Highly-Efficient Optical Sampling Based on Two-Photon Absorption in a Semiconductor Micro-Cavity Device

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Abstract: We demonstrate a highly-efficient optical sampling system based upon the nonlinear process of Two-Photon Absorption in a specially designed semiconductor microcavity. The sensitivity of the system is around 0.1mW^2 and the temporal resolution is 2ps.

OCIS codes: (060.4510) Optical communications; (190.4360) Nonlinear optics, devices

1. Introduction

The future development of high capacity Optical Time Division Multiplexed (OTDM) networks operating at aggregate data rates greater than 100Gbit/s will require a sensitive and ultrafast technique for precise measurement of the optical signal pulse [1]. Presently, the characterisation of such systems is usually performed using fast photodetectors in conjunction with high-speed oscilloscopes. However, this method of characterisation is limited to a maximum bit rates of about 40Gbit/s. Thus for systems operating at aggregate data rates in excess of 100Gbit/s all-optical sampling based on instantaneous optical nonlinearities is required [2].

One such method is to use the nonlinear optical-to-electrical process of Two-Photon Absorption (TPA) in a semiconductor device [3]. Since TPA is an instantaneous nonlinearity, the temporal resolution is limited only by the duration and jitter of the sampling pulses used. The main difficulty with using TPA for high-speed applications, such as optical sampling and switching, is its inherent inefficiency. In order to utilise this nonlinearity, either high optical intensities or very long detectors are required, which may make it unsuitable for high-speed telecommunications applications. However we have recently undertaken work aimed at significantly enhancing the TPA response by using a micro-cavity structure [4,5].

2. TPA Micro-cavity Device

In order to overcome the efficiency problem associated with TPA, a Fabry-Perot micro-cavity was used to greatly enhance the optical intensity by increasing the interaction length in the device [6]. It is hoped that such a device will improve the TPA efficiency to a level that may enable the implementation of practical switching and sampling elements for high-speed optical communications systems.

In order to initially characterise the device, a tunable 10GHz mode-locked laser source, producing 1.8ps pulses 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

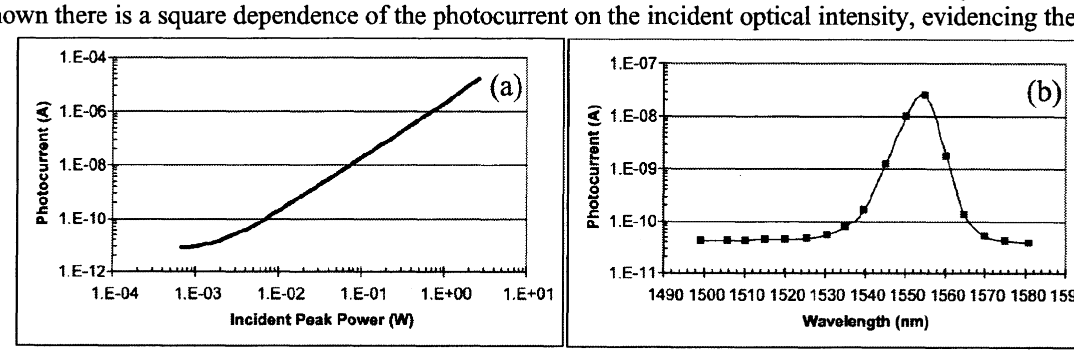

Fig. 1. (a) Photocurrent as a function of Incident Optical Power (b) Micro-cavity Resonance

process. Fig.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.

3. Principle of TPA Sampling 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 [3]. 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 $2E_{ph}$. 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 sampling.

To use TPA for optical sampling we require an optical sampling pulse $I_{sam}(t-\tau)$ whose duration is significantly shorter than that of 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 $i(\tau)$ due to TPA in the device is measured as a function of the sampling delay τ, to obtain an intensity cross-correlation between I_{sig} and I_{sam}. 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 [7].

4. Experimental Set-Up

Fig.2 shows the experimental set-up used for all-optical sampling based on TPA in a semiconductor microcavity. The tunable pulse source that was used for the initial characterization was also used for the sampling experiments. The pulse duration was approximately 1.8ps (Jitter <500fs) and the operating wavelength was set to 1554nm to coincide with the wavelength resonance of the microcavity. The 10GHz optical pulse train was then amplified and passed through a 1x4 optical coupler. O/P 1 and O/P 4 were used as signal and sampling pulse respectively for the sampling of a single optical pulse, whereas O/P 2 and 3 were used for the creation of a quasi 160GHz pulse train. When O/P 1 was not in use it was connected to an

