# Ultra–High Speed All–Optical Demultiplexing based on Two–Photon Absorption in a Laser Diode

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## Abstract

We describe how the nonlinear process of two–photon absorption in a commercial laser diode may be used for all–optical demultiplexing in Tbit/s OTDM networks. Switching windows of 650 fs in duration are presented, and the switching energies required are around 5 pJ.

## Introduction

The availability of a stable and compact ultrafast switch for demultiplexing ultrahigh bit rate Optical Time Division Multiplexed (OTDM) signals is essential for the future development of high capacity networks. To achieve demultiplexing in very high capacity OTDM systems it is necessary to use all–optical switching devices based on instantaneous optical nonlinearities. Two common high speed all–optical demultiplexers are the nonlinear optical loop mirror (NOLM) [1], based on the Kerr effect in optical fibres, and the Terahertz Optical Asymmetric Demultiplexer (TOAD) [2], based on nonlinearities associated with carrier depletion in semiconductor optical amplifiers (SOA). Although recent NOLM and TOAD–based demultiplexers have demonstrated all–optical demultiplexing in systems operating at up to 640 Gbit/s [3,4], a number of factors limit the performance of these devices. For example, high speed switching in the NOLM requires speciality fibre and precise wavelength control of signal and control pulses about the fibre zero dispersion wavelength, and with TOAD gain depletion in the SOA has been shown to limit the minimum control pulse width and thus the maximum switching speed [5]. Because of these limitations of presently available all–optical switches, it is important to consider alternative optical nonlinearities for ultrafast demultiplexing. In this letter, we demonstrate the first use of the two–photon absorption (TPA) nonlinearity in a commercial laser diode as an ultrafast, all–optical switch for demultiplexing.

## Principle of TPA demultiplexer

The phenomenon of TPA is a nonlinear optical–to–electrical conversion process where two photons are absorbed in the generation of a single electron–hole carrier pair. It occurs when a photon of energy $E_{ph}$ is incident on the active area of a semiconductor device with a bandgap exceeding $E_{ph}$ but less than $2E_{ph}$. TPA in semiconductor devices has been a subject of considerable research [6, 7], and it has been recently demonstrated that commercially–available 1.3 μm laser diodes are ideally suited to TPA detection of incident pulses at 1.5 μm, with experiments demonstrating highly–sensitive ultrashort pulse autocorrelation, and ultrafast optical thresholding in optical networks [6].

Figure 1 shows the principle of operation of an all–optical TPA demultiplexer. The system uses optical control pulses to demultiplex a high speed OTDM channel via TPA in a semiconductor device. The high speed OTDM signal and the control pulses (at the repetition rate of the individual channels in the multiplex), are optically coupled together and are incident on the device with their relative arrival time adjusted via a variable delay in the control arm. TPA in the semiconductor device leads to a delay–dependent response due to the signal and control in the detector, and the nonlinear nature of this response ensures that there is strong contrast between the TPA signal generated when the control and signal pulses overlap and that generated when they arrive independently. Background subtraction of the constant signal due only to the control pulse can then be conveniently carried out to result in a high contrast demultiplexed signal output.

For optimal operation, the control pulse is adjusted to have a larger intensity than the signal pulse, for example, a control–to–signal power ratio of 20:1. In this case, with the relative delay adjusted for the independent arrival of signal and control pulses, the electrical response due to the signal is 400 times (26 dB) less than that due to the control, so that there is a constant background dominated by the control pulses. With adjustment of the delay so that the signal and control pulses overlap in the detector, the

TPA response is now determined by the superposition of signal and control pulses. After background subtraction of the control pulses, the output consists of the demultiplexed signal and the negligible unswitched signal channels (which do not overlap with the control), with an extinction ratio of 16 dB between them. The negligible TPA response to the independently arriving signals also ensures that detector saturation does not occur in high bit rate systems.

