Incoherent-to-Coherent Wavelength Conversion Using Semiconductor Optical Amplifier

Mourad Menif
École des Communications de Tunis
(SupCom) 2083 El Ghazala Ariana, Tunisia
mourad.mnif@supcom.rnu.tn

Pascal Lemieux, Walid Mathlouthi, Leslie Ann Rusch
Center for Optics, Photonics and Lasers (COPL),
Université Laval, Québec, Canada G1K 7P4
rusch@gel.ulaval.ca

Abstract—This paper reports for the first time an all-optical wavelength conversion of an incoherent optical signal to a coherent optical signal using the cross-gain modulation in semiconductor optical amplifiers. Wavelength division multiplexed networks using broadband sources have performance limited by beat noise; conversion from a non-coherent to a coherent signal eliminates beat noise and enables the elimination of the bit error rate floor.

Keywords-Semiconductor optical amplifiers, cross-gain modulation, all-optical wavelength conversion, broadband source, beat noise.

I. INTRODUCTION

Incoherent broadband optical communication systems like optical code-division-multiplexed access (OCDMA) [1] and spectrum-sliced wavelength division multiplexing (SS-WDM) [2] offer low cost alternatives to conventional wavelength division multiplexed (WDM) networks. The major weakness of systems using broadband sources generated from spontaneous emission is the beat-noise generated by square-law photodetection [3]. As the bit rate increases, the detected optical noise becomes large, degrading network quality of service and limiting system performance. A bit error floor rate exists for SS-WDM due to signal dependent noises, as opposed to coherent systems without such a floor. In order to avoid the bit error rate (BER) floor, and/or accommodate a higher bit rate, a wider optical bandwidth is required for SS-WDM, reducing the spectral efficiency and increasing the effects of dispersion. Similarly for OCDMA, reduction of beat noise is essential to exploit the advantages of sharing the same spectr al band by several users at the same time: increased network capacity, enhanced network flexibility and ease of support for an increasing subscriber base.

We use the cross-gain modulation mechanism in semiconductor optical amplifiers (SOAs) to reduce the beat noise via conversion of the modulated incoherent optical signal into a coherent signal before the detection process. A continuous-wave (CW) probe beam together with the incoherent modulated channel is injected into the SOA. The incoherent optical signal modulates the gain of the SOA by depleting the carriers. The CW laser encounters the modulated gain and will carry the inverted data carried initially by the incoherent optical signal. The proposed scheme can not only eliminate the beat-noise effect due to broadband sources but also can operate as an all optical converter for optical signals from last miles system using spectrum sliced sources to a WDM network using coherent signals.

II. SOA MODEL

Many SOA models presented in the literature [4-7] use simplifying assumptions that do not permit accurate prediction and understanding of the cross-gain modulation effect. We use the wideband model for a bulk In-InGaAsP SOA presented by Connely in [8] which adequately accounts for internal parameters, dynamic behavior and can be characterized using measurable external variables such as output power and amplified spontaneous emission (ASE).

This wideband model is based on numerical solution of coupled equations for carrier-density rate and traveling-wave (or photon rate) equations for forward and backward propagating signals, and spectral components of amplified spontaneous emission powers. In the amplifier, the spatially varying component of the field due to each signal is defined by equation (31) of [8], where the number of injected signals, can be decomposed into two complex traveling-waves equations for the signal field $E^+_s$ and $E^-_s$, propagating in the positive and negative z directions, respectively. Each signal obeys the complex traveling-wave equations [8]:

$$\frac{dE^\pm_s(z)}{dz} = \left\{ j\beta_s \pm \frac{1}{2} \left[ \Gamma g_m(\nu_s,N(z))-\alpha \right] \right\} \left| E^\pm_s(z) \right|$$

where $\beta_s$ is the signal propagation coefficient, $\Gamma$ the optical confinement factor, $g_m(\nu_s,N(z))$ the material gain coefficient, $N(z)$ the carrier density, and $\alpha$ is the material loss coefficient. It is assumed that the squared modulus of the amplitude of the traveling-wave is equal to the photon rate of the wave in that direction, so $N^\pm_s = \left| E^\pm_s \right|^2$.

