Optical Subcarrier Label Swapping by Semiconductor Optical Amplifiers

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***Abstract*—The semiconductor optical amplifier (SOA) can be used as an efficient high-speed modulator. This paper presents optical subcarrier multiplexed label swapping/reinsertion utilizing this device associated to the wavelength converter block in packet-switched all-optical networks. For that purpose, the modulation response and nonlinear behavior of SOAs are analyzed and experimentally demonstrated.**

***Index Terms*—Modulation properties, packet-switched optical network, semiconductor optical amplifier, subcarrier multiplexed label swapping.**

I. INTRODUCTION

TELECOMMUNICATION networks are experiencing a dramatic increase in demand for capacity, much of it related to the exponential takeup of the Internet and associated services. Transport networks are evolving to provide a reconfigurable optical layer with high bandwidth. In the future, bandwidth efficiency will be associated with all-optical packet switching to ensure economical use of the network resources. In the packet-switched network there are no dedicated routes; packets may go on different ways, yielding more efficient utilization of the bandwidth. Packet-switched data transfer is faster if only optical devices are applied in the optical network because the electrical–optical transformations and relatively slow electrical circuits are eliminated from the traffic route [1].

II. LABEL SWAPPING IN ALL OPTICAL NETWORKS

Two methods have been proposed and are currently under investigation for coding the optical label: the serial label (SL) [2] and the optical subcarrier multiplexed label (SCML) techniques [3]–[6]. The bit-serial label is encoded as a baseband signal on the same optical wavelength as the packet. A fixed bit rate label is multiplexed at the head of the packet, and the two components are separated by an optical guard-band for the safe detection. In the SCML approach, a baseband digital label is modulated onto a radio-frequency (RF) subcarrier and then multiplexed (electronically or optically) with the packet on the same wavelength. The label is transmitted in parallel with the packet; therefore it is only necessary that the label fit within the boundaries of the packet. It has the advantage that subcarrier labels allow for relatively easy separation of the subcarrier header from the baseband data payload compared to conventional time-domain header techniques. It means simplified label detection and processing because it can be removed and replaced more asynchronously than in the serial case. Furthermore, the subcarrier label can be directly extracted in the optical domain by the use of optical filtering techniques, keeping the data payload intact [5]. An initial drawback of this technique is the possible RF cancellation effect that can arise due to fiber dispersion, which may affect the optical label [7]. Several solutions have been proposed to overcome the effect of chromatic dispersion and its impact on the possible fading of the RF labels. The most interesting approaches rely on the use of single sideband (SSB) optical modulation or multiple subcarriers [8], [9].

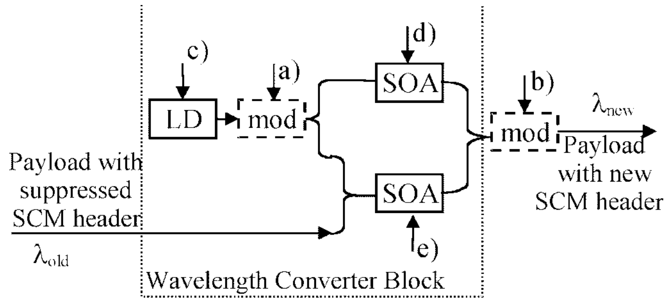

Fig. 1. SCM label remodulation.

On the other hand, the reconfigurable networks capable of dynamic provisioning of bandwidth require two key functions: wavelength conversion and all-optical regeneration. These functions can be achieved through cross-phase modulation (XPM) performed in a semiconductor optical amplifier (SOA)-based Mach–Zehnder interferometer. An all-active Mach–Zehnder wavelength converter shows a high input signal sensitivity with a low conversion penalty at high-speed operation [10], [11].