**Experiment**

To demonstrate this technique, we have performed experiments using 500 fs duration control and signal pulses at 1.5 μm generated using a passively–modelocked fibre figure–of–eight laser followed by a soliton compression stage. Figure 2 shows the experimental set–up. Initially, the laser pulses are split into control and signal pulse trains having orthogonal polarisations to avoid interferometric contributions. To simulate a 330 Gbit/s signal, the signal pulse was further split in two and subsequently recombined with a delay of 3 ps between pulses. The relative intensities of the control and signal pulses were adjusted to give a control to signal pulse power ratio of 10:1. This corresponds to control and individual signal pulse peak powers of 10 and 1 W respectively. The control and signal pulses were then recombined before being coupled into a commercially–available InGaAsP 1.3 μm Fabry–Perot laser diode (NKL1301CCA), which has previously been shown to be a highly–sensitive semiconductor device suitable for TPA measurements [6].

To determine the duration of the switching window, the control pulse was swept across the two signal pulses by adjusting the relative delay between control and signal, and the peak TPA signal from the laser diode was measured using a 32 GHz oscilloscope. Figure 3(a) displays the peak photovoltage as a function of delay, after background subtraction of the control pulse signal, clearly showing that switching of a 330 Gbit/s pulse stream can be achieved. In addition, the switching window duration of around 650 fs indicates that the demultiplexing at bit rates in excess of 1 Tbit/s is possible. The switching windows shown in this figure are essentially the crosscorrelation function of the signal and control pulses. Thus it is simply their pulse durations which determine the maximum switching speed obtainable, as the TPA response is essentially instantaneous. Figure 3(b) displays the pulse which is switched out and detected via

TPA (after background subtraction) when the control is synchronised and overlapped with one of the two signal pulses. The TPA signal generated by the adjacent signal pulse 3 ps away is negligible, since this signal and the control do not overlap. The baseline in Figure 3(b) shows the negligible signal obtained when the optical signal pulse overlapping with the control is blocked, indicating a good extinction ratio. The electrical response time of the laser diode is around 200 ps (from Figure 3 (b)) which would allow individual data channels at a bit–rate of up to 2.5 Gbit/s to be used.

**Conclusion**

The results obtained here indicate that all–optical switching at bit rates in excess of 1 Tbit/s are feasible using a TPA–based all–optical demultiplexer. The switching energy required is of the order of 5 pJ, and the maximum bit rate of the individual channels in an OTDM system would be limited to 2.5 Gbit/s by the electrical response of the diode. Improved performance should be obtainable with optimisation of the exact waveguide design for particular applications. This demultiplexer is extremely compact and stable and it does not require exact signal and control wavelengths for correct operation.

## References

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**Figure Captions**

Fig. 1 A TPA based demultiplexer for use in an OTDM network.

Fig. 2 Experimental Set–up used to demonstrate all–optical switching based on TPA.

Fig. 3 (a) Switching window obtained by sweeping the control pulse across the two signal pulses. (b) Output electrical TPA signal for control pulse synchronised with one signal pulse. Base line obtained by blocking the switched signal pulse, indicating negligible TPA signal generated by the adjacent signal pulse.

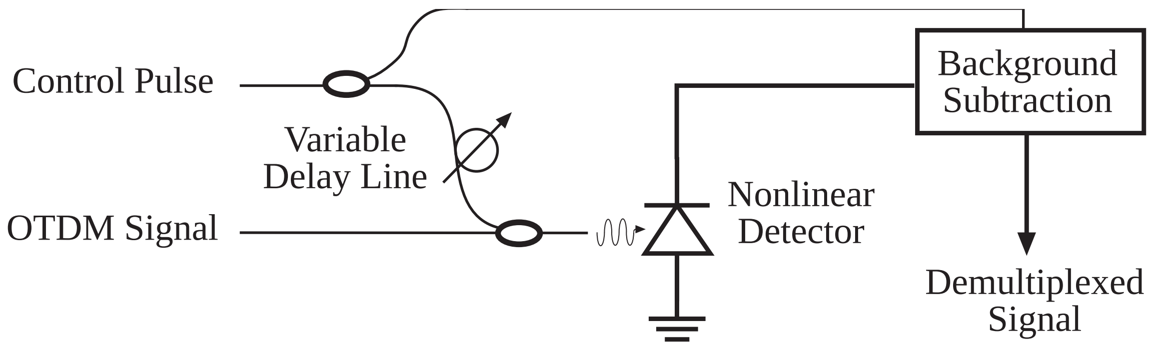
Control Pulse
Variable
Delay Line
OTDM Signal
Background
Subtraction
Nonlinear
Detector
Demultiplexed
Signal

