFA is kept at a constant 13 dBm. The amplified

optical signal is subsequently sent to the photodetector via a VOA which ensures that the optical power falling on the photodetector is maintained at -2 dBm.

A 70 GHz photodetector is used to generate the electrical mm-wave signal from the received optical signal. This electrical signal contains the desired OFDM signal at 59.1 GHz and an undesired component at 49.5 GHz. The electrical signal is passed through a 56.2 to 62 GHz Electrical Band Pass Filter (EBPF) before being amplified. The filtered OFDM signal is amplified and then down-converted with a 54.3 GHz sinusoidal RF signal using an external mixer. The down-converted OFDM data signal at 4.8 GHz is filtered with a 7.46 GHz Electrical Low Pass Filter (ELPF) before being sent to the Real-Time Scope (RTS). The down-converted OFDM signal is presented in Figure 4.8e (point (e) in Figure 4.7). Digital Signal Processing (DSP) including down-conversion, time synchronisation, channel estimation and phase correction, is applied to demodulate the Intermediate Frequency (IF) OFDM signal and BER calculations are performed offline using Matlab.

#### 4.3.2.2 Results and Discussion

In order to correctly adjust the tunable delay line in Ch. 2, it was necessary to examine the beat tone spectra after the WSS (point (a) in Figure 4.7). The beat tone spectra was also examined after the demux for BTB transmission and transmission over 50 km of SSMF with and without delay compensation at point (e) in Figure 4.7. To do this, the setup in Figure 4.9a is used for the WSS case and the setup in Figure 4.9b is used for the cases after transmission. The beat tones, without data modulation, for each case are beat together on the photodetector and the resulting signals are down-converted to 4.8 GHz and shown in Figure 4.10.

The cyan line showing the beat tone for the BTB case demonstrates low phase noise similar to the blue line corresponding to the beat tone after the WSS. The elec-



Figure 4.9: Setups to demonstrate the phase noise (a) before the demux and (b) after transmission through fibre.

trical spectra for the beat tone after transmission through 50 km of fibre with and without compensation are illustrated by the pink and red lines respectively. Comparing the pink and red lines, it can be seen that the optical phase decorrelation due to the chromatic dispersion induces significant phase noise on the 59.1 GHz beat tone.

The time delay induced by chromatic dispersion between the two optical tones after 50 km of fibre can be estimated using the following equation [8]:

$$\tau_0 = DL\Delta\lambda \tag{4.9}$$

where, *D* is the dispersion parameter which is 17 ps/km.nm (SSMF at 1550 nm), L is the length of the fibre and  $\Delta\lambda$  is the wavelength offset of the two optical tones which is 0.47 nm, corresponding to 59.1 GHz (at 1540 nm). Therefore, the time



Figure 4.10: Electrical spectra of the down-converted unmodulated mm-wave signal.

delay induced by the chromatic dispersion is estimated as 400 ps.

It is important to precisely compensate for the time delay if an optical comb source with a large linewidth on each line is employed, as even a very short delay induced by chromatic dispersion can affect the phase noise of the RF beat tone and therefore, limits system performance. The effective reduction of the phase noise of the 59.1 GHz signal through pre-compensating for the time delay between the optical tones is demonstrated in Figure 4.10.

The effectiveness of the pre-compensation is also illustrated by the constellations of the 16 QAM-OFDM signals in Figure 4.11 for BTB transmission and transmission over 50 km of fibre with and without the optical length compensation. Examining Figure 4.11b, it is evident that the phase noise due to the optical phase decorrelation caused by the chromatic dispersion can seriously distort the OFDM



Figure 4.11: Constellations for a 16 QAM-OFDM 59.1 GHz signal over (a) BTB or (b) 50 km of SSMF without time delay compensation and (c) 50 km of SSMF with time delay compensation.

signal if a large linewidth source is employed. Pre-compensation through adjusting the length of the tunable delay line in Ch. 2 allows for the mitigation of the chromatic induced phase noise impact. This is demonstrated by the constellation of the OFDM signal in Figure 4.11c for transmission over 50 km of fibre using the pre-compensation.

BER measurements for the transmission of a 16 QAM-OFDM 59.1 GHz signal at 25 Gb/s as a function of the received optical power for BTB transmission and transmission over 50 km of SSMF when using the pre-compensation to ensure minimal phase noise on the generated mm-wave signal are shown in Figure 4.12. The measured BERs are below the FEC limit ( $BER = 4.4 \cdot 10^{-3}$  [9]) for both the BTB and the 50 km of fibre cases. There is no power penalty when transmitting over the fibre. In fact, the BER results with 50 km of SSMF are slightly better than the BTB case as the optical length matching for the BTB case may not have been as ideal as for the 50 km transmission case.



Figure 4.12:  $-\log_{10}$ BER v received optical power (dBm) for BTB transmission and transmission over 50 km of fibre with pre-compensation for the time delay between the optical channels.

## 4.3.3 Linewidth Reduction of a Distributed Feedback Laser Using External Injection

In Chapter 3, the system performance was limited due to chromatic dispersion, initially causing bit-walk off in the On-Off Keying (OOK) system and subsequently optical phase decorrelation in the Quadrature Phase-Shift Keying (QPSK) system. Similarly, the system in Section 4.3.2 is limited by the optical phase decorrelation between the two optical comb lines caused by chromatic dispersion. In Section 4.3.2, a time delay pre-compensation technique is used in the system to mitigate the chromatic dispersion induced phase and improve system performance. However, another method to reduce the phase noise and increase the tolerance of the time delay is to externally inject the gain switched DFB laser with a low linewidth laser to generate a low linewidth OFC. In this case even if the optical lines become decorrelated due to dispersion in the transmission fibre, the low linewidth of the comb lines ensures that the additional phase on the beat signal is not large enough to significantly degrade system performance.

