# An Improved Approach of Optical Loss Measurement Using Photocurrent and Optical Transmission in an Electroabsorption Modulator

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***Abstract*—We report an improved method to extract the optical absorption coefficient of a semiconductor electroabsorption modulator. Only the transmission and photocurrent data are needed with this method. The method makes it possible to obtain the optical coupling efficiency between laser and modulator, photocurrent conversion efficiency, and optical absorption coefficients from experimental data.**

***Index Terms*—Absorption process, electroabsorption modulator (EAM), optical loss, photocurrent.**

## I. Introduction

SEMICONDUCTOR multiple quantum-well (MQW) electroabsorption modulators (EAMs) are widely considered for the use in analog and digital optical communication links [1]–[3]. The previous reports show that most modulators based on the quantum confined Stark effect (QCSE) suffer a large insertion loss ranging from 6 to 12 [dB] [4]. The insertion loss consists of coupling loss to optical fibers, waveguide scattering and radiation losses, and the residual interband absorption loss. Those different losses play different roles on the performance of an EAM. For the purposes of material characterization and device optimization, separating of those different optical losses is very valuable.

A number of methods have been proposed for the determination of the optical gain–loss in a waveguide device the Hakki–Paoli method is based on the Fabry–Pérot (FP) resonance [5], [6]. In order to apply these methods, an EAM should have finite facet reflections as well as low propagation loss such that the peaks and valleys of individual FP resonance can be discriminated. However, the resonances of an EAM are hardly observed at operation wavelength since the residual optical loss is usually large to assure a high QCSE. Furthermore, the facets of an EAM are coated with antireflection films for high light coupling. A simple and direct optical loss measurement method based on photocurrent and transmission was proposed by Wood [7]. In this approach, a sum of waveguide scattering loss and radiation loss $\alpha_i$ must be assumed at first, and the internal quantum efficiency $\eta_i(V)$, namely photocurrent conversion efficiency, was assumed nearly constant as one at high bias. Then the residual loss $\alpha_{\mathrm{cv},o}$ was deduced. However, the value of $\alpha_{\mathrm{cv},o}$ is sensitive to the guessed value of $\alpha_i$. Chin improved Wood's method by using an iteration of the residual optical loss $\alpha_{\mathrm{cv},o}$ and $\eta(V=0)$, where $V$ is applied bias voltage [8]. The best value $\eta(0)$ was chosen to give $\eta(V)$ close to one at high bias. The method eliminated the ambiguity of $\alpha_i$ in [7] by assuming that $\alpha_i$ is negligibly small compared to the interband absorption loss $\alpha_{\mathrm{cv},o}$. Thus, it can be applicable only in the limited case such as well-fabricated waveguide device. Therefore, the previous reports have a difficulty to distinguish the waveguide optical loss $\alpha_i$ from the total propagation loss $\alpha_{\mathrm{tot}}$.

This letter presents an improved measurement method of optical losses based on photocurrent and transmission in a semiconductor EAM. The model allows us to extract the waveguide scattering and radiation losses $\alpha_i$, the residual interband absorption loss $\alpha_{\mathrm{cv},o}$, optical coupling efficiencies among the devices, and the bias dependent photocurrent efficiency $\eta_i(V)$ without assuming that $\alpha_i \ll \alpha_{\mathrm{cv},o}$.

## II. Analysis Procedure

There are several optical absorption processes existing in an EAM. Waveguide scattering loss $\alpha_{\mathrm{sc}}$, waveguide radiation loss $\alpha_{\mathrm{rad}}$, free carrier absorption $\alpha_{\mathrm{fc}}$, and intervalence band absorption loss $\alpha_{\mathrm{IVBA}}$ can reduce the photon number, but make no contributions to generate electron-hole pairs. We represent optical losses that do not generate electron-hole pairs as the optical loss coefficient of $\alpha_i$. Since an EAM is usually operated under the reverse bias, it is expected that $\alpha_{\mathrm{fc}}$ and $\alpha_{\mathrm{IVBA}}$ may not be significant compared to $\alpha_{\mathrm{sc}}$ and $\alpha_{\mathrm{rad}}$. Here, we assumed that $\alpha_{\mathrm{sc}}$ and $\alpha_{\mathrm{rad}}$ are much larger than $\alpha_{\mathrm{fc}}$ and $\alpha_{\mathrm{IVBA}}$. In this case, $\alpha_i$ can be considered as a constant regardless of applied bias voltages. We denote the optical loss coefficient $\alpha_{\mathrm{cv}}$ standing for the electron-hole pair generation process between the valance band and the conduction band. Thus, the carriers generated only by $\alpha_{\mathrm{cv}}$ process can contribute the photocurrent generation. We define the photocurrent conversion efficiency $\eta_i(V)$ as the number of electron-hole pairs contributing to photocurrent per the number of electron-hole pairs generated by photons, which is the same as Wood's definition of the internal quantum efficiency [7]. At low voltages, $\eta_i(V)$ will be low. But when the voltage applied to the device is sufficient to sweep out all the carriers, $\eta_i(V)$ will be constant and approximately unity.