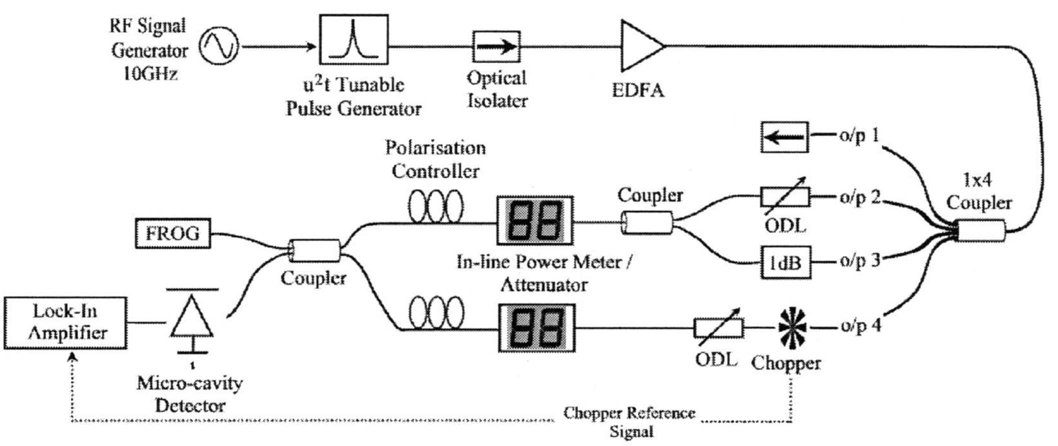

Fig. 2. Experimental Set-Up for Synthesised 160Gbit/s Sampling

optical isolator to prevent any backward reflections. An optical chopper was placed in the sampling arm to allow a lock-in amplifier to measure the TPA photocurrent after the micro-cavity. The sampling pulse then passes through an Optical Delay Line (ODL), which is used to introduce the sampling delay τ. To synthesise the quasi 160GHz signal, the pulse train from O/P 2 was delayed by approximately ~7ps (corresponding to the pulse separation of 160GHz pulse train) by the ODL. To compensate for any insertion loss associated with ODL, the pulse train from O/P 3 was attenuated 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 micro-cavity 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 is independently verified by comparing the resulting output of the TPA sampling with the corresponding results from an SHG-FROG [8] measurement of the same pulse.

5. Experimental Result

Fig.3a shows the TPA sampling output for a single pulse (dotted line) and the SHG-FROG measurement (solid line). The pulse duration from the TPA sampling was calculated as ~2.4ps whereas the SHG-FROG measurement carried out indicated a pulsewidth of ~1.8ps. This deviation can be accounted for by the cavity lifetime, and the temporal resolution of the sampling set-up as determined by the jitter and duration of the sampling pulse. The average peak power of the signal and sampling pulses were 2.7mW and 8.6mW respectively. Fig.3b shows the sampling and SHG-FROG trace of the quasi 160GHz signal. Again the deviation between the measured and SHG-FROG can be accounted for as described above. As the pulse

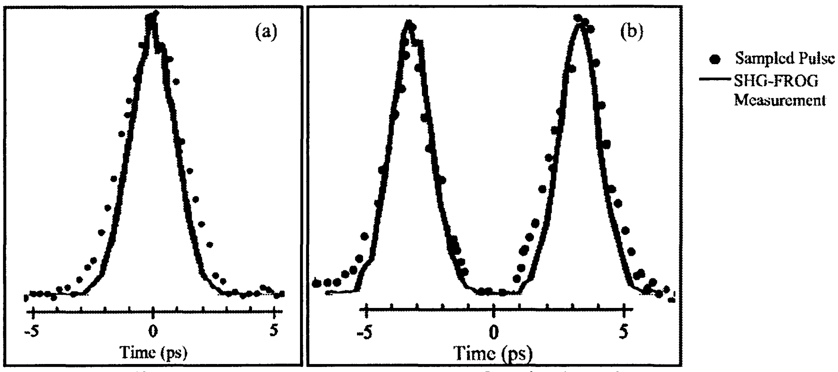

Fig. 3. (a) TPA Sampling versus FROG measurement for single pulse (b) TPA Sampling versus FROG measurement for synthesized 160GHz signal.

separation is approximately 7ps, this highlights that sampling of a 160Gbit/s signal should be possible. An overall system sensitivity was calculated to be $0.1mW^2$ by determining the minimum optical power levels required to successfully sample the pulse.

6. Conclusion

We have shown that by using a micro-cavity device, we are able to enhance the TPA efficiency to a level that can be used for high-speed optical sampling. Our initial results show that TPA can be used for sampling of a 160Gbit/s signal, with a sensitivity of ~ $0.1mW^2$. In our set-up this equates to peak pulse power level around 1 mW. It should be noted that the sensitivity of the TPA sampling system was achieved without any post-amplification of the electrical TPA photocurrent. It is anticipated that the sensitivity could be improved with the addition of a low noise amplifier. Also with a sampling pulse duration and jitter of 1.8ps and 500fs respectively, the minimum temporal resolution possible is ~2ps. Thus by reducing the pulse duration of the sampling pulse, it is hoped that the temporal resolution can be further reduced.

7. References

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