Semiconductor Optical Amplifier for Detection Function in Subcarrier Multiplexed Systems

Eszter Udvary, ***Member, IEEE*** **, Tibor Berceli,** ***Fellow, IEEE***
Budapest University of Technology and Economics, Department of Broadband Infocommunication System
H-1111 Budapest, Goldmann György tér 3, Hungary

ABSTRACT

The paper demonstrates that in broad-band networks in-line semiconductor optical amplifiers that provides system gain can also be used as simultaneous transceiver. The SOA branching stages for bus configuration are studied and presented. We have made a small signal approximation using an equivalent circuit based the rate equations for laser amplifiers used for detection. The theory enables to explain the detection functionality, the optimal working state of the multifunctional SOA and analyses noise properties. The measurements support the calculations. So the SOA-transceivers are potentially useful in subcarrier multiplexed access system

Keywords: detection, intensity modulation, semiconductor optical amplifiers, subcarrier multiplexing.

1. INTRODUCTION

Nowadays, two complementary technologies, the optical fiber and wireless communications drive explosive growth in communications [1]. In an optically supported millimeter wave cellular radio system the noise figure or output signal to noise ratio and intermodulation free dynamic range are the most important parameters. These parameters can be determined by the optical devices and depend on frequency and level of optical reflection.

SOA traditionally can be used in any system that is loss limited to compensate for the optical losses. Local area network and the fiber radio system, where the main losses comes from optical power splitters, branching and taps are also loss limited and can benefit from optical amplifiers. The SOA produces wide band optical noise, it can be suppressed by the application of a narrow band optical filter. It will else decrease the signal to noise ratio, but it depends on the position of the device [2]. Same time the RF response of the optical link without SOA has deep notches. These notches are shifted to higher frequencies and the microwave or millimeter-wave carrier suppression effect is reduced, because of the negative chirp of the SOA [3]. Additionally the nonlinearity of external optical modulator can be revised by saturated SOA. Summarizing, the well adjusted SOA can improve the transmission performance of analog optical link [4].

2. SYSTEM CONCEPT

The operation of the SOA is controlled by both the electrical pump and the input optical power. So the SOA may be well used as a multifunctional device for the branching function in SCM systems (Fig.1) [5]. The SOA operates as a modulator to add a new channel, as a detector to drop the needed channels and as an amplifier to amplify the channels. It realizes a compact, small size and cost-effective radio repeater for signal distribution. The separation of add and drop channels can be achieved by an electrical branching filter (the realization of a reconfigurable add/drop multiplexer is difficult) or an electrical circulator (an electrical filter is needed). In the drop branch the signal is amplified by a high power RF amplifier, than it is radiated via the antenna. In the add branch a low noise pre-amplifier provides the suitable SNR. It is difficult to give individual optimization of bias current for the SOA, because different bias points are optimal for amplifier, modulator and detector functions. It seems important to understand whether SOA's can be used as efficient high-speed modulators and detectors.

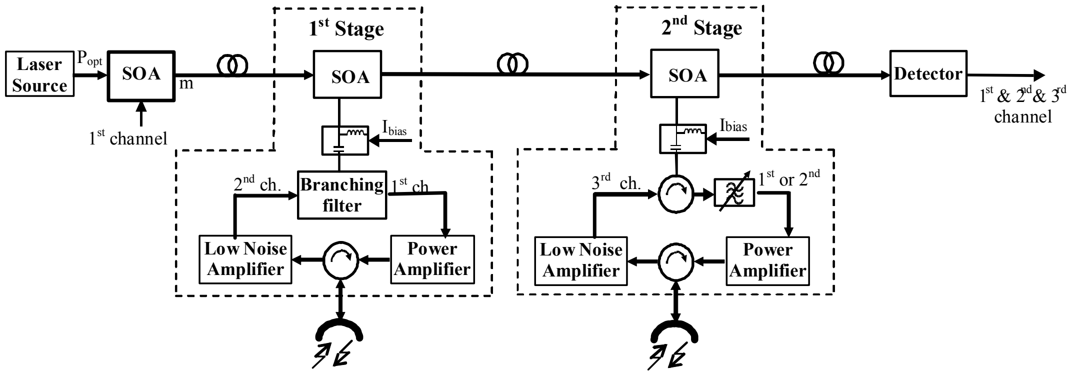

Fig. 1. Block diagram of the simplified system setup.