**FIGURE 1**

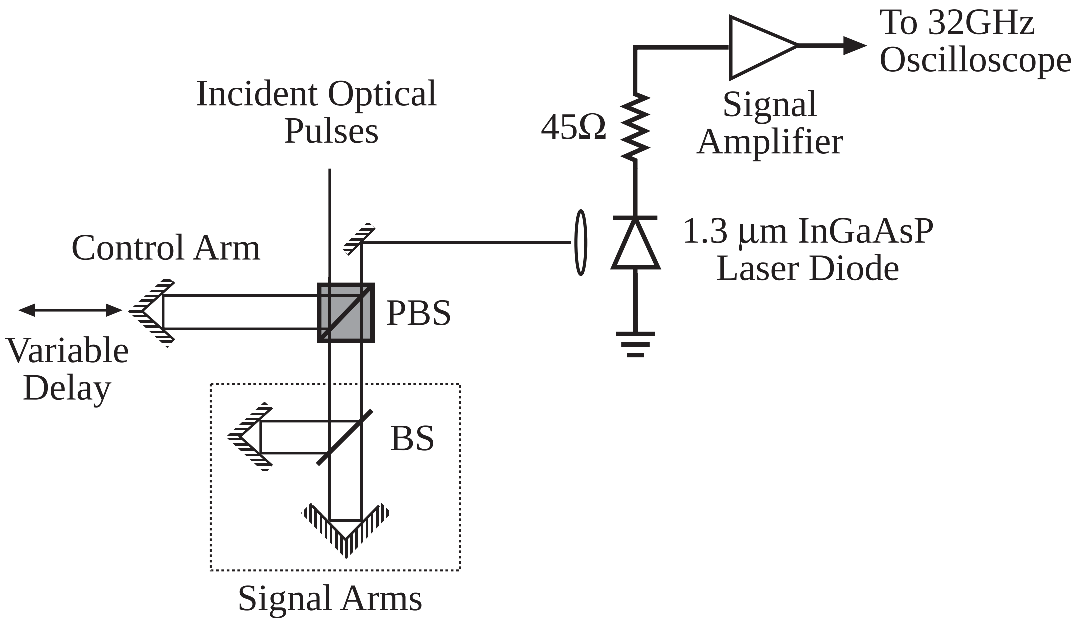
To 32GHz
Oscilloscope
Incident Optical
Pulses
45Ω
Signal
Amplifier
Control Arm
1.3 µm InGaAsP
Laser Diode
PBS
Variable
Delay
BS
Signal Arms

**FIGURE 2**

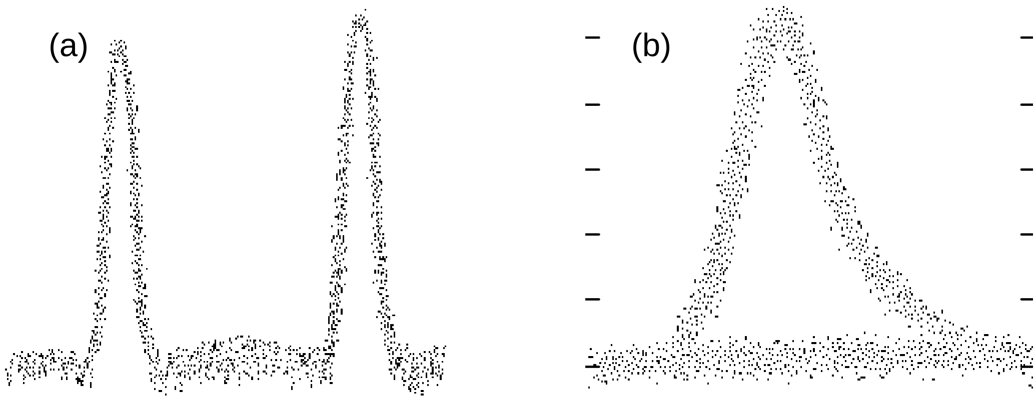


**FIGURE 3**