Simulation of a High-Speed Demultiplexer based on Two-Photon Absorption in Semiconductor Devices

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Abstract:
In this paper we present a theoretical model of an all-optical demultiplexer based on Two-Photon Absorption in a specially designed semiconductor micro-cavity for use in an Optical Time Division Multiplexed system. We show that it is possible to achieve error-free demultiplexing of a 250Gbit/s OTDM signal (25 x 10 Gbit/s channels) using a control-to-signal peak pulse power ratios of around 30:1 with a device bandwidth of approximately 30GHz.

Index Terms:
Optical Communications, Demultiplexing, Two-Photon Absorption, Optical Time Division Multiplexing, Micro-cavity.

Introduction

The future development of high capacity Optical Time Division Multiplexed (OTDM) networks will require a stable and ultra-fast switch for demultiplexing ultra-high bit rate signals [1]. The majority of all-optical switching techniques for OTDM take advantage of nonlinear effects that are present in optical fibres and semiconductor devices. Since these nonlinear effects occur on timescales in the order of a few femtoseconds they are ideal for high-speed switching. Two all-optical demultiplexers that are based on these nonlinear effects are the Nonlinear Optical Loop Mirror (NOLM) [2], based on the Kerr effect in optical fibres, and the Terahertz Optical Asymmetric Demultiplexer (TOAD) [2], based on the nonlinearities associated with carrier depletion in semiconductor optical amplifiers (SOA's). There are a number of factors that limit the performance of these devices for high-speed switching. The NOLM requires speciality fibre and precise control of the wavelength of the control and signal pulses around the zero dispersion wavelength, while the gain depletion in the SOA limits the control pulse width and thus may limit the maximum switching speed of the TOAD [3]. Due to these limitations it is necessary to consider alternative optical nonlinearities for ultra-fast switching. One such method is to use the nonlinear optical-to-electrical process of Two-Photon Absorption (TPA) in a semiconductor device to carry out all-optical switching at data rates above 100Gb/s [4,5]. The main difficulty with using the TPA effect for high-speed demultiplexing is its inherent inefficiency, however we have recently undertaken work aimed at significantly enhancing the TPA response by using a micro-cavity device [6,7]. In this paper we present a TPA micro-cavity device with enhanced TPA efficiency that may be used for high-speed demultiplexing, and we theoretically investigate an optical demultiplexer (based on TPA in a micro-cavity device) for use in an OTDM communication system. The main device parameters used in the model, such as the Two-Photon Absorption co-efficient, are taken from results obtained from the characterisation of a specially fabricated micro-cavity sample received. Using this model, the operation of the demultiplexer is examined when various system parameters are varied.

TPA Micro-cavity Device

As already mentioned, the TPA process is a very inefficient, nonlinear process. In order to utilise this nonlinearity, high optical intensities are required, which makes it unsuitable for applications, such as optical sampling and switching, in high-speed telecommunications networks. One possible way to overcome this efficiency problem is to use a Fabry-Perot micro-cavity to greatly enhance the optical intensity by increasing the interaction length in the device. It is hoped that such a simple and compact device will improve the TPA efficiency to a level that may enable the implementation of practical switching and sampling elements for high-speed optical systems.

The device that is specially fabricated for TPA at 1550nm is a GaAs/AlAs PIN micro-cavity photodetector grown on a GaAs substrate. It comprises a 0.459 µm GaAs active region embedded between two GaAs/AlAs Bragg mirrors. The front p-doped (C~10^{18}cm^{-3}) mirror consists of 9 pairs while the back n-doped (Si~10^{18}cm^{-3}) mirror contains 18 pairs designed for reflectivity at 1550nm. The device studied was a 100µm diameter vertical structure [7,8]. The cavity lifetime of the device structure, taking into account the reflectivity of the Bragg mirrors, is in the order of 1ps.