On the other hand, $N^+_s$ and $N^-_s$ are defined as the spontaneous emission photon rates for a particular polarization in a frequency spacing $K_w \Delta \nu_m$ centered on frequency $\nu_j$ traveling in the positive and negative z directions, respectively where $\nu_j$ is defined by equation (31) of [8], $K_w$ is a positive...
integer, and \( \Delta N_m \) is the longitudinal mode frequency spacing described by equation (33) of [8]. Those spontaneous emission photon rates observe the following equation [8]:

\[
\frac{dN^+_j(z)}{dz} = \pm [\Gamma g_m(v_j, N(z)) - \alpha] N^+_j(z) + R_m(v_j, N(z))
\]

where \( R_m(v_j, N(z)) \) represents the spontaneously emitted noise coupled into \( N^+_j \) or \( N^-_j \). The carrier density \( N(z,t) \) at \( z \) acquires the form [8]:

\[
\frac{dN(z)}{dt} = \frac{I}{edLW} - R(N(z)) - \Gamma \sum_{j=1}^{N_s} g_m(v_j, N(z)) \left( N^+_j(z) + N^-_j(z) \right)
\]

\[
-2\Gamma \sum_{j=1}^{N_s} g_m(v_j, N(z)) K_j \left( N^+_j(z) + N^-_j(z) \right)
\]

where \( I \) is the bias current, \( e \) electric charge, \( d \) active region thickness, \( L \) active region length, \( W \) central active region width, \( R(N(z)) \) recombination rate term, \( N_s \) number of injected signals as mentioned before, and \( N_m \) number of spectral components of amplified spontaneous emission powers.

For the steady-state solution, we used an iterative solution based on splitting the amplifier into a number of sections labeled from \( i = 1 \) to \( N_s \) and assuming the steady-state numerical algorithm described with further details in [8]. Time evolution of carrier density rate depends only on current bias level and the input fluxes. In other words, we adjust the carrier density and then we compute the coefficients of the traveling-wave equations. Subsequently, the signal fields and noise photons densities are predicted.

III. EXPERIMENTAL DEMONSTRATION

Our experimental setup is depicted in Fig. 1. A continuous-wave signal from a tunable DFB laser is injected into a Kamelian optical pre-amplifier SOA, via an optical isolator, in counter-propagation. This laser will be extracted from the other side of SOA via the third port of an optical circulator. The first port of the circulator is connected to the active region, whereas the second port is connected to the SOA. Either a coherent DFB laser or an incoherent optical signal is input to the external modulator. The incoherent signal was obtained by slicing the ASE from an EDFA using 1.2 nm tunable bandpass filter.

In order to evaluate the effectiveness of the conversion of a modulated incoherent broadband source to a modulated coherent signal, we adopt the extinction ratio as a figure of merit. We compare the extinction ratio before and after conversion for two cases: 1) conversion of a modulated incoherent input signal to a coherent output, and 2) wavelength conversion of a modulated coherent input signal to a coherent output. For our experiment the output coherent signal is at 1520 nm, as determined by the CW DFB laser introduced in counter-propagation. The coherent input source is a DFB laser at 1553 nm, while the incoherent signal is centered at 1553 nm with an optical bandwidth of 1.2 nm. Both are externally modulated at 622 Mb/s, with extinction ratio of 11 dB. The incoherent signal is generated by slicing the ASE from an EDFA using a 1.2 nm tunable bandpass filter. The center frequency was of 1553 nm was selected as it maximizes the extinction ratio at the output of the SOA, subject to maximizing the power in the SS-WDM signal (about -6.86 dBm around the area of the 1550 nm).

