All-Optical Sampling based on Two-Photon Absorption in a Semiconductor Microcavity for High-Speed OTDM

P.J.Maguire[a] and L.P.Barry[a], T.Krug[b], M.Lynch[b], A.L.Bradley[b] and J.F.Donegan[b], H.Folliot[c]

[a]Research Institute for Networks and Communications Engineering, School of Electronic Engineering, Dublin City University, Dublin 9, IRELAND ;

[b]Semiconductor Optronics Group, Physics Department, Trinity College, Dublin 2, IRELAND ;

[c]Laboratoire de Physique des Solides, INSA, Rennes, FRANCE

ABSTRACT

Future high-speed optical communications networks operating at data rates in excess of 100Gbit/s per channel will require a sensitive and ultrafast technique for precise optical signal monitoring.[1] The standard way of characterising high-speed optical signals to use a fast photodetector in conjunction with a high-speed oscilloscope. However, this method is limited to a maximum data rate of approximately 40Gbit/s. An alternative is to employ all-optical sampling techniques based on ultrafast optical nonlinearities present in optical fibres, optical crystals and semiconductors. One such nonlinearity is the optical-to-electrical process of Two-Photon Absorption (TPA) in a semiconductor. This paper presents an optical sampling technique based on TPA in a specially designed semiconductor microcavity. By incorporating the microcavity design, we are able to enhance the TPA efficiency to a level that can be used for high-speed optical sampling.

Keywords: Optical Communications, Optical Time Division Multiplexing, Hybrid WDM/OTDM, Optical Sampling, Two-Photon Absorption, Microcavity

1. HIGH-SPEED OPTICAL MULTIPLEXING TECHNIQUES

Due to the continued growth of the Internet and the introduction of new broadband services such as video-on-demand and mobile telephony, there will be a need to better exploit the enormous bandwidth that optical fibre provides in the network. The conventional method employed by many network providers is to use optical multiplexing techniques to increase the number of carriers per optical fibre. The most common variant, Wavelength Division Multiplexing (WDM), divides up the optical spectrum into a large number of non-overlapping wavelength bands and transmits each individual channel using a different wavelength over a single fibre. To increase capacity in WDM networks, new transmitter/receiver pairing (operating at a different wavelength) can be added, but this is expensive. A second option is to increase the data rate transmitted per channel, but this is limited by the speed of electronics in current integrated circuits. An alternative to multiplexing in the wavelength domain, as in WDM, is to carry out multiplexing in the time domain.

Optical Time Division Multiplexing (OTDM)[2] uses short optical pulses to represent data and multiplexes in the time domain by allocating each channel specific bit slots in the overall multiplexed signal. The basic configuration for a bit-interleaved OTDM transmitter is shown in Figure 1. The main component in a bit-interleaved OTDM system is an ultrashort optical pulse source. The optical pulse train generated is at a repetition rate R and is split into N copies by a passive optical coupler, where N corresponds to the number of electrical channels to be multiplexed. Each copy is then modulated by electrical data which is at a data rate R. The resulting output from the modulator is an optical data channel where the electrical data is represented using short optical pulses. The modulated optical signal then passes through a fixed fibre delay length, which delays each channel by 1/RN relative to adjacent channels in the systems. This ensures that the optical data channels arrive at the output at a time corresponding to its allocated bit slot in the overall OTDM signal. The

---

For further information, E-mail:maguirep@eeng.dcu.ie, Ph: +353 (0) 1 700 5884, Fax: +353 (0) 1 700 5508

Opto-Ireland 2005: Optoelectronics, Photonic Devices, and Optical Networks, edited by
J. G. McInerney, G. Farrell, D. M. Denieffe, L. P. Barry, H. S. Gamble, P. J. Hughes, A. Moore,
Proc. of SPIE Vol. 5825 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.604835

N modulated and delayed optical data channels are then recombined using a second passive optical coupler to form the OTDM data signal. To increase the overall capacity, shorter optical pulses can be used. However as the capacity approaches 1Terabit/s, the duration of the optical pulses used will have to be less than 1ps. The generation of pulses of this type can be complicated and laborious task, and in addition, the dispersion encountered as these optical pulses travel through the fibre may become difficult to compensate for due to their broad spectral width.