The Power Spectral Density (PSD) of the frequency fluctuation of the DFB laser with and without injection locking is characterised using the technique outlined in [10]. The frequency modulation noise spectrum can be defined as the PSD of the instantaneous frequency fluctuation which is obtained by differentiating the phase noise. The Frequency Modulation (FM)-noise contains a  $\frac{1}{f}$  component and a white noise component, (*S*<sub>0</sub>). The FM-noise spectrum for the DFB laser employed in this research is illustrated in Figure 4.13.

The  $\frac{1}{f}$  noise contribution for the RF phase noise can be considered negligible for a short delay, low power heterodyning system [11]. The FM-noise also has a resonance peak at the relaxation oscillation frequency and drops off above that frequency. This effect may be important in systems where the symbol rate approaches the relaxation frequency [11]. However, this is not the case in the current RoF system.

The FM-noise comprised of the  $S_o$  component is ~30 MHz for the DFB laser in the absence of external injection, evident in Figure 4.13. When the laser is injection locked, the  $S_o$  component is significantly reduced to ~10 kHz which is comparable to that of the master laser.

The estimated 3-dB linewidth from the FM-noise spectra, determined from the white noise region can be expressed as [10]:

$$\gamma_{o1} = \frac{\pi S_{o1}}{2} = 47.12 MHz \tag{4.10}$$

$$\gamma_{o2} = \frac{\pi S_{o2}}{2} = 15.71 kHz \tag{4.11}$$

As the phase noise impact induced by the  $\frac{1}{f}$  noise can be considered negligible, the linewidth of the DFB laser is ~47 MHz. This can be reduced to ~16 kHz when the laser is externally injected. This significantly improves the tolerance of the RoF to the time delay between the optical channels and the mm-wave phase noise induced by chromatic dispersion without the requirement of pre-compensation or complex DSP [8]. This is essentially because the low linewidth comb lines have much larger coherence lengths. The externally injected laser was used in lieu of the pre-compensation technique in the following section.



Figure 4.13: FM-Noise Spectrum for DFB laser with (blue line) and without external injection (red line).
### 4.3.4 60 GHz Orthogonal Frequency Division Multiplexing Radio over Fibre System Using an Externally Injected Gain Switched Distributed Feedback Laser

In this section, the gain switched DFB laser used in Section 4.3.2.1 is externally injected with a low linewidth laser to generate a low linewidth OFC. Such a highly coherent OFC source renders a higher tolerance to the time delay thereby resulting in negligible mm-wave phase noise after fibre propagation, without the need for pre-compensation.

#### 4.3.4.1 Experimental Setup

The experimental setup presented in Figure 4.14 is used to achieve transmission of a 25 Gb/s OFDM signal on a mm-wave. The DFB slave laser is gain switched using an 18.1 GHz sinusoidal RF signal with an amplified RF power of 24 dBm. The slave laser is externally injected using an External Cavity Laser (ECL) as the master laser. The master laser is tuned to match the wavelength of the slave laser. The spectral output of the externally injected gain switched DFB is an OFC with a FSR of 18.1 GHz, illustrated in Figure 4.15a (point (a) in Figure 4.14).

The remainder of the Central Station (CS) configuration is similar to that in Section 4.3.2.1 with the exception of the optical delay line in Ch. 2 being removed as the external injection negates the requirement of pre-compensating the time delay between the optical channels. The filtered optical tones after the WSS are illustrated in Figure 4.15b (point (b) in Figure 4.14). Ch. 1 is modulated with the same OFDM data as summarised in Table 4.1. Ch. 1 and Ch. 2 are presented in Figure 4.15c and Figure 4.15d (points (c) and (d) in Figure 4.14).

The two channels are recombined before being amplified with an EDFA. The sys-



Figure 4.14: Experimental setup for a 25 Gb/s OFDM 60 GHz RoF system utilising an externally injected GSL.

tem is also analysed with an additional delay of 5 m of SSMF in Ch. 2. The delay is added to demonstrate the robustness of the OFC source as even with large time delays between the optical tones (5 m is equivalent to a relative delay of 24.5 ns), a low phase noise mm-wave can still be generated. The recombined channels prior to BTB transmission and transmission over 25 km of SSMF are presented in Figure 4.15e (point (e) in Figure 4.14). The received optical signal is passed through a VOA which is used to vary the power falling on the detector for BER measurements. It is important to note that an additional EDFA is used in the receiver architecture of Section 4.3.2 and the received optical power is measured before this EDFA and therefore, the receiver sensitivities in Sections 4.3.2.2 and 4.3.4.2 are not directly comparable.

A 70 GHz photodetector is used to generate a 59.1 GHz electrical OFDM signal from the received optical signal. The generated mm-wave is subsequently passed through an EBPF (56.3 to 62 GHz) before being amplified. The bandpass filter is used to select the OFDM signal at a frequency of 59.1 GHz and to suppress the



Figure 4.15: Optical Spectra for RoF systems based on an externally injected GSL: (a) optical frequency comb; (b) filtered comb lines separated by 54.3 GHz; (c) Ch. 1, modulated data channel; (d) Ch. 2, unmodulated free channel; and (e) recombined channels before transmission over fibre. Electrical spectrum: (f) received OFDM data down-converted from 59.1 GHz to 4.8 GHz, amplified and filtered prior to offline processing.

54.3 GHz carrier and the lower frequency OFDM mm-wave signal. The filtered OFDM signal is amplified and then down-converted with a 54.3 GHz sinusoidal RF signal using an external mixer. The OFDM data signal centered at 4.8 GHz is filtered with a 7.46 GHz ELPF before being sent to the RTS. The down-converted OFDM signal is presented in Figure 4.15f (point (f) in Figure 4.14).

Wireless transmission with 1 and 2 m wireless links using a very basic directly aligned horn antenna setup with a perfectly clear Line of Sight (LOS) is also tested. Each horn antenna possesses a gain of 20 dB. The wireless link is placed directly after the 60 GHz RF amplifier with an additional RF amplifier being required in the receiver. DSP of the received OFDM signal and BER calculations are performed offline using Matlab.