The modulation response of SOAs is analyzed and experimentally demonstrated [6]. It was shown that SOA-modulator provides acceptable nonlinear distortion for SCM telecommunication systems. The temperature and the optical reflection effects were investigated and the frequency chirping is treated [7].

978-1-4244-2626-3/08/$25.00 ©2008 IEEE

Authorized licensed use limited to: Eszter Udvary. Downloaded on July 8, 2009 at 07:58 from IEEE Xplore. Restrictions apply.

The detection properties have been treated by several authors. However other, lower frequency applications were studied. The detected signal is used for feedback control of gain [8], automatic frequency control of laser [9], low speed, baseband control channel receiver (100 MHz) [10], etc. Hence the detection properties have not been analyzed in order to determine how the amplifier parameters will affect the electrical signal and how an optimization could be done although the frequency response can be expected to be limited by the carrier lifetime.

3. DETECTION FUNCTION

Two different mechanisms induce detection in the SOA. Operated at an injection current corresponding to an electron density below transparency, the device works as a photodetector and the detection signal arises from absorption of the injected light and the creation of electron-hole pairs. Above transparency, that is the usable amplifying regime, the injected optical signal will cause stimulated transitions, which will reduce the carrier density in the gain medium. Due to these two different mechanisms of interaction, it is clear that the detected electrical signal will change polarity at transparency. The optical detector is characterized by the responsivity, the sensitivity and frequency response. The magnitude and purity of the detected signal depend on the modulation signal, the bias current, the input power and the operation parameters of the SOA.

3.1 DC characteristics

Fig.2 depicts the electrical current as a function of the input optical power, temperature and operation point of SOA-detector. The detector responsivity can be realized from this curve. This static photodetection current is not given data of a traditionally used SOA. In unsaturated regime this curve can be approximate calculated from the optical gain (proportional with Gain) and the input optical power (proportional with Pin).

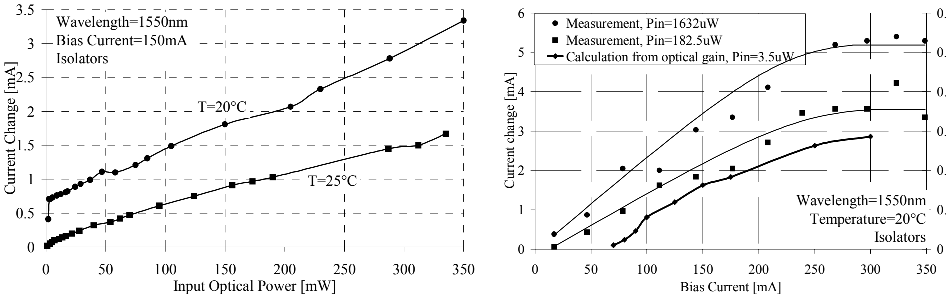

Fig. 2. Change of current versus average optical power and SOA operation point.

3.2 Detection of intensity modulated signal

The detected electrical power versus bias current diagram (Fig.3) follows the nature of the optical gain curve, the optimum bias current is same from the point of the detection and amplification function. The detected current is directly proportional to the modulation depth, hence the difference between the two curves is about 14 dB. The result of the detection experiment over input optical power is depicted in Fig.3. In the unsaturated regime the detected electrical signal is square proportional to the optical power, but in the saturation regime the relation goes to linear proportionality. The detection is also temperature sensitive (Fig.3).

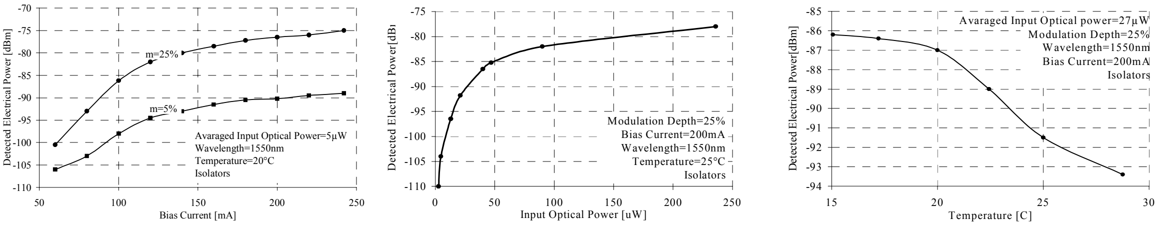

Fig. 3. Detected electrical power versus operation point, average input optical power, operation temperature.