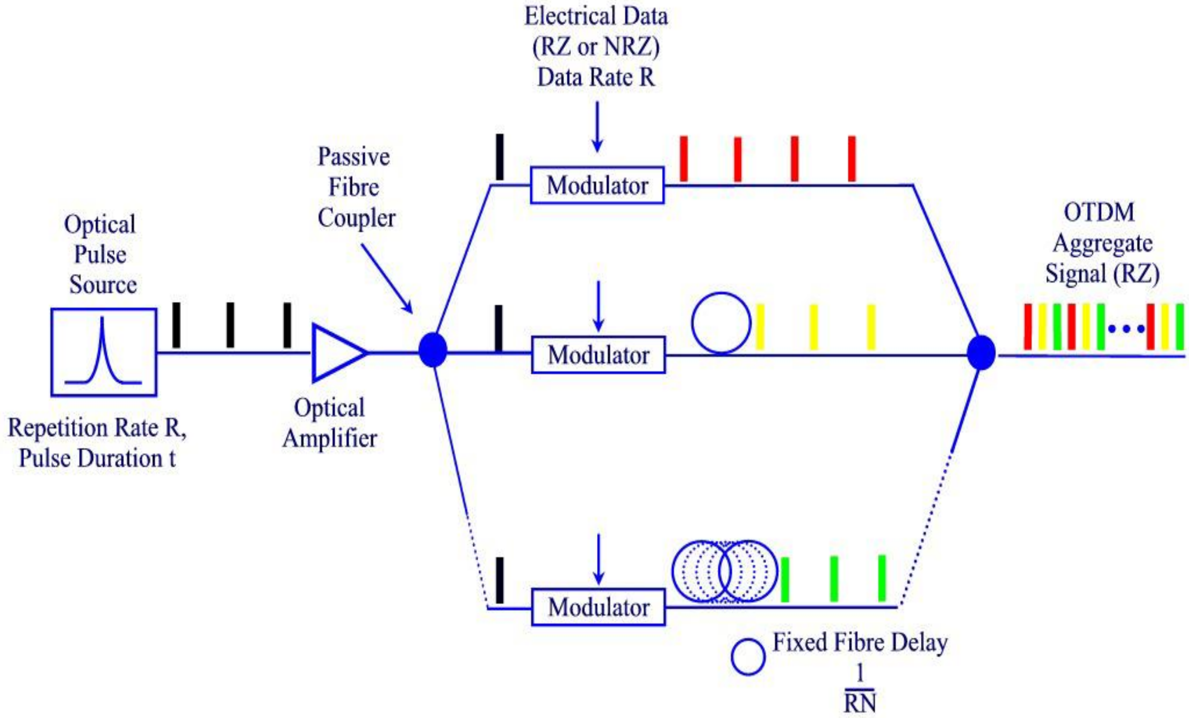

Figure 1. Bit-Interleaved OTDM Transmission System

An alternative technique, that pushes neither WDM nor OTDM to its limits, is to combine the two, to form a hybrid WDM/OTDM multiplexing scheme.[3] This approach uses OTDM to enhance the bandwidth of a number of WDM wavelength channels by placing OTDM coding on top of the channels provided by WDM. This results in a smaller number of channels operating at a much higher individual channel data rates, and may overcome some of the problems associated with WDM and OTDM. Such an approach exploits the parallelism of WDM architecture and the speed of OTDM resulting in a highly flexible and spectrally efficient multi-terabit/s optical network.[3] A possible layout for a 4 channel hybrid WDM/OTDM is shown in Figure 2. It comprises of four bit-interleaved OTDM multiplexing schemes, each operating at a different wavelength ($\lambda1$, $\lambda2$, $\lambda3$, $\lambda4$). The individual OTDM signals, each operating at an aggregate data rate of 160Gbit/s, are combined in a passive optical coupler to form the 640Gbit/s hybrid data signal. The duration of the optical pulses used to represent the data is extremely important in determining the maximum overall data rate that can be achieved, with the overall data rate of an OTDM system being defined by the temporal separation between channels in the multiplexed signal. For the 160Gbit/s bit-interleaved OTDM system described, the temporal separation between channels is 6.25ps, requiring optical pulse durations of $\sim$2ps. The duration of the optical pulses used to represent the data is usually kept to 1/3 of the temporal separation between channels in order to avoid intersymbol interference occurring due to pulse broadening. In order to successfully operate at data rates in excess of 100Gbit/s per channel, networks will require a sensitive and ultrafast technique for precise optical signal monitoring.[1]

