Chromatic Dispersion Monitoring of 80-Gb/s OTDM Data Signal via Two-Photon Absorption in a Semiconductor Microcavity

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***Abstract*—In this letter, a novel method of chromatic dispersion monitoring via two-photon absorption (TPA) is investigated. A specially designed semiconductor microcavity is employed as a TPA detector for monitoring data signals operating at rates up to 80 Gb/s. As the microcavity has a wavelength-dependent response, a single device can be used to monitor multiple channels in a multiwavelength optical telecommunication system.**

***Index Terms*—Dispersion monitoring, microcavity, two-photon absorption (TPA), wavelength-division multiplexing (WDM).**

I. INTRODUCTION

DUE TO continued growth of optical communication networks, it is expected that during the next 5–10 years individual channel data rates may exceed 100 Gb/s [1]. One of the major limitations for high-speed long-distance optical transmission systems is chromatic dispersion (CD). Various methods have been proposed to increase systems tolerance to CD such as the prechirp technique [2] or using a data modulation format resulting in a narrower optical spectrum, e.g., duobinary signaling [3]. However, compensation of accumulated CD is likely to be required for any high-speed telecommunication link. A commonly used optical technique is dispersion-management. This method allows only for complete dispersion compensation of a single wavelength with residual dispersion remaining in the other wavelength channels. Furthermore, some additional CD fluctuations may occur due to unstable environmental conditions, e.g., temperature fluctuations [4], mechanical stress or routing the data signals through different optical paths. These variations of CD became a serious problem in ultrafast systems operating with rates exceeding 40 Gb/s. Therefore, there is a need to continuously monitor the amount of CD and compensate it in real time. Various adaptive dispersion equalization schemes have already been proposed employing nonlinear detection to monitor the time domain optical pulse distortion resulting from CD [5], [6]. In this letter, the first demonstration of CD monitoring by employing a specially designed two-photon absorption (TPA) semiconductor microcavity is presented. This device can be used to monitor multiple channels in a wavelength-division-multiplexed (WDM) system.

II. TPA-BASED DISPERSION MONITORING

TPA is a nonlinear optical-to-electrical conversion process that occurs in semiconductors when two photons are simultaneously absorbed to generate a single electron–hole pair. The TPA photocurrent is proportional to the square of the incident optical power falling on the detector [7]. It is this nonlinear response, combined with TPA's ultrafast response time (10^{-14} s at 1550 nm [8]), which enables TPA to be considered for high-speed optical signal processing such as CD monitoring of individual wavelength channels.

One of the major problems of using the TPA process is the requirement for high optical intensities due to TPA's low efficiency. One way to overcome this problem is by the adoption of resonance cavity enhancement (RCE) technology. We have already demonstrated TPA enhancement of four orders of magnitude within the microcavity, in comparison to noncavity devices [7]. Recently, we have presented an experimental realization of optical sampling using a TPA microcavity structure which achieved a system sensitivity of 0.009 mW^2, demonstrating the high TPA efficiency [9]. One interesting feature of using an RCE-based device is the fact that the incident signal is only enhanced over a narrow wavelength range determined by the device design [7] and can be optimized for specific telecommunication systems operating at different data rates. This characteristic of the microcavity can be employed to monitor a single WDM channel without the necessity of using an additional external optical filter. Furthermore, the resonance peak of the cavity can be easily tuned by tilting the device, giving a possibility of sequentially monitoring different WDM channels with a single device [10].

The TPA effect can be employed for CD monitoring since its response to optical signals depends on the pulsewidths for the same incident average power. According to [11], assuming that the incident optical pulses have a Gaussian shape and the cavity resonance enhancement is given by wavelength-dependent function $\eta(\lambda)$, the average photocurrent generated by the TPA microcavity in the absence of single-photon absorption (SPA) by a pseudorandom binary sequence (PRBS) incident op-

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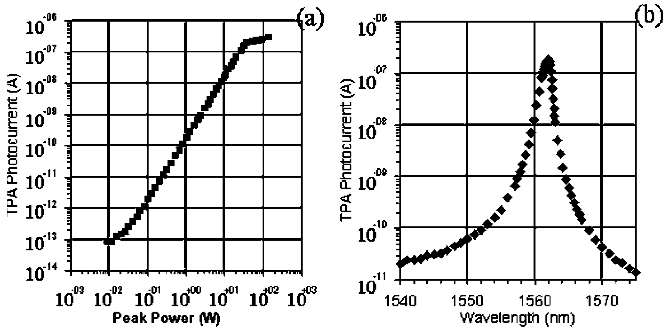

Fig. 1. Characterization of TPA microcavity: (a) square dependence of TPA photocurrent on incident optical power; (b) the cavity response as a function of incident wavelength.