3.3 Responsivity calculation

The real responsivity of the SOA-detector can be calculated from the measurement. We shall consider sinusoidal intensity modulated input optical signal, the detected electrical current has cosinusoidal component. The SOA-detector responsivity (R) can be computed from the detected electrical power (P_{detSOA})

$$\Delta I_{\det SOA} = R \cdot m \cdot \frac{P_{DC}}{a_{in}} \Rightarrow R = \sqrt{\frac{2 \cdot a_{in}^2 \cdot P_{\det SOA}}{m^2 \cdot P_{DC}^2 \cdot Z}}, \tag{1}$$

where P_{DC} is the constant optical power, a_{in} is the optical loss before the SOA-detector, m is the modulation depth, I_{DC} is the constant detected current, ΔI_{detSOA} is the modulation information detected by the SOA.

Authorized licensed use limited to: Eszter Udvary. Downloaded on July 8, 2009 at 07:58 from IEEE Xplore. Restrictions apply.

3.4 Rate equation model

An equivalent circuit can be applied for modelling of SOA detector operation mode, which can be derived from the rate equations with time dependent input optical power.

$$\frac{dN}{dt}=\frac{I}{e\cdot V}-R_{sp}(N)-v_g\cdot\Gamma\cdot g_m\cdot S,\qquad\qquad \frac{dS}{dz}=(\Gamma\cdot g_m-\alpha)\cdot S \tag{2}$$

where N is the carrier density, I the injection current, e the electron charge, V the volume of active layer, $R_{sp}(N)$ the spontaneous recombination rate, v_g the group velocity, Γ the confinement factor, g_m the material gain, α the internal loss and S the photon flux density. The generated current due to the injected optical signal is:

$$i_{sig}=\Gamma\cdot g_{m0}\cdot e\cdot V\cdot S_{sig}=\frac{\Gamma\cdot g_{m0}}{\Gamma\cdot g_{m0}-\alpha}\cdot\frac{e\cdot\lambda}{h\cdot c}\cdot(G-1)\cdot P_{in} \tag{3}$$

where λ is the optical wavelength, h is the Plank's constant, c is the velocity of light in vacuum, G is the optical gain, P_{in} is the input optical power. The diode junction resistance and capacitance are:

$$R_i=\frac{1}{e\cdot V}\cdot\left(\frac{dR_{sp}(N)}{dN}+\Gamma\cdot\frac{dg_m}{dN}\cdot S_{sig0}\right)^{-1}\cdot\frac{dU_f}{dN},\qquad\qquad C_i=e\cdot V\cdot\left(\frac{dU_f}{dN}\right)^{-1} \tag{4}$$

The electrical equivalent circuit is shown in Fig.4. C_i represents the parasitic contact capacitance, R_s is the series resistance of the bulk or MQW material as well as the contact resistance (on the order of a few ohms). The external electrical circuits are represented by the load resistance, (R_L = 50 ohm). The circuit can be extended by a series bond wire inductance and a parallel laser amplifier submount parasitic capacitance. When spontaneous emission is taken into account further circuit branches have to be added. However the parallel resistances of spontaneous branches typically are two orders of magnitude larger than R_i.

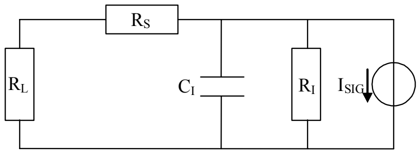

Fig. 4. Electrical equivalent circuit of the SOA detector.