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We can formulate the following equations for the optical transmission and the photocurrent using the absorption coefficients discussed above [7], [9]:

$$P_{\text{out}} = K_p P_{\text{in}} e^{-\alpha_i L} e^{-\Gamma(\alpha_{\text{cv},o}+\Delta\alpha_{\text{cv}})L} \tag{1}$$

and

$$I_{\text{ph}} = K_h P_{\text{in}} \frac{\Gamma(\alpha_{\text{cv},o}+\Delta\alpha_{\text{cv}})}{\alpha_i + \Gamma(\alpha_{\text{cv},o}+\Delta\alpha_{\text{cv}})} \times \left\{1 - e^{-\alpha_i L} e^{-\Gamma(\alpha_{\text{cv},o}+\Delta\alpha_{\text{cv}})L}\right\} \tag{2}$$

where $P_{\text{out}}[\text{mW}]$, $P_{\text{in}}[\text{mW}]$, and $I_{\text{ph}}[\text{mA}]$ represent the optical output power, the optical input power, and the modulator photocurrent, respectively. $\alpha_{\text{cv},o}$ denotes $\alpha_{\text{cv}}(V=0)$ which corresponds to the residual optical loss due to the interband absorption and $\Delta\alpha_{\text{cv}}(V) = \alpha_{\text{cv}}(V) - \alpha_{\text{cv}}(0)$ is the optical loss change at a bias voltage $V$. $\Gamma$ and $L$ are the optical confinement factor and the modulator length, respectively. The constants $K_p$ and $K_h$ in (1) and (2) can be expressed as follows:

$$K_p = C_{\text{LD}-m} C_{m-\text{PD}} (1-R_f)^2 \tag{3}$$

and

$$K_h = \eta_i(V)(q/h\nu) C_{\text{LD}-m}(1-R_f) \tag{4}$$

where $C_{\text{LD}-m}$ is the optical coupling efficiency between the laser and modulator and $C_{m-\text{PD}}$ between the modulator and photodiode. $R_f$ is the facet reflectivity. $q$ and $h\nu$ represent the electron charge and the photon energy, respectively. $\eta_i(V)$ is the photocurrent efficiency.

Equations (1) and (2) can be derived by assuming that $\eta_i(V)$ and $\alpha_{\text{cv}}(V)$ are uniform along the propagation direction. Thus, our method gives the average absorption rather than the detailed spatial distribution of absorption. By combining (1) and (2), the photocurrent $I_{\text{ph}}$ in (2) can be rewritten as follows:

$$\frac{I_{\text{ph}}(V)}{1 - e^{-\alpha_i L} e^{-\Gamma\alpha_{\text{cv},o} L} T_n(V)} = b - \frac{c}{a - \ln T(V)} \tag{5}$$

where

$$T(V) = P_{\text{out}}(V)/P_{\text{in}} \tag{6}$$

$$T_n(V) = T(V)/T(0) \tag{7}$$

$$a = \ln(K_p) = \ln\{C_{\text{LD}-m} C_{m-\text{PD}} (1-R_f)^2\} \tag{8}$$

$$b = K_h P_{\text{in}} = \eta_i(V)(q/h\nu) C_{\text{LD}-m}(1-R_f) P_{\text{in}} \tag{9}$$

and

$$c = (\alpha_i L)(K_h P_{\text{in}}). \tag{10}$$

Equation (5) is the key equation in our analysis. $I_{\text{ph}}(V), T(V)$, and $T_n(V)$ are experimental date we have. Since $\eta_i(V)$ can be assumed as constant and unity for $V \geq V_{\min}, a, b$, and $c$ becomes constant in this range. The minimum bias voltage $V_{\min}$ can be deduced from the reported results as the bias voltage [7], [8]. We used the value of $V_{\min}$ as the voltage where normalized transmission $T_n$ less than $-6$ dB.

