Carrier Reuse With Gain Compression and Feed-Forward Semiconductor Optical Amplifiers

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***Abstract*—The results of two techniques for optical carrier regeneration and wavelength reuse using semiconductor optical amplifiers (SOAs) are presented in this paper. The main objective is to recover an optical carrier by erasing its amplitude modulation. The first technique employs gain compression of deeply saturated SOAs. The second technique uses a feed-forward approach, where a delayed current signal is injected into the SOA with the same shape of the incoming optical pulse. The second technique could be capable to recover the optical carrier with less than 3-dB noise. However, it was observed that the SOA gain recovery time limits the maximum usable bit rate. Theoretical simulation showed good agreement with experimental results.**

***Index Terms*—Optical carrier regeneration, optical pulse reshaping, optical wavelength reuse, semiconductor optical amplifier.**

I. Introduction

The use of a cascade of semiconductor optical amplifiers (SOAs) has been proposed to support bypass routing, data receiving, data extinction, and modulation in wavelength division multiplexing (WDM) optical networks [1]. The data extinction is the removal of the received data signals from the optical carrier. In this way, the same wavelength channel could immediately be wavelength reused after the data-extinction process, with a possible improvement of the network switch efficiency. However, because of the large extinction ratio (ER) of the incoming pulses, the gain-compression effect cannot erase the data completely, and the optical output carrier still have amplitude transitions. Alternatively, this paper proposes a technique for data extinction and optical carrier regeneration by using an SOA with feed-forward current-injection (FFCI) gain control [2]. Simulation and experimental results for both gain compression and FFCI SOAs are presented for bit rates from 10 Mbit/s to 1 Gbit/s. In addition, a description of the gain-compression technique and feed-forward approach employing SOAs with block diagrams of the optical circuits to be employed is presented.

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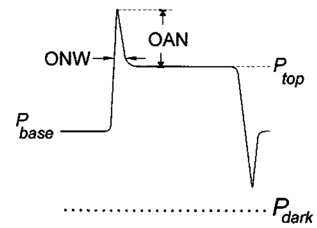


Fig. 1. Definitions of optical pulse levels: OAN and ONW.

II. Gain-Compression Technique

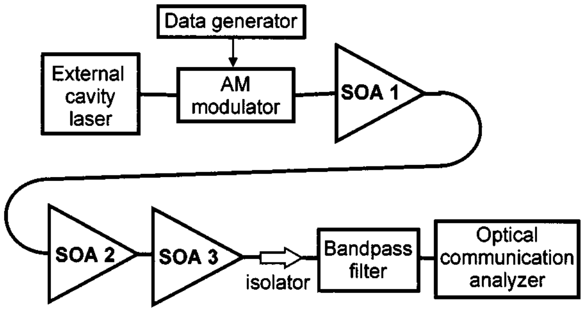
A digital AM optical carrier has two power logical levels: i.e., the low-logic level $P_{\rm base}$ and the high-logic level $P_{\rm top}$, as shown in Fig. 1. The optical pulse ER can be defined as

$$\mathrm{ER} = 10 \log \left[\frac{(P_{\rm top} - P_{\rm dark})}{(P_{\rm base} - P_{\rm dark})} \right] \tag{1}$$

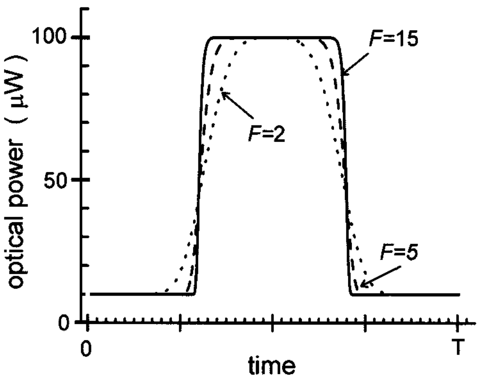
where $(P_{\rm top} - P_{\rm dark})$ is the most prevalent high-logic level and $(P_{\rm base} - P_{\rm dark})$ is the most prevalent low-logic level.