In order to initially characterise the device, a tunable mode-locked laser source, producing 1.5ps pulses at 10GHz over 100nm wavelength range, was employed. Firstly, we performed a photocurrent measurement as a function of the incident optical power close to the cavity resonance (Fig.1a). As clearly shown there is a square dependence of the photocurrent on the incident optical intensity, evidencing the TPA process. Figure 1b shows how the cavity resonance response is dependent on the incident wavelength, with a cavity resonance of 1554nm and a measured cavity linewidth of 5nm.

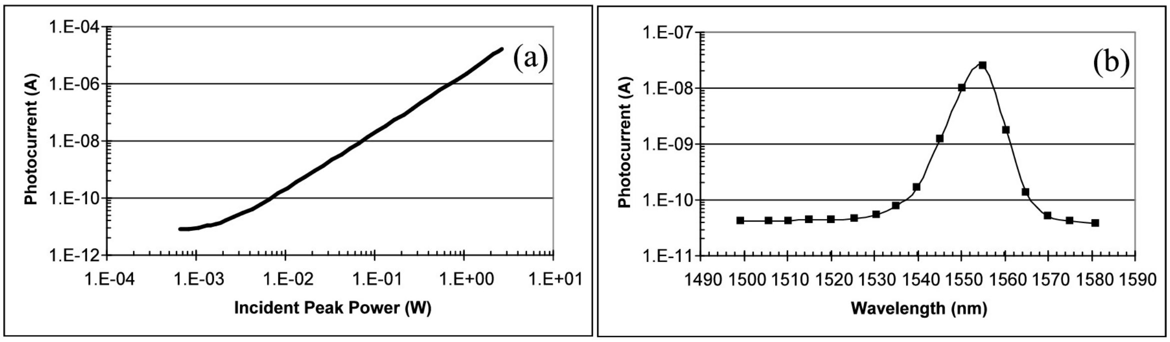

Figure 1: (a) Photocurrent as a function of Incident Optical Power (b) Micro-cavity Resonance

Principle of TPA Demultiplexer Operation

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 [4]. The generated photocurrent is proportional to the square of the intensity, and it is this nonlinear response that enables the use of TPA for optical switching. The demultiplexer uses optical pulses to switch out data from a single channel in a high-speed OTDM system via the TPA effect in a semiconductor device. The control pulses, which are at the repetition rate of the individual channels in the multiplex, are optically coupled together with the high-speed OTDM data signal and are incident on the device. The arrival time of the control pulses is varied using an optical delay line so that they arrive at the demultiplexer at a time corresponding to the data pulse to be switched out (Figure 2). The TPA effect in the semiconductor device leads to a delay-dependent response from the signal and the control pulses in the detector. Due to TPA's nonlinear quadratic response, there is a strong contrast between the electrical TPA signal generated when the control and data pulses overlap on the detector and that generated when the adjacent channels arrive independently. The constant background signal due to the control pulse can be conveniently subtracted electrically, resulting in a high contrast demultiplexed output signal. Thus the TPA demultiplexer is able to simultaneously carry out the process of channel selection and electrical detection in an OTDM communication system [4,5].

Since the generation of electron-hole pairs by the TPA effect is essentially instantaneous, the maximum switching speed is determined by the duration of the data and control pulses, allowing Terabit/s data rates to become feasible [4]. It also allows for simpler optical alignment since it does not require phase-matching as required for applications utilizing nonlinear crystals [9]. In addition, by making use of semiconductor micro-cavities [6,7] we can now overcome the problem of TPA inefficiency.