At first, the analysis is done for $V \geq V_{\min}$. We assume $\alpha_i$ and $\Gamma\alpha_{\text{cv},o}$. The left term $f_l(V)$ in (5) is calculated in the range of $V \geq V_{\min}$ by using measured date of $I_{\text{ph}}(V)$ and $T_n(V)$. Next, $f_l(V)$ is plotted as a function of $\ln T(V)$ in order to fit the expression shown in the right term of (5). The constants $a, b$, and $c$ are extracted from the data set of $(f_l, \ln T)$. Then $K_p, K_h$, and $\alpha_i$ are calculated from the extracted values of $a, b$, and $c$. We know from (1), (2), (6), and (7) that

$$\Gamma\Delta\alpha_{\text{cv}}(V) = -(1/L)\ln(T_n(V)) \tag{11}$$

and

$$\Gamma\alpha_{\text{cv},0} = \frac{1}{L}\ln\left(\frac{K_p}{T(V)}\right)\frac{I_{\text{ph}}/K_h P_{\text{in}}}{1 - T(V)/K_p} - \Gamma\Delta\alpha_{\text{cv}}(V). \tag{12}$$

Equations (10) and (12) give new values of $\alpha_i$ and $\Gamma\Delta\alpha_{\text{cv},o}$. We compare the obtained values of $\alpha_i$ and $\Gamma\alpha_{\text{cv},o}$ to initially assumed ones. If the errors are negligibly small, then we stop the iteration procedure. Otherwise, we repeat the calculation procedure with the obtained values of $\alpha_i$ and $\Gamma\alpha_{\text{cv},o}$ as the initial values. After the iteration process in the range of $V \geq V_{\min}$, we know the constant values of $C_{\text{LD}-m}C_{m-\text{PD}}, C_{\text{LD}-m}\eta_i, \alpha_i$, and $\alpha_{\text{cv},o}$. The measured data of $I_{\text{ph}}(V)$ and $T(V)$ are used to find $\alpha_{\text{cv}}(V), \alpha_{\text{tot}}(V)$, and $C_{\text{LD}-m}\eta_i(V)$ as a function of the bias voltages.

Even though our method gives correct values of $C_{\text{LD}-m}(1-R_f)\eta_i$ for $V \geq V_{\min}$, it does not allow us to know the values of $C_{\text{LD}-m}$ and $\eta_i(V)$ separately. But $\eta_i(V \geq V_{\min})$ can be considered as nearly one when the voltage applied to the device is sufficient to sweep out all the carriers. Furthermore, $R_f$ can be neglected when the modulator facets are coated with antireflection film. In these situations, $C_{\text{LD}-m}$ and $\eta_i(V)$ are found separately from the extracted value of $b$ and (2). The photocurrent conversion efficiency $\eta_i(V)$ is expressed as a function of applied bias in (13)

$$\eta_i(V) = \frac{h\nu}{q}\left(\frac{\alpha_{\text{tot}}}{\Gamma\alpha_{\text{cv}}}\right)\frac{I_{\text{ph}}(V)}{C_{\text{LD}-m}(1-R_f)P_{\text{in}}\left(1 - e^{-\alpha_{\text{tot}}L}\right)} \tag{13}$$

where $\alpha_{\text{cv}} = \alpha_{\text{cv},o} + \Delta\alpha_{\text{cv}}$ and $\alpha_{\text{tot}} = \alpha_i + \Gamma\alpha_{\text{cv}}$.

## III. Experimental and Discussions

We applied the method described in Section II to find the changes of optical losses in our MQW EAM [10]. The MQW structure consists of 10 tensile-strain wells (InGaAsP, $-0.35\%$, 12 nm) and 11 compressive-strain barriers (1.1-$\mu$m InGaAsP, $+0.57\%$, 7 nm). The active region is sandwiched between p-InP and n-InP cladding layers. The total thickness of the intrinsic layer is about 300 nm. A 300-$\mu$m-long and 2-$\mu$m-wide ridge-waveguide device is fabricated. The optical confinement factor $\Gamma$ is 0.2. The facets are coated by antireflection films.

Fig. 1 shows the optical transmission $T$, the normalized transmission $T_n$,and the photocurrent $I_{\text{pc}}$ under the different reverse bias voltages. An input light wavelength was selected as 1553 nm. The laser power was set to 0.25 mW with transverse-magnetic (TM) polarization. Fig. 2 shows the three different photocurrents with respect to $\ln(T)$. The dotted points are the redrawn experimental $I_{\text{pc}}$ data from Fig. 1. The straight and dashed lines correspond to the left and right terms in (5) after converging process. The least square method was used to obtain $a, b$, and $c$ constants from the fitting. In this analysis, we assumed that $\eta_i$ is one for $V > 1V$ which corresponds

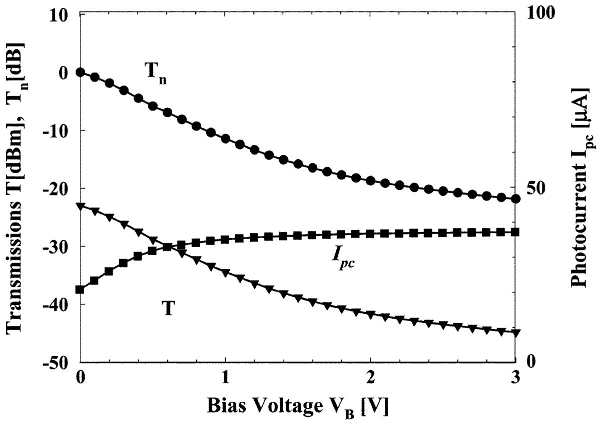


Fig. 1. Experimental data of the transmission $T$, normalized transmission $T_n$, and photogenerated current $I_{\rm pc}$ as a function of bias voltage.

