Ultra Sensitive All-Optical Sampling Scheme for use in high capacity telecommunication systems at 1.5 µm

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Abstract

We demonstrate a simple and ultra-sensitive all-optical sampling system suitable for the characterization of high capacity (> 100 Gbit/s) single channel systems operating around 1.5 µm. The system is based on the nonlinear effect of two-photon-absorption in a commercial 1.3 µm semiconductor laser and, using only direct detection of the unamplified two photon absorption photocurrent, we have achieved a temporal resolution of around 2 ps, and a sensitivity of less than 2 mW^2.

Introduction

The development of high-capacity single-channel optical communications systems using ultra-short pulses [1] will require sensitive measurement techniques possessing ultrafast time response [2, 3]. Currently, the characterization of such systems is usually performed using fast photodetectors in conjunction with high speed oscilloscopes, but this method of characterization is limited to maximum bit rates of about 40 Gbit/s. For system characterization at bit rates exceeding 100 Gbit/s, all-optical sampling using two-photon-absorption (TPA) in semiconductors has recently been shown to be a particularly promising technique [3]. Since TPA is an instantaneous nonlinearity, the temporal resolution is limited only by the duration and jitter of the sampling pulses used, and the sensitivity is determined by the TPA efficiency of the particular semiconductor device used. The sensitivity of a TPA sampling system is defined as the product of the peak power of the pulse under test and the average power of the sampling pulse. In the experiments reported in reference [3], a sensitivity of around 40 mW^2 and a time resolution of 2 ps were reported using TPA in an avalanche photodiode in conjunction with a 20 dB electrical amplifier. In this paper, we report a highly sensitive and simple optical sampling oscilloscope operating at 1.5 µm, based on TPA in a commercial 1.3 µm semiconductor laser. The use of a semiconductor waveguide for TPA leads to an order of magnitude improvement in sensitivity over previously-reported results, achieved without any additional amplification of the electrical signal from the TPA device. We report a system sensitivity is 2 mW^2 and a temporal resolution of 2 ps.

Principle of TPA Optical Sampling

TPA in semiconductors 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 [4, 5], and it has recently been shown that commercially–available 1.3 ?m laser diodes are ideally suited to ultra-sensitive TPA waveguide detection at 1.5 ?m, with experiments reporting highly–sensitive ultrashort pulse autocorrelation [4], and ultrafast optical thresholding [5].

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 semiconductor 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}.

$$i(\tau) \propto \langle I_{sam}(t-\tau) I_{sig}(t) \rangle \tag{1}$$

For the practical implementation of a TPA sampling system, it is convenient to use a sampling pulse with a peak intensity which is very much larger than the signal intensity. In this case, for a sufficiently short sampling pulse duration, the measured signal represents the signal pulse waveform on a constant background. In order to provide the sampling delay between the signal pulses and the sampling pulses we follow the method used in [2], where the sampling pulse is generated at a frequency f_{sam} such that it is slightly detuned from a subharmonic of the signal frequency f_{sig}.

$$f_{sam} = \frac{f_{sig}}{n+\delta}, \qquad n \text{ -integer, } \delta \ll 1 \tag{2}$$

This results in a scanning rate $f_{scan} = f_{sig}\dfrac{\delta}{n+\delta}$ which is easily displayed on a standard high-impedance oscilloscope.

Experimental Demonstration

Figure 1 shows the experimental set-up of the TPA waveguide optical sampling oscilloscope. The sampling pulses were generated using a 1.5 µm DFB laser diode gain-switched at a repetition rate of $f_{sam} = 497.011194\text{MHz}$. To reduce the temporal jitter on these sampling pulses, self-seeding from an external loop mirror was used [6]. The individual pulses were characterised using frequency-resolved optical gating [7], yielding an output pulse duration (FWHM) of 9.6 ps. These pulses were then compressed using a two stage fibre pulse compressor. The first stage involves linear compression of the gain-switched pulses in dispersion compensating fiber, and the second stage involves amplification of the pulses in an erbium doped fibre amplifier (EDFA) followed by nonlinear compression using a combination of dispersion shifted and standard fibre. The final FWHM of the sampling pulses after compression was 1 ps.

