Coherent-to-Incoherent Light Conversion for Optical Correlators

Paola Parolari, Lucia Marazzi, Damiano Rossetti, Guido Maier, and Mario Martinelli

***Abstract*—The authors present a novel coherent-to-amplified spontaneous emission (ASE) converter based on SOA's cross-gain modulation (XGM) in a counterpropagating configuration. Experimental characterizations of the ASE converter with bit-error rate (BER) measurements at 2.5 and 5 Gb/s are shown. The device capabilities are exploited in a delay lines optical recognizer at 2.5 Gb/s. Recognition is based on a coherent-to-incoherent light conversion followed by a fiber array correlation filter. Experimental evidence here reported shows performance improvement in comparison with a scheme which adopts a standard telecom source.**

***Index Terms*—Cross-gain modulation (XGM), fiber optics communications, frequency conversion, optical correlators, semiconductor optical amplifiers (SOAs).**

I. Introduction

In VIEW of very high bit-rate optical networks, all-optical processing subsystems for digital sequence recognition are likely to attract a great deal of interest. In fact, sequence recognition is a fundamental function in many communication operations, such as packet or frame delineation, address or label identification, control messaging, and many others [1], [2]. Traditional systems usually perform this operation in the electronic domain by converting the optical information, or part of it, into electronic signals. On the other hand this conversion can be avoided operating only in the all-optical domain, where recognition is commonly obtained through correlation operation. One of the most interesting solutions proposed in the literature is represented by fiber delay lines correlation filters, where correlation is obtained by summing properly delayed replicas of the pattern to be recognized. The target keyword, with K ones, is encoded in K delay fiber array. The autocorrelation occurs when the keyword enters the filter, in this case K logical ones sum up, giving the autocorrelation peak. In all of the other cases the keyword is cross-correlated to the input sequence and only low intensity cross-correlation peaks are present. Discrimination between autocorrelation and cross-correlation peaks is provided by a threshold. Thus, any interference phenomenon which occurs during replica recombination is undesired and may affect the correlation peak detection.

The spectral properties, i.e., the coherence, of the optical signal entering the correlator heavily condition the quality of the filter output signal. In the analysis of the correlator circuit, a multiple arm Mach–Zehnder structure, two parameters in particular are useful: the minimum interferometer differential time delay T and the source coherence time τ_C. Two main operation regimes are identified by T/τ_C ratio values. When $T/\tau_C \ll 1$, the correlator operates into coherent regime and interference between the optical fields in the correlator arms occurs. If no care is taken to fix the relative phases of the interfering fields, the total output correlation intensity can be expected to vary strongly, thus preventing recognition. On the other hand when $T/\tau_C \gg 1$, interference is reduced. This condition is not easily achieved when operating the delay-line-based correlator at growing bit rates. In fact, T in the fiber correlator is inversely proportional to the data flow bit rate. The coherence time of many standard telecommunications laser sources, typically ranging in the order of tens of nanoseconds, results in a bit rate limitation of hundreds of megabits per second. On the other hand, this device can be usefully exploited only in high bit-rate networks where T is very short. The solution to this conflict is the use of incoherent light, e.g., light emitted by LED's or ASE sources. In fact, the incoherent light allows us to exploit these interferometric-like structures avoiding beating noise even when the delays between the fiber lines are extremely short, i.e., a few microns.

II. Coherent-to-Incoherent Light Converter

The aim of this work is to present a coherent-to-incoherent light conversion, achieved by an all-optical amplified spontaneous emission (ASE) converter which can be locally employed before entering the fiber correlator subsystem. The communication optical signal, whose carrier can have any spectral linewidth and most likely a narrow one, is thus locally converted into an optical signal having a low coherence time. The converter employs a semiconductor optical amplifier (SOA) and exploits the cross-gain modulation (XGM) phenomenon. The locally generated ASE is cross-modulated by the incoming optical signal, and the output light has the same coherence time of ASE, whose τ_C can be estimated in hundreds of femtoseconds.

As stemmed in recent literature [3], the XGM phenomenon in SOA's has been extensively exploited for wavelength conversion of coherent signals; an intensity modulated signal, the drive, saturates the SOA gain, then a second signal, the CW

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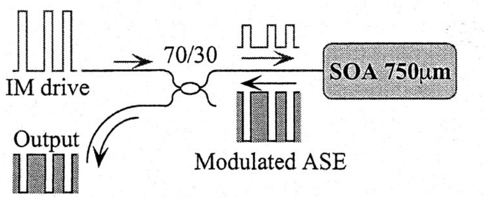


Fig. 1. ASE converter device, a schematic.

