Reduction of MAI and Beat Noise in OCDMA Systems Using an SA-SOA-TPA-Based Receiver

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***Abstract*—In this letter, we investigate the removal of multiple access interference and optical beat noise from a two-channel optical system that simulates the output from a time-spread optical code-division multiple access system operating at a data rate of 100 Mb/s. Both noise sources were removed using a saturable absorber semiconductor optical amplifier two-photon absorption receiver structure. Experimental results show error-free operation when all three devices are used together.**

***Index Terms*—Multiple access interference, optical beat noise, saturable absorber (SA), semiconductor optical amplifier (SOA), two-photon absorption (TPA).**

I. Introduction

OPTICAL code-division multiple access (OCDMA) has emerged as an alternative to current multiplexing techniques in current fiber deployments such as fiber-to-the-home due to a number of inherent advantages [1]. While optical coding can be performed using a number of different methods [1]–[3], each coding technique suffers from multiple access interference (MAI) and beat noise from interfering channels. These two phenomena severely degrade system performance due to the interference level scaling as the number of channels increases.

To combat MAI noise in an OCDMA system some form of optical thresholding [4] or optical time gating [5] can be employed. While both techniques are successful for combating MAI noise, they can require lengths of fiber typically $>$100 m and can also require a synchronized narrow optical clock pulse. Optical beat noise can be overcome by increasing the code length used or by employing some level of synchronization between the channels. However, this has the effect of limiting the transmission data rate and reducing the bandwidth efficiency of the system, respectively, while also increasing system cost and complexity.

It has been previously shown that a two-photon-absorption (TPA)-based detector operating at the signal data rate can be used to suppress MAI in an OCDMA system [6] and a saturable absorber (SA) used in conjunction with a TPA-based detector can further improve performance [7]. However, neither device can effectively deal with beat noise generated by interfering channels. In this letter, we present a proof-of-concept experiment using a gain saturated semiconductor optical amplifier (SOA) in conjunction with a SA and TPA detector to suppress both optical beat noise and MAI.

Manuscript received May 27, 2009; revised July 28, 2009. First published September 09, 2009; current version published October 28, 2009. This work was supported by the Higher Education Authority PRTLI (2007–2011) via the INSPIRE programme.

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Digital Object Identifier 10.1109/LPT.2009.2031086

II. Characterization of Nonlinear Devices

A. TPA-Based Detector

TPA is a nonlinear optical-to-electrical conversion process where the bandgap energy of the device is greater than the energy of a single photon but is less than twice the photon energy such that $E_{\rm ph} < E_{\rm bg} < 2E_{\rm ph}$ [8]. This results in a nonlinear optical-to-electrical conversion of the incoming light into electrical photocurrent. Due to this response, a TPA device can act as a thresholder by only allowing higher power optical signals to be converted. The TPA-based detector used in this experiment was an unbiased commercially available InGaAsP 1.3 μm Fabry–Pérot laser (ML 1030 from Modulight Inc.). The output photocurrent as a function of the incident optical peak power is shown in Fig. 1(a). At low optical powers, the resultant photocurrent from the TPA detector is due to linear absorption. However, at an optical peak power of $\sim$1 W, the generated photocurrent begins to shift from linear absorption to TPA with higher powers resulting in an ideal square response.

B. Saturable Absorber

An SA can also be used to suppress MAI in an OCDMA system due to its high losses at low optical powers while allowing high power signals to pass through [9]. The SA used in this experiment was a commercially available resonant SA mirror , from BATOP Optoelectronics, with a resonance wavelength of 1556 nm which can be tuned using temperature effects by up to $\sim$6 nm. The relaxation time of the SA is 5 ps. The optical loss as a function of input optical power for the SA is shown in Fig. 1(b). For low optical powers below -5 dBm, the optical loss experienced upon reflection from the device was measured as 15.3 dB. The optical loss of the SA is reduced by 3 dB at an input average power of 7 dBm. The transmission exhibits a maximally nonlinear response at the cavities resonance wavelength of 1556 nm, as shown in the inset of Fig. 1(b).

C. Semiconductor Optical Amplifier

Optical beat noise between two channels at similar wavelengths results in the need for optical thresholding of the one level. It has been shown in [10] and [11] that a gain-saturated SOA can be used to remove optical beat noise and intensity noise in passive optical networks and wavelength-division-multiplexed systems, respectively. The optical gain of the SOA as a function of input power is shown in Fig. 1(c). It can be seen that as the input power increases