There are several different SCM encoded packet label updating techniques in connection with an all-active Mach–Zehnder wavelength converter block (Fig. 1) [3]–[6]. One of them applies an external modulator based typically on electrooptical or electroabsorption effect, but any other external optical modulator may be used. It can be placed before the wavelength conversion (a) or after the wavelength converter block (b). The electrooptical external modulator has three disadvantageous properties: it demands high electrical bias and modulation voltages, it has high insertion loss, and the linear behavior of the system is degraded because of the cosine characteristic of the modulator. Additionally, it needs one more expensive optical device for every wavelength channel in the node. Fig. 1 represents two more possibilities for label reinsertion by the wavelength converter. The new label is

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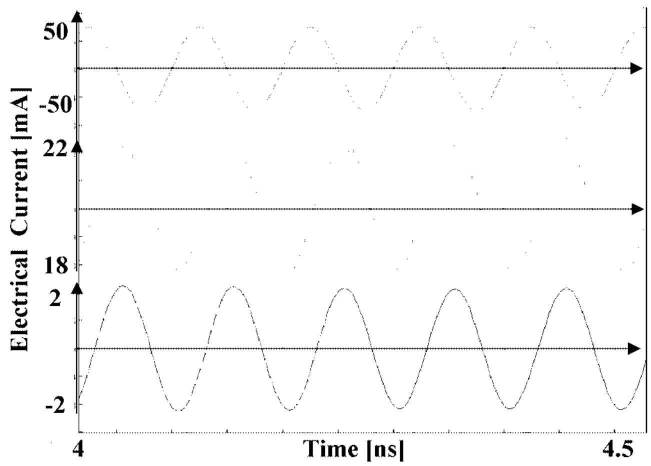

Fig. 2. Modulation and detected electrical signals.

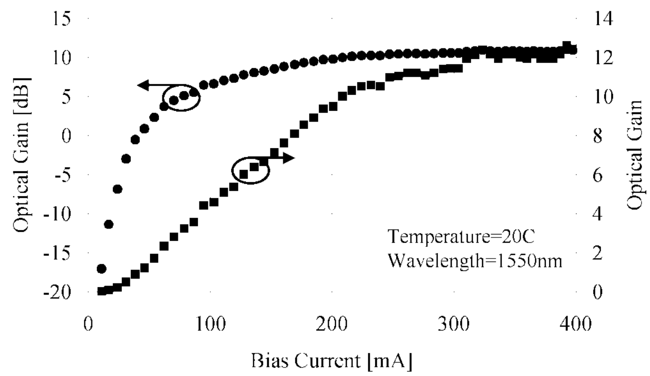

Fig. 3. Optical gain dependent on the bias current.

premodulated onto the laser (c) or current modulation of the SOA in one arm of the wavelength converter is used to add a new label (d), (e). However, the laser modulation is not effective in wavelength-division multiplexed (WDM) systems because it has significant frequency chirp. On the other hand, the bias current modulation mode of operation of the SOA has not been dealt with extensively, although it seems important to understand whether SOAs can be used as efficient high-speed modulators in the future all optical networks. This paper focuses on the (d) and (e) solutions, that is, the modulation properties of the SOA, the application possibilities, and the comparison of the different setups.

III. Modulation Properties of SOA

The SCM optical label addition function means RF-to-optical conversion. For that function, the SOA is used as an external modulator. The electrical bias current is modulated, the material gain is modulated, and consequently in case of continuous-wave (CW) input the intensity of the output power will be modulated [13]–[16]. In this paper, the characteristics of the intensity modulation imposed on an injected CW optical beam are analyzed.

If small signal sinusoidal current modulation is considered, the electrical signal consists of an invariant (dc) and a sinusoidal modulation parts. From the rate equations for carrier and photon densities, it is clear that the number of carriers and photons is also time-dependent, and the shape of these parameters is similar to the shape of the modulation signal. Consequently, the number of carriers and photons also consists of a sinusoidal modulation part [13].

Fig. 2 shows the modulation operation based on the rate equation concept. The intensity modulated optical signal is detected by traditional pin photodiode. Fig. 2 represents the time functions of the simulated modulation (upper trace in the graph) and the detected electrical signals before (middle trace) and after (bottom trace) electrical filtering in the case of small signal modulation (linear operation mode). The attenuation and the time delay of the optical system can be seen. The nonlinear parameter of the element of the optical transmission system and the additive optical and electrical noise cause distortion in the signal shape. The undesired electrical components can be eliminated by an electrical filter. The magnitude and purity of the signal depend on the modulation signal (linear relation), the bias current, and the input power of the SOA.

Practically, the average optical gain and the slope of the optical gain-bias current curve determine the optimum working state of the SOA as a modulator. We have to compromise from the viewpoint of the modulation depth, the average optical output power, and the nonlinear behavior. It is a complex problem, because there is no one parameter that guarantees the best tradeoff between these three competitive aspects. Moreover, we have to take into consideration that the wavelength conversion effect depends on the operation point of the SOAs too [10]. It requires more accurate and well-thought-out amplifier-modulator working state planning.