The output extinction ratio is determined by the difference in gain observed between the wavelengths of the intensity modulated input channel and the CW channel. The measured extinction ratio of the converted signal versus the CW input power for coherent and incoherent case is shown in Fig. 2, where the bit rate of the modulated signal is fixed at 622 Mb/s. It is important to mention that in order to justly compare these two cases, we fix the average input power and the input extinction ratio of the modulated channel approximately around -6.86 dBm and 11 dB, respectively. We obtain the maximum extinction ratio for both cases around -15 dBm for the CW input power with a minimum extinction ratio penalty of 1.5 dB and 4 dB, respectively for coherent-to-coherent conversion and incoherent-to-coherent conversion. Note that although the extinction ratio is degraded for the non-coherent signal, the bit error rate can still manifest improvement given a coherent signal is now incident on the photo-detector.

Figure 1. Experimental set-up.
IV. SIMULATION RESULTS

The Kamelian SOA used in our experiment was optimized to have flat gain profile over a wide input bandwidth. As the output extinction ratio is determined by the difference in gain for the input wavelength and CW probe wavelength (i.e., the conversion wavelength), the use of a SOA with more peaked gain vs. wavelength would be more appropriate for this application. We now turn to simulation to show the output extinction ratio that can be accomplished by such a SOA (in particular using parameters from Connelly [8]) vs. the Kamelian SOA. We compare the output extinction ratio for each SOA as a function of both 1) input extinction ratio, and 2) conversion wavelengths. Whereas the parameters from Connelly are given in [8], we must infer these parameters from measurements of the Kamelian SOA, as described in the next section.

A. SOA characterization

In order to predict extinction ratio improvement, we must characterize the Kamelian SOA through static measures to model it. This characterization takes into account the output power level and the ASE profile in order to approximate the material gain coefficient $g_m(\nu_k, N(z))$ and the spontaneously emitted noise $R_m(\nu_j, N(z))$. While referring to [8], the spontaneously emitted noise would be $R_m(\nu_j, N(z)) = \Gamma g_m'(\nu_j, N(z))$ where $g_m'$ represents a gain coefficient defined by equation (16) of [8]. We model the material gain as having a Lorentzian lineshape and fit this with experimental measurements.

$$g_m(\nu_k, N(z)) = \frac{a[N(z) - N_0]}{1 + \left(\frac{\lambda - \lambda_0}{\Delta \lambda}\right)^2}$$

where the gain constant, $a$, is $7.10 \times 10^{-20}$ m$^2$; the carrier density at the transparency, $N_0$, is $1.2 \times 10^{24}$ m$^{-3}$; the 3-dB bandwidth of the linear gain coefficient, $\Delta \lambda$, is 122.5 nm; and the spectral shift, $\lambda_{N_0}$, is represented by $\lambda_{N_0} = \lambda_0 - \kappa_0 (N(z) - N_0)$ where the peak wavelength at transparency, $\lambda_0$, is 1639 nm and $\kappa_0$ is a constant characterizing the gain-peak shift. As results with this approximation, we obtain Figures 3 and 4 showing the simulations results and experimental measures for the Kamelian SOA under a variety of operating conditions.

In Fig. 3, the modeled and measured SOA output power spectrum as a function of wavelength; input signal at 1550 nm; -20 dBm input power; bias current 130 mA.

In Fig. 3, the modeled and measured SOA output spectrum is presented; input signal power is -20 dBm at 1550 nm and bias current is 130 mA. The difference between the predicted and experimental signal gain is less than 0.2 dB but this model is less precise for the ASE power level. Indeed, the difference in predicted and measured ASE reaches 5 dB in the region of 1450 nm.

Figure 3. Predicted and measured SOA output power spectrum as a function of wavelength; input signal at 1550 nm; -20 dBm input power; bias current 130 mA.

Figure 4. Predicted (markers) and measured (line) fiber-to-fiber signal gain, (a) as function of wavelength with -20 dBm input power, (b) as function of input power for a signal wavelength of 1535 nm; bias current 130 mA.
Fig. 4(a) and (b) show the predicted and measured fiber-to-fiber signal gain as a function of wavelength and input power, respectively. In Fig. 4(a), the gain is shown for different wavelengths while keeping constant the input power at -20 dBm and the current bias at 130 mA. With the solid line, we plot the simulated gain using the same material gain coefficient $g_m(\nu, N(z))$ and same parameters as described in Table 1 from [8]. The two other curves, which represent the Kamelian optical pre-amplifier SOA, have the same profile with some dissimilarity.

