Large Enhancement of Linearity in Electroabsorption Modulator with Composite Quantum-Well Absorption Core

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SUMMARY We proposed a novel structure that improved the linear characteristics of electroabsorption modulator (EAM) with composite quantum-wells as an absorption core layer. We fabricated three types of EAM’s whose active cores were 8 nm thick, 12 nm thick and a composite core with 8 nm thick and 12 nm thick quantum-well (QW), respectively. The transfer functions of EAM’s were investigated and their third-order inter-modulation distortion (IMD3) was obtained by calculation. The spurious free dynamic range (SFDR) was measured and compared with three types of QW. The linearity of the device with composite quantum-well showed a large enhancement in SFDR by 9.3 dBHz−2/3 in TE mode and 7.0 dBHz−2/3 in TM mode compared with the conventional EAM.

key words: electroabsorption modulator, linear transfer function, composite quantum-well, SFDR

1. Introduction

As an E/O converter, an external modulator has advantages for a RF photonics link because one can avoid large nonlinear distortion by the frequency chirping that is common in a direct modulating laser diode. An electroabsorption modulator (EAM) is well known to be a good candidate for a key component in RF-photonics link [1] due to its small size, low driving voltage, large bandwidth and potential for monolithic integration with other devices like a photodiode or a laser diode [2]. It has exponentially decaying transfer function behavior and more complicated nonlinearity than a LiNbO3 modulator. Especially for analog fiber-optic application, an optical modulator should be characterized in terms of the RF link efficiency, the RF bandwidth and the RF spurious free dynamic range (SFDR) of the link. The improvement of the linearity of EAM’s is essential in order to enhance the dynamic range and to achieve high-quality RF link [3].

There are three categories of linearization in use. The first was analog electronic correction of the distorted electro-optic devices because the complete transmitter was linear [4], [5]. The second is correction by digital processing after the link output had been detected and fed to an analog-to-digital converter [6]. The third type, sometimes called ‘optical linearization’ was to modify the modulator itself in such way that it produces smaller distortion of signal; for example, an optical feedforward linearization technique [7], dual wavelength operation [8], electrical predistortion method [9], dual parallel modulation scheme [10]. ‘Optical linearization’ could deliver significant improvements in performance by simply modifying the modulator, but this modification often proved to have difficult fabrication tolerances and/or difficult control problems. Although there were improved SFDR and low distortion by these methods, it was necessary to make predistortion electronic circuit additionally, which had response limit and another optical source or a modulator [11]. There was another approach which utilized a linear combination of two electroabsorption effects (the Franz-Keldysh effect and the quantum-confined Stark effect) to improve the SFDR of the modulator [12].

In this paper, we proposed a simple and novel structure of EAM to improve its linear characteristics with composite quantum-well (QW) as an absorption core layer. The transfer functions of EAM with composite QW’s were investigated and their third-order inter-modulation distortion (IMD3) was obtained by calculation. The SFDR was measured and compared with two conventional EAM’s which had different single type QW structure, respectively.

2. Design of Devices

The transfer function of EAM was determined by absorption characteristic of QW known as quantum-confined Stark effect that was related to the bias voltage and the effective well width. The shift of absorption edge with the bias voltage was quartically proportional to the effective well width. To linearize the transfer function of an EAM, we made use of combining the transfer function of different QW. The concept of linearization of transfer function was as follows. In a low bias voltage, the ‘wide’ quantum well strongly pulls down the large transmission of the ‘narrow’ quantum well while weakly in a high bias voltage. So, if we combined the ‘narrow’ and ‘wide’ QW properly, the linearity of transfer function could be improved at the desired bias voltage. Transfer function of composite QW with two types of QW, that is, ‘wide’ and ‘narrow’ well are described as follows. Consider a composite QW layer; wide QW whose absorption coefficient α1(V) and well width W1 and narrow QW whose absorption coefficient α2(V) and well width W2. Since the material composition of both wide and narrow well is identical, the optical confinement factor (Γ) is proportional only to the well width. If the numbers of wide and narrow QW’s are set m and n, respectively, the ratio of the Γ

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for QW’s would be

\[ \Gamma_{W_1} : \Gamma_{W_2} = \sum_{i=1}^{m} \int_{W_i}^{W_1} |F_i(x)|^2 dx : \sum_{j=1}^{m} \int_{W_1}^{W_2} |F_j(x)|^2 dx, \quad (1) \]

where \( F(x) \) is the electrical field representing the optical wave at a certain position in the active core of composite QW.

