Detuning Dependence of Four-Wave Mixing Between Picosecond Pulses in a Multi-Quantum Well Semiconductor Optical Amplifier

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***Abstract* — Four-wave mixing is investigated experimentally using frequency resolved optical gating in a multi-quantum well semiconductor optical amplifier. Demultiplexing is carried out from 80 GHz to 10 GHz using two picosecond pulses. The pump-probe detuning is varied and it is found that the probe phase is preserved in the four-wave mixing signal across the central portion of the pulse. Also, the pedestals present in the four-wave mixing waveform are measured and it is found that the impact of these pedestals increases as a function of the detuning due to the carrier dynamics in the device.**

***Index Terms* — Demultiplexing, optical pulse measurements, optical signal processing, semiconductor optical amplifiers.**

I. Introduction

Due to the demand for higher bandwidth in current telecommunication networks, much work has focused on developing all-optical signal processing techniques for use in all-optical networks. Such a solution would remove the 'bottleneck' introduced by electrical components currently required to carry out signal processing functions. One of the most attractive devices which has been put forward is the Semiconductor Optical Amplifier (SOA) due to its high nonlinearities, high gain, small size, integratability and relatively low cost. There are several techniques which can be used to perform all-optical signal processing in SOA devices. These include Cross-gain Modulation (XGM), Cross-Phase Modulation (XPM) and Cross-Polarization Modulation (XPolM) [1-3]. However, none of these techniques are truly transparent and the phase of the original signal is not preserved. These disadvantages may be overcome using a technique known as Four-Wave Mixing (FWM). This is a process whereby two signals, a pump and a probe, are injected into the SOA with a frequency detuning between the signals, given by Ω. Due to third order nonlinearities, the gain of the SOA is modulated leading to the creation of new components in the spectrum. The spacing of the new components is determined by the frequency detuning between the pump and the probe signals [4,5]. An interesting property of the generated FWM component is that the phase of this signal is the conjugate of the phase of the injected probe signal. This phase preservation cannot be achieved using any of the other techniques that may be used for all-optical signal processing with SOA's and has huge potential for use in optical systems. One good example is the possibility to perform wavelength conversion and demultiplexing with Differential Phase-Shift Keying (DPSK) format data in all-optical networks [6,7].

If FWM is to be used to perform all-optical signal processing, a detailed understanding of the process of FWM between picosecond pulses must be achieved. Recently much work has focussed of this application of FWM, but the majority of this work has been theoretical and no experimental results have been presented which provide a full intensity and phase characterization of FWM between picosecond pulses, to the best of the author's knowledge. Furthermore, an important aspect of FWM is the detuning between the pump and the probe signal. Care must be taken in the choice of the detuning in the case when pulses are considered. This detuning must be greater than the spectral width of the pulses under test. However, as the detuning is increased, the efficiency of the FWM process reduces due to the dominance of weaker gain dynamics such as CH and SHB.

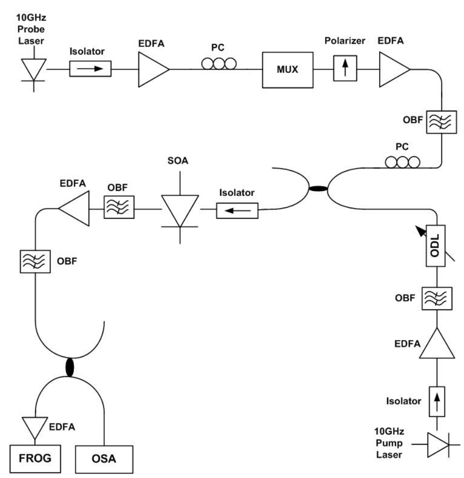

Figure 1. Experimental Setup.

In this paper experimental results are presented for the demultiplexed FWM component generated due to the beating between picosecond pulses in the SOA. The pump signal consisted of 4 ps pulses at a repetition rate of 10 GHz, whilst the probe consisted of 2 ps pulses at a repetition rate of 80 GHz, resulting in a FWM component demultiplexed to 10 GHz. The intensity and phase of both

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the injected pump and probe pulses were measured. It is shown that the phase is preserved in the FWM component, as is expected from the theory. The intensity profile of the FWM signal is also presented and it is shown that the influence of the weak pedestals present in the wings of the injected pulses is significantly enhanced in the conjugate signal. The effect of the enhanced pedestals has been presented before in the case of a single pulse being amplified in the SOA and was attributed to gain depletion effects [8].