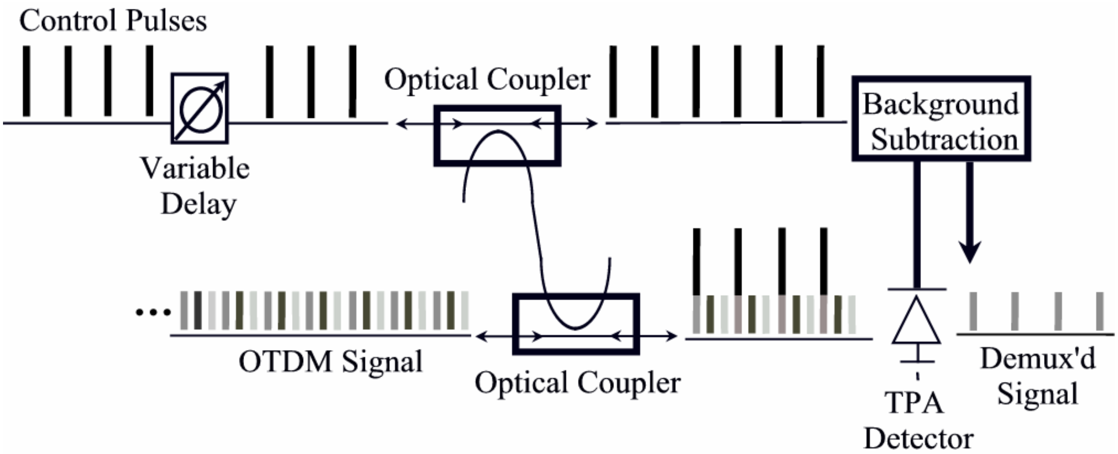

Figure 2. Schematic of TPA Demultiplexing.

Simulation Model

The purpose of the simulation is to determine how various system parameters affect the suitability of using a TPA device to switch a high-speed OTDM signal. The system parameters that are examined are as follows;

- Number of channels in the OTDM network
- Ratio between the peak power of the control signal and data signal
- Bandwidth of the TPA detector

The model initially creates a certain number of channels, each consisting of a Pseudo Random Bit Stream (PRBS) with a pattern length of 2^7-1, which are then multiplexed together using optical pulses (representing the data bits) to create an OTDM data signal. The optical pulse width used was kept to one quarter of the bit period of the overall aggregate OTDM data rate in order to avoid interference in adjacent channels. The number of channels used and the data rate of each channel can be set in the model. The peak power of the data pulses can be set to a specific value with a fixed level of noise then added. This has the effect of limiting the optimum Bit Error Rate (BER) that can be achieved by the system. The OTDM data signal is then combined with optical control pulses, which are at the repetition rate of the individual channels in the OTDM signal, with the control pulses synchronized with one of the OTDM channels. The duration of the control pulses is set to the same value as that of the signal pulses, and the peak power of the control pulses can be set to any value. The OTDM signal and the control pulses are then incident on the TPA detector. The TPA detector is modeled as described in [6]. For our model we have chosen a Single-Photon Absorption (SPA) coefficient (α) and a TPA coefficient (β) of 0.01cm^{-1} and 3x10^{-10} m/W respectively, from measurements carried out in [9]. Figure 3 is a theoretical plot of the photocurrent generated versus the optical intensity using the parameters taken from experiments carried out on the devices fabricated. This plot clearly shows that the nonlinear TPA response is limited on the lower side by Single-Photon Absorption and on the higher side by total absorption. This gives the dynamic range (~ 40dB) over which the TPA affect can be used for high-speed switching.