tical return-to-zero (RZ) signal is given by

$$i_{\mathrm{ave}} = \frac{eV\beta T\eta(\lambda)}{h\nu\sqrt{\pi}\tau} I_{\mathrm{ave}}^2 \tag{1}$$

where V is the volume of the active region of the TPA detector, β is the TPA coefficient, T is the period of the incident pulse stream, τ is the pulsewidth coefficient ($\tau = 1.7\tau_{\mathrm{FWHM}}$), and I_{ave} is the average intensity of the modulated (PRBS) incident optical signal. The equation is true as long as pulses in adjacent bit slots are not overlapping ($T \gg \tau$). As pulses start spreading into adjacent bit slots due to the effect of CD, (1) is no longer valid, with the resultant output from the TPA detector tending toward a constant value

$$i_{\mathrm{const}} = \frac{eV\beta\eta(\lambda)}{2h\nu} I_{\mathrm{ave}}^2. \tag{2}$$

The above equation was obtained assuming that overlapping pulses combine incoherently.

III. DEVICE CHARACTERIZATION

In order to characterize the device TPA response for different incident peak powers, a 600-fs 10-MHz pulse laser operating at a fixed wavelength of 1558 nm was employed. Fig. 1(a) shows a plot of generated photocurrent as a function of incident optical peak power. It shows a square dependence of the photocurrent generated on the incident optical intensity, which is evidence of the TPA process. For low incident energies some residual SPA can be seen, at high incident optical powers, carrier saturation occurs. From the plot the device sensitivity is 0.0004 mW^2, limited by SPA at low powers. The resonance response of the TPA microcavity was characterized by employing a 10-GHz wavelength tunable (1480–1580 nm) pulse source generating pulses with durations around 2 ps. Fig. 1(b) displays the cavity TPA response as a function of the incident wavelength, with the resonance peak of 1561.5 nm, and spectral linewidth of 2 nm. The generated photocurrent at resonance is around four orders of magnitude greater than the photocurrent generated for off-resonance wavelengths.

IV. EXPERIMENTAL SETUP

The experimental setup is presented in Fig. 2. In order to simulate the effects of CD, the same optical signal was propagated through various lengths of single-mode fiber (SMF). This resulted in optical pulses with durations from 2 to 20 ps being incident on the TPA detector. The same 10-GHz optical pulse that was used for the device characterization was also used here. The generated optical pulse train was modulated with a $2^7 - 1$ PRBS, created by a pulse pattern generator. The signal was then multiplexed to higher bit rates using an OTDM multiplexer. To overcome the loss of the multiplexer, the generated data signal was amplified with an erbium-doped fiber amplifier to a peak power level of 420 mW (which ensures that nonlinear effects can be neglected in 1 km of SMF). Then the signal was passed through different lengths of SMF, ranging from 40 m to 1 km to introduce CD pulse broadening. The fiber lengths were chosen to be short enough such that polarization-mode dispersion (PMD) will not influence the propagated pulses. The fiber used had the following characteristics: $D = 16.77$ ps/km $\cdot$ nm, dispersion slope 0.0872 ps/km $\cdot$ nm^2, $\alpha = 0.189$ dB/km, and $\gamma = 2.4\ (\mathrm{W} \cdot \mathrm{km})^{-1}$, PMD ≤ 0.1 ps/$\sqrt{\mathrm{km}}$ (all measured at 1550 nm). The optical signal was amplified again due to the high optical power requirement for autocorrelation measurements. The signal was split by 10 : 90 optical coupler, with 90% of output power entering an SHG-based autocorrelator which allowed for the measurement of the optical pulse durations after fiber propagation. The remaining output signal from the coupler entered an inline attenuator/power meter allowing the average optical intensity to be continuously monitored. The average incident power was fixed at 1 dBm and incident on the TPA detector. The polarization controller was used to optimize the device response (the polarization sensitivity resulting from the TPA process and nonperfect device alignment was measured to be around 1.5 dB). The generated TPA photocurrent was measured using a picoammeter.

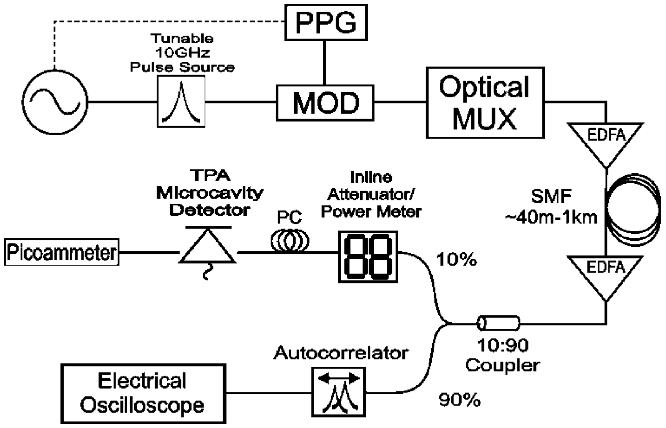

Fig. 2. Experimental setup for demonstrating CD monitoring via TPA in a semiconductor microcavity.

