Linearity enhancement of EA modulator using SOA

Sang-Kook Han, Chang-Hyun Lee, Sung-Il Sohn
Department of Electrical and Computer Engineering, Yonsei University
Shinchon-dong, Seodaemoon-gu, Seoul, Korea

ABSTRACT

Nonlinearity of Electroabsorption modulator (EAM) resulting from its near exponential transfer function decreases SNR in analog optical transmission. Since the transfer function of semiconductor optical amplifier (SOA) is inverse to that of EAM, the intermodulation distortion of EAM can be reduced by using SOA that connect with EAM in series and operating in gain saturation region. To improve the nonlinearity compensation of EAM, the increased gain of SOA is required and the slope of gain saturation, the ratio of gain to input SOA power, needs to be steep. However, the signal-spontaneous beat noise that is the dominant system noise increase in proportion to the gain. Thus, the noise power level of system is increased and the spurious free dynamic range (SFDR) of EAM is reduced. We have analyzed the SFDR variation of EAM including SOA gain and ASE noise. An enhancement of 9dB in SFDR was theoretically obtained and the gain of SOA for an optimum operation is mentioned. The proposed scheme is easy to implement and can be monolithically integrated with other optical devices useful for an efficient linear analog optical transmitter.

Keywords: electroabsorption modulator (EAM), linearity, semiconductor optical amplifier (SOA), intermodulation distortion (IMD), spurious dynamic range (SFDR)

I. INTRODUCTION

Intensity-modulated optical analog links are available for many applications, including optical CATV and antenna remoting of wireless communication system to utilize microwave signal. External optical modulator is indispensable for high frequency analog optical communication due to their low transmission loss and high compatibility with radio frequency systems. For externally modulator, $LiNbO_3$ Mach-Zehnder modulator (MZM) and EAM mainly have been investigated. EAM takes advantages of low driving voltage, small size, broad bandwidth, and monolithic integration with other components in contrast to MZM. But EAM has complicated nonlinear transfer of near exponential style and cause the intermodulation distortion (IMD) in subcarreir multiplexing (SCM) transmission of analog microwave signal and limits the optical link performance. The reported linearization schemes mainly relied on the electrical implementation of high-frequency circuit and MZM.[1-3]

In this paper, we propose a linear modulator scheme using SOA that has near log transfer function is used to compensate the nonlinearity of EAM and is connected in series. The change of transfer curve of EAM using SOA is analyzed and ASE noise that influences the noise level in optical receiver stage is also investigated. Improvement of 9dB

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SFDR and 6 dB composite second-order distortion (CSO) in broadband application for two-tone test has been achieved. SFDR of EAM in analog optical link increases because of relations of transfer function of EAM and SOA, and gain of SOA. This scheme is relatively easy to embody to other schemes and has the virtue of integration with DFB-LD, EAM, and SOA. So low chirping, low insertion loss, and low polarization dependence are attained.

II. LINEARIZATION PROCESS

Transfer function of EAM is known to be near exponential form. For EAM of bulk type, transfer function is written

$$T(V) = \frac{P_{out}}{P_{in}} \exp(-\Gamma \alpha(V) L) \tag{1}$$

where P_{in} represents the input optical power, Γ is optical confinement factor, α is absorption coefficient and L is length of EAM. We can infer that the nonlinear characteristic of EAM is derived from the absorption coefficient as a function of the bias voltage, modulator length, and wavelength detuning of each modulator. Figure 1 shows the transfer function of EAM with different wavelength detuning. In this simulation, we assumed that EAM is ridge waveguide structure of type, thickness of InGaAsP active layer is 0.25μm, length of 200μm, and the optical confinement factor is 0.684.