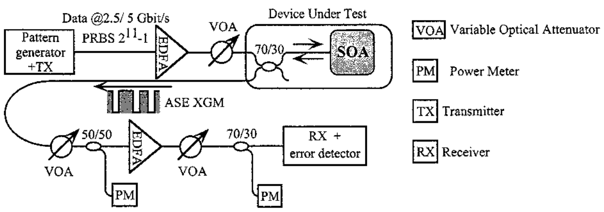
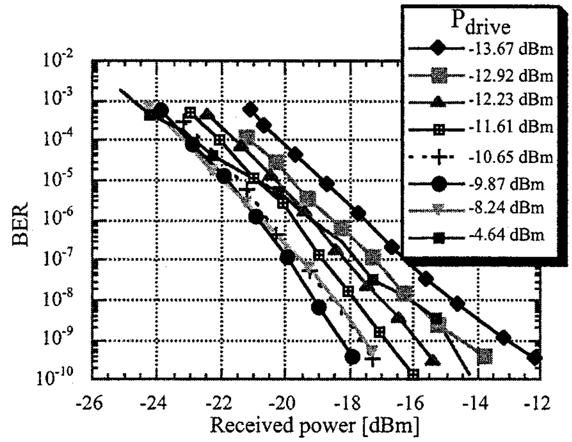


Fig. 2. Experimental setup for BER measurements at 2.5 and 5 Gb/s using $2^{11}-1$ PRBS sequences.



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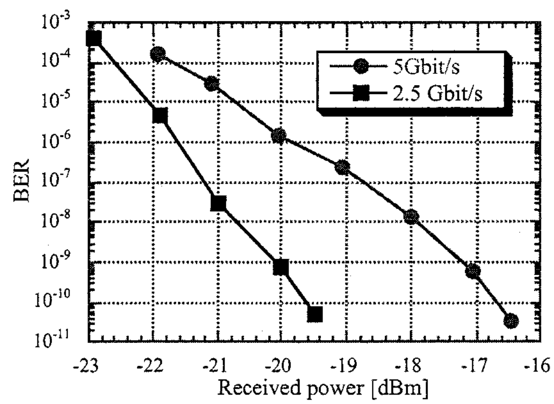


(b)

Fig. 3. (a) BER measurements at 2.5 Gb/s when varying drive power. Optimum condition is achieved with −9.87 dBm. (b) Penalty of 2.8 dB between ASE conversion at 2.5 and 5 Gb/s. In both cases SOA bias current was of 299 mA and $2^{11}-1$ PRBS sequences were employed.

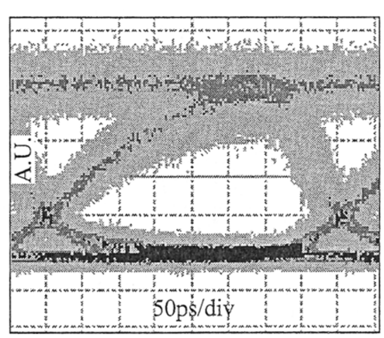


Fig. 4. Eye diagram of the converted ASE signal at 2.5 Gb/s with $P_{\text{drive}} = -9.87$ dBm. Different rise and fall times are distinguishable.

probe, propagating in the same SOA, experiences the intensity modulation induced by the drive. Thus the drive IM information is transferred to the probe with inverted logic. The same basic approach can be exploited for conversion of a coherent signal into incoherent light, i.e., ASE, which, in this case, acts as the probe.

Our device is shown in Fig. 1: a 70/30 coupler feeds the SOA with the IM drive and outputs the converted ASE. As can be seen, a counterpropagating configuration is adopted. In fact only this solution, which avoids signals filtering, allows us to obtain an ASE source by cross-gain modulating the spontaneous emission generated in the SOA itself. On the other hand, in counterpropagating configurations the SOA length limits the conversion bit rate [4] and thus a compromise has to be reached between efficiency in terms of needed drive power and available ASE power and conversion speed. In our case the available SOA is 750 μm long and thus limitations due to SOA length should arise at bit rates higher than 10 Gb/s. As for coherent signal wavelength conversion, bit-rate limitations arise also from the amplification mean carrier lifetime. It can be expected that high bit-rate operation and a good extinction ratio can be achieved at gigabits/s bit rates by pre-amplifying the transmission line signal, i.e., the drive signal. Unfortunately, due to the specific application, speed enhancement techniques such as optical pumping [5] used for coherent signals conversion cannot be adopted as injection of a CW optical signal would affect ASE generation.