#### 4.3.4.2 Results and Discussion



Figure 4.16:  $-\log_{10}(BER)$  v received optical power (dBm) with constellation plots inset (a), (b) & (c) for: BTB; 25 km; and 25 km with a 5 m delay between the channels.

The system was analysed for three initial transmission configurations; BTB, and 25 km of SSMF with and without the 5 m delay in Ch. 2. Non-linear impairments of fibre transmission were controlled by limiting the launch power into the fibre to <4 dBm [7]. The results obtained are displayed in Figure 4.16, showing BERs measured below the FEC limit. Evident in Figure 4.16 is a negligible penalty when transmitting through 25 km of SSMF. Furthermore, there is no additional penalty when a 5 m delay is placed in the unmodulated channel, Ch. 2. This exhibits a lack of any phase noise induced from the time delay between the two separated channels as a result of the low linewidth (large coherence length) of the optical comb lines.

To reinforce this aspect of the system, the beating of the two comb lines separated by 54.3 GHz is examined using the setup in Figure 4.9a to demonstrate the phase noise before the demux and the setup in Figure 4.9b to demonstrate the phase noise



Figure 4.17: Electrical spectra of the comb lines separated by 53.4 GHz beating together after the WSS and for various delays between the unmodulated channels after the demux.

after the demux with 0 and 5 m delay in Ch. 2. The resulting electrical spectra are plotted in Figure 4.17. The two comb lines filtered by the WSS before the demux are detected and down-converted to 4.8 GHz. Figure 4.17 shows that the phase noise is extremely low as the beating comb lines are narrow at the bottom. The comb lines are then split by the demux and OBPFs, recombined without modulation, detected and down-converted. Similar to the WSS case, for 0 m delay between the channels, the beating comb lines exhibit low phase noise in Figure 4.17. Finally, with a 5 m delay in Ch. 2, Figure 4.17 shows a slightly broadened spectrum at the bottom of the peak indicating an increase in phase noise. However, the increase is minimal and does not affect system performance. It should be noted that no complex offline DSP is required to adjust for the time delay between the split optical channels.

The system is also tested for 1 and 2 m wireless links after transmission through 25 km of SSMF. BER measurements below the 7% FEC limit are shown in Fig-



Figure 4.18:  $-\log_{10}(BER)$  v received optical power (dBm) with constellation plots inset (a) & (b) for: 25 km with 1 and 2 m wireless links.

ure 4.18. At the FEC limit, there is a 1.5 dB penalty due to insertion loss when the 1 m wireless link is added with a further 4 dB penalty when the link is 2 m.

### 4.4 Conclusion

Two high-speed 60 GHz OFDM RoF systems have been demonstrated. Initially a low complexity gain switched DFB laser with a large linewidth per comb line is used to transmit a 25 Gb/s OFDM signal using a pre-compensation technique to overcome the optical phase decorrelation induced by chromatic dispersion. Using the pre-compensation the transmission of a 25 Gb/s OFDM signal over 50 km of fibre with a BER below the 7% FEC limit is achieved.

To overcome the RF phase noise due to optical phase decorrelation, without the need for precise compensation techniques, the DFB was externally injected to generate a low linewidth coherent comb source. A robust mm-wave RoF system with negligible phase noise penalties without the need for complex phase noise suppression. Performance below the 7% FEC limit is achieved in the case where a 25 Gb/s OFDM mm-wave signal is transmitted over 25 km of SSMF and 2 m wireless.

These two systems represent solutions to transmit high data rate advanced modulation formats utilising OFDM in a RoF configuration. The two systems, based on a gain switched laser, demonstrate the capability to transmit a 25 Gb/s OFDM mm-wave over a minimum of 25 km of fibre without the need for complex phase suppression algorithms or DSP.

## References

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### Chapter 5

# Coherence Measurements of a Passively and Actively Mode Locked Laser

### 5.1 Introduction

The importance of high speed wireless networks for current and future communication networks, stemming from the increasing demand for a greater total capacity in wireless transmissions systems, has been discussed in previous sections. One solution put forward to increase the capacity is to use higher frequency bands. Higher frequency bands such as the Millimetre Wave (mm-wave) frequency bands receive a great deal of research focus due to the unlicensed spectrum at these frequencies, in particular the 7 GHz of bandwidth at 60 GHz. However, not only are mm-wave frequency bands experiencing a great deal of attention but also higher frequencies in the THz region. For future wireless systems the THz frequency range of 275-3000 GHz is important as it has not yet been defined for specific uses [1]. Therefore, there is a large amount of available bandwidth to allow for high data rates to be used. However, as with mm-wave radiation, THz radiation suffers attenuation due to atmospheric oxygen, making it difficult for outdoor use. Therefore, THz radiation will be used in the same manner as mm-wave radiation for indoor wireless communications utilising a Radio-over-Fibre (RoF) architecture.

In order to generate the THz radiation required to transmit data in the THz region, Optical Frequency Comb Sources (OFCSs) can be used. As discussed in Section 2.4.2, Optical Frequency Combs (OFCs) can be generated using not only gain switching techniques but also through the use of Mode Locked Lasers (MLLs). A MLL will generate an OFC which will allow for two comb lines separated by the desired THz frequency to be filtered off and subsequently beat on a photodetector to generate the electrical THz signal. In this chapter, mode-locking is discussed and coherence measurements of a passively and actively mode-locked Quantum Dash Semiconductor (QDash) laser are carried out to investigate it's potential as a coherent source for mm-wave and THz radiation.