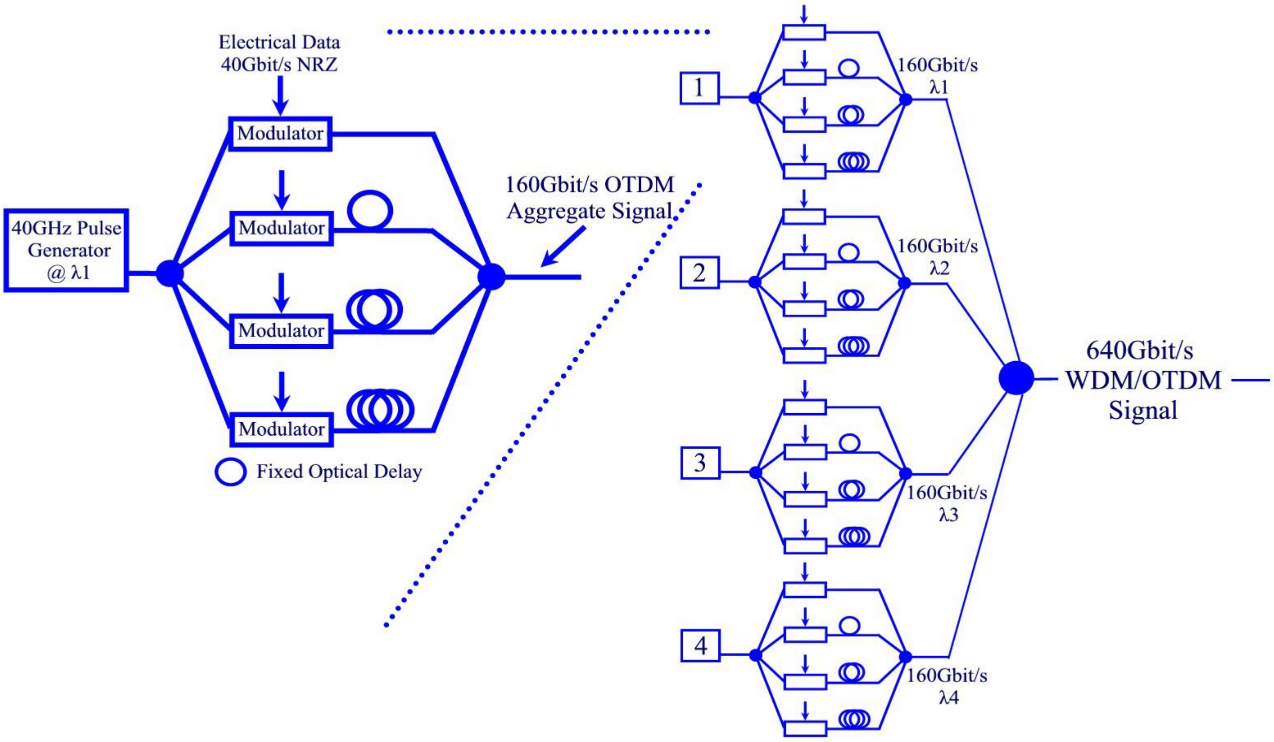

Figure 2. Schematic of the Possible Layout of a 640Gbit/s Hybrid WDM/OTDM Multiplexing Scheme

2. OPTICAL SAMPLING

The standard way of characterising high-speed optical signals utilises a fast photodetector in conjunction with a high-speed sampling oscilloscope. However current electronic monitoring techniques are limited to bandwidths of approximately 80GHz due to difficulties associated with the design of high-speed electronic components.[4] These are just capable of accurately measuring data rates of 40Gbit/s, and as individual channel data rates are expected to exceed this by the end of the decade, current electrical sampling techniques will be unable to accurately characterise high-speed data signals. Critical information such as pulse duration, pulse separation and pulse rise-time, which are crucial for the optimisation of the networks performance, will be distorted.

Nonlinear optical effects, which are present in optical fibres, semiconductor devices and optical crystals, occur on time scales in the order of a few femto-seconds ($10^{-15}s$), and are therefore ideal for performance monitoring and high-speed optical demultiplexing of data. One such nonlinear effect currently being considered for optical sampling takes advantage of Second Harmonic Generation (SHG) in optical crystals. This method involves combining a high-power optical pulse train to the data signal being analysed and generating the mixing product of both signals in the optical crystal. The energy of the mixing product pulse represents the amplitude of the data signal and can be detected by a slow photodetector. Unfortunately there are a number of disadvantages of using the SHG process which may limit its use for optical sampling in a high-speed network. These include:

- Using very high optical intensities for the sampling pulse due to poor efficiency of the SHG process
- Stability problems associated with the use of free-space optics
- Need for phase matching at different wavelengths

As a result it is necessary to consider alternative optical nonlinearities for optical sampling. One such nonlinearity is **Two-Photon Absorption (TPA)** in a semiconductor.

3. TWO-PHOTON ABSORPTION (TPA)

3.1. TPA Process

Standard semiconductor photodetectors generate a current when incident photons, with energy greater than the band gap of the active region of the photodetector, are absorbed, causing the excitation of an electron from the ground state (valence band) to the excited state (conduction band), resulting in the creation of an electron-hole pair. These are then separated by the electric field present across the active region, resulting in a current (photocurrent) flowing in an external circuit. Individual photons with energy less than the band gap of the photodetector, will not be absorbed, and will not contribute to the photocurrent generated. However, under certain operational conditions, two photons can be simultaneously absorbed to produce a single electron-hole pair. The resulting photocurrent produced is proportional to the square of the incident optical power falling on the detector. This nonlinear optical-to-electrical conversion process is known as Two-Photon Absorption (TPA).[5]

TPA was first theoretically proposed when Göppert-Mayer, in 1931, described an imaginary third-order nonlinear susceptibility,[6] with the first demonstration of the process by Kaiser and Garrett in 1961.[7] The TPA process occurs when a photon of energy E_{ph} is incident on the active region of a semiconductor device with a band gap energy exceeding E_{ph} but less than $2E_{ph}$. Under these conditions, individual photons do not possess sufficient energy to produce an electron-hole pair. However, as stated, an electron-hole pair can be produced by the simultaneous absorption of two photons, were the summation of the individual photon energies is greater than the band gap energy. The absorption of the two photons can be explained using a intermediate *virtual* state between the conduction band and the valence band within the band gap of the device. This is shown in Figure 3, were the energy of the first photon is used to excite an electron from the valence band to the virtual state, were it is almost instantaneously moved to the conduction band by the energy of a second photon.