The effect of increasing the pump-probe detuning is then investigated. The chirp profile is found to develop nonlinear components in the wings of the pulse, as the detuning is increased, but the chirp is preserved over the central portion of the pulse. In terms of the pulse shape, the influence of the pulse pedestals increases as a function of detuning, leading to a reduced signal-to-noise ratio for the FWM signal. These effects should be taken into consideration if FWM is to be realized for all-optical processing in future all-optical networks.

II. Experimental Setup

The experimental setup is illustrated in Figure 1. 2 ps pulses were generated using two actively injected mode-locked laser sources. The repetition rate of both signals was 10 GHz and the wavelength of the pump laser was 1550 nm for each measurement taken. This wavelength is close to the peak gain wavelength of the device under test. The wavelength of the probe laser was varied between 1555 nm and 1565 nm. The resulting FWM may be described as wavelength down conversion. The probe signal was amplified using an Erbium Doped Fibre Amplifier (EDFA) and injected into a multiplexer in order to multiplex the pulses from 10 to 80 GHz. After the multiplexer, the signal was amplified once more and a Band-Pass Filter (BPF) was used in order to remove any Amplified Spontaneous Emission (ASE) introduced by the EDFAs. The probe signal was then coupled with the pump pulses before injection into the SOA device. The pump signal was amplified and then filtered by a BPF with a passband of 1 nm. This narrow passband had the effect of broadening the pulsewidth from 2 ps to 4 ps. This broadening allowed for FWM components generated due to the beating between the pedestals of the probe signal and the broadened section of the pump signal to be examined. The average powers of the pump and probe signals at 10 GHz and 80 GHz were 4 dBm and 0.25 dBm, respectively. An Optical Delay Line (ODL) was placed in the pump arm of the setup to allow for the optimum overlapping of the two signals to produce the most efficient FWM signal. The SOA under test was a multi-quantum well device biased at 200 mA, with a peak gain of 25 dB. At the output of the SOA, a BPF was used to isolate the FWM component from the output spectrum. The FWM component was then examined using second-harmonic generation Frequency Resolved Optical Gating (FROG) [9]. The FROG technique generates a three-dimensional spectrogram, which is a time-frequency representation of the pulse. A phase retrieval program is then applied to allow for the electric field of the pulse to be determined, giving the complete temporal and spectral characterization of the pulse [10]. Due to the power requirements of the FROG measurement, an EDFA is used to amplify the pulses before they are input into the FROG measurement system. This gives the pulse a larger signal-to-noise ratio resulting in more accurate retrievals of the electric field of the pulse. The EDFA used was designed for the amplification of 2 ps pulses. Low errors of $\approx 4\text{x}10^{-5}$ were recorded for the retrieved pulses, indicating that the retrievals were accurate [9].

III. Results

The intensity of the injected pump and probe signals is shown in Figure 2(a). The probe signal has a pulsewidth of 2 ps. The pedestals in the wings of the probe signal are located approximately 40 dB from the peak of the pulse. These pedestals are introduced in the mode-locking process in the source laser. The broadening introduced by the 1 nm BPF in the pump arm can be seen in the intensity profile of the pump signal, which has a pulsewidth of 4 ps. The chirp present for both the pump and probe signals is shown in Figure 2(b). The linear chirp introduced across the central part of the pulse is very similar for both pump and probe signals. This is to be expected as the pulses are generated in mode-locked laser sources with similar specifications. The slight difference in the slope of the chirp is thought to be due to the BPF present in the pump arm of the setup.