Suppose that the transfer function of each QW is given as

\[ T_1(V) = P_0 \exp(-\alpha_1(V) \cdot \Gamma \cdot L) \]
\[ T_2(V) = P_0 \exp(-\alpha_2(V) \cdot \Gamma \cdot L) \quad (2) \]

where \( L \) is the active waveguide length, \( P_0 \) is the output optical power at 0 V. The absorption layer width for the different EAM’s whose active layers are single type and composite type QW’s is assumed to be identical; also, \( \Gamma \) is the same as well. Then, the total transfer function of the EAM consisting of active layer of composite QW is expressed as

\[ T(V)_{total} = P_0 \exp\left(-\alpha_1(V) \frac{\Gamma_{W_1}}{\Gamma_{W_1} + \Gamma_{W_2}} L \right) \]
\[ \times \exp\left(-\alpha_2(V) \frac{\Gamma_{W_2}}{\Gamma_{W_1} + \Gamma_{W_2}} L \right) \]
\[ = \left[ P_0 \exp(-\alpha_1(V) \cdot \Gamma \cdot L) \right]^{\Gamma_{W_1}} \Gamma_{W_1} + \Gamma_{W_2} \]
\[ \times \left[ P_0 \exp(-\alpha_2(V) \cdot \Gamma \cdot L) \right]^{\Gamma_{W_2}} \Gamma_{W_1} + \Gamma_{W_2} \]
\[ = T_1^{\Gamma_{W_1}/\Gamma_{W_2}}(V) \cdot T_2^{\Gamma_{W_2}/\Gamma_{W_1}}(V) \quad (3) \]

Figure 1 shows the calculated and observed transfer functions of EAM whose active layer had single type QW (8 nm and 12 nm, respectively) and composite type QW which had 3:1 ratio of narrow (8 nm) and wide (12 nm) QW’s. They were measured with a wavelength of 1550 nm at room temperature. The input optical power is 0 dBm. Polarization dependence of transfer functions for TE and TM mode was less than 0.5 dB in the entire range of operating voltage for all of different active core types [13]. The transfer function of a solid line in Fig. 1 was obtained by calculation with the ratio of \( T_{8 \text{nm}}/T_{12 \text{nm}} = 3:1 \) [14]. The \( \Gamma \) is proportional to electrical field intensity quadratically and not constant through the active core region of EAM. Therefore, the ratio of \( \Gamma \) between wide QW and narrow QW depends on positions of each QW in active core region of EAM with composite QW. For this reason, both the positions of each QW and the composite ratio of QW should be considered simultaneously.

From Fig. 1, we concluded that Eq. (3) was very powerful tool to find out the transfer function of composite QW for any composite ratio without fabrication of EAM. For a given EAM of composite QW, third-order inter-modulation distortion (IMD3) is considered to estimate the nonlinearity of the transfer function in a sub-octave link. It is well known that the third-order inter-modulation product could be minimized and a high SFDR could be achieved if a modulator is biased at the null point of the third derivative of the transfer curve [15]. In two-tone modulation, \( V \) could be expressed as

\[ V = V_b[1 + m_e(\cos \omega_1 t + \cos \omega_2 t)], \quad (4) \]

where \( V_b \) and \( m_e \) are the DC bias voltage, and electrical modulation depth, respectively. \( \omega_1 \) and \( \omega_2 \) are two-tone RF angular frequencies. The IMD3 is then determined when we expand \( T(V) \) with respect to \( V \) at DC bias voltage \( V_b \). After simple calculation, IMD3 could be expressed as

\[ \text{IMD3} = 20 \cdot \log \left( \frac{T^{m_e}(V_b)}{ST^{m_e}(V_b)} \cdot (m_e V_b)^3 \right). \quad (5) \]

3. Fabrication and Characteristics of Devices

We fabricated EAM’s whose active layers had 8 nm thick, 12 nm thick and composite QW composed of 8 nm thick and 12 nm thick QW with the ratio of 3:1. The layers consisted of 0.5 \( \mu \text{m} \) n-InP for n-metal contact, 0.5 \( \mu \text{m} \) InP for cladding, tensile strained quantum wells (~0.38\%) and strain compensated barriers (0.5\%) for active core, 0.6 \( \mu \text{m} \) InP for cladding and 0.1 \( \mu \text{m} \) p\textsuperscript+ InGaAs for metal contact on semi-insulating InP substrate. The passive waveguide was butt jointed by MOCVD after reactive ion etching. The optical waveguide was 2.0 \( \mu \text{m} \) wide and 1.5 \( \mu \text{m} \) deep. The active waveguide lengths were 100 \( \mu \text{m} \). After ridge waveguide formation, the sidewalls were passivated with polymide followed by a silicon nitride layer to reduce the device capacitance. Then, travelling wave electrode of ground-signal-ground was formed on the top of it. The detailed device fabrication processes and epitaxy structure had been published in [16], [17].