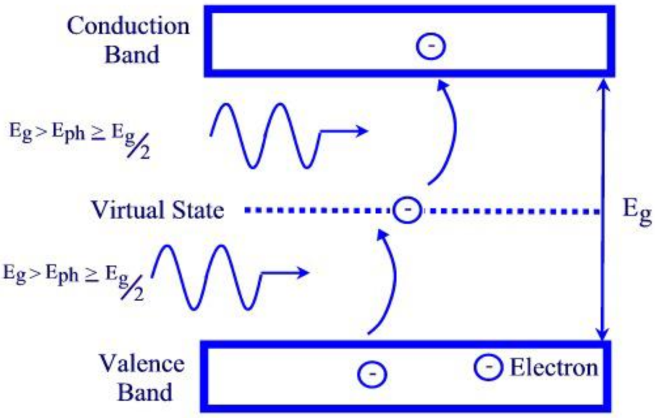

Figure 3. Two-Photon Absorption via Intermediate Virtual State

The TPA process needs to be distinguished from a two-step absorption process in which photons are absorbed individually due to linear absorption. Such a process would require a real intermediate state, with a finite lifetime, and it would have a different intensity-dependent absorption relationship.[8] TPA involves the simultaneously absorption of two photons via a *virtual* state, which results in the generated photocurrent being proportional to the square of the optical intensity. It is this nonlinear response, combined with TPA's ultra-fast response time ($10^{-14}s$ at 1550nm[9]), that enables TPA to be considered for use in high-speed optical signal processing. The photocurrent produced via the TPA process in a semiconductor pn-junction may be represented by:

$$I = \alpha I_{SPA} + \beta I_{TPA}^2 \tag{1}$$

where α represents the linear absorption term due to Single Photon Absorption (SPA), and β represents the quadratic absorption arising from the TPA process.[10] Therefore to observe the TPA process, the semiconductor material is chosen so that the band gap is greater than the energy of the incident photons but less than twice photon energy. As a result TPA photogeneration will dominate, with only a residual amount of linear absorption due to lattice imperfections or the thermal excitations of carriers with the detector.[5]

3.2. TPA Microcavity

It has been demonstrated that a commercially available 1.3μm laser diode can be used for the detection of 1.5μm optical pulses via the TPA process.[11] Since the band gap of such a device is greater than the energy of the incident photons, there is little chance of single-photon absorption occurring. However, such a device required high optical intensities in order to generate a significant TPA photocurrent. This arises from the fact that TPA is a very inefficient process,[12] requiring either high optical intensities typically not found in an optical communications network, or a long interaction length for response enhancement.[5] A long interaction length would decrease the response time of the device, limiting its application in high speed OTDM systems. However, by using a Fabry-Perot microcavity structure, the TPA efficiency can be greatly enhanced.

The microcavity works by placing mirrors at either end of the active region of the semiconductor, resulting in the formation of very strong optical fields within the cavity. This can be viewed as an increase in the interaction length of the active region. An example of the length-enhancement factor achieved using the Fabry-Perot microcavity is given in,[5] where a microcavity with a thickness of 0.3μm has the same response as a 7.5mm long noncavity device. This leads to a reduction in the capacitance of the device, as well as a significant enhancement of the TPA generated photocurrent by four orders of magnitude when compared to noncavity devices.[13] Such an increase in the photocurrent should allow the development of a simple and compact device for optical sampling in a high-speed optical communications system. An illustration of the structure of the specially fabricated TPA microcavity is shown in Figure 4. It consists of two GaAs/AlAs distributed Bragg reflector (DBR) surrounding an undoped GaAs active region. The active region is 460nm thick with a bandgap energy of 1.428eV.[14] The mirrors consist of alternating 134.3nm AlAs and 115.7nm GaAs layers, with the top p-doped (C$\approx 10^{18} cm^{-3}$) mirror consisting of 9 periods of AlAs/GaAs whereas the bottom n-doped (Si$\approx 10^{18} cm^{-3}$) mirrors consists of 18 periods of AlAs/GaAs. The device length is designed to an integral of the absorption wavelength to enhance the TPA efficiency within the 1.5μm wavelength range, with the cavity lifetime of the device structure, taking into the account of reflectivity of the Bragg mirrors,[14] is in the order of 1ps.