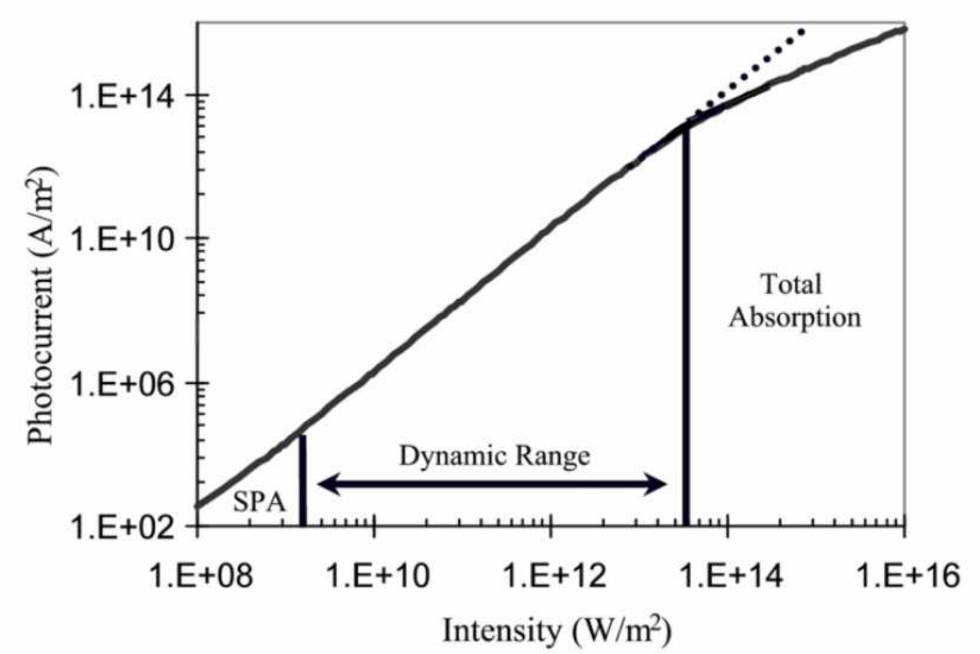

Figure.3. ***Simulation of the*** Output Photocurrent Density as a Function of the Input Optical Power Density for $\alpha = 0.01cm^{-1}$ and $\beta = 3x10^{-10}$ m/W.

The TPA model also takes into account the bandwidth of the TPA detector. As previously mentioned, the TPA effect (generation of electron-hole pairs) is essentially instantaneous which allows any overall data rate possible and is limited only by the duration and jitter of the optical pulses used for signal and control, and the cavity lifetime of the device (which is dependent on the reflectivity of the Bragg mirrors [8]). However the extraction of the carriers (current produced) is affected by the carrier lifetime of the micro-cavity, which affects the maximum data rate of the individual channels in OTDM signals. Therefore the bandwidth of the TPA detector will be restricted by the carrier lifetime of the device. The minimum bandwidth required to temporally demultiplex one channel from the overall OTDM signal is 10GHz, assuming that the individual channel data rate is 10Gbit/s. However, even with this bandwidth, noise will be introduced on the demultiplexed channel from the electrical signals generated by the other OTDM channels that are not synchronized with the control pulse.
To overcome this limitation it may be necessary to have a large control-to-signal ratio which will increase the contrast ratio between the detected channel synchronized with the control, and unsynchronized channels, and thus increase the Signal-to-Noise Ratio (SNR) of the demultiplexed channel. By increasing the bandwidth of the device, the noise contribution from the other OTDM channels is reduced. As can be seen, it is vitally important to consider all the parameters in order to achieve optimum performance.
The simulation model finally calculates the Optical Bit-Error-Rate (OBER) of the signal before the detector and the Electrical Bit-Error-Rate (EBER) after the TPA based

demultiplexer. The overall goal is to determine the operating characteristics such that EBER of the demultiplexed/detected signal is the same as the OBER of the signal before the TPA detector, indicating that the demultiplexing process is not introducing additional errors. The OBER takes into account any initial noise introduced by the transmitter in the system and is calculated from the signal power and the noise power inputted at the start of the simulation. From the resulting SNR, the OBER is calculated [10]. The EBER on the other hand takes into account noise introduced by the demultiplexing process. In order to calculate the EBER, the TPA photocurrent generated by the incident optical signal is first determined, taking into account the optical noise already present on the signal. The photocurrent takes into account the band gap of the device, which is optimized for TPA, the length of the detector (100μm as per the sample fabricated) and the SPA and TPA co-efficients [6]. Next the thermal noise introduced by the detector and the accumulated channel noise is added to the signal. The amount of thermal noise is user defined. The accumulated channel noise takes into account the other channels not synchronized with the control pulse and arises due to the demultiplexing process being dependent on the bandwidth of the detector. Once the noise has been added, the resultant electrical signal is compared to a threshold value, and assigned a bit value. This bit value is then compared to the original PRBS signal and the number of errors determined, resulting in the EBER.