V. EXPERIMENTAL RESULTS

The experimental results are presented on Fig. 3(a) and (b), for 40 and 80 Gb/s, respectively. The diamond and square points present the experimentally measured TPA photocurrents for varied incident optical pulsewidths. According to (1), the generated TPA photocurrent is inversely proportional to the incident temporal pulsewidth τ, as long as τ is much lower then signal repetition rate T. For signals operating with rates 40 and 80 Gb/s, the bit periods are $T_{40} = 25$ ps and $T_{80} = 12.5$ ps, respectively. The solid lines in Fig. 3 are the best fits of (1)

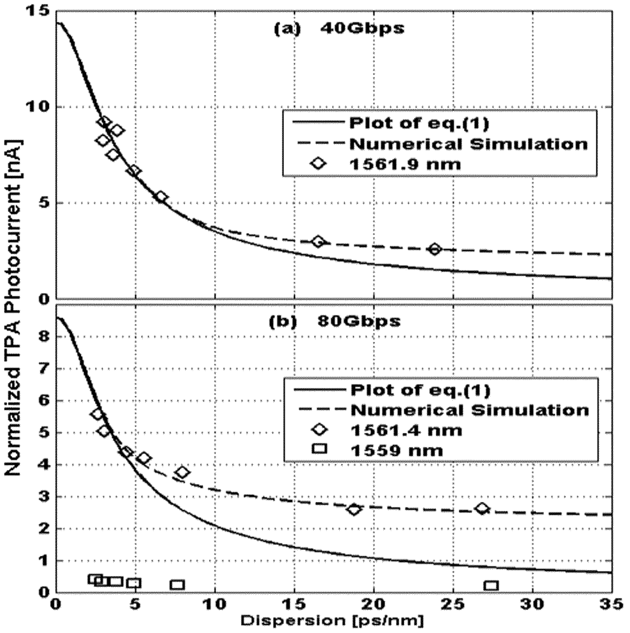

Fig. 3. Experimental results for resonance incident wavelengths (diamond points) and incident wavelengths shifted away from resonance (square points). Solid line is a plot of (1) and dashed line is a numerical simulation including the effect of pulse overlap.

to the experimental results obtained for pulses not exceeding single bit slot $\tau < T_{40/80}$. For wider pulses, the effect of pulse overlap causes deviations from the plot of (1). This can be clearly seen by looking at the results of the numerical simulations (which include the effect of overlap) shown by dashed line on Fig. 3(a) and (b). For the simulation, incident 40- and 80-Gb/s PRBS data (represented by Gaussian pulses with different pulsewidths) was generated by an incoherent combining of overlapping pulses, and then a TPA response of the resultant signal was calculated. The incoherent overlapping of the optical pulses was assumed since the time interleaving process of the optical multiplexer severely degrades the coherency of adjacent pulses. Numerical calculations were compared with experimental results obtained for wavelengths near the cavity resonance peak (diamond points). The good agreement between the numerical simulations and the experimental results is clear. The results show the device sensitivity for incident CD with range limited by the pulse overlapping to $\sim$30 ps/nm for 40 Gb/s and $\sim$15 ps/nm for 80 Gb/s.

In order to test the suitability of using a single device to monitor multiple wavelength channels, the same experiment (at 80 Gb/s) was carried out for the incident optical wavelengths slightly detuned from the resonance peak of 1561.5 nm. This result is plotted as square points in Fig. 3(b). As the incident optical signal wavelength is moved away from the resonance peak, the cavity response decreases. From this figure, we can see that the TPA response decreases by one order of magnitude when the incident optical signal was shifted 2.4 nm away from the resonance (square points) compared to the response on resonance (diamond points). This decrease of the cavity enhancement is as expected from analysis of the device resonance characteristic shown in Fig. 1(a), and demonstrates how the device maybe used to monitor CD of a single wavelength in a WDM system. For practical implementation, the required enhancement of the TPA response for the monitored channel at the cavity resonance, relative to the TPA response off resonance for the adjacent channels, will depend on the channel spacing and number of channels employed in the WDM system.

VI. CONCLUSION

Near future ultrafast communication networks will demand continuous monitoring of pulse broadening due to CD. A novel technique based on the nonlinear TPA process in a semiconductor microcavity has been proposed and experimentally verified showing potential for those future applications. Successful dispersion monitoring has been carried out for 40- and 80-Gb/s PRBS optical RZ signals. Furthermore, wavelength selectivity of the TPA microcavity was demonstrated. This type of device could thus be employed for monitoring of individual channels in a WDM system, and could be employed in conjunction with a tunable dispersion equalizer [5] for continuous system performance optimization. Furthermore, the monitoring range, although limited by pulse overlapping, could be improved by adding an additional monitoring channel in the WDM system, which would operate at a lower repetition rate than the data channels, and could thus handle higher dispersion levels before overlapping occurs.

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