Data extinction by gain compression is based on the saturation property of an optical amplifier where the low-logic-level signal has a higher gain than that of the high-logic-level signal. Therefore, when an AM signal is amplified, the ER decreases. This is even more evident in heavily saturated SOAs. Therefore, if the AM signal crosses a sequence of heavily saturated optical amplifiers, the ER after the last amplifier is expected to be considerably close to 0 dB in such a way that it would be hard to distinguish between both the low- and high-logic levels. A typical shape of the output pulse after passing trough a cascade of optical semiconductor amplifiers is shown in Fig. 1. A pulse overshoot noise might be present and the associated parameters are named here: overshoot amplitude noise (OAN) and overshoot noise width (ONW). The OAN represents the optical pulse overshoot amplitude just after the pulse built up and the ONW is measured at a level equal to $P_{\rm top} + 0.1$ OAN.

A completely data extinction would need an output ER of 0 dB and an OAN equal to zero. It is important to note that the ONW limits the maximum bit rate since the ONW must be much narrower than the pulsewidth. The ONW measured value is around 500 ps for the SOA used here. Smaller ONW



(a)



(b)

Fig. 2. (a) Experimental setup for testing data erasing with SOA gain compression. (b) Optical input stream simulated by SGPs with shape parameters of 2, 5, and 15.

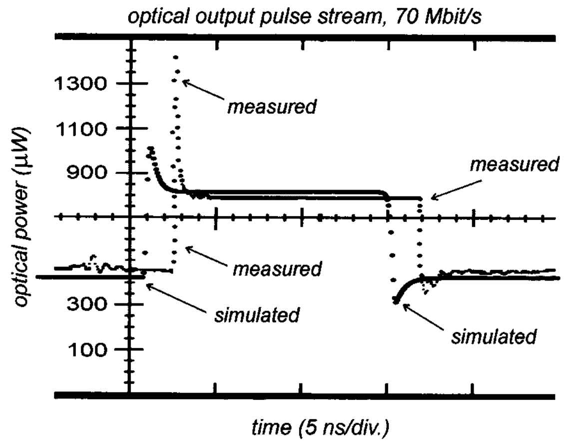


Fig. 3. Simulated and measured optical output pulses at 70 Mbit/s after SOA cascade gain compression.

values could be achieved with the faster switching properties of multiquantum well (MQW) SOAs [3]. In contrast, an erbium-doped optical amplifier would have a very large ONW value (in the order of 200 μs) due to its very long carrier lifetime.

The proposed gain-compression scheme is shown in Fig. 2(a). It uses an external modulated optical carrier as the input bit stream signal and a cascade of three SOAs to enable operation in deep saturation. The AM optical input carrier was simulated by a super Gaussian pulse (SGP) stream expressed by

$$P(t) = P_{\text{base}} + P_{\text{top}} \left(1 - \frac{P_{\text{base}}}{P_{\text{top}}}\right) \exp - \left[5\left(\frac{t}{T} - \frac{1}{2}\right)\right]^{2F} \tag{2}$$

where P is the envelope power, t is the time, T is the SGP bit stream period, and F is the SGP format. As an illustration, SGPs with $ER = 10$ dB, $P_{\text{base}} = 10\ \mu$W, and F values of 2, 5, and 15 are shown in Fig. 1(b).

The experimental setup used three SOAs (E-TEK-HSOA-1550), kept under temperature control (0.05 K) and biased with a precise dc current source for optimum small-signal gain. The cascade was followed by a 47-dB fiber isolator (0.8-dB insertion loss) and an optical bandpass filter (4-dB insertion loss). Polarization control before each SOA was also provided. All connectors had a return loss better than 55 dB. The optical carrier (1550 nm, 2 mW) was generated by an external cavity laser (Photonetics-Nanotunic) and amplitude-modulated by a Mach–Zehnder intensity modulator (UTP-APE MZM-3.0 GHz), driven by both a pulse generator with pseudorandom binary sequence (HP-8133A) and a dc source (ER adjustment). The output pulses were analyzed in a 30-GHz bandwidth optical-communication analyzer (HP-83480A/HP-83482A). The optical spectrum was also monitored. The bit rate was varied from few megahertz to 3 Gbit/s.