The optical gain-bias current curve can be divided into three parts (Fig. 3). In the first part, the amplification just starts and it is not effective, then there is an almost linear region, and after that the slope of the optical gain starts to decrease. The most linear region of the graph is the most suitable. The middle of this region should be chosen as the operation point because of the low static nonlinear distortion effect and the high slope.

During the experimental work, the SOA modulator under test was driven by the sum of bias (dc) current and sinusoidal modulation signal via a bias tee. The polarization state of the incoming optical power was optimized by polarization controller because the measured SOAs were polarization sensitive. The harmful effect of the optical reflection was eliminated by optical isolators. The required optical power and wavelength were produced by a tunable laser source. The intensity modulated optical signal was detected by a photodetector. The setup was controlled by a computer program; hence the measurement parameters were carefully set by the program and the measurement results were processed and stored.

The detected electrical power was measured with different parameters. Fig. 4 describes the typical experimental results.

The upper curve shows the detected power as a function of the bias current of the SOA modulator. The three regions are well seen in this figure too. The injection current is not enough for the expected work, and the detected power is low in the first part. The power is near constant in the second linear part, and after that the detected product starts to decrease because the slope

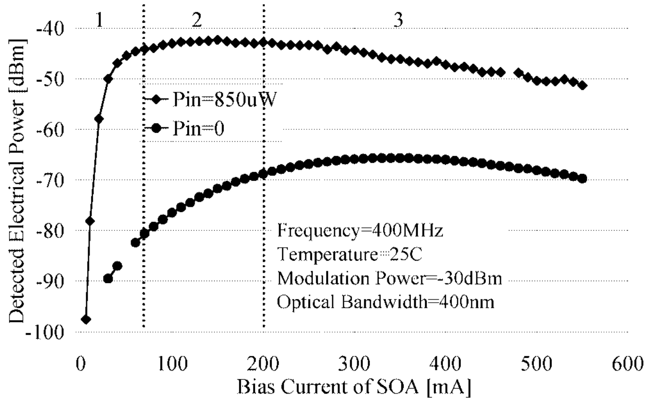

Fig. 4. Modulation properties of the SOA.

of the gain curve falls. The lower curve represents the result without input optical power, i.e., just the amplified spontaneous emission power (ASE) produces the modulated signal and the broadband optoelectronic converter can detect this poor fluctuation. This effect can be dramatically decreased by a narrow-band optical bandpass filter.

The modulation operation can be derived based on the slope of the measured optical gain curve (m_{d}) and the average optical gain (G_0).

The current and the gain of the device are

$$\mathrm{I}(t) = \mathrm{I}_0 + \Delta\mathrm{I}_{\mathrm{mod}} \cdot \cos(\omega t)$$
$$\mathrm{G}(t) = \mathrm{G}_0 + \Delta\mathrm{G} \cdot \cos(\omega t) \quad (1)$$

where I_0 is the constant (dc) current, $\Delta\mathrm{I}$ is the current modulation amplitude, G_0 is the constant optical gain of SOA, and $\Delta\mathrm{G}$ is the modulation part. Hence the optical signal at the output of the SOA modulator takes the form

$$P_{\mathrm{out}} = \mathrm{G}_0 \cdot P_{\mathrm{in}} \cdot (1 + m \cdot \cos(\omega t)) \quad (2)$$

where the modulation index (m) is

$$m = \frac{\Delta\mathrm{G}}{\mathrm{G}_0} = \frac{m_d \cdot \Delta\mathrm{I}_{\mathrm{mod}}}{\mathrm{G}_0} = \frac{m_d}{\mathrm{G}_0} \cdot \sqrt{\frac{2 \cdot P_{\mathrm{mod}}}{Z}} \quad (3)$$

where P_{mod} is the modulation electrical power and Z is the microwave impedance of SOA.

The output signal of the SOA modulator is detected by an optical–electrical converter. P_{det} is the detected electrical modulation power

$$P_{\mathrm{det}} = \eta^2 \cdot \frac{P_{\mathrm{in}}^2}{a^2} \cdot m_d^2 \cdot P_{\mathrm{mod}} \quad (4)$$

where η is the detection efficiency and a is the optical loss between the SOA and the detector.