Simulation Results

The initial parameter that was investigated was the ratio of the control-to-signal pulse power, and we examined how this parameter affected system performance as a function of the number of channels multiplexed together. The number of channels was varied from 25 to 100, with a data rate of 10Gb/s per channel (250Gb/s to 1Tb/s aggregate OTDM data rates). The signal peak power was kept constant at 80mW, and the detector bandwidth was set to 10GHz, the minimum required to prevent ISI between adjacent data bits in the demultiplexed channel. Figure 4 illustrates the received BER vs. control-

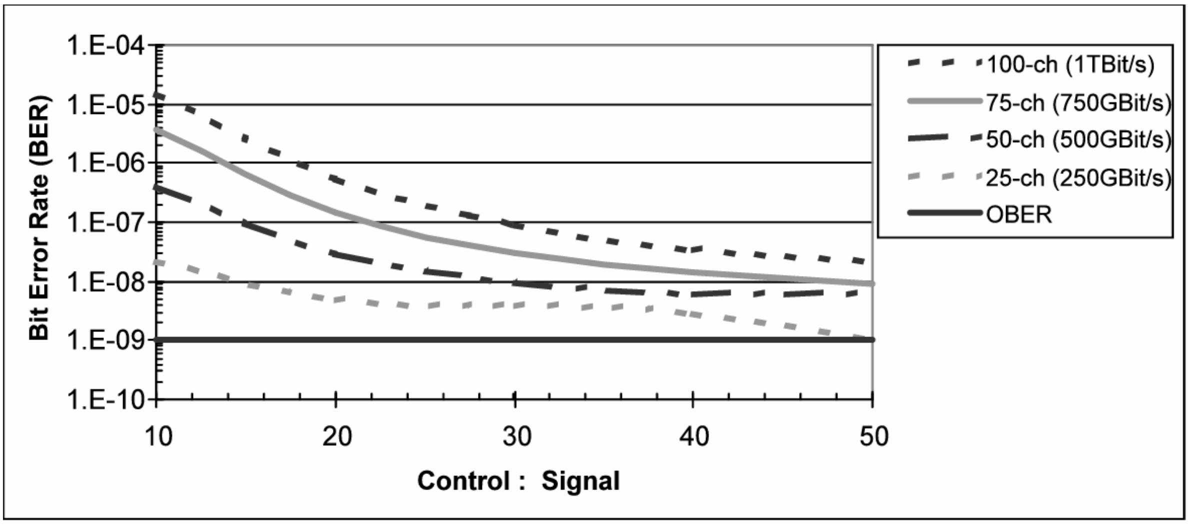

Figure 4. BER Vs. Control-to-Signal Power as the number of channels (with base rate of 10Gbit/s per channel) is varied.

to-signal ratio as the number of channels is varied. It can be clearly seen that as the control-to-signal ratio is increased, the EBER approaches the OBER. This occurs due to the fact that as the control-to-signal peak power ratio is increased, the contrast ratio between the data signal synchronised with the control pulse and those not synchronised widens. Thus the noise level added to the demultiplexed signal, due the detection of all the adjacent channels, is reduced as the control-to-signal ratio increases. This improves the resultant SNR, and improves the BER of the received signal. For a given control-to-signal ratio, the BER is degraded as more channels are added to the system, due to the increased noise from these added channels on the received signal. It is worth noting that for the 25-channel system (250Gbit/s aggregate OTDM data rate), the EBER reached the OBER for a control to signal ratio beyond 50:1, corresponding to a control pulse peak power of 4W. During the initial characterization of the micro-cavity samples that were fabricated, a maximum peak optical power of 20W was applied to the device without any damage being incurred. This suggests that a control pulse peak power of 4W is well within the operating range of the micro-cavity structure, even if it is slightly large for practical applications.