The low frequency responsivity (R) and the frequency answer of responsivity (R(ω)) can be calculated:

$$R\approx-\frac{\lambda\cdot\tau}{h\cdot c\cdot e\cdot V}\cdot\frac{dE_f}{dN},\qquad\qquad R(\omega)=\frac{R}{\sqrt{1+(\omega\cdot\tau)^2}} \tag{5}$$

where ω is the angular modulation frequency, τ is the carrier lifetime. The responsivity depends on the signal wavelength, the length of the detector section, on the polarization, etc. The detection bandwidth is limited by the speed at witch the carrier density can be charged, this is usually limited by the spontaneous lifetime of the carriers. The SOA has a short carrier lifetime (in the nanosecond range), this means that its gain will rapidly deplete if the pump is changed. Reducing the length of the device will give a higher carrier density (lower carrier lifetime). Thereby the short SOA increases the bandwidth but reduces the responsivity. Additionally, 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 and it is often limited by the bounding and the driving electrical circuit.

3.5 Noise calculation

There are several contributions to the total noise power of SOA-detector. Shot noise and thermal noise are well known. Then there are a number of noise processes originating from the light amplification. These are amplified signal shot noise, spontaneous emission shot noise, beat noise between signal and amplified spontaneous emission, beat noise between spontaneous emission components and signal excess noise. The variance of the detected current due to the photon noise can be obtained from the variance of photons in the amplifier medium.

$$i_{shot}^2=2\cdot e\cdot I\cdot B_0,\ \ i_{therm}^2=\left[\frac{1}{R_L}+\frac{1-F}{R_N}\right]\cdot4\cdot k\cdot T\cdot B_0,\qquad i_{ph}^2=e^2\cdot(\Gamma\cdot g_m\cdot L)^2\cdot\overline{\sigma}^2\cdot B_0 \tag{6}$$

where R_N is a standard 50Ω resistance, F is the electrical amplifier noise figure, k is the Boltzmann constant, T is the temperature, B_0 is the detection bandwidth, L is the device length, $\overline{\sigma}^2$ the photon variance averaged over the amplifier length. In the case of a travelling wave amplifier the variance of the detected current [12]:

Authorized licensed use limited to: Eszter Udvary. Downloaded on July 8, 2009 at 07:58 from IEEE Xplore. Restrictions apply.

$$i_{ph}^2 = e^2 \cdot (\Gamma \cdot g_m \cdot L)^2 \cdot \frac{(G-1)^2}{\ln G} \cdot B_0 \cdot \left[2 \cdot \left(n_{sp} + \frac{1}{G-1} \right) \cdot \frac{\lambda}{h \cdot c} \cdot P_{in} + \left(n_{sp} - 2 \cdot (n_{sp} - 1) \cdot \frac{G - \ln G - 1}{(G-1)^2} \right) \cdot n_{sp} \cdot \Delta f + \frac{G+1}{G-1} \cdot \left(\langle n_{in}^2 \rangle - \langle n_{in} \rangle^2 - \langle n_{in} \rangle \right) \right] \quad (7)$$

The different noise components depend on the optical signal level and the SOA operation point with different aspect. Hence different noise component will dominate in case of different operation parameters (Fig.5).

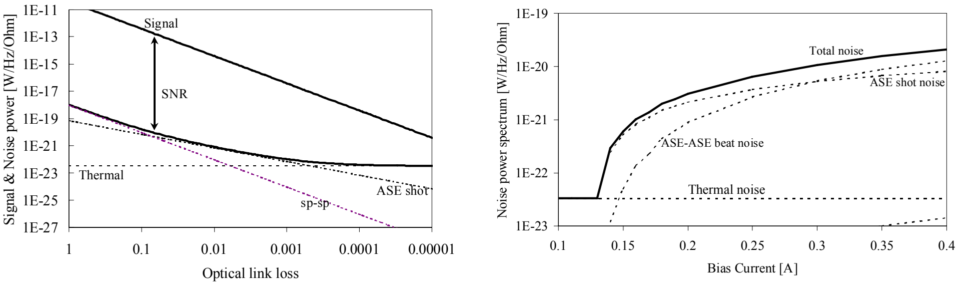

Fig. 5. Noise and signal power versus optical link loss and bias current of the SOA.