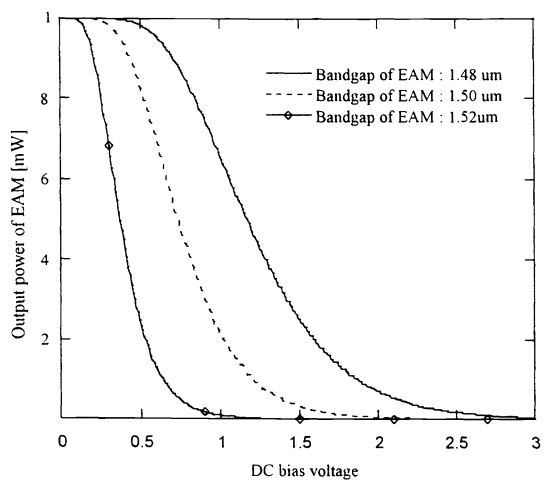

Figure 1. Change of transfer function in electroabsorption modulator (EAM) due to bandgap

The nonlinear characteristic of an EAM can be evaluated by expanding its transfer function using Talyor series about the DC bias voltage.[4] When the EAM is biased at the dc voltage V_b and a modulating signal V_m, Eq.1 as a function of V can be represent as follows[5]:

$$T(V) = T(V_b) + \frac{V - V_b}{1!} T^{(1)}(V_b) + \frac{(V - V_b)^2}{2!} T^{(2)}(V_b) + \frac{(V - V_b)^3}{3!} T^{(3)}(V_b) \ldots \tag{2}$$

Each term of Eq.2 indicates the specific order distortion of the transfer function and the transfer function can be approximated by a polynomial equation. In the case of two-tone modulation signal, V is defined as Eq.3 and m_0 represents the modulation depths.

$$V = V_b[1 + m_0(\cos w_1 t + \cos w_2 t)] \tag{3}$$

The second order term and the third order term mainly cause CSO and composite triple-beat distortion (CTB). CSO and CTB represent Eq.4 and Eq.5.

$$CSO = 10\log_{10}\left[\frac{\sum w_1 \pm w_2 \,|_{power}}{w_1 \text{ or } w_2 \,|_{power}}\right] \tag{4}$$

$$CTB = 10\log_{10}\left[\frac{\sum 2w_1 - w_2 \,|_{power}}{w_1 \,|_{power}}\right] \text{ or } 10\log_{10}\left[\frac{\sum 2w_2 - w_1 \,|_{power}}{w_2 \,|_{power}}\right] \tag{5}$$

Specially, CSO is the dominant IMD product in broadband application. As we can see, an EAM has the nonlinear transfer function and it causes the IMD product in analog optical transmission.

To linearize the transfer function of EAM of exponential type, a log shaped transfer function that is reverse shaped to exponential will be helpful. Figure 2 shows the transfer function of SOA at bias current 80mA. Because of the inherent gain saturation in SOA, the input vs. output transfer function of SOA shows a near log function curve and the gain saturation characteristic as input current increases. In this simulation, rate equation of SOA refers to the reported paper[6-8] and SOA supposed that it is traveling-wave type amplifier with no reflection, structure is buried-hetero (BH) structure, thickness is InGaAsP bulk active layer is 0.15μm, length is 500μm, optical confinement factor of active layer is 0.308529, and material peak gain is 1.55μm, and waveguide loss is ignored. Figure 3 shows the scheme of linear modulator utilizing SOA to compensate the nonlinearity of EAM. In this figure, the continuous optical wave is emitted by DFB-LD and modulated by external radio frequency signal. This schematic assumed that operation wavelength of DFB-LD is 1.55μm, output power of DFB-LD is 1mW, bandgap of EAM is 1.50μm, and the bias voltage to suppress the CSO was 0.6V.