III. ASE Converter Experimental Characterization

In order to fully characterize the ASE converter behavior, before employing it in the correlation subsystem, we performed BER measurements at 2.5 and 5 Gb/s using $2^{11}-1$ PRBS sequences; in Fig. 2 the adopted experimental setup is shown. In Fig. 3(a) converted ASE BER curves are plotted versus the received power for various values of the drive power, ranging from −13.67 to −4.64 dBm. An optimum drive power of −9.87 dBm guarantees best device performances at 2.5 Gb/s. This condition corresponds to a trade off between high extinction ratios (high drive power) and fast recovery times, prevented by severe carriers depletion. In Fig. 4 the converted ASE eye diagram is

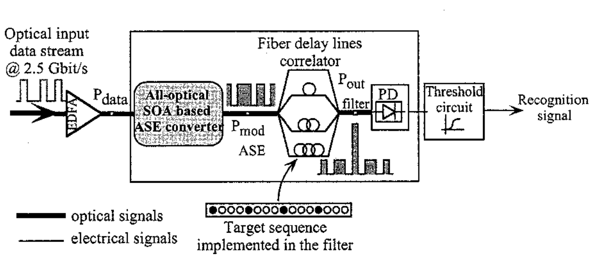
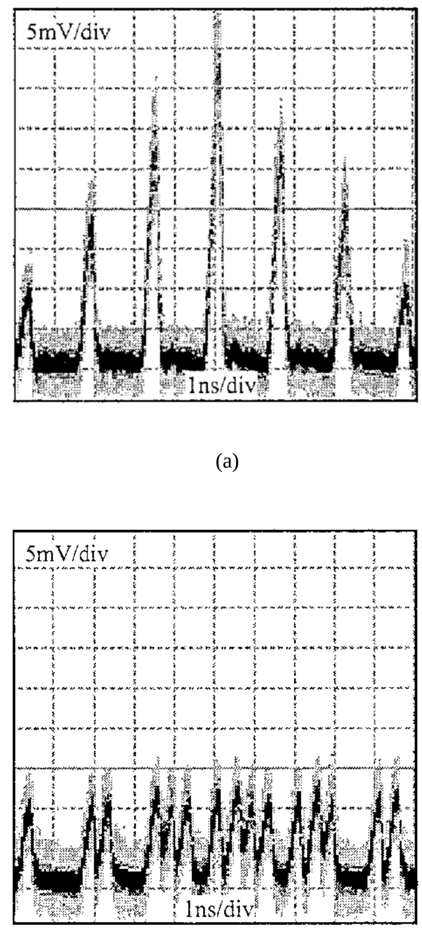


Fig. 5. Schematic of the correlation subsystem based on coherent-to-incoherent light conversion made by the ASE converter. During the experiments a sampling oscilloscope was in place of the threshold circuit.

shown. Although rise and fall times are not very different, the slower gain recovery time is still evident when the drive signal moves from high to low levels. All these measurements were performed with SOA maximum bias current, i.e., 299 mA. In fact in this condition higher carrier/photon interaction leads to faster operation. Only 2.8 dB of penalty were measured at 10^{-9} BER, doubling the bit rate from 2.5 to 5 Gb/s. As shown in Fig. 3(b), the slower slope of 5 Gb/s measurements points out that conversion at this bit rate is approaching the 750 μm-long SOA inherent speed limit. Better performance in terms of operation speed and drive power budget are expected with longer SOAs which present higher gains and thus higher spontaneous emission levels and extinction ratios [4]. On the other hand, to guarantee good performance at 10 Gb/s in order to keep the SOA transit time (15 ps) at least one order of magnitude less than the bit period (100 ps), SOAs no longer than 1.5 mm should be used.

Setup optimization requires substitution of the 70/30 coupler with a circulator.



(a)

(b)

Fig. 6. (a) Autocorrelation persistence diagram of the sequence 1000100010001000. (b) Crosscorrelation persistence diagram of the sequence 1000100010001000 with the OOC 1000010000100001.

IV. Application of the ASE Converter to All-Optical Correlation

As briefly mentioned in Section I, one of the possible applications of the proposed converter is in recognition systems based on fiber delay lines correlation filters. In fact, with respect to systems which employ standard telecom sources without operating an active phase control, conversion into incoherent light offers some advantages in terms of the output stability [6]. Encouraging results obtained during ASE converter characterization have been confirmed during the experimentation of the complete correlation subsystem, whose schematic is presented in Fig. 5. The data stream coming from the transmission line, after proper amplification, represents the drive optical signal of the coherent-to-ASE converter. Its output is fed into the correlator; an electrical threshold circuit performs recognition by discriminating between autocorrelation and cross-correlation. To test the device behavior we considered a two-code optical orthogonal code (OOC) family [7] of 16 bits and weight, i.e., K, 4: the target keyword implemented in the fiber array is 1000100010001000, while the orthogonal word is 1000010000100001.