### 5.1.1 Mode-Locking

Mode-locking is a technique which allows for the generation of laser pulses with durations of nano and picoseconds [2] [3]. Mode-locking occurs when the cavity modes oscillate with comparable amplitudes and locked phases [4] [5]. If there are several longitudinal optical modes present in the laser cavity at the same instant, and they possess a fixed phase relationship with the other optical modes, the optical modes constructively interfere and short pulse formation occurs. In the MLL, the optical modes are equally spaced by the Free Spectral Range (FSR) and their relative phases are locked [2] [3]. This phase relationship can be introduced through

a variety of techniques which fall under the categories of passive and active mode locking [6].

#### 5.1.1.1 Passive Mode Locking

Passive mode locking is an approach used for the generation of ultra-short optical pulses which exploits non linear optical effects in the device [7]. The most common method to achieve passive mode locking is the introduction of a saturable absorber into the laser cavity.

Typically, a laser capable of achieving passive mode-locking will have a gain region and a region of saturable absorption [8]. In the steady state, the loss in the cavity is greater than the gain. For simplicity, consider a single short pulse circulating in the laser resonator which has a fast absorber. Each time the pulse hits the saturable absorber, it saturates the absorption and allows for the peak of the pulse to travel through. In this brief period of time, the gain is greater than the loss and a short duration pulse of light is amplified. The recovery time of the absorber must be quicker than that of the gain section. This ensures that the loss as soon as the peak is amplified [9]. This results in the leading and trailing edges of the light pulse experiencing loss while the peak experiences gain causing a short pulse duration.

#### 5.1.1.2 Active Mode Locking

Active mode-locking can be achieved through periodic modulation of the cavity losses or, of the round trip phase changes being synchronised with resonator round trips [5]. This can produce ultra-short pulses usually in the order of picoseconds. The modulation can be realised through the use of a semiconductor electro-absorption modulator, an acousto-optic modulator or a Mach-Zehnder Modulator (MZM) placed in the cavity and driven by an external signal [10]. To actively mode-lock the laser, it is necessary to synchronise the modulating signal with the round trip time of the resonator, the FSR, or a factor or multiple integer of it in order to achieve stable mode locking operation. Only during the peak of the external signal pulse will the optical gains overcome the losses in the cavity and short optical pulse will be generated.

### 5.1.1.3 Passive Mode-Locking Through Four-Wave Mixing in a Fabry-Pérot Semiconductor Laser

As previously discussed, a saturable absorber is the most common element associated with passively MLLs. However, the nonlinear response of the active region of a semiconductor laser can be sufficient to provide mechanisms for modelocking [11]. The passive mode-locking can occur due to the nonlinear interactions between the longitudinal modes that induce dynamic modulation of both the gain and the refractive index of the active region [12] [13]. The nonlinear interactions between longitudinal modes can be greatly improved when the active region consists of a quantum structure (dot, dash, well). The quantum structure gives better optical confinement and a smaller active cross section which intensifies the interactions between the optical modes in the active region [14]. The nonlinear effect which results in the passive mode-locking of the longitudinal modes is Four-Wave Mixing (FWM). The interactions between the optical modes inside the laser cavity through FWM are illustrated in Figure 5.1.

An optical field generated in a laser cavity can be expressed as a monochromatic wave with slowly varying amplitude therefore  $\vec{E}_k$  can represent the electromag-

netic field associated with each k<sup>th</sup> mode as follows:

$$\vec{E}_k(t) = A_k(t)exp(-j(\omega_k t - \phi_k(t))\vec{\mu}$$
(5.1)

with amplitude  $A_k$ , angular frequency  $\omega_k = 2\pi v_k$  where the linear frequency  $v_k$  is an integer multiple of the FSR,  $\phi_k$  is the instantaneous frequency and  $\vec{\mu}$  is the polarisation vector. For simplicity, the beating between modes  $E_1$  and  $E_2$  are to be considered and in the example can be assumed to be the origin of mode-locking. The beating between  $E_1$  and  $E_2$  results in the modulation of the gain with a frequency corresponding to the difference between the two optical modes,  $v = \frac{(\omega_2 - \omega_1)}{2\pi}$ . This modulation generates equidistant side bands  $S_1$ ,  $S_3$  and  $S_2$ ,  $S_4$  around the modes  $E_1$  and  $E_2$ . The sidebands can be expressed as follows [14]:

$$S_1 = \alpha_1 \cdot E_1 \cdot E_1 \cdot E_2^* = \alpha_1 \cdot E_{12}^{2*}$$
(5.2)

$$S_2 = \alpha_2 \cdot E_1 \cdot E_1^* \cdot E_2^* \tag{5.3}$$

$$S_3 = \alpha_3 \cdot E_1 \cdot E_1^* \cdot E_2^* \tag{5.4}$$

$$S_4 = \alpha_4 \cdot E_1^* \cdot E_{22} = \alpha_4 \cdot E_1^* \cdot E_2^2 \tag{5.5}$$

where  $\alpha_k$  are the coupling efficient factors and  $E_k^*$  are the complex conjugates of the respective fields,  $E_k$ .  $S_4$ , whose amplitude and phase are related to modes  $E_1$  and  $E_2$ , pulls the mode  $E_3$  from the Fabry-Pérot (FP) resonant position and correlates the phase of mode  $E_3$  with the two modes,  $E_1$  and  $E_2$  (in Figure 5.1 the FP resonant modes are represented by a dotted line). Similar processes result from the beating modes  $E_2$  and  $E_3$  and transfer the phase information to  $E_1$ . The sidebands created through this FWM process acts as optical injection signals for modes leading to a mutual injection-locking phenomenon [15] [16]. This is a simple representation of three modes which can be further extended to a large number of optical modes.



Figure 5.1: Mutual injection regime through modulation sidebands from FWM.  $E_1$ ,  $E_2$  and  $E_3$  represent the lasing modes while  $S_1$  to  $S_5$  are the sidebands resulting from FWM.