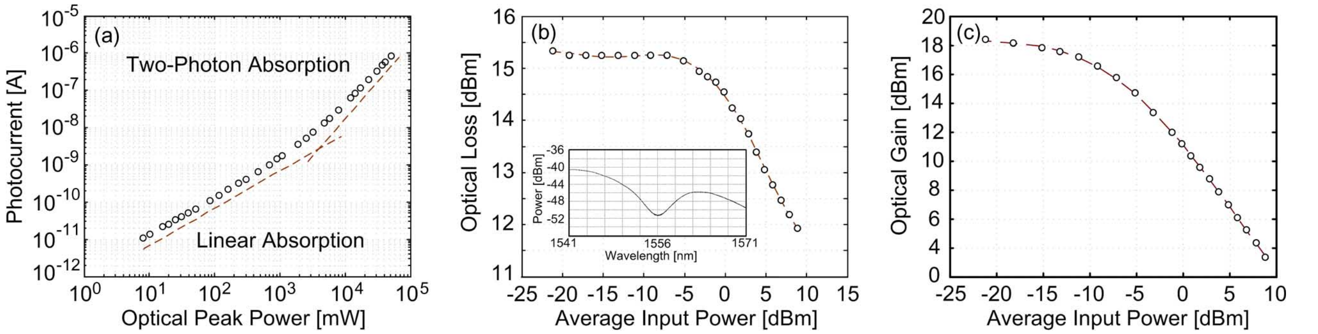

Fig. 1. (a) Plot of TPA photocurrent as a function of input peak power. (b) Plot of optical loss as a function of input power for the SA. (c) Plot of optical gain as a function of input power for the SOA. Each device was characterized with 25-ps optical pulses at a repetition rate of 100 MHz.

above −5 dBm the gain begins to saturate at an output power of 11 dBm. By ensuring that the one level of the optical signal is close to the saturation point of the device, an SOA acts as an optical intensity limiter thereby reducing the amount of beat noise and improving the overall system performance.

III. Experimental Setup

It has been previously shown in [6] that a TPA-based detector can be used to suppress MAI in a four-channel time-spread (TS) OCDMA system. Each channel in this OCDMA system used 31-chip, 40-Gchip/s quaternary phase-shifted codes with a chip duration of 25 ps operating at a data rate of 100 Mb/s. In the experimental setup shown in Fig. 2, we aim to simulate the output from one decoder of this OCDMA system without actually performing the encoding/decoding process. This is achieved by assuming that the correctly decoded channel has a pulsewidth of 25 ps, i.e., the chip duration, while the incorrectly decoded channel remains spread over the entire bit period of 10 ns. To generate both of these simulated OCDMA channels, continuous-wave (CW) light with a central wavelength of 1556 nm was split equally through an optical coupler. In one arm an electroabsorption modulator (EAM) was used to pulse carve optical pulses at 10 GHz, with a pulsewidth of ∼25 ps, [Fig. 2(A)]. This 10-GHz pulse train was then gated down to 100 MHz and modulated with a pseudorandom bit sequence (PRBS) signal, simulating the correctly decoded OCDMA signal [Fig. 2(B)]. The second arm of the coupler was fed to a second Mach–Zhender modulator (MZM) which carved out a 100-MHz PRBS signal over the entire bit period of 10 ns, simulating an improperly decoded OCDMA channel assuming the interference was spread out equally over the entire bit slot [Fig. 2(C)] resulting in MAI. In this type of OCDMA system where the channels are at the same wavelength, optical beat noise can occur because the channels may experience different path lengths and have only partial coherence. As a result, when they are recombined, they interfere randomly, producing beat noise. Optical attenuators were used to control the average power in each arm before the two signals were recombined [Fig. 2(D)]. The resultant signal was then amplified before passing through one of three different receiver structures.

The SA-SOA-TPA receiver is shown in Fig. 3. Three variations of this receiver were used in the experiment. The first consisted of a variable optical attenuator (VOA) followed by an erbium-doped fiber amplifier (EDFA), a 2-nm optical filter, and a second EDFA followed by a TPA-based detector. The electrical

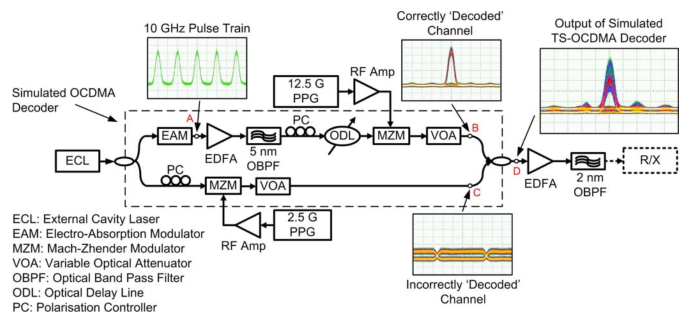

Fig. 2. Experimental setup to simulate the output signal from an OCDMA decoder with MAI and beat noise. Oscilloscope traces shown were measured using a 50-GHz photodiode.