In order to theoretically analyze the pulse propagation behavior of an SOA, the formulation of Agrawal and Olsson [4] has been used. Discrete numerical time steps were set for the time-gain variation and the fourth-order Runge–Kutta method was applied to solve the rate equations with signal variation along the longitudinal direction of the SOA active region. The following SOA active region parameters have been used at 1550 nm for the theoretical analysis [4]: refractive index = 3.4, guide confinement factor = 0.4, transversal gain $= 2 \times 10^{-16}$ cm^2, carrier concentration at transparency $= 2 \times 10^{-18}$ cm^{-3}, saturation energy $= 4.5$ pJ, attenuation coefficient $= 20$ /cm, and a volume equal to $1.4 \times\ 0.2 \times 350\ \mu$m^3, respectively. Other theoretical values were linewidth enhancement factor $= 5$; trapping, spontaneous, and Auger carrier recombination coefficients [5], [6] given by $A = 5 \times 10^7$ s^{-1}; $B = 5 \times 10^{-10}$ cm^3/s; and $C = 7.5 \times 10^{-29}$ cm^6/s. The SOA insertion loss was assumed to be equal to 3 dB, the SOA cavity loss was assumed to be equal to 3 dB, and the facet reflection was assumed to be equal to 10^{-4}. The above parameters furnish a theoretical carrier lifetime at transparency of 740 ps and a current to achieve transparency of 42.3 mA. It is important to note that the amplitude spontaneous noise (ASE) was disregarded in the analysis since only large optical pulses are employed in the experiments shown here.

To test the data extinction with gain compression, an input pulse bit stream with the following parameters was applied to the circuit shown in Fig. 2: bit rate of 70 Mbit/s, $P_{\text{base}} = 40\ \mu$W, $P_{\text{top}} = 138\ \mu$W, and $ER = 5.4$ dB. In order to obtain deep SOA saturation, the SOAs in sequence (Fig. 2) were biased at 130, 45, and 30 mA, leading to fiber-to-fiber measured SOA small-signal gains of 11.7, 3.7, and 1.3 dB, respectively. In order to simulate the input bit stream, an SGP with $F = 15$ was fitted to the experimental input pulse. Also, a 4.8-dB insertion loss was added to simulate the isolator and optical bandpass filter losses. The simulated and measured output pulse streams after gain compression in the SOA cascade are shown in Fig. 3. The experimental output pulses achieved the values of $P_{\text{base}} =$

455 μW, $P_{\rm top} = 785\ \mu$W, and $ER = 2.4$ dB. The simulated values were 410 and 800 μW, with an $ER = 2.9$ dB, respectively. There is good agreement between measured and calculated ER. The experimental and simulated ONW are similar, with a value of 850 ps. This value is slightly larger than the optical carrier lifetime. The measured OAN is higher (smaller) than the simulated OAN during the pulse built up (decay). The differences might be attributed to approximations in the theoretical model such as not to consider second-order derivatives.

Additional simulation results (not shown here) indicate that very high levels of optical signals are required for data extinction in AM modulated optical carriers using the SOA gain-compression technique. However, our experiments have shown that if we tried to decrease the ER by an SOA operation in deep saturation, there was an increase in the OAN. In addition, an SOA with much lower carrier lifetime would be necessary to achieve low values of OWN if the bit streams are higher than 500 Mbit/s. Therefore, the complete optical erasing by gain compression might not be obtained by employing a present-day SOA due to its thermal-limited maximum optical power density and its finite carrier lifetime.

III. Feed-Forward Approach

An alternative way to provide data extinction might need some kind of synchronous active optical gain control. One way to implement such an idea is to use an SOA with FFCI gain control [2]. The technique consists of modulating the bias current of an SOA with an electrical current signal whose shape matches that of the amplitude-modulated optical carrier being simultaneously coupled into the active region of the SOA. However, the electrical injected current should have a phase shift of 180° in relation to the optical signal. One way of providing the required shape matching and the 180° phase shift is by converting a sample of the incoming optical pulse into an electronic signal and inverting this signal. This current-converted electronic signal is then feed-forwarded into the SOA through its bias current, provided that the optical signal and the inverted current signal are synchronized in relation to each other. The signal synchronization leads to an interesting effect. As the pulse rises toward its high level, the current pulse moves toward its minimum. This results in a lower overall SOA gain as the carrier population decreases due to a smaller current pulse injection and higher photon population. However, for lower optical pulse levels, the opposite effect occurs and the SOA gain rises from its average value. Therefore, higher optical signal levels will be amplified with a lower optical gain, and lower level signals with higher SOA gain. In this way, the ER of the resulting optical pulse will be close to 1 dB if a convenient amount of feed-forward current is injected into the SOA terminal.