The modulation depth is proportional to the slope of the gain curve and the electrical modulation power but is in inverse relation to the average optical gain (3). However, the detected electrical power increases with the modulation power (direct relation), the slope of the gain curve, and the input optical power of the SOA modulator (quadratic relation) increase (4). The same conclusions can be observed from the experiments.

Naturally, the modulation depth realized by the SOA modulator can be computed from the measured detected electrical power with the knowledge of the modulation power and the input average optical power of the detector

$$m = \frac{2 \cdot a^2 \cdot P_{\mathrm{det}}}{P_{\mathrm{in}}^2 \cdot \mathrm{G}_0^2 \cdot \eta_{\mathrm{det}}^2 \cdot Z} = \frac{2 \cdot P_{\mathrm{det}}}{P_{\mathrm{det}}^{\mathrm{opt}} \cdot \eta_{\mathrm{det}}^2 \cdot Z} \quad (5)$$

where $P_{\mathrm{det}}^{\mathrm{opt}}$ is the average optical power at the input of the detector. Based on this calculation, the experimentally realized optical modulation depth is 5–10% with sufficiently low (−30 dBm) modulation power.

The modulation bandwidth is limited by the speed at which the carrier density can be charged; this is usually limited by the spontaneous lifetime of the carriers in the SOA. The SOA has a short carrier lifetime (in the nanosecond range); this means that its gain will rapidly deplete if the pump (drive current) is changed. The lifetime in the presence of a strong (saturating) input signal is reduced due to stimulated recombination. The real speed depends on the structure of the device, but in general it is larger than 10-GHz speed [13]–[16].

IV. Nonlinear Behavior of SOA Modulator

Cascadability is critically important in photonic switched networks where label replacement is performed on the same packet at multiple nodes. The old label is erased and replaced in the node, but degradation of the updated label and baseband package will occur due to two mechanisms: the crosstalk due to the incomplete suppression of the original SCM label and intermodulation distortion due to partial upconversion of the baseband payload into the label passband during remodulation. The first effect can be neglected in case of suitable optical filtering. However, the second one is significant because the upconverted baseband information can overlap with the original package. This is the reason why the second order intermodulation will be more important in the optical SCM label reinsertion application than in traditional SCM systems.

Additionally, the nonlinear behavior of the SOA modulator became more significant in the case of an improved, modified network concept. The application of two subcarrier is a effective solution for the chromatic dispersion problem. The two subcarriers are modulated with the same digital label and transmitted via the optical fiber. At the next node, the subcarriers are detected and the label is produced with an algorithm. The method is similar to the antenna and frequency diversity concept in mobile communication systems. There are two other subcarrier system approaches, where one subcarrier carries the label and the other one is responsible for the network management information. The concepts require additional electrical signal processing, but the optical part does not change. In the intermodulation experiments, the SOA modulator was biased and modulated by the sum of two microwave signals. The output noise and signal levels were measured for the fundamental (P1), the second- (P2), and the third- (P3) order harmonic mixing products. It depends on many things: bias current, temperature, laser structure, and optical reflection [17]. The determination of the spurious-free dynamic range (SFDR), the second-order intercept point (IP2), and the third-order intercept point (IP3) are presented in Fig. 5.

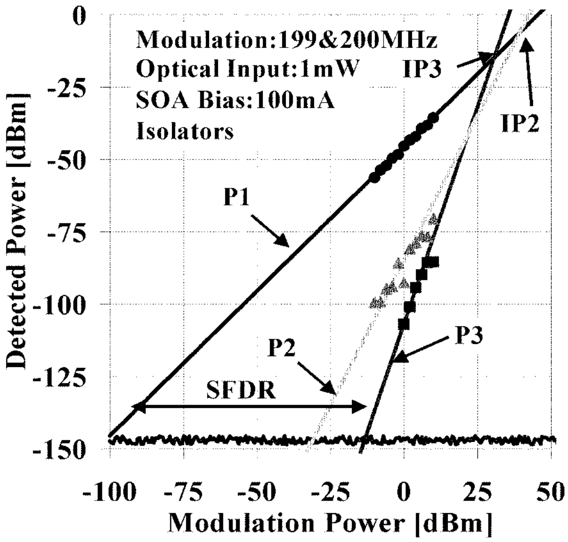

Fig. 5. Determination of SFDR, IP2, IP3.