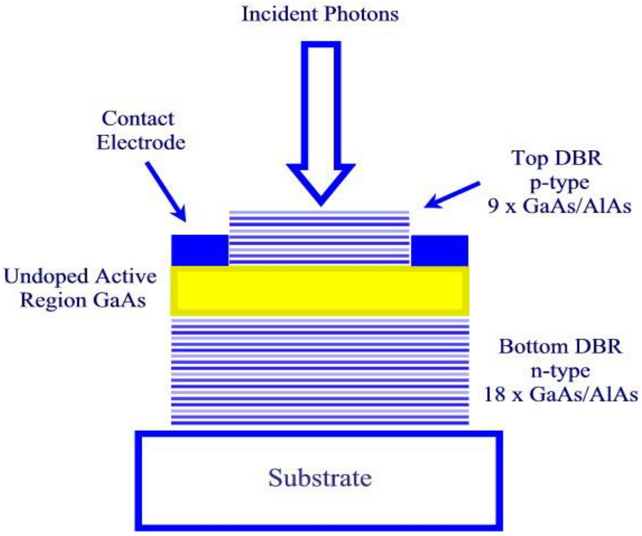

Figure 4. Schematic of Microcavity Device Structure

As already mentioned in Section 3.1, the generation of electron-hole pairs by the TPA effect is essentially instantaneous. This allows any overall data rate possible, with the only limitations being the pulsewidth and jitter of the optical pulses used for the sampling pulse and the signal pulse, and the cavity lifetime of the device, which as mentioned already is a function of the reflectivity of the mirrors used. However, the extraction of the photocarriers produced by the TPA process is affected by the carrier lifetime of the microcavity, which sets a limit to the maximum data rate of the individual channels in the OTDM signal. However, by utilising smaller device sizes, improving the cavity design, and the use of high-speed packaging the bandwidth of the TPA microcavity can be improved to allow high-speed applications.

For the characterisation of the devices, a photocurrent measurement as a function of the incident optical power close to the cavity resonance (Figure 5(a)) was performed. As clearly shown there is a square dependence of the photocurrent on the incident optical intensity, evidencing the TPA process. The lower side of the response is limited by Single Photon Absorption, whereas the total absorption limits the nonlinear TPA response on the higher intensity side. Figure 5(b) 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.

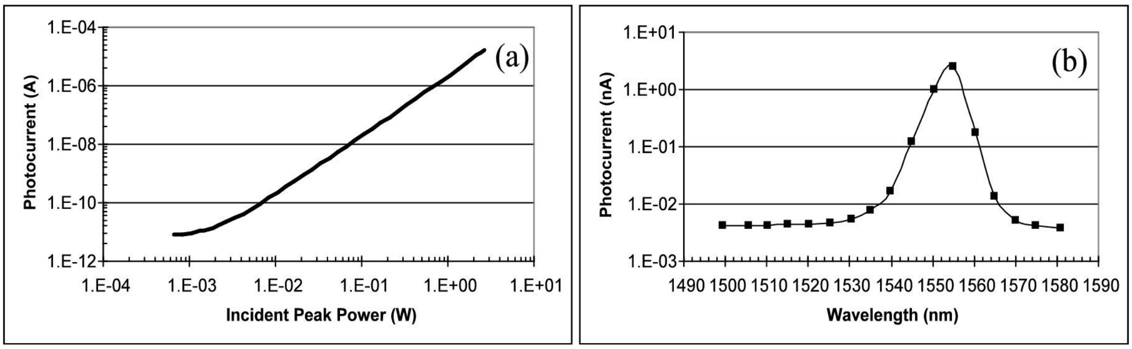

Figure 5. (a) Photocurrent as a function of Incident Optical Power (b) Microcavity Resonance

4. PRINCIPLE OF TPA SAMPLING

TPA sampling utilises optical pulses to monitor pulse shape, pulse duration and pulse separation of optical data pulses from a single high speed optical channel. The duration of the optical sampling pulse $I_{sam}(t-\tau)$ used must be significantly shorter than the optical signal pulses $I_{sig}(t)$ under test. The signal and sampling pulses are then incident on the microcavity device and the electrical signal $i(\tau)$ generated by the TPA process in the device is measured as a function of the sampling delay τ. This results in an intensity cross-correlation measurement between I_{sam} and I_{sig};

$$i(\tau) \propto \langle I_{sam}(t-\tau) I_{sig}(t) \rangle \tag{2}$$

where $\langle\rangle$ denotes time averaging. For the practical implementation of a TPA sampling system, it is convenient to use a sampling pulse with a peak intensity much larger than the signal intensity. In this case, for a sufficiently short sampling pulse, the measured signal represents the signal pulse waveform on a constant background.[15]