### 5.2 Experimental Setup for Coherence Measurements

In this section, Radio Frequency (RF) beat tone measurements are carried out for a QDash laser when passively mode-locked and injection mode-locked using electrical and optical master signals. QDash MLLs are a promising technology fit for the generation of mm-wave and THz radiation owing to their low power requirements, mm-scale device footprint, and monolithic manufacturability [17]. With a spectral Full-Width Half Maximum (FWHM) of 1.6 THz, passively mode-locked QDash lasers have previously been shown to have an RF beat tone of ~10 MHz at a 1 THz spectral mode separation [18]. Quantum dot-based lasers can also achieve the THz bandwidths, but require either passive mode-locking with a saturable absorber, or active mode-locking [19]. QDash lasers, on the other hand, have demonstrated passive mode-locking without the use of a saturable absorber section [17] [18].

### 5.2.1 Laser Setup

The device used in this research is a 42.7 GHz QDash FP mode-locked laser, fabricated at III-V Labs . A temperature probe, a Peltier cooler, and a microwave V-type connector have been integrated with the QDash laser into a butterfly module [20]. Throughout this research the QDash laser was driven by a Direct Current (DC) bias current of 100 mA and held at a constant temperature of 26°C. Figure 5.2 demonstrates the three laser setups used. Figure 5.2a illustrates the passively mode-locked QDash laser setup. Figure 5.2b depicts the setup for the electrically mode-locked QDash laser where 4 dBm of electrical power from a 42.7 GHz RF synthesizer was used to actively lock the laser. Figure 5.2c shows the mode-locking of the QDash laser through optical injection. Approximately 1 dBm of optical power is injected inside the cavity of the QDash module through an optical circulator. The optical signal is generated using an External Cavity Laser (ECL) modulated by a MZM and a 42.7 GHz RF synthesizer. The optical spectrum from the QDash when it is passively mode-locked is illustrated in Figure 5.3.

The electric field of the QDash laser was measured for the three distinct methods of mode-locking using the stepped heterodyne measurement technique outlined in [21]. The spectral field and temporal field of similar QDash lasers have been presented in prior literature [18] [21], and the device used in this study displayed the characteristic square spectral intensity profile with a bandwidth of ~1.6THz and possesses a large group delay dispersion of ~2 ps<sup>2</sup> for all three mode-locking mechanisms. The dispersion profile was characterised using the stepped heterodyne measurements and compensated for using the programmable optical filter (Wavelength Selective Switch (WSS)). The transform-limited pulse duration for the passively, electrically and optically-injected mode-locked QDash laser was 637 fs, 636 fs and 611 fs, respectively.



Figure 5.2: QDash setup: (a) passively mode locked, (b) electrically mode-locked using a 42.7 GHz RF synthesizer and (c) mode-locked by optical injection, using an ECL modulated with an MZM and 42.7 GHz RF synthesizer.

### 5.2.2 Coherence Measurements of Adjacent Tones

To measure the RF linewidth of two adjacent modes, an 80 GHz bandwidth bandpass filter, created by the WSS, was used to filter off two adjacent modes separated by 42.7 GHz. Subsequently, the two tones beat together on a photodetector and the RF beat-tone linewidth is measured using an Electrical Spectrum Analyser (ESA). The setup for measuring the RF beat tone linewidth of the adjacent tones is illustrated in Figure 5.4. This process was carried out across the entire spectrum of the QDash laser for each mode-locking scenario demonstrated in Figure 5.2.



Figure 5.3: Optical Spectrum of the QDash laser when passively mode-locked.

The passively mode-locked QDash laser possesses an RF linewidth of approximately 7 kHz for the adjacent tones. A measurement of 30 Hz was taken for the actively mode-locked QDash laser for both the electrical and optical injection setups. The low value for the RF linewidth is attributed to the low phase noise of the 42.7 GHz signal generator used in the actively mode-locked QDash laser setups.



Figure 5.4: Setup used to measure the RF linewidth of the adjacent tones of the QDash laser when set up as demonstrated in Figure 5.2.

#### 5.2.3 Coherence Measurements of Non-Adjacent Tones

As the RF beat-tone for the non-adjacent modes is too high in frequency (>80 GHz) to use conventional electrical domain measurement techniques, a method which utilises optical down-conversion is employed. Initially, a set of non-adjacent modes are filtered off corresponding to a mode separation greater than 42.7 GHz. The two modes (at angular frequencies  $\omega_1$  and  $\omega_2$ ) are combined with two 20 mW ECLs. The ECLs are used as pumps for a FWM based wavelength converter utilising a Semiconductor Optical Amplifier (SOA). The operating principle of the wavelength conversion technique is shown in Figure 5.6, where two widely spaced spectral modes are converted down to a small frequency separation through the careful choice of the pump frequencies. This arrangement generates two degenerate FWM idlers at frequencies of  $2\omega_2 + \omega_1$  and  $2\omega_3 - \omega_4$ . This allows for the generation of two FWM idlers with a frequency separation of less than 10 GHz. Unlike the previous setup, it was not possible to measure the RF beat-tone linewidth of the two idlers using a photodetector and an ESA. This was due to the limited short-term frequency stability of the two ECLs which meant that the beat frequency generated by the two idlers would move by hundreds of MHz during the minimum scan time of the ESA (~50 ms). To overcome this, a Real-Time Scope (RTS) was used to measure the beat signal over a considerably shorter time window of 3.2  $\mu$ s (128,000 samples at a 40 GS/s sampling rate). Therefore, the low frequency drift of the ECL carrier frequency was eliminated. The setup for this measurement technique is demonstrated in Figure 5.5. The experiment was carried out for the passively and actively mode-locked QDash laser setups shown in Figure 5.2 for non-adjacent modes out to the  $26_{th}$  harmonic, corresponding to a mode separation of 1.1 THz.



Figure 5.5: Setup used to measure the RF linewidth of the non-adjacent tones of the QDash laser when set up as demonstrated in Figure 5.2.