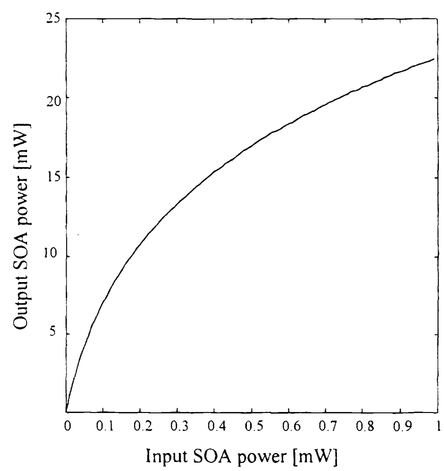

Figure 2 Transfer function of SOA at 80mA

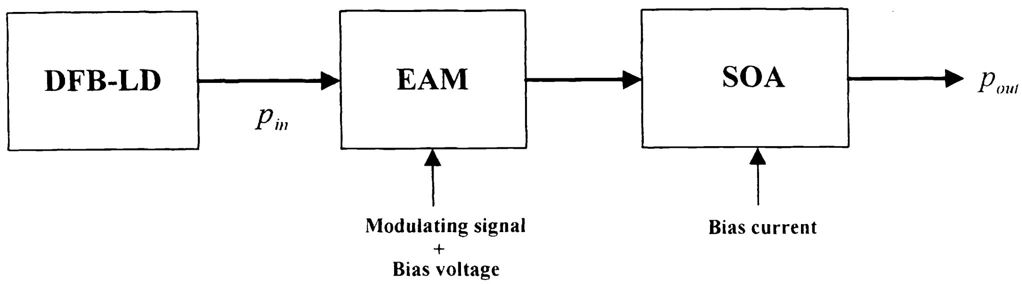

Figure 3. Schematic of compensating nonlinearity of EAM using SOA

To obtain a linear EAM, a large amplification is required for small optical output power of EAM and a smaller amplification is required for a relative large output power around the CSO bias voltage. For this reason, an SOA needs to operate in gain saturated. The slope of gain saturation region of SOA needs to –1dB/dBm to suppress the nonlinearity of EAM and this value is acquired in simulation. The slope of gain saturation of SOA is close to –1dB/dBm as SOA gain increases.[9] Because the enhancement of optical gain in SOA is achieved by increasing the bias current, the nonlinear compensation of EAM can be accomplished by operating the SOA properly. Figure 4 shows the calculated SFDR of EAM using SOA in broadband operation. This figure did not yet consider the amplified spontaneous noise (ASE) noises as noise level in detection stage and only considered the gain of SOA and set the same optical input power into the photo-detector with and without SOA for a fair of comparison. The SFDR increases in proportion to the bias current of SOA.

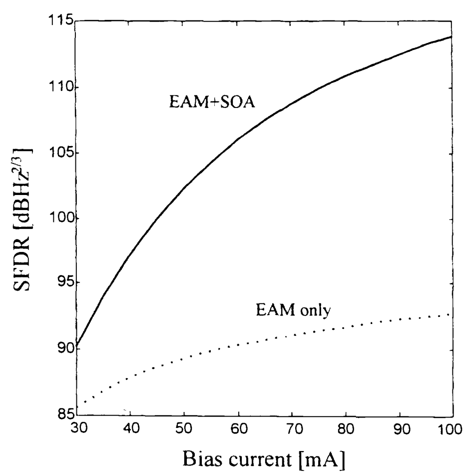

Figure 4. Nonlinearity compensation by SOA without ASE noise

III. NOISE EFFECT

An SOA has noise known as an amplified spontaneous emission (ASE) noise after the photo-detection because the detector is inherently a square-law device. An ASE noise are classified into two type, signal-spontaneous beat noise (Eq.6) and spontaneous-spontaneous beat noise (Eq.7) .[11]

$$\sigma^2{}_{sig-sp} = 4e\left(\frac{e}{hv}\right)P_{SOA\ in}G(G-1)n_{sp}B_e \tag{6}$$