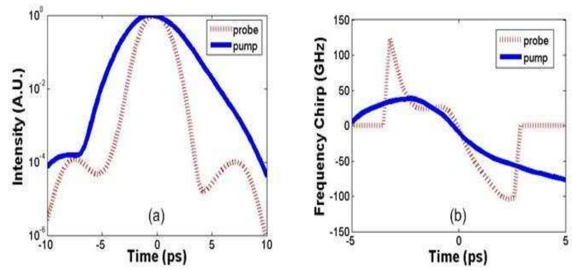

Figure 2. (a) Intensity and (b) chirp of the pump and probe signals injected into the SOA.

In Figure 3 the intensity and chirp of the injected probe signal, FWM component and amplified probe signal, after passing through the SOA in co-propagation with the pump, are shown. As discussed in relation to Fig. 2(a), the pedestals which are present on the initial probe pulses are located approximately 40 dB below the peak of the pulse. After propagation through the SOA the pedestals have increased in significance and are located approximately 20 dB below the peak of the pulse on the trailing edge. The amplification of the probe pulse pedestals has been explained through the effects of gain saturation [8]. However, in this reference the largest amplification of the pedestals was measured on the leading edge, due to the larger gain seen by this pedestal prior to the depletion of the gain caused by the main pulse. The larger amplification of the trailing edge pedestal in relation to the peak of the pulse, shown in Figure 3(a), is thought to be related to the gain-induced refractive index dispersion, which may cause the pump pulses to travel through the SOA at a faster velocity than the probe pulses [11]. Therefore, the leading edge probe pedestals may be amplified during the depleted regime of the SOA gain whilst the trailing edge pedestals may receive a larger gain than both the leading edge pedestals and the main portion of the probe pulse, as the gain will have started to recover by this time.

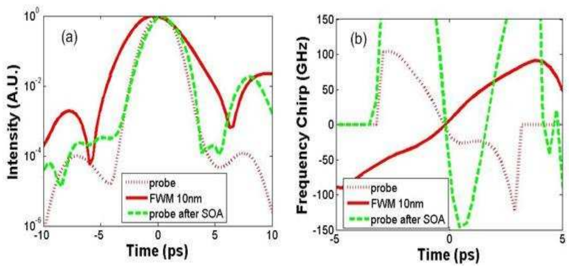

Figure 3. (a) Intensity and (b) chirp of the probe, amplified probe and FWM signals at the output of the SOA.

The FWM signal generated at the beat frequency determined by the detuning between the pump and the probe signals is also shown in Figure 3. The FWM signal is at a lower wavelength, 1540nm, than the probe signal therefore the conversion is wavelength down conversion. From Figure 3(a), it can be seen that there is an increase in the influence of the pedestals for the FWM signal in comparison with the amplified probe signal. This is particularly the case for the pulses located on the leading edge of the pulse. The pedestals are located approximately 20 dB from the peak of the pulse on the trailing edge of the pulse and approximately 27 dB from the peak of the pulse on the leading edge. The increase in the leading edge pedestal is believed to be caused by the combined effects of FWM and SPM in the active region of the device. It may also be seen from Figure 3(a) that the FWM signal is considerably wider than the injected and amplified probe signals. This is thought to be primarily due to the two BPFs located at the output of the SOA device, as illustrated in Figure 1. The frequency chirp present for the FWM signal, solid line, together with the initial probe frequency chirp, dotted line, is shown in Figure 3(b). As the FWM component is the phase conjugate of the injected probe signal, the frequency chirps have opposite slopes. The magnitudes of the chirps are very similar and the FWM component has a linear chirp as does the initial probe signal. It can be seen that no large nonlinear components are introduced to the chirp due to the FWM process. This may be compared to the chirp introduced to the amplified probe signal, dashed line, also shown in Figure 3(b). A large nonlinear chirp component is introduced due to Self-Phase Modulation (SPM) in the SOA. The shape of the chirp introduced due to SPM is similar to that which is discussed in the literature [12]. This is another potential advantage of using FWM for all-optical processing in SOA's, as compared with other techniques, as the chirp introduced due to SPM is not necessarily transferred to the FWM conjugate signal.