Figure 5.6: Illustration of the degenerate FWM scheme employed to achieve correct phase conjugation, where  $\omega_1$  and  $\omega_4$  are the two spectral modes to be wavelength converted, and  $\omega_2$  and  $\omega_3$  are the ECL pumps.

#### 5.2.4 Results

The RF beat-tone linewidth of the non-adjacent spectral modes was determined by fitting a Lorentzian lineshape to the Power Spectral Density (PSD) of the measured beat signal. The RF beat-tone linewidth measured using this technique has a minimum value of at least the sum of the optical linewidths of the two ECL pumps which is equal to 330 kHz in this case. Inset of Figure 5.7 demonstrates the PSD of the measured temporal beating of two idlers after two non-adjacent spectral modes of the QDash laser undergo degenerate FWM, the red line is a nonlinearly regressed Lorentzian fit to the measured data. The dual-pump degenerate FWM conversion scheme can not accurately measure RF beat-tone linewidths less than 330 kHz, but instead infers that the spectral modes exhibit excellent coherence.



Figure 5.7: Measured RF beat-tone linewidths for two spectral modes as a function of increasing spectral mode separation when passively, optically and electrically mode locked.

The RF beat-tone measurements are conveyed in Figure 5.7 as a function of the spectral mode separation. The red dots specify the RF beat-tone linewidths of the QDash measured for the passive mode locking case and follows a trend in agreement with measurements performed on a similar device [18]. A quadratic trend is fitted to the measured data, indicated by the solid red line, following theory outlined in [22]. The microwave power spectrum of passively mode-locked lasers, the RF linewidth,  $\Delta \omega_{RF_m}$ , of the *m*<sup>th</sup> frequency harmonic is described by,

$$\Delta\omega_{RF_m} = \frac{4\pi^2}{M^2} \Delta\omega_t m^2 \tag{5.6}$$

where,  $M = \frac{T}{\tau}$  is the ratio of the pulse width,  $\tau$ , and the pulse repetition period, T, which is the number of spectral modes within the spectral FWHM. For the passively mode-locked QDash, M = 37 spectral modes. As M is known, the microwave

linewidth factor,  $\frac{\Delta\omega_t}{(2\pi)}$ , can be found using the measured data for  $\Delta\omega_{RF_m}$  for each harmonic to regressively fit the theory to the data. The average microwave linewidth factor is found to be 285.7 kHz and this value is used for the regressed fit shown in Figure 5.7 as the solid red line. The theory predicts the RF linewidth of the first harmonic (adjacent spectral modes) to be  $\frac{\Delta\omega_{RF_1}}{(2\pi)}$  = 8.3 kHz, in good agreement with what is measured using an ESA (7 kHz). The measured RF beat-tone linewidths of the QDash for the electrically and optically injected mode-locked QDash setups are represented by green diamonds and blue triangles, respectively. The fit also found an RF linewidth offset of 330.2 kHz is in agreement with the measured linewidth resolution limitation imposed by the FWM-based wavelength converter. The resolution limitation imposed by the FWM-based wavelength converter masks the expected quadratic trend for the active mode-locked cases. For both the electrically and optically mode-locked cases the RF beat-tone linewidths possess a mean value of 490 kHz with a standard deviation of 90 kHz, implying excellent coherence of spectral modes out to a frequency separation of 1.1 THz.

### 5.3 Conclusion

The evolution of the spectral mode coherence of a passively and actively modelocked QDash over 1 THz spectral bandwidth has been investigated. For the passively mode-locked laser the RF linewidth follows a quadratic evolution with respect to increasing spectral mode separation and is in good agreement with theory. The actively mode-locked schemes revealed consistently low RF linewidths out to the 26<sup>th</sup> frequency harmonic, or 1110.2 GHz. In conclusion, the QDash lasers are a promising technology fit for the generation of mm-wave and THz radiation owing to their high coherence, low power requirements, mm-scale device footprint and monolithic manufacturability.

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### **Chapter 6**

# **Conclusion and Future Works**

### 6.1 Conclusion

An increase in the number of broadband connections has given rise to the growth of overall internet traffic. The total number of Fibre to the Home (FTTH) subscribers increased by 29% in 2013. In tandem with the increased number of broadband subscribers, an increasingly large proportion of internet traffic is wirelessly delivered to, or from, portable and mobiles devices with trends showing a 25% Compound Annual Growth Rate (CAGR) increase over the next five years. The content delivered to the portable and mobile devices is predominately internet video. The large ever-growing demand for such online services, with a focus on moving towards higher quality video streaming (i.e 4k or Ultra High Definition Television (UHDTV)), incentivises Internet Service Providers (ISPs) and governments to invest in higher capacity access networks with seamless connectivity between the wired and wireless networks. The method advocated in this thesis to achieve the seamless communication between the wired and wireless networks is Millimetre Wave (mm-wave) Radio-over-Fibre (RoF) systems.

At higher frequencies, such as the mm-wave range, unlicensed bandwidth is widely available. The systems in this thesis operate at the 60 GHz frequency band which possesses at least 5 GHz of continuous bandwidth in the majority of countries. This large amount of available bandwidth is capable of providing the required bandwidth for high quality online video services. However, mm-wave signals experience high attenuation in atmospheric oxygen and therefore are unsuitable for long range transmission. As a result, the 60 GHz band can be used exclusively for short-range indoor communications (<50 m) where the attenuation due to the atmospheric oxygen becomes negligible. To extend the transmission distances of the mm-waves, and to provide the seamless convergence of the wired and wireless access networks, RoF networks are the most promising solution.

RoF systems can provide for the centralisation of the data modulation and system control processes in a shared location, the Central Office (CO) or the Central Station (CS). Optical fibre is used to distribute the mm-wave signals from the CS to the Remote Antenna Unit (RAU) where the wireless signal is transmitted to the end-user's device. The RoF system allows for the simplification of the RAU as only optoelectronic conversion, filtering and amplification may be required. RoF allows for the installation of the expensive components required for the data modulation and system control process in a single shared location, the CS. This centralisation causes a reduction in both the Capital Expenditure (CAPEX) and Operating Expenditure (OPEX).