$$\sigma^2{}_{sp-sp} = 4e^2(G-1)^2 n_{sp}{}^2 B_e B_o \tag{7}$$

where $\sigma^2{}_{sig-sp}$ is signal-spontaneous beat noise variance, $\sigma^2{}_{sp-sp}$ is spontaneous-spontaneous beat noise variance, v is the frequency of input signal, P_{in} is input power of SOA, G is the gain of SOA, n_{sp} is spontaneous emission factor, B_e is electrical detector bandwidth, and B_o is optical filter bandwidth.[11] A signal-spontaneous beat noise increases in proportion to the input power and gain of SOA. But this noise is not eliminated by band-pass optical filter due to narrow bandwidth of signal-spontaneous beat noise. A spontaneous-spontaneous beat noise is distributed over the wide frequency range of SOA and it can be decreased by optical filter. Figure 5 shows the noise power level variance as a function of SOA gain in the case of 0dBm DFB-LD.

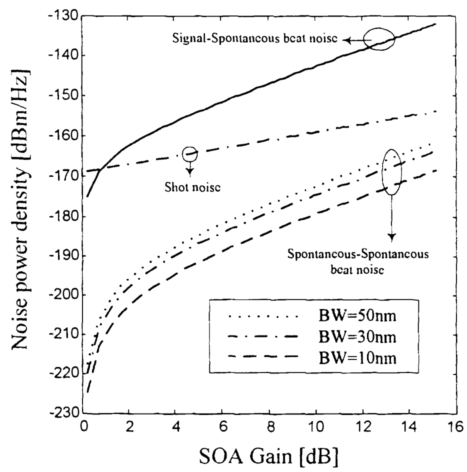

Figure 5. The noise power density vs. SOA gain

A signal-spontaneous beat noise becomes dominant noise source as the gain of SOA increases. The system noise level increases in proportion to the gain of SOA and SFDR of EAM is decreased. In this simulation, a shot noise power density was estimated to –175dBm/Hz, and the thermal variation and the effect of dark current were ignored. The SFDR of EAM with and without SOA by considering an ASE noise is shown in figure 6. The maximum SFDR is achieved at the SOA bias current of 45mA and output power of EAM without an SOA was set equal to the output power of EAM with SOA to compare the ASE noise effect on SFDR in fig. 6. Consequently, we could infer that the linearity enhancement by using the gain saturation of SOA becomes smaller because of the inherent ASE noise in SOA. An ASE noise becomes larger than the shot noise in high gain region.

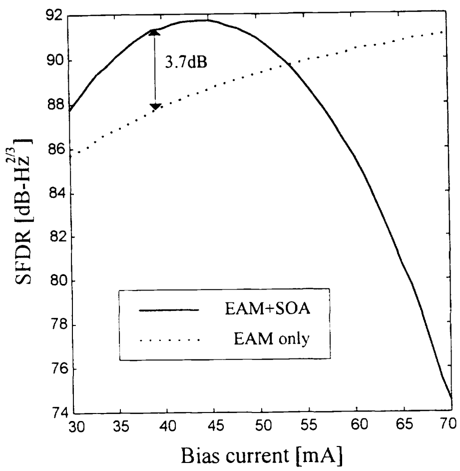

Figure 6. SFDR variation considering the ASE noise as SOA bias current

Figure 7 shows the change of transfer function of EAM using an SOA at bias current of 45mA. To compare the change of transfer function of EAM, output power of EAM was set equal to the output power of EAM with SOA. Considering the gain of SOA, this linear scheme is higher modulation efficiency than EAM only.