B. Simulation of output extinction ratio

Whereas for our experiment we consider only one input extinction ratio, one conversion wavelength and one input power, in our simulations we consider three input extinction ratios, and the gamut of conversion wavelengths. We will compare output extinction ratios for the two SOAs under these various operating conditions. Recall that in experimental measurements we reached the maximum output extinction ratio on the converted signal, for both DFB laser and SS-WDM inputs, with CW input power of -15 dBm at 1520 nm and modulated input power of -6.86 dBm and an input extinction ratio of 11 dB at 1553 nm.

![Figure 5. Output extinction ratio of the converted CW signal as function of its wavelength for two different SOAs and for three different input extinction ratios. Input modulated broadband signal at 1553 nm and -5 dBm input power; maximum power of the CW channel -15 dBm.](image)

In Fig. 5 we present the output extinction ratio for two different SOAs as a function of the wavelength of the probe CW laser signal. There are six curves, three for each SOA. The three curves correspond to input extinction ratios of 15, 10 and 5 dB (represented by the solid, dashed and dotted curves, respectively) for the input modulated broadband source. The three curves for the Kamelian SOA show little sensitivity to the wavelength of the probe CW signal, while the Connelly SOA (bold lines) shows clearer maxima for wavelengths in the vicinity of 1515 nm. In all cases the Connelly SOA shows greater output extinction ratio than the Kamelian SOA, as expected due to the more peaked response of this SOA’s gain profile. We see that the maximum output extinction ratio is within 0.5 dB of the input extinction ratio, meaning little penalty in the conversion process. In all the simulations, the input modulated broadband signal is placed at 1553 nm with -5 dBm as input power and the bias current is 130 mA and the power of the CW channel is -15 dBm.

In spite of the penalty on the output extinction ratio during the conversion process (and particularly for the Kamelian SOA), it is important to mention that initially we have a broadband modulated data and after the conversion process, we will get a coherent inverted modulated data. So the importance of this penalty can be reduced if we are interested on the performance achieved by this conversion.

V. BER MEASUREMENT

As a final step of this validation, we recently reported in [9] a measured bit error rate for a spread-spectrum WDM channel without and with the incoherent-to-coherent conversion for different levels of optical received power as shown in Fig. 6. The incoherent signal was obtained by slicing the ASE from an EDFA using a 1.2 nm tunable bandpass filter and was externally modulated at 2.5 Gb/s and received in the first series of measurements without passing throw the SOA. In the second series, the same signal was routed to the Kamelian optical pre-amplifier SOA, via an optical circulator, in co-propagation as presented in Fig. 1. The DFB laser at 1520 nm enters the SOA in counter-propagation and is routed to the BER tester after passing throw a 0.25 nm band-pass optical filter.

![Figure 6. BER measurement for SS-WDM and converted signal, respectively for bit rate of 2.5 Gb/s and Bo = 1.2 nm](image)

The SS-WDM curve shows a BER floor at -15 dBm received power; even for higher signal powers the best attainable bit error rate is $10^{-10}$. The curve for the converted channel shows both the elimination of the BER floor, and a performance improvement of 6 dB at $10^{-9}$. In our experiments we were able to achieve error free transmission at received power of -22 dBm.

VI. CONCLUSION

We have presented for the first time conversion of an optical incoherent signal to an inverted optical coherent signal
using the cross-gain modulation in semiconductor optical amplifier. This process can be useful for the all-optical conversion of broadband signals for 1) spectrum-sliced WDM, 2) last mile systems of SS-WDM joining coherent WDM networks, and 3) OCDMA systems such as FFH-CDMA. Our experimental setup demonstrated the efficiency of this conversion. We measured the output extinction ratio of the converted signal. This result has been verified using a large signal numerical analysis.

ACKNOWLEDGMENT

The authors would like to thank APN Inc., Québec, Canada for many helpful discussions.

REFERENCES