The signal pulses were generated with a 1.5 µm DFB laser gain-switched at a repetition rate of around 3 GHz such that the scanning rate f_{scan} is 6 Hz. This laser was also operated in a self-seeded configuration to minimize temporal jitter, and the resulting pulses had a duration of 10.6 ps. The signal and sampling pulses were combined together in an optical fiber coupler and injected into an antireflection coated InGaAsP 1.3 µm Fabry–Perot laser diode (NTT – NKL1301CCA), previously shown to be a highly–sensitive semiconductor device suitable for TPA autocorrelation [4]. The electrical output of the TPA detector was fed directly into the 1 MΩ input of a digitizing oscilloscope. Figure 2 shows the sampling oscilloscope output (solid line) for (a) a single signal pulse and (b) a synthesised double pulse generated from two signal pulses with a relative delay of 20 ps. The dashed lines show the corresponding pulse characterisation performed using a commercial high speed 25 GHz photodetector in conjunction with a 32 GHz HP digital oscilloscope. The FWHM of the pulses as measured by the sampling technique is 10.8 ps.

It is clear from Figure 2 that the pulse characterisation using the TPA sampling system is far superior to the conventional method using a high speed detector and oscilloscope. For these results, the input signal and sampling pulse average powers were 830 µW and 61 µW respectively, which corresponded to signal and sampling pulse peak powers of around 28 mW and 120 mW respectively. This implies a system sensitivity of 1.7 mW^2 a factor of 20 improvement over the highest sensitivity previously reported [3]. We also stress that this sensitivity was obtained without post-amplification of the TPA photocurrent, and that improved sensitivity is expected with the addition of a low noise amplifier. We attribute the excellent TPA sensitivity obtained with this device to the carrier confinement achieved in its quantum well structure. When assessing the suitability of this TPA sampling scheme for systems applications, it is also important to consider the temporal resolution which depends on both the sampling pulse duration and jitter, t_{sam} and j_{sam} respectively:

$$t_{res} = \left(t_{sam}{}^2 + j_{sam}{}^2\right)^{1/2}. \quad (2)$$

The measured sampling pulse duration is 1 ps, and the expected jitter from the self-seeded gain switched laser is expected to be ~ 0.5 ps [] , giving an expected minimum temporal resolution of around 1ps. The temporal resolution can be obtained experimentally from a comparison of the sampled signal pulse duration of 10.8 ps with the value of 10.6 ps obtained from the FROG measurements. This yields a measured resolution of 2 ps, which is expected to be reduced with reduction in the sampling pulse duration using an optimised compression stage, and improved self-seeding to reduce the jitter on the sampling pulses.

Conclusion

In conclusion, these results have demonstrated the operation of a simple real-time optical sampling oscilloscope based on TPA in a commercially available 1.3 μm laser diode. We have achieved a sensitivity of 1.7 mW^2, and the temporal resolution of 2 ps corresponds to a bandwidth of around 300 GHz. These results represent the most sensitive ultrafast TPA optical sampling system reported to date. We anticipate such TPA-based sampling systems will find wide application in high-speed systems characterisation.

References

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Figure Captions

Figure 1 Experimental configuration for optical sampling system based on two photon absorption in a 1.3 µm laser diode.

Figure 2 The solid line shows results for the TPA sampling oscilloscope showing (a) single pulse and (b) double pulse characterization. The dashed line shows conventional results obtained using a high speed photodiode and oscilloscope.