The FFCI scheme is presented in Fig. 4. The experimental optical AM carrier was generated as described in Section II and applied to the feed-forward SOA circuit of Fig. 4. Part of the optical signal was photo-detected, generating an electronic signal that was amplified and fed into the SOA (E-TEK, HSOA-1550) by a high-speed voltage-to-inverted-current converter. It is important to note that the photodetector circuit cuts off any dc component.

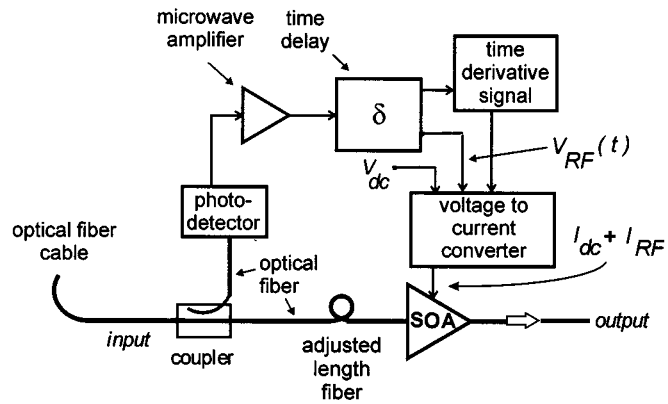


Fig. 4. Block diagram of the SOA with FFCI.

In this way, only the transitions of the detected optical signal are amplified, and an RF voltage $V_{\rm RF}$ is generated. It can be expressed by

$$V_{\rm RF} = K\big[P(t+\delta)\big] \tag{3}$$

where K is a constant that depends on the photodetector, the microwave amplifier circuit P is the optical power of (3) , and δ is the adjustable time delay.

The other part of the incoming optical signal of Fig. 4 was coupled into the SOA active region. A proper time delay compensation was provided (sliding line and adjusted fiber length) in order to set the value of δ close to zero. This value provides the synchronization between the feed-forward current and the optical pulse amplification process, ensuring that the SOA gain changes in a opposite way in relation to the optical input signal-intensity variation. The technique results in an increase (decrease) of the SOA gain in relation to the negative (positive) difference between the optical signal and its average component. The overall effect yields an equalization of the pulse transitions in the output of the feed-forward circuit and an ER close to 1 dB can be achieved for the optical output bit stream. The SOA feed-forward injected current $I_{\rm FF}$ is given by

$$I_{\rm FF}(t) = G\left(V_{\rm dc} - V_{\rm RF}\right) \tag{4}$$

where G is the transcondutance of the voltage-to-current converter, $V_{\rm dc}$ is the bias voltage, and $V_{\rm RF}$ is the RF voltage.

In order to test both the FFCI scheme and the simulation software, an input signal with very low ER was generated. The input pulse parameters were: bit rate of 26 Mbit/s, $P_{\rm base} = 5\ \mu$W, $P_{\rm top} = 174\ \mu$W, and ER equal to 15.4 dB. The SOA polarization current and the microwave amplifier gain were adjusted for optimum FFCI performance and the output pulse-stream waveforms are shown in Fig. 5. The experimental output pulse parameters had $P_{\rm base} = 6\ \mu$W, $P_{\rm top} = 9\ \mu$W, and $ER = 1.8$ dB. However, the measured OAN levels are very high in this case, and they appear at the edge of the optical pulse transitions. To simulate the optical input pulses, SGP with $F = 20$ was employed. The results, displayed in Fig. 5, show that the simulated output pulses are very close to the measured pulses. However, due to the SGP approximation, the time lags between the overshoots are different for simulated and measured pulse streams.

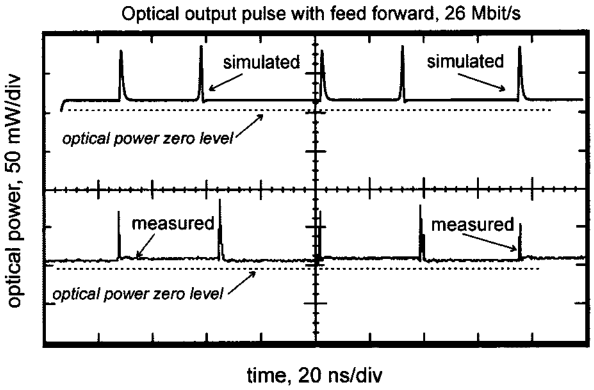


Fig. 5. Optical output pulse bit stream after a feed-forward SOA.