The fiber delay lines correlator is thus composed of four delay lines and designed for a bit-rate of 2.5 Gb/s. The delays are, respectively, of 96, 64, and 32 cm, as an 8-cm fiber length corresponds to a bit duration of 400 ps. The average powers involved in the experiment are: −4.5 dBm for $P_{\rm data}$, 3.8 dBm for $P_{\rm modASE}$, and −6.7 dBm for $P_{\rm outfilter}$, which correspond, respectively, to the average power levels of the cross-modulating amplified data stream, the output of the coherent-to-ASE converter and the output signal of the fiber delay lines correlator. The almost 9-dB losses in the fiber delay lines correlator are due to employment of a 1×8 coupler instead of a 1×4 one which was not available.

Good correlator performance is related to power equalization in each arm and precise tuning of the fiber delay lines length. As fiber attenuation coefficient is quite low, the path differences corresponding to hundreds of megabits per second bit-rates do not cause large power unbalances. In Fig. 6(a) and (b) the autocorrelation of the keyword 1000100010001000 and the cross-correlation with the sequence 1000010000100001 are presented, respectively. The figure shows the persistence diagram of the device output obtained from a 20-GHz bandwidth photodiode, displayed on a sampling oscilloscope. Due to the inherent chosen code properties the autocorrelation diagram shows all the four obtainable levels. The mean values of these four logical levels are plotted in Fig. 7, demonstrating the

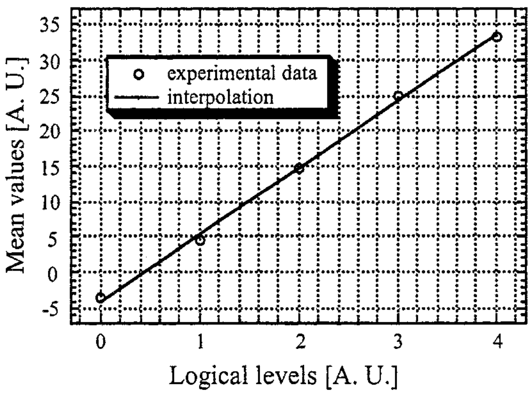
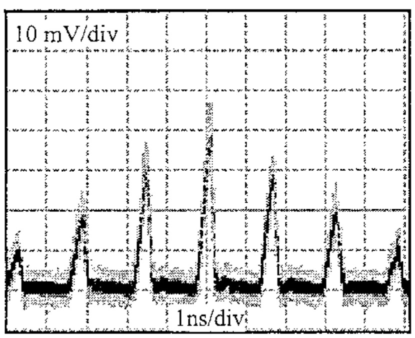
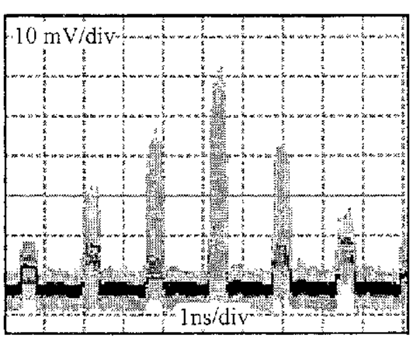


Fig. 7. The mean values of the device four logical levels shows the correlator filter linearity.



(a)



(b)

Fig. 8. (a) Autocorrelation persistence diagram of the sequence 1000100010001000 when using local ASE conversion. (b) Autocorrelation persistence diagram of the sequence 1000100010001000 when using a coherent source with $\tau_C = 150$ ps.

linearity of the correlator filter when employing local ASE conversion. This result shows that, due to the local conversion process, the correlator operates exactly as estimated by theory. In particular, the filter sums bit power levels without introducing interference terms. For comparison in Fig. 8(a) the autocorrelation persistence diagram, obtained when employing the ASE converter, is shown together with Fig. 8(b) where a coherent data source, without coherent-to-ASE conversion, is used. In case (b) the employed laser source has a coherence time of nearly 150 ps corresponding to a coherence length of 3 cm. As can be seen coherent-to-ASE conversion allows an improvement of the output stability performance as expected from theory. Moreover, optimization of the ASE converter and of the fiber delay lines filter setup would diminish the overall system losses, improving the modulated signal extinction ratio and the received signal quality.

V. Conclusion

We have demonstrated a coherent-to-incoherent converter based on SOA XGM. The device behavior has been characterized by BER tests both at 2.5 and 5 Gb/s confirming expected results with the employed 750 μm-long SOA. Higher bit rates are likely achievable with longer SOA's, though the counterpropagating configuration limits the maximum allowable SOA length. Moreover, the proposed converter has been used together with an all-optical fiber delay lines correlator in order to improve the filter output stability as shown by the comparison of the autocorrelation persistence trace with and without local ASE conversion.

All-optical sequence recognition is only one of the possible applications of the proposed converter which can be employed whenever a local coherent-to-incoherent conversion is needed. In fact, the converted signal is an ASE light, which is, due to its inherent characteristics, more suitable for local processing than for transmission.

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