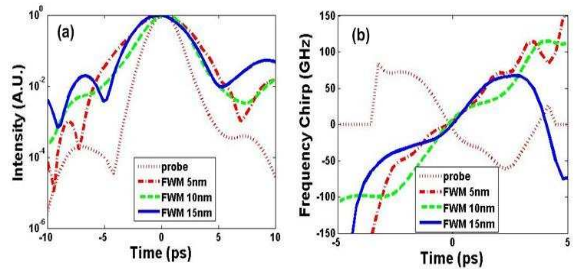

Figure 4. (a) Intensity and (b) chirp of the injected probe and FWM signals at detunings of 5, 10 and 15 nm.

The variation of the intensity and frequency chirp of the FWM signal measured as a function of detuning is shown in Figure 4. The FWM signal was measured using the FROG at pump-probe detunings of 5, 10 and 15 nm. The intensity profile is shown in Figure 4(a). The most significant variation in the pulse shape as a function of detuning is in terms of the level of the pulse pedestals with respect to the peak of the pulse. As discussed in relation to Figure 3(a), the trailing edge pedestal is stronger than the leading edge pedestal. For a detuning of 5 nm the leading edge pedestal is located approximately 30 dB from the peak of the pulse and the trailing edge pedestal is located approximately 19 dB from the peak of the pulse. From [5] an increase in the detuning leads to a narrower pulse width, due to the reduced coupling coefficient between the two pulses. However, it can also be seen from Figure 4(a) that an increase in the detuning also leads to a large increase in the level of the pulse pedestals, with respect to the peak of the pulse. This increase in the pulse pedestals is particularly significant on the leading edge with the pedestal moving from 30 dB below the peak of the pulse to 19 dB below the peak of the pulse for an increase in the detuning from 5 nm to 15 nm. On the trailing edge the increase in the level of the pedestals as a function of detuning is smaller increasing from 19 dB to 15 dB below the peak of the main pulse as the detuning is increased from 5 nm to 15 nm.

One possible explanation for this effect is the pump signal travelling through the SOA faster than the probe signal, due to the gain-induced refractive index dispersion [11]. This explanation would be consistent with the results presented in Figure 3. A faster velocity of the pump signal would cause the peak of the pump signal to be located closer to the leading edge pedestal of the probe signal. This would lead to a larger FWM component generated due to the beating between the probe pedestal and the pump signal. Similarly, the shift of the pump signal towards the leading edge of the probe signal would reduce the FWM component generated due to the beating of the peak of the probe signal with the pump signal. This would also explain the large increase in the leading edge pedestal of the FWM component with respect to the amplified probe signal measured in Figure 3(a). An increase in the pump-probe detuning causes a higher level of gain-induced refractive index dispersion, resulting in a larger temporal mismatch between the pump and the probe signal. This causes the pump signal to be more closely matched to the probe leading edge pedestal. This leads to a larger FWM leading edge pedestal component. Likewise, the increased temporal mismatch results in a smaller FWM component due to the main section of the probe signal, as it is temporally overlapped with a lower level of pump intensity. This analysis is consistent with the results shown in Figure 4(a).

The frequency chirp measured for the FWM component as a function of detuning, along with the frequency chirp of the injected probe signal is presented in Figure 4(b). It can be seen that across the central portion of the pulse the frequency chirp is very similar, as the detuning is increased. This is important as it shows that the pump-probe detuning may be varied in order to suit requirements without any significant variation in the phase of the signal. However, it should be noted that in the wings of the FWM signal, the frequency chirp varies quite significantly as the detuning is increased. This variation may be related to the increased significance of the pulse pedestals, which has already been discussed.

IV. CONCLUSIONS

Results have been presented showing demultiplexing from 80 GHz to 10 GHz based on FWM in a multi-quantum well device. The FWM signal was measured using the FROG technique, allowing for its complete characterization. The chirp of the converted FWM signal is presented demonstrating the preservation of the phase. The impact of the pulse pedestals is also analyzed. It is shown that these pedestals have a large impact on the FWM signal. Results are also presented showing the pulse shape and frequency chirp as a function of pump-probe detuning. It is shown that the level of the pulse pedestals increases significantly as a function of detuning. The frequency chirp is shown to be consistent as a function of the frequency detuning over the central portion of the pulse. It is shown that several considerations should be taken into consideration when varying the pump-probe detuning for future all-optical processing elements based on FWM in the SOA.

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