A Circuit Model of Traveling Wave Electroabsorption Modulator

Jiyoun Lim, Sanghoon Jeon*, Jeha Kim** and Songcheol Hong

Korea Advanced Institute of Science and Technology, Taejon, 305-701, Korea
*Knowledge*on Inc., 513-37, Eoyang-dong, Iksan, 570-210, Korea
**Electronics Telecommunication Research Institute, Taejon, 305-600, Korea

Abstract — **A circuit model of TWEAM in which optical and electrical waves are considered at the same time is proposed. The model represents the optical response of TWEAM with an equivalent circuit. This allows to understand the relation between the electrical and the optical responses and helps to design device structure for aimed performances. The model is implemented in commercially available circuit simulators.**

I. Introduction

Recently, traveling wave electroabsorption modulator (TWEAM) was proposed for high-speed digital and analog optical links. There have been some reports on a quasi-static equivalent circuit model [1] to analyze only the microwave aspects of TWEAM. However, to optimize TWEAM structure, both the optical and the microwave characteristic should be understood at the same time, since a TWEAM modulates optical signal with microwave signal. In this paper, we proposed a circuit model which can describe both the electrical and the optical responses. This utilized the distributed model we have reported previously [2].

II. A Circuit Model

A. A Circuit Model

Considering distributed effects of traveling waveguide, a TWEAM is modeled as a transmission line consisted of many unit cells. Each unit cell is assumed to be so small that it can be considered as an electronically lumped element and the amount of optical absorption is quite small.

Fig. 1 shows the equivalent circuit of unit cell. Each unit cell has four ports, which designate input and output ports for electrical and optical waves. Port 1 and 2 are for electrical signal and port 3 and 4 are for optical signal. The voltage between port 3 and 4 denotes power of optical wave. In order to describe the propagation of electrical wave, resistance R, inductance L, capacitance C and series resistance R_S per unit length were used in the same manner as in reference [1].

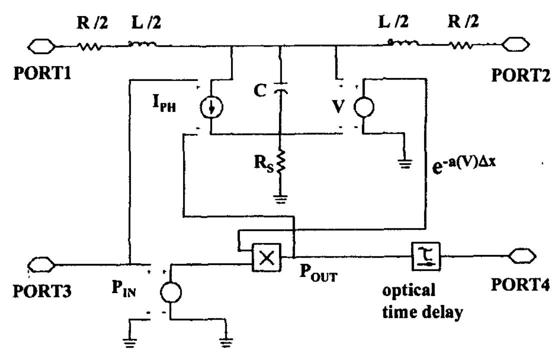

Fig. 1. Circuit diagram of unit cell

Non-linear components such as voltage-controlled-sources (VCVS), multiplier and time delay were used to describe the optical wave modulated by electrical wave. The relation between optical input and output power can be expressed as

$$P_{out} = P_{in} e^{-\alpha(V)\Delta x} \quad (1)$$

where α(V) is the absorption coefficient as a function of voltage and Δx denotes the length of the unit cell. This relation is modeled using two voltage-controlled-voltage sources (VCVS) and a multiplier as depicted in Fig. 1. Propagation of optical wave can be described using time delay. On the other hand, the effect of optical wave power on electrical wave can be considered using a voltage-controlled-current source (VCCS). The VCCS is connected between the node of input and output optical power, since the photocurrent *Iph* induced by optical wave intensity is expressed as

$$Iph = \eta\left(\frac{q\lambda}{\hbar c}\right)\left(P_{in} - P_{in}e^{-\alpha(V)\Delta x}\right) \quad (2)$$

where η, q, λ, $\hbar$ and c are quantum efficiency, charge of electron, wavelength of light, Planck's constant divided by 2 and velocity of light at vacuum, respectively.

0-7803-7239-5/02/$10.00 © 2002 IEEE

B. Model parameters

When the model is used in simulation, some information of device should be provided by model parameters. The model parameters describing electrical and optical wave behaviors, and some interaction coefficients between electrical and optical signal are also needed.

For electrical part, L, R, C and R_S value should be determined from measured S-parameter. In order to describe the propagation of optical wave, optical time delay should be determined. Optical time delay τ_{opt} is calculated from optical refractive index of the waveguide and length of a unit cell. In the model simulation we used optical refractive index n_o of 3.4. Electrical and optical wave are related through the absorption coefficient $\alpha(V)$ as shown in equation (1). The absorption coefficient was fitted as a fourth-order polynomial from the measured voltage-to-optical power transfer curve as shown in [2]. Although optical wave is modulated by electrical wave, the optical wave also influences the electrical characteristics. The amount of photocurrent induced by optical power affects the characteristic impedance and the propagation constant of microwave. To model this effect, quantum efficiency η is introduced

C. Simulation Range

Because a TWEAM is represented as a series of cascaded unit cells, the number of unit cells determines the accuracy of simulation results. The minimum number of unit cell and the maximum simulation frequency are estimated from assumptions of model.

There are two assumptions in the circuit model. First, we assumed that the amount of optical absorption in a unit cell is quite small. Therefore minimum number of unit cell can be determined as shown in equation (3)

$$\alpha_{max}\frac{L}{N} << 1 \qquad \therefore N_{min} >> \alpha_{max} L \tag{3}$$

Secondly, unit cell is assumed to be an electrically lumped section. The length of unit cell should be much shorter than the wavelength of electrical wave for all the frequencies. Generally, a device shorter than one-tenth of the wavelength of microwave is regarded as a lumped device [3]. The maximum simulation frequency is determined as shown in equation (4)

$$\frac{L}{N} < \lambda_{elec} \qquad \therefore \; f_{max} < \frac{1}{10}\frac{c}{n_{elec}}\frac{N}{L} \tag{4}$$

We chose unit cell length shorter than 20 μm in the simulation to model the waveguide of 800 μm-long at the frequency up to 80 GHz

III. Model Validation

Simulation results are shown for the cases of an ideal lossless electrode and fabricated TWEAM. The measured electrical-to-optical response and the simulation results will be compared. For the lossless and impedance matched case, 600 μm-long transmission line consisted of 40 unit cells is used. The refractive indices of electrical and optical waves are assumed 6.8 and 3.4, respectively. Bias voltage of 1 V and electrical signal power of 0dBm is applied at port 1 and optical power of 0 dBm at port 3.

The waveform of electrical and optical waves at 10