4.1. Sampling of a Hybrid WDM/OTDM Multiplexing Scheme

Figure 6 illustrates the possible layout for the optical sampling of a hybrid WDM/OTDM described in Section1. The system consisting of four different OTDM channels, each operating at a different wavelength (red, green, blue, yellow). The hybrid signal first passes through a passive optical coupler that splits the signal in two, with 10% of the optical power being combined with a high-power sampling pulse train. The remaining 90% of the hybrid signal is free to continue on its journey across the network. The sampling pulse, which is at a sub-harmonic of the repetition rate of the individual OTDM channels, passes through a variable optical delay, which ensures that the sampling pulses arrive at the TPA detector at a time corresponding to the bit slot of the signal to be monitored. As there are four different wavelengths in the hybrid signal, the sampling pulse is scanned across the each of the four (red, green, blue, yellow) signal pulses in the bit slot of interest (as shown). The sampling delay is provided by generating the sampling pulse at a frequency slightly detuned from a sub-harmonic of the high-speed bit-rate. The TPA microcavity then carries out simultaneous filtering and detection of the signal pulse train, with the electrical TPA signal generated by the device measured as a function of the sampling delay. This results in the intensity cross correlation between the data signal and the sampling pulse. In Figure 6, the resonance of the microcavity has been set to the red wavelength channel and this is the only one that experiences any enhancement as all other channels are outside the region of interest. The resulting TPA signal can then be displayed on a low-speed electrical oscilloscope. As the sampling pulse has a shorter duration and higher optical intensity when compared to the signal pulse, and the measured signal represents the signal pulse waveform on a constant background.

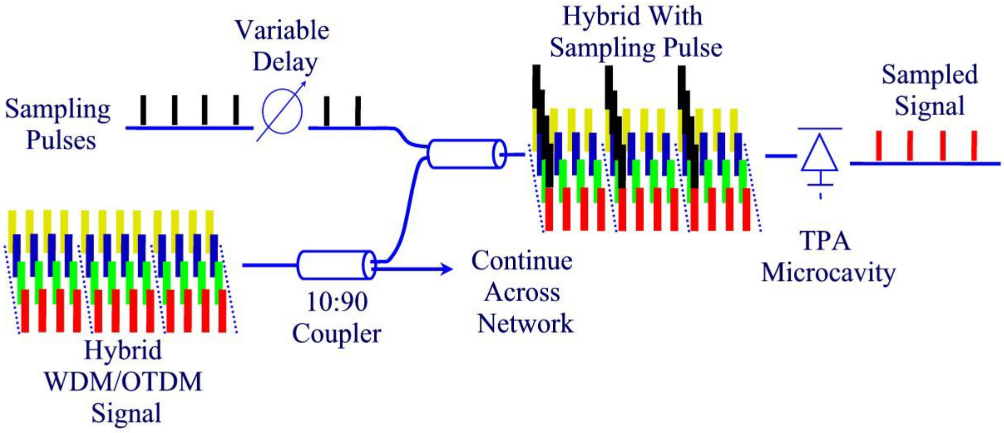

Figure 6. Schematic of Possible Sample Set-Up in Hybrid WDM/OTDM Network

5. EXPERIMENTAL SETUP

Figure 7 shows the experimental set-up used for the optical sampling of an optical pulse and quasi-160GHz data signal. A tunable 10GHz pulse source, producing optical pulses with durations of ∼1.8ps (jitter <500ps) was tuned to the resonance wavelength of the microcavity, which from the characterisation carried out in Section 3.2, was 1554nm. The same pulse source was used to generate the sampling and the signal pulse for the experiment. The 10GHz optical pulse train was first amplified by an Erbium Doped Fibre Amplifier (EDFA) before passing through a 1x4 optical coupler. For the sampling of the optical pulse, O/P1 was used for the signal pulse, with the other two outputs connected to an optical isolator to prevent any backwards reflections. The setup shown in Figure 7 is for the sampling of a quasi-160GHz signal, hence O/P1 is connected to the isolator. An optical chopper was placed in the sampling arm to allow a lock-in amplifier to measure the TPA photocurrent after the microcavity. The sampling pulse passes through an Optical Delay Line (ODL), which is used to introduce the sampling delay τ. To synthesis the quasi-160GHz signal, the pulse train from O/P2 was delayed using a second ODL by approximately 7ps (corresponding to the pulse separation of 160GHz data signal) with respect to the pulse train propagating in O/P3. To compensate for any insertion loss associated with using the ODL, the pulse train from O/P3 was attenuated by 1dB using a fixed inline optical attenuator. Both pulse trains were then recombined at the coupler to form the quasi-160GHz signal. The signal and sampling pulse trains then pass through inline power meters/attenuators and polarisation controllers before being recombined at a coupler. The power meters allow for easy measurement and attenuation of both signal and sampling pulses allowing the sensitivity of the system to be monitored. Finally the sampling and signal pulse are incident on the microcavity with the photocurrent generated by the device fed into the lock-in amplifier. The electrical output was then recorded as a function of the sampling delay τ. The quality of the TPA sampling technique was verified by comparing the resulting output of the TPA sampling with the corresponding results from an SHG-FROG[16] measurement of the same pulse.