We subsequently went on to examine how the bandwidth of the TPA detector affected its operation as a demultiplexer in an OTDM system. Once again we plot the BER as function of the control-to-signal ratio, but this time we also vary the bandwidth of the device. These results are presented in Figure 5, and it should be noted that a 25-channel system is employed (250Gbit/s aggregate OTDM data rate), as this was the only one that gave optimum performance at a reasonable control-to-signal ratio. As the bandwidth is increased, the BER of the received signal is improved. This is attributed to the fact that

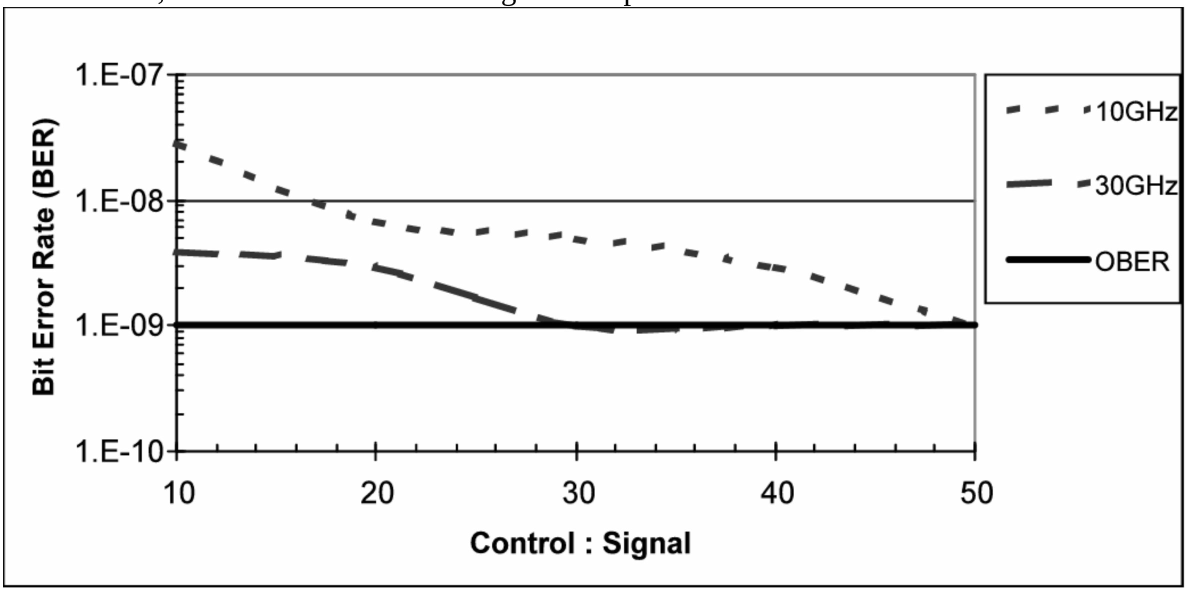

Figure 5. BER Vs. Control-to-Signal Power as the temporal response is varied for a 250Gbit/s (25 channel x 10 Gbit/s) OTDM System.

as the bandwidth is increased the number of adjacent channels that add noise to the detected channel decreases, thus improving the received BER. This allows a smaller control-to-signal ratio to be used to offer the same overall performance. For a 25-

channel system, a bandwidth of 30GHz allows us to obtain good performance with a control-to-signal ratio of around 30:1. From recent experimental work carried out on the characterization of the micro-cavities, the device bandwidth of the 100µm sample was determined to be 1GHz. It is hoped that with smaller device size, an improved cavity design and the use of high-speed packaging, the device bandwidth can be improved. As the device is based on a PIN structure, bandwidths in excess of 10GHz should be readily feasible.

Conclusion

We have modeled the performance of a TPA based demultiplexer in an OTDM communication system. The performance of the demultiplexer was evaluated by comparing the electrical BER (EBER) of the demultiplexed/detected channel after the detector to the optical BER (OBER) of the signal before the demultiplexer. Our results have shown how the ratio of the control-to-signal pulse power, number of OTDM channels, and bandwidth can affect the performance of a TPA based demultiplexer for use in a practical OTDM system. Using the parameters we have chosen for the TPA device, (including SPA coefficient, TPA coefficient, and temporal response) which we have taken for measurements of newly developed samples, we have shown that it should be possible to achieve error-free demultiplexing of a 250 Gbit/s OTDM signal (25 x 10 Gbit/s channels), using a control-to-signal ratio of around 30:1, for a TPA device with a bandwidth of 30GHz. By further optimizing the existing cavity design, it is hoped that the device can be further improved to allow for the successful demultiplexing of higher-speed data signals approaching 1Tbit/s.

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