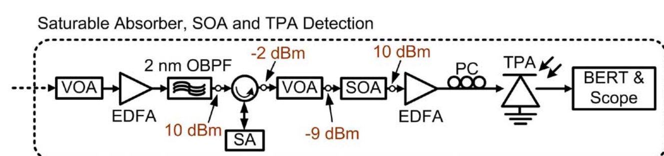

Fig. 3. SA-SOA-TPA receiver structure used to remove MAI and optical beat noise.

output of the TPA detector was amplified and analyzed using a bit-error-rate tester (BERT) and an oscilloscope. The second receiver expanded on the first and employed an SA between the 2-nm optical filter and the second EDFA. The SA was placed before the TPA detector in order to improve the extinction ratio by suppressing the MAI while also filtering out amplified spontaneous emission (ASE) from the first EDFA. Finally, the third receiver employed the SOA directly after the SA in the second receiver. The purpose of the SOA was to remove any beat noise that is present on the one level due to the mixing of the channels. An additional VOA was used before the SOA to optimize the performance achieved from the SOA.

IV. Experimental Results

Fig. 4(a) shows the bit-error-rate (BER) results using the TPA-based detector for single channel (△) and two channels with the same average power (○). There is a power penalty of ∼20 dB at an error rate of 1×10^{-9} when the interfering channel is introduced. If the power in the interfering channel is increased to 3 dB higher than the desired channel, the eye opening of the detected signal becomes so degraded that the corresponding BER cannot by measured (shown by the inset

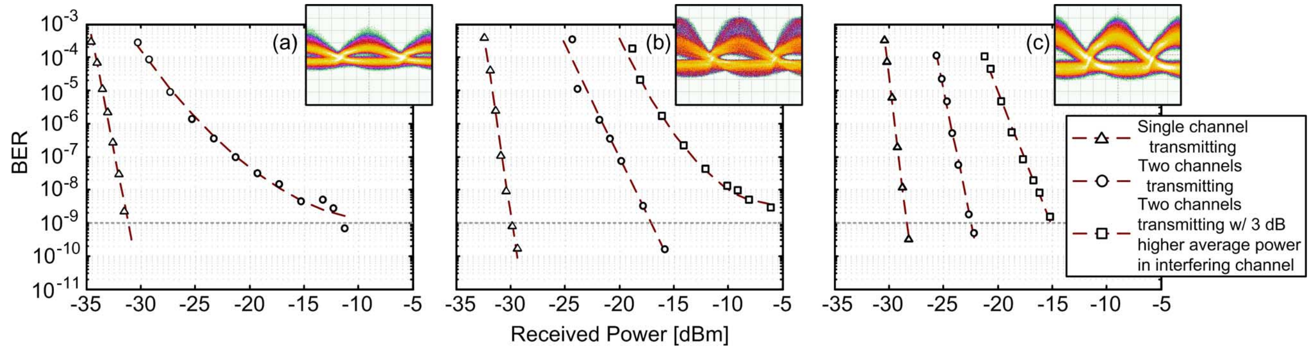

Fig. 4. BER plots for (a) TPA-based detector, (b) SA and TPA detector, and (c) SA, SOA, and TPA detector. The insets show the eye diagrams when the interfering channel is 3 dB higher than the desired channel with a received average power of -15 dBm.

eye diagram for a received power of -15 dBm). Increasing the interfering channel power by 3 dB simulates the level of interference that would be present if a third transmitting channel, or a second interfering channel, was added to the system.

Fig. 4(b) shows the curves obtained when using both the SA and TPA detector at the receiver. It can be seen that the addition of the SA results in error-free performance for both the single-channel and two-channel operation with a power penalty of ~13 dB, a 7-dB reduction in comparison to just the TPA detector on its own. The third BER result shown by the squares (□) in Fig. 4(b) is for both channels transmitting data with the interfering channel having an average power that is 3 dB higher than the desired channel. This extra 3 dB of power is similar to the amount of interference generated by a third channel. Even with this increased level of interference, the receiver can still produce an error rate of $\sim 5 \times 10^{-9}$, albeit with a power penalty of 12 dB. The inset eye diagram is shown for this case where the received power is -15 dBm. When compared to the eye diagram for the TPA detector, the increase in beat noise on the one level is clearly noticeable due to the nonlinear response of the SA.

Finally, Fig. 4(c) shows the BER results obtained using the SA, SOA, and TPA detector devices together. For this scenario, all three transmitting scenarios can achieve a BER of 1×10^{-9} with power penalties of 5 and 7 dB when moving from the single channel to two channels and increasing the interfering channel average power by 3 dB, respectively. Examining the inset eye diagram, it can be seen that the large amount of beat noise present on the eye in Fig. 4(b) has been significantly removed by the saturated SOA. As a result, the eye opening has widened giving lower error rates with smaller power penalties.

V. Conclusion

In this letter, we have presented an optical receiver structure that incorporates an SA, an SOA, and a TPA-based detector. This receiver has been experimentally shown to successfully remove both MAI and beat noise in a system that simulates the output of a 31-chip TS-OCDMA system. The experimental results show that the receiver using an SA, SOA, and TPA device incurs a power penalty of 5 dB when an additional interfering channel is added. This is a reduction of 13 dB when compared to a receiver using only a TPA-based detector. One advantage of using such a receiver structure is the possibility of integration into a single, higher speed, small area device that could be used in future OCDMA applications.

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