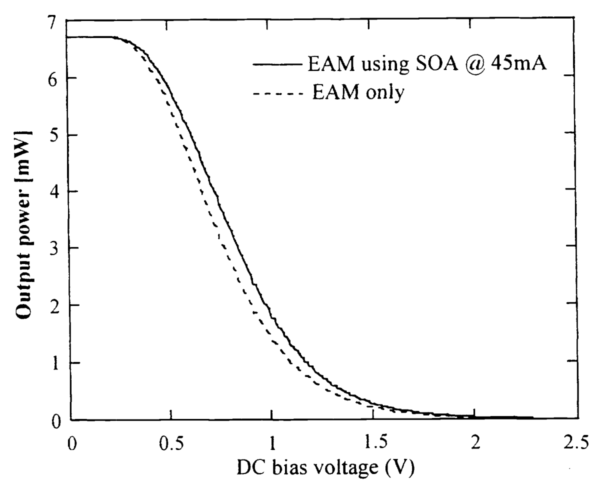

Figure 7. The change of transfer function of EAM using an SOA

By fixing the input power to EAM as 1mW, a CSO variation and the SFDR variation of EAM that connects an SOA in series is shown in figure 8 and figure 9. 6dB enhancement of CSO and 9dB of SFDR is achieved compared to the case of a single EAM operation by 8dB gain of an SOA at the bias current 45mA that gives 8dB optical gain. Then, because of trade-off relation between the gain of SOA and signal-spontaneous beat noise, an SOA that has steeper slope of gain saturation region should be need for higher linearity enhancement in EAM.

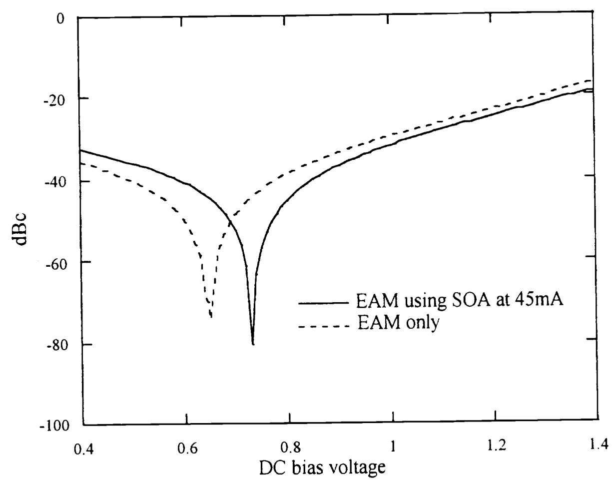

Figure 8. CSO of EAM using SOA and EAM only

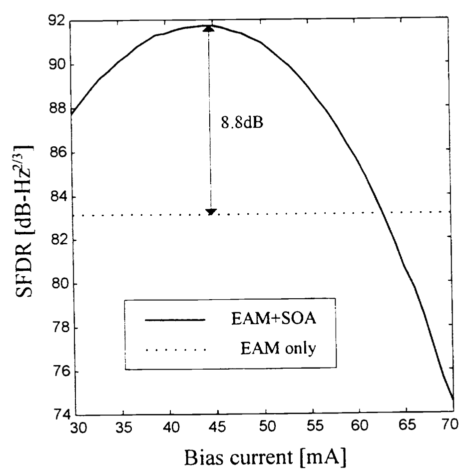

Figure 9. SFDR enhancement of EAM

IV. CONCLUSION

The nonlinearity compensation in EAM has been achieved by using an SOA that has nearly inverse transfer function in comparison to the EAM. An SOA is connected in series to EAM. The change of transfer function of EAM by SOA amplification was analyzed and accompanying enhancement of CSO and SFDR in broadband operation. Additionally, an ASE noise that influences the noise level in optical detection stage was investigated. The nonlienarity enhancement of EAM in analog optical modulation has been increased due to the suppression of intermodulation product and the gain of SOA. An SOA needs to be operated in gain saturation region for nonlinear compensation of EAM, and the maximum compensation was acquired with the slope of gain saturation of −1dB/dBm. From the simulation, 9dB SFDR and 6dB CSO improvement of EAM was obtained by 8dB optical gain of SOA. To acquire the more nonlinear compensation, an SOA that has steeper slope of gain saturation region is needed. The proposed scheme could be implemented as an integrated device including DFB-LD, EAM and SOA such that a low insertion loss, low chirp, low polarization dependence, and high modulation efficiency can be accomplished.

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Correspondence: E-mail: skhan@yonsei.ac.kr ; Telephone : 82-2-361-4016; Fax 82-2-361-3565