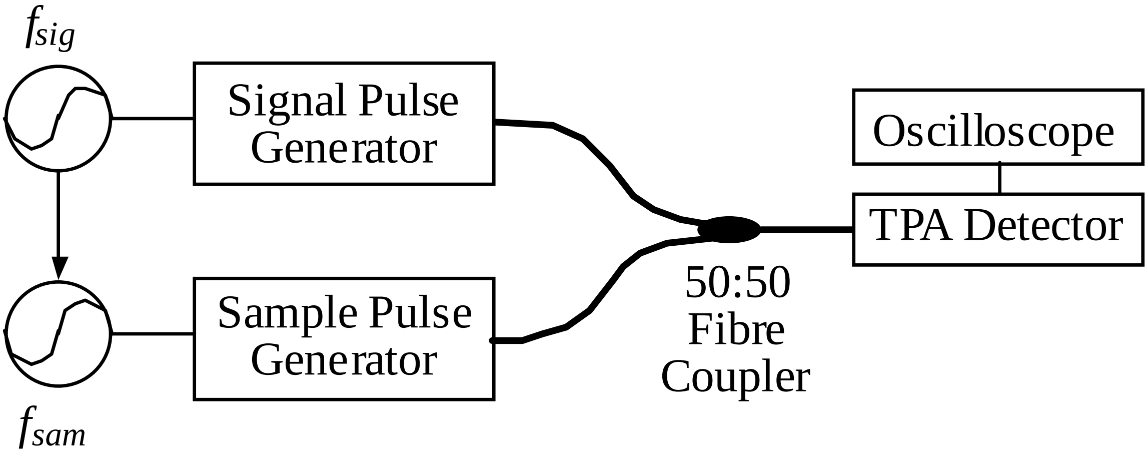
f_{sig}
Signal Pulse Generator
Oscilloscope
TPA Detector
50:50 Fibre Coupler
Sample Pulse Generator
f_{sam}

FIGURE 1

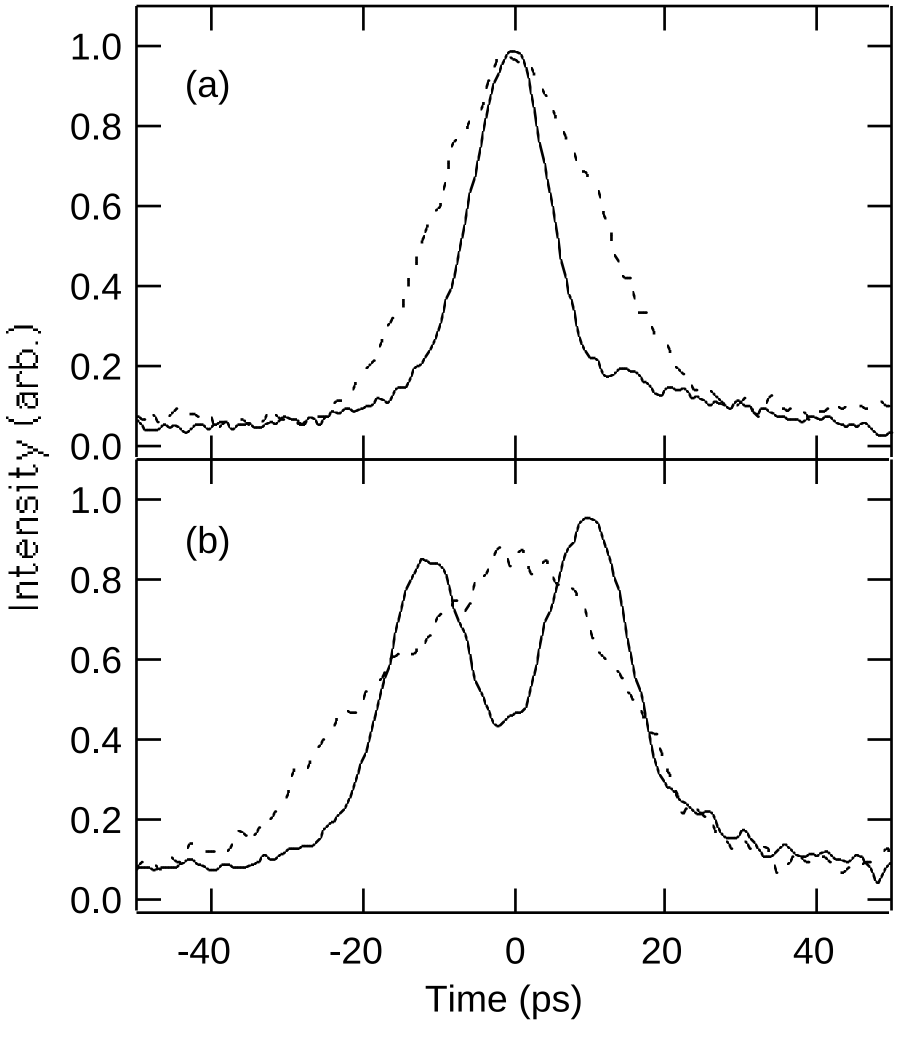

FIGURE 2