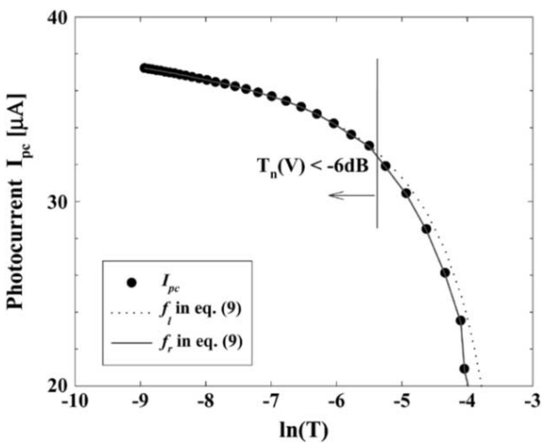


Fig. 2. Experimental data and fitted curves of photogenerated currents as a function of $\ln(T)$.

TABLE I
EXTRACTED PARAMETERS

| $L[\mu m]$ | $K_p$ | $K_h[A/W]$ | $C_{LD-m}[dB]$ | $C_{m-PD}[dB]$ | $\alpha_i[cm^{-1}]$ | $\Gamma\alpha_{cv,o}[cm^{-1}]$ |
|---|---|---|---|---|---|---|
| 300 | 0.061 | 0.16 | -8 | -4 | 17 | 160 |

to $T_n < -6$ dB. Other useful parameters are obtained from (8)–(12). Table I summarizes the extracted parameters.

Fig. 3 shows the calculated modal optical loss. The dependence of total optical loss coefficient $\alpha_{\rm tot}(=\ \alpha_i + \Gamma\alpha_{\rm cv})$ on the bias voltage $V$ is determined mainly by the change of the interband absorption coefficient $\Gamma\alpha_{\rm cv}$. We also know that there exists a residual optical loss in $\alpha_{\rm tot}$ at $V = 0$ Volt, which consists of $\alpha_i = 17\ {\rm cm}^{-1}$ and $\Gamma\alpha_{\rm cv} = 160\ {\rm cm}^{-1}$. Thus, in order to reduce the residual loss at $V = 0$ Volt, the reduction of $\Gamma\alpha_{{\rm cv},o}$ is more important than that of $\alpha_i$ in this case. Fig. 3 also shows the change of $\eta_i(V)$. $\eta_i$ slightly increases as the applied voltage increases in the range of $0 < V < 1V$ and remains a constant $V > 1V$. Thus, we believe that our EAM seems to be completely depleted around at 1 V.

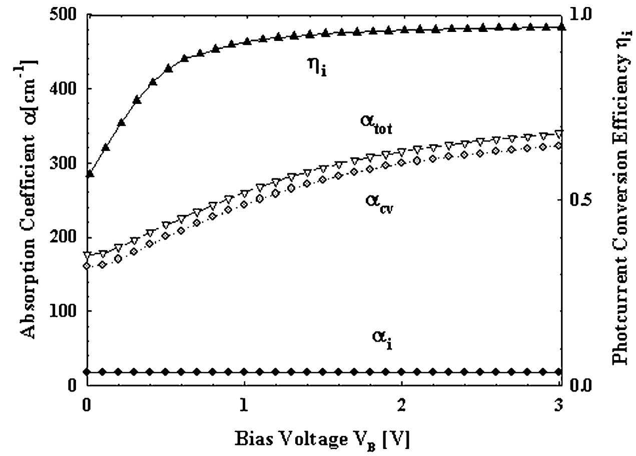


Fig. 3. Changes of optical losses and photocurrent conversion efficiency $\eta_i$ versus bias voltage $V$ at the input light with $\lambda = 1553$ nm. $\alpha_i, \Gamma\alpha_{\rm cv}$, and $\alpha_{\rm tot}$ represent the absorption coefficient changes due to the intrinsic absorption, interband absorption, and the sum, respectively.

## IV. CONCLUSION

We have presented a simple and self-consistent method to determine optical losses separately in an EAM such as the intrinsic optical losses consisting of waveguide scattering, the residual optical loss due to the interband optical absorption, the fiber coupling losses. The bias-dependent internal quantum efficiency and absorption coefficient also can be derived. This method uses only the measured transmission as well as photogenerated current data.

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