3.6 Nonlinearity

In optical SCM networks several electrical subcarriers are transmitted on the same optical signal. Degradation of the transmission system will occur due to the crosstalk (nonlinearity) and noise expansion (ASE). The second and third order intermodulations will be considered, because of the crosstalk between the channels and the partial up-conversion of the baseband payload into the subcarrier. As the number of subcarriers increases the linearity becomes more and more serious problem because many third order mixing products appear in the used band.

Based the rate equation model the photodetection harmonic and intermodulation distortion in a SOA can be analyzed [13]. The results show, that the traditionally used electro-optical optical modulator with cosine type characteristic has more significant nonlinearity. So the SOA can be treated as linear device.

4. CONCLUSIONS

This paper presents the applications of Semiconductor Optical Amplifiers (SOAs) in subcarrier multiplexed (SCM) fiber radio systems. In these multi-channel analogue optical fiber links high signal to noise ratio and at the same time low non-linear distortion are required. The paper suggests a concept with semiconductor optical amplifier branching stages and the optimal operation point is studied. According to the simulation and experimental results the SOA-detector gives favorable properties, hence SOA offers a fine solution for the add/drop functions problem. Furthermore, it doesn't demand additional optical device, just a simple electrical supplementary circuit is necessary.

REFERENCES

[1] A.J. Seeds: "Broadband Fibre-Radio Acces Networks", *MWP'98*, October 12-14 1998, Princeton, US.

[2] T. Marozsák, E. Udvary, T. Berceli: "Transmission Characteristics of All Semiconductor Fiber OpticLinks Carrying Microwave Channels", *30th EuMC*, vol. 2. pp.52-55, Paris, France, 3rd-5th October 2000.

[3] J. Herrera, F. Ramos, J. Marti: "Semiconductor Optical Amplifier Chirp Model for Dispersive and Nonlinear Transmissions Through Single-mode Fibers in Microwave Optical Link", *MWP2002*, pp.201-204, 2002.

[4] Sang-Yun Lee, *et al.*: „Reduction of Chromatic Dispersion Effects And Linearization of Dual-Drive Mach-Zehnder Modulator By Using SOA in Analog Optical Links", *ECOC2002*, Copenhagen, Denmark, 2002.

[5] H. Ogawa, *et al.*: "Application of Semiconductor Optical Amplifiers to Microwave Signal Processing", *IEEE MTT-S Diges*t, pp. 1177-1180, 1995.

[6] E. Udvary, T. Berceli: "Optical subcarrier label swapping by semiconductor optical amplifiers", *J. Lightwave Technol.*, vol. 21 , no. 12 , pp. 3221–3225, Dec. 2003.

[7] E. Udvary, T. Berceli: "Linearity and chirp investigations on SOA as an external modulator in SCM systems", *EUMA, Special Issue on Microwave Photonics*, vol. 3, pp. 217-222, Sept. 2007.

[8] K. Emura, *et al.*: "Coherent Optical Tapping Using Semiconductor optical Amplifier", *IEEE Photonic Technology Letters*, vol.2, no.8, Aug. 1990.

[9] S. Kobayasi, T. Timura: "Automatic frequency controll in a semiconductor laser and an optical amplifier", *J. Lightwave Technol.*, LT-1, 394-402, 1983.

[10] K. T. Koai, R. Olshansky, P. M. Hill: "Dual-Function Semiconductor Laser Amplifier in a Broad-Band Subcarrier Multiplexed System", *IEEE Photonic Technology Letters*, vol. 2, no. 12, pp. 926-928, Dec. 1990.

[11] P. G. Eliseev, V. V. Luc: "Semiconductor optical amplifiers: multifunctional possibilities, photoresponse and phase shift properties", *Pure Appl. Opt.* 4, pp. 295-313, 1995.

[12] M. Gustavsson, A. Karlsson, L. Thylen: "Traveling wave semiconductor laser amplifier detectors", *J. Lightwave Technol.*, vol. 8, pp. 610-617, 1990.

[13] A. Sharaiha: "Harmonic and Intermodulation Distortion Analysis by Perturbation and Harmonic Balance Methods for In-Line Photodetection in a SOA", *IEEE Photonic Technology Letters*, vol. 10, no. 3, pp. 421-423, March 1998.

Authorized licensed use limited to: Eszter Udvary. Downloaded on July 8, 2009 at 07:58 from IEEE Xplore. Restrictions apply.