Figure 2(a) shows the calculated IMD3 for single type and composite type QW’s. In IMD3 calculation, the electrical modulation depth \( m_e \) of 5\% was used. In addition to a low IMD3, slope efficiency, signal clipping and optical loss at an operating bias voltage should be considered transmitting the analog signal through the EAM. An 8 nm QW showed the lowest IMD3 at −0.5 V but the slope efficiency
The linear characteristics of EAM for optical analog application were investigated by measuring the SFDR, an important figure of merit for the linearity of EAM. Figure 3 showed the schematic diagram for two-tone experiments. Two-tone sources were combined and loaded to the modulator through a bias-Tee. The modulated optical signal was converted to an RF signal by photodiode and monitored with an RF spectrum analyzer. Fundamental and 3rd order signals were measured with bias voltages.

Figure 4 showed that the RF output power from the photodiode versus the incident RF modulation power of modulator with composite quantum wells absorption core. The fundamental tone was \( f = 5 \text{ GHz} \) and frequency difference of two tones was \( \Delta f = 100 \text{ kHz} \). Measurements of the

was 0.18/V which was the minimum value in three types of QW’s as shown in Fig. 2(b). Therefore, the operating bias point should be moved to \(-2.3 \text{ V}\) of the second minimum IMD3 where slope efficiency was 0.33/V. However the increased slope efficiency was obtained at the expense of the optical loss of \(-23 \text{ dB}\) as shown in Fig. 2(c). On the other hand, for a 12 nm QW, the IMD3 and slope efficiency were \(-88 \text{ dBc}\) and 1.2/V at \(-0.4 \text{ V}\) and the optical loss was \(-22 \text{ dB}\). Although the values were acceptable, the bias voltage was too low to avoid signal clipping. Finally, the composite QW had the IMD3 of \(-91 \text{ dBc}\), the slope efficiency of 0.58/V and the optical loss of \(-21 \text{ dB}\) at \(-0.76 \text{ V}\).

Table 1 summarized the parameters for three types of QW’s. Our result implied that the proper combination of wide and narrow QW’s in an active layer could improve the linearity of an EAM. IMD3, slope efficiency, signal clipping and optical loss should be considered simultaneously for analog application [18]. For the practical use of EAM in optical analog application, it should be considered the gain of whole modulated optical link which included RF parts as well as optical parts. The basic approaches to obtain a high link gain in an external modulated link are to have low insertion loss, high optical power handling, and high slope efficiency at the modulator. The applicable limited values of these parameters are dependent on the RF components and optical components used in the link. It is also necessary that the optical input power to the module should be carefully adjusted for optimal data transmission. The optical power would cause a change of transfer function curve of the modulator so that the optimal position of operation in external bias would possibly be deviated.

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The fundamental and IMD3 were carried out as a function of a bias voltage. It was assumed that the thermal noise limited noise floor was only $-174 \text{ dBm/Hz}$ [19]. The SFDR was determined by subtracting the signal level from the noise level at the input power where the extrapolated inter-modulation distortion equalled the noise level. The SFDR of different QW was plotted with bias voltage as above in Fig. 5. The SFDR of composite type had lower values than those of other two types in some bias region. The SFDR of composite type had the maximum value $98.0 \text{ dB} \cdot \text{Hz}^{2/3}$ at $-1.0 \text{ V}$ in TE mode and $99.2 \text{ dB} \cdot \text{Hz}^{2/3}$ at $-1.5 \text{ V}$ in TM mode. It was enhanced by $3.6 \text{ dB} \cdot \text{Hz}^{2/3}$ and $4.2 \text{ dB} \cdot \text{Hz}^{2/3}$ compared with the maximum values of conventional EAM with $8 \text{ nm}$ QW absorption core, respectively. In the viewpoint of the SFDR, the composite type QW was most appropriate for analog EAM in three types of QW’s.

**Fig. 3** Schematic diagram for two-tone experiments.

**Fig. 4** Two-tone experiment of modulator with composite quantum wells absorption core for (a) TE mode and (b) TM mode.

**Fig. 5** SFDR for three types of devices with different quantum well absorption core for (a) TE mode and (b) TM mode.

**4. Conclusion**

In the scheme of electroabsorption modulator with composite quantum-well absorption core, we found that the linear characteristics of EAM with composite type QW are largely improved compared to the single type QW. The spurious free dynamic range (SFDR) of composite type was as large as $98.0 \text{ dB} \cdot \text{Hz}^{2/3}$ at bias voltage $-1.0 \text{ V}$ in TE mode and $99.2 \text{ dB} \cdot \text{Hz}^{2/3}$ at bias voltage $-1.5 \text{ V}$ in TM mode. It was enhanced by $3.6 \text{ dB} \cdot \text{Hz}^{2/3}$ in TE mode and $4.2 \text{ dB} \cdot \text{Hz}^{2/3}$ in TM mode compared with the conventional EAM with $8 \text{ nm}$ QW absorption core. We concluded that the linear EAM consisting of composite QW is advantageous in an analog fiber-optic link in terms of IMD3, slope efficiency, optical loss, and bias voltage.
References


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