### 6.1.1 Gain Switched Laser for Mm-Wave Systems

In Chapter 3, the technique of gain switching a laser diode to produce an Optical Frequency Comb (OFC) is used to generate a highly stable mm-wave for use in RoF systems. The OFC generates a number of lines equally spaced in the frequency domain by the frequency of the driving signal. Two modes of the OFC separated by 60 GHz are filtered off and used to generate a highly stable 60 GHz optical mmwave signal. The optical signal is externally modulated with a 2.5 Gb/s On-Off Keying (OOK) signal. Transmission with receiver sensitivities as low as -34 dBm for transmission over 24 km is demonstrated. Using this 2.5 Gb/s OOK Gain-Switched Laser (GSL) setup, the merits of suppressing unwanted comb lines was carried out where unwanted comb lines of the OFC were not fully suppressed and their effects on the system was analysed for Back to Back (BTB) transmission and transmission over 12 km. The analysis found that suppression of the unwanted comb lines by <15 dB caused a major detrimental effect on the system causing a reduction in system performance. Therefore this highlights the importance of optical filters which can provide suppression >15 dB in the RoF system. Finally, using the GSL setup, pre-compensation of chromatic dispersion to combat the limiting effects of bit-walk off on the maximum transmission distance is carried out. Results demonstrate that using a single multi-functional programmable optical filter to filter off unwanted comb lines and pre-compensate for 12 km of dispersion was possible. The transmission distance of this system is limited due to bit-walk off caused by chromatic dispersion.

Chapter 3 also demonstrates a 60 GHz RoF system based on the GSL which utilises low cost electronics to implement a baud rate/modulation format scalable Single Sideband (SSB) Sub Carrier Multiplexed (SCM) Quadrature Phase-Shift Keying (QPSK) system. The experiment achieves successful error-free transmission of a 1.25 Gbaud/s QPSK signal over 25 km of Standard Single Mode Fibre (SSMF). While this system mitigates the effects of bit-walk off by using SSB modulation, optical phase decorrelation of the optical tones occurs due to chromatic dispersion, once again limiting system performance.

Both of these systems demonstrate simple and cost-effective RoF systems which

not only utilise cheap analog electronics but also do not require costly low linewidth lasers at the CS or complex Digital Signal Processing (DSP). However, performance of both systems are limited due to chromatic dispersion.

### 6.1.2 25 Gb/s Orthogonal Frequency Division Multiplexed 60 GHz Radio over Fibre System

In Chapter 4, a technique based on Wavelength Division Multiplexing (WDM) is used to simplify the GSL RoF transmitter by allowing for the modulation of a single optical tone individually. This technique overcomes the limitations associated with bit-walk off and allows for the use of Orthogonal Frequency Division Multiplexing (OFDM) to increase the spectral efficiency of the RoF system and therefore, the achievable data rate. Using this transmitter, two high-speed 60 GHz OFDM RoF systems are realised. The initial system utilises a low complexity gain switched Distributed Feedback (DFB) laser with a large linewidth per comb line. This system is capable of transmitting a 25 Gb/s OFDM signal over 50 km of SSMF with a Bit-Error Rate (BER) below the 7% Forward Error Correction (FEC) limit. However, this system requires a pre-compensation technique to overcome the optical phase decorrelation between the optical comb lines induced by chromatic dispersion.

The second system overcomes the Radio Frequency (RF) phase noise resulting from the optical phase decorrelation without the need for precise compensation techniques. The GSL is externally injected to generate a low linewidth coherent comb source. The system demonstrates negligible phase noise penalties and performance below the 7% FEC limit is achieved for transmission of a 25 Gb/s OFDM 60 GHz signal over 25 km of SSMF and 2 m wireless.

The two systems represent two potentially cost effective methods to transmit high

data rate OFDM mm-waves in a RoF configuration.

#### 6.1.3 Quantum Dash Semiconductor Laser

While the previous chapters focused on using mm-wave frequency bands, for future wireless system, the THz frequency range of 275-3000 GHz is important as it has not yet been defined for specific uses. As with mm-wave radiation, THz radiation suffers attenuation due to atmospheric oxygen and therefore will be used in RoF configurations in the same manner as mm-waves. Chapter 5 uses a Quantum Dash Semiconductor (QDash) semiconductor laser to generate an OFC which can be used for not only generation of mm-waves but also THz radiation.

In this chapter, the evolution of the spectral mode coherence for the QDash laser when it is passively and actively mode-locked is investigated. Results demonstrate that the RF linewidth of the passively mode-locked laser follows a quadratic trend with respect to increasing spectral mode separation. When the laser is actively mode-locked, either optically or electrically, the measured RF linewidths out to the 26<sup>th</sup> harmonic, or a frequency separation of 1110.2 GHz, are consistently low with a mean value of 490 kHz. This implies excellent coherence of the spectral modes. The QDash laser also possess low power requirements, mm-scale device footprint and monolithic manufacturability and could be a promising fit for the generation of mm-wave and THz radiation.

### 6.2 Future Work

The research in this thesis has shown the potential of RoF to satisfy the demands of the seamless integration of wired and wireless next generation optical access networks. However, many areas directly related to this work remain in need of further investigation.

### 6.2.1 Systems Experiments Utilising the Gain Switched Laser at Higher Frequencies

The experimental work carried out in this thesis utilising a GSL was at the frequency of 60 GHz. While the 60 GHz frequency band is the most popular band in the mm-wave range, interest has also spread to the paired bands of 71-76/81-86 GHz which are allocated for outdoor commercial use over distance of several kilometres in the US, Europe and other countries. Other bands around 100 GHz and higher in the mm-wave range have not yet been allocated to specific applications and therefore have the potential to cater for high data rates and in particular ultra fast close proximity bulk data transfer. As a result, future research utilising the GSL's OFC to generate mm-waves at frequencies of higher than 60 GHz would be of interest.