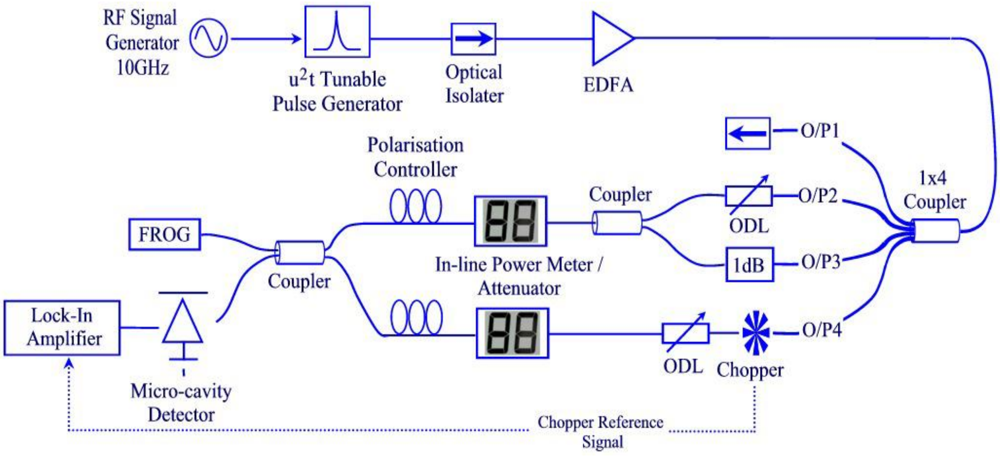

Figure 7. Experimental Set-Up for the Sampling of a Qausi-160GHz OTDM Signal

6. EXPERIMENTAL RESULTS

Figure 8 (a) compares the pulsewidth and shape obtained using TPA sampling (dotted line) with that measured by the SHG-FROG (solid line) for the same optical pulse. The measured pulsewidth from the TPA sampling was calculated to be ∼2.4ps, whereas SHG-FROG measurement recorded at pulsewidth of ∼1.7ps. for the same pulse. This deviation can be accounted for by the cavity lifetime of the microcavity,[13] and the temporal resolution of the sampling set-up. The temporal resolution of the system is determined by the duration and jitter of the sampling pulses[17] $(t_{res} = \sqrt{(t_{sam}^2 + j_{sam}^2)} \approx 2ps)$. The peak power of the signal and sampling pulses were 2.7mW and 8.6mW respectively. Figure 8 (b) compares the response of both methods for the quasi-160GHz signal. It verifies that the optical pulses were separated by ∼7ps highlighting the possibility of using the TPA microcavity for sampling of a 160Gbit/s OTDM signal. The overall system sensitivity was calculated to be $0.1mW^2$ by determining the minimum optical power levels required to successfully sample the pulse. This corresponds to a signal and sampling peak powers of 1.6mW and 4mW respectively.

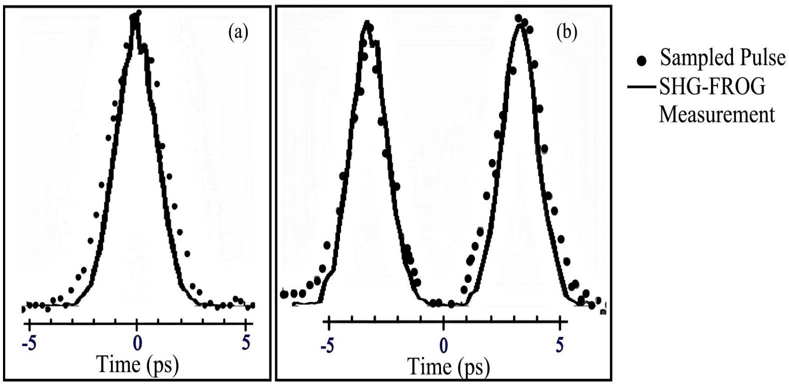

Figure 8. (a) TPA Sampling versus FROG Measurement for Single Pulse; (b) TPA Sampling versus FROG Measurement for Quasi-160GHz Signal

CONCLUSIONS

We have shown that by using a microcavity device, we are able to enhance the TPA efficiency to a level that can be used for the successful sampling of a 160Gbit/s optical signal. The sensitivity of the sampling system was calculated ot be $0.1mW^2$, which corresponds to a signal peak power of 1mW, and a temporal response of $\approx 2ps$. This represents the most sensitive ultra-fast TPA optical sampling system reported, and was achieved without the need for any post-amplification of the electrical TPA photocurrent. With the addition of a low noise electrical amplifier after the detector, the sensitivity should be improved further. Also as the minimum temporal resolution of the system is limited by the duration (1.8ps) and jitter (500fs) of the sampling pulse, the temporal resolution could be further reduced by using shorter duration sampling pulses. Therefore, it is anticipated that all-optical TPA sampling employing a microcavity could have applications for the monitoring of high-speed data signal in future OTDM/WDM communication systems.