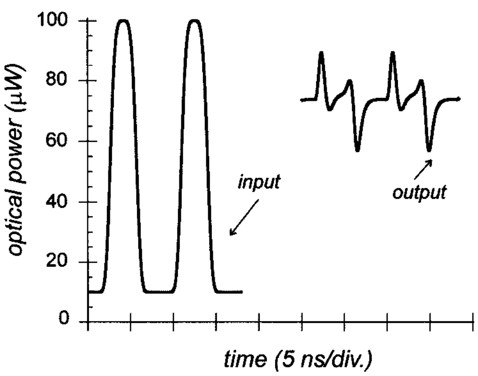


Fig. 6. Input and output optical bit stream pulse at 200 Mbit/s, after a feed-forward SOA with additional impulse injection.

The OAN levels can be decreased if the FFCI is combined with an appropriate current impulse. The current impulse should be applied in the SOA during every optical pulse built-up transition. In the following, the current impulse is obtained by extracting the time derivative of the RF voltage, as depicted in Fig. 4. It can be expressed by

$$I_D(t) = -\left(\Omega \frac{\partial V_{\rm RF}}{\partial t}\right) \tag{5}$$

where I_D is the current impulse and Ω is an adjustable constant of the voltage-to-current converter. Its important to note that, during an entire pulse period, I_D will have a zero mean value with negative and positive impulses. By using an RF rectifier circuit, it is possible to apply only the negative impulse to the SOA during the optical pulse built-up transition. In this way, a substantial decrease of the OAN can be obtained.

For every bit rate, a proper choice of K, δ, and Ω lead to a optimum OAN format. The simulated results are presented for an input signal at 240 Gbit/s, with $P_{\rm base} = 10\ \mu$W, $F = 2$, and $ER = 10$ dB. Typical input and output bit streams are shown in Fig. 6. It can be noted that the output ER is much closer to 0 dB than the previous results of Fig. 3 and the OAN is smaller than those presented in Fig. 5. In addition, in this particular case, the output OAN value has been decreased to 47% of the mean optical output power level.

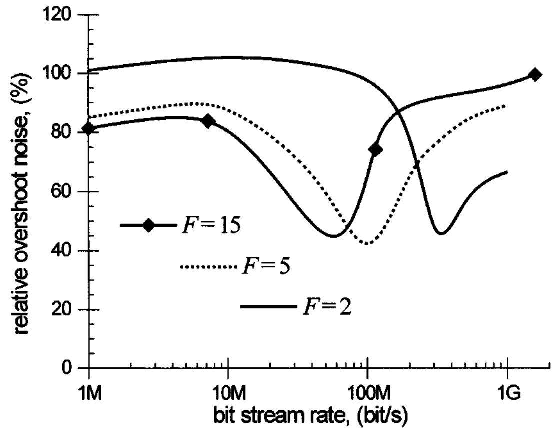


Fig. 7. OAN versus bit stream rate for SGP form of 2, 5, and 15.

Data extinction was simulated from 1 Mbit/s to 1 Gbit/s. The correspondent OAN theoretical values are shown in Fig. 7. It is interesting to note that, for each SGP shape parameter F, there is a bit rate where the OAN has a minimum value below 50%. The bit rate where the OAN attains its minimum value is a function of the input pulse rise time and the SOA carrier lifetime. The maximum bit rate that could be achieved with the FFCI technique is limited by the SOA carrier lifetime, and is equal to 1 Gbit/s for the simulated SOA.

IV. Conclusions

Two SOA-based techniques for optical carrier regeneration with the partial extinction of the optical AM-modulation have been presented in this paper. The first technique uses the gain-compression property in a dc-biased SOA and the second incorporates a current impulse injection generated by a feed-forward scheme. The last technique can provide a much better optical carrier recovery. However, overshoot noise exists and represents the main drawback for a complete regeneration of the optical carrier. The employed SOA has a carrier lifetime at transparency of 740 ps, and operation at several gigabits per second would need much faster SOAs.

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