### 6.2.2 Mode Locked Laser to Generate Millimeter Waves for use in a Radio over Fibre System

In this research, coherence measurements of a QDash semiconductor laser were carried out. It would be interesting research to further assess this laser as a promising technology fit for generating mm-wave and THz radiation by carring out various systems experiments using this QDash laser. Using the Mode Locked Laser (MLL) source, experiments such as the ones carried out using the GSL in this research with various modulation formats and data rates could be completed. The MLL could also be used in systems experiments for higher frequencies in the mmwave range and the THz range.

### 6.2.3 Photonic Integration

An important technology to research and to aid moving the RoF systems in this thesis towards practical implementation is photonic integration. Currently, the systems demonstrated have consisted of discrete components. Examining the externally injected GSL setup, these discrete components include the slave and master lasers and passive optical components such as optical fibres, a polarisation controller and connecting fibres. This arrangement potentially suffers from various external sources of instability and noise in the injection path, i.e. polarisation dependence, temperature variation and mechanical vibration. These two lasers could be photonically integrated in order to alleviate these issues while also reducing insertion loss and the actual physical device footprint. There is also the possibility of photonically integrating the optical filtering onto a single chip and allowing for the comb lines separated by the desired mm-wave frequency to be modulated either together or individually before recombination. Future work to create such a single chip device would provide an extremely cost-effective transmitter solution for future practical mm-wave RoF systems.

## Appendix A

# List of Publications Arising From This Work

### A.1 Referred Journal Papers

- T. Shao, E. Martin , P. Anandarajah, C. Browning, V. Vujicic, R. Llorente and L. Barry. DM-DD OFDM-RoF System With Adaptive Modulation Using a Gain-Switched Laser, Photonics Technology Letters, Jan. 2015.
- E. Martin, T. Shao, P. Anandarajah, C. Browning, V. Vujicic, R. Llorente and L. Barry. 25 Gb/s OFDM 60 GHz Radio over Fibre System Based on a Gain Switched Laser (Invited Paper), Journal of Lightwave Technology, Vol. 33, Iss. 6, Jan. 2015.
- T. Shao, E. Martin, P. Anandarajah, and L. Barry. 60 GHz Direct Modulation-Direct Detection OFDM-RoF System Using Gain-Switched Laser in Photonics Technology Letters, IEEE, ISSN 1041-1135, Oct. 2014.
- 4. T. Shao, E. Martin, P. Anandarajah, C. Browning, V. Vujicic, R. Llorente and

L. Barry. Chromatic Dispersion Induced Optical Phase Decorrelation in a 60 GHz OFDM-RoF System in Photonics Technology Letters, IEEE, ISSN 1041-1135, Aug. 2014.

- E. Martin and L. Barry. Side Mode Suppression and Dispersion Compensation Analysis of a 60 GHz Radio-over-Fibre System Based on a Gain Switched Laser in Optics Communications, Vol. 313, Pages 36-41, ISSN 0030-4018, Feb. 2014.
- E. Martin, R. Watts, L. Bramerie, and L. Barry. THz-Bandwidth Coherence Measurements of a Quantum Dash Laser in Passive and Active Mode-Locking Operation in Optics Letters Vol. 37, Iss. 23, pp. 4967-4969, 2012.

### A.2 Conference Papers

- E. Martin, T. Shao, P. Anandarajah, C. Browning, V. Vujicic, R. Llorente and L. Barry. Impact and Reduction of Fibre Nonlinearities in a 25 Gb/s OFDM 60 GHz Radio over Fibre System. Microwave Photonics (MWP), Sapporo, Japan, Oct. 2014.
- E. Martin, P. Anandarajah, and L. Barry. 60 GHz SSB SCM QPSK Radio over Fibre System. Microwave Photonics (MWP), Sapporo, Japan, Oct. 2014.
- E. Martin, T. Shao, P. Anandarajah, C. Browning, V. Vujicic, R. Llorente and L. Barry. 25 Gb/s OFDM 60 GHz Radio over Fibre System Using an Externally Injected Gain Switched Distributed Feedback Laser. European Conference on Optical Communications (ECOC), Cannes, France, Sept. 2014.
- 4. E. Martin and L. Barry. 60 GHz Millimeter-Wave System Based on an Optical Frequency Comb Generated by a Gain Switched Laser. Photonics Ireland,

Belfast, Ireland, 2013.

- E. Martin, R. Watts, L. Bramerie, and L. Barry. Mm-wave and THz Radiation Generation Using Quantum-Dash Semiconductor Lasers at Research Colloquium on Communications and Radio Science into the Twenty First Century, Dublin, Ireland, 2012.
- 6. L. Bramerie, E. Martin, R. Watts, L. Barry, M. Gay and P. Besnard. Analyse THz d'un laser a Batonnets Quantiques en regime de verrouillage de modes passif et actif. Annual Optics and Microwave Meeting, Institute of Electronics, Microelectronics and Nanotechnology (IEMN), Lille, France, 2012.

# Appendix **B**

# **Consumer Services Adoptions**

Service	2013	2014	2015	2016	2017	2018	CAGR
Digital TV	1029	1163	1292	1383	1440	1517	8.07%
PVR	131	147	162	175	186	198	8.61%
VoD	306	342	378	412	431	451	8.10%
<b>Residential VoIP</b>	955	1015	1073	1127	1173	1216	4.95%
Social Networking	1288	1393	1481	1571	1649	1726	6.02%
Online Music	1141	1240	1351	1443	1525	1608	7.10%
Online Video	1205	1367	1513	1656	1777	1912	9.66%
Online Gaming	1129	1232	1320	1400	1467	1534	6.33%

Table B.1: Residential services global adoption (Millions of Subscribers or Users)

Source: Cisco VNI Sevice Adoption Forecast, 2013 - 2018