ACKNOWLEDGMENTS

This work is supported under Enterprise Ireland's Advanced Technology Research Programme (ATRP/2002/301a)

REFERENCES

1. S. Kawanishi, "Ultrahigh-Speed Optical Time-Division-Multiplexed Transmission Technology Based on Optical Signal Processing," *IEEE Journal of Quantum Electronics* **34**(11), pp. 2064–2079, 1998.
2. D.M.Spirit, A.D.Ellis, and P.E.Barnsley, "Optical time division multiplexing: systems, networks," *IEEE Communications Magazine* **32**(12), pp. 56–62, 1994.
3. B.K.Mathason, H.Shi, I.Nitta, G.A.Alphonse, J.Abeles, J.C.Connolly, and P.J.Delfyett, "Multiwavelength All-Optical TDM switching using a semiconductor optical amplifier in a loop mirror," *IEEE Photonics Technology Letters* **11**(3), pp. 331–333, 1999.
4. R.L.Jungerman, G.lee, O.Buccafusca, Y.Kaneko, N.Itagaki, and R.Shioda, "Optical Sampling Reveals Details of Very High Speed Fiber Systems," pdf document, Agilent Technologies, www.agilent.com, 2004.
5. H.Folliot, M.Lynch, A.L.Bradley, T.Krug, L.A.Dunbar, J.Hegarty, J.F.Donegan, and L.P.Barry, "Two-photon-induced photoconductivity enhancement in semiconductor microcavities: A theoretical investigation," *Journal of the Optical Society of America B: Optical Physics* **19**(10), pp. 2396–2402, 2002.
6. N. Bloembergen, "Nonlinear Optics: Past, Present, and Future," *IEEE Journal of Selected Topics in Quantum Electronics* **6**(6), pp. 876–880, 2000.
7. W.Kaiser and C.G.B.Garrett, "Two-photon excitation in CaF_2:Eu^{2+}," *Physical Review Letters* **7**(6), pp. 229–231, 1961.
8. H.P.Weber, "Two-photon absorption laws for coherent and incoherent radiation," *IEEE Journal of Quantum Electronics* **7**(5), pp. 189–195, 1971.
9. J. Donegan, "Two-photon absorption speeds optical switching," *Lightwave europe* **July 2002**, p. 31, 2002.
10. F.R.Laughton, J.H.Marsh, D.A.Barrow, and E.L.Portnoi, "The Two Photon Absorption Semiconductor Waveguide Autocorrelator," *IEEE Journal of Quantum Electronics* **30**(3), pp. 838–845, 1994.
11. L.P.Barry, B.C.Thomsen, J.M.Dudley, and J.D.Harvey, "Autocorrelation and Ultrafast Optical Thresholding at 1.5μm using a Commercial ingaasp 1.3μm laser diode," *Electronics Letters* **34**(4), pp. 358–360, 1998.
12. L.P.Barry, P.Maguire, T.Krug, H.Folliot, M.Lynch, A.L.Bardley, J.F.Donegan, J.S.Robert, and G.Hill, "Design of microcavity semiconductor devices for highly efficient optical switching, sampling applications," in *Lasers and Electro-Optics Society Annual Meeting-LEOS, Conference Proceedings, Glasgow,* **2**, pp. 839–840, 2002.
13. H.Folliot, M.Lynch, A.L.Bradley, L.A.Dunbar, J.Hegarty, J.F.Donegan, L.P.Barry, J.S.Roberts, and G.Hill, "Two-photon absorption photocurrent enhancement in bulk algaas semiconductor microcavities," *Applied Physics Letters* **80**(8), pp. 1328–1330, 2002.
14. T.Krug, M.Lynch, A.L.Bradley, J.F.Donegan, L.P.Barry, H.Folliot, J.S.Roberts, and G.Hill, "High-Sensitivity Two-Photon Absorption Microcavity Autocorrelator," *IEEE Photonics Technology Letters* **16**(6), pp. 1543–1544, 2004.

15. B.C.Thomsen, L.P.Barry, J.M.Dudley, and J.D.Harvey, "Ultra Sensitive All-optical Sampling Scheme for use in high capacity telecommunication systems at 1.5μm," *Electronics Letters* **35**(17), pp. 1483–1484, 1999.
16. R. Trebino, K. W.DeLong, D. N.Fittinghoff, John.N.Sweetser, M. A.Krumbugel, and B. A.Richman, "Measuring ultrashort laser pulses in the time-frequency domain using frequency-resolved optical gating," *Rev. Sci. Instrum - American Institute of Physics* **68**(9), pp. 3277–3295, 1997.
17. B.C.Thomsen, L.P.Barry, J.M.Dudley, and J.D.Harvey, "Ultra-sensitive all-optical sampling at 1.5um using waveguide two photon absorption," *Electronics Letters* **35**(17), pp. 1483–1484, 1999.