In a linear regime, the SOA modulator shows low, unmeasurable nonlinearity because the noise generated by the SOA modulator will dominate in the system.

The intermodulation products overcome the noise floor in the case of extraordinary high modulation indexes and in the saturated operating region. Fig. 6 shows the noise level, IP2, IP3, and SFDR versus SOA working state in the saturation region. The results represent that in the first part of the graph, the gain of the device increases; hence the IP3 and the SFDR improve. In the second part, the optical gain does not change significantly but the noise level and intermodulation products rise; hence the IP3 and the SFDR decrease. The noise effect and the nonlinear distortion products are more significant in the case of strong optical reflection level, i.e., without optical isolators. The device ensures efficient SFDR for general optical networks (>90 dB) in this nonlinear operation region too.

Summarizing, the SOA modulator requires low modulation power. The detected electrical power is high because of the optical gain of the SOA in contrast to the optical insertion loss of other external modulators. The SOA has rapid response time; hence the electrical circuits determine the modulation bandwidth. In the linear operation range, it provides lower nonlinear distortion than the other external modulators. The SOA has relevant optical noise, and the inherent design tradeoff between modulation efficiency, wavelength conversion efficiency, and linearity demands more advanced amplifier-modulator working state planning.

V. Simulation Results on the Whole Wavelength Converter Block

The simulations show that the SOA in the branches of the wavelength converter [Fig. 1(d) and (e)] can add the label with same properties. Namely, the added subcarrier has the same properties, and after label detection, the eye diagram and the bit error rate (BER) of the label will be same in the case of the two different modulation places. The same modulation in both branches is not effective because of the interferometer operation. However, the push–pull electrode concept is possible and has the same advantages as in MZ modulators.

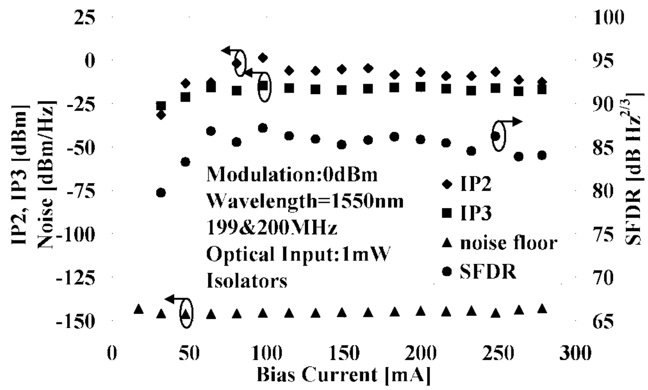

Fig. 6. Nonlinear behavior of SOA modulator.

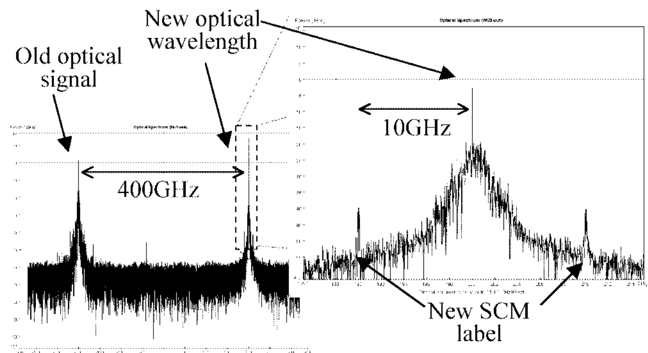

Fig. 7. Output optical spectrum of wavelength converter.

The simulated output optical spectrum can be seen in Fig. 7. It represents the incoming original wavelength with the baseband payload and the new, converted optical carrier with the baseband payload plus the label on the subcarrier inserted by the SOA modulator. An optical passband filter will eliminate the old wavelength channel; then the information package and the label of this packet on the new wavelength can be transmitted in the next optical node.

VI. Conclusion

The paper analyzes and experimentally demonstrates the application of SOAs in packet-switched all-optical networks for optical subcarrier multiplexed label reinsertion. This label type provides an easier manageable and treatable solution in packet-switched optical networks than the serial label. According to the simulation and experimental results, the SOA modulator gives favorable modulation and linear behavior, i.e., it is efficiently used for this approach. Furthermore, it does not demand an additional optical device; just a simple electrical supplementary circuit is necessary.

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Eszter Udvary (S'03), photograph and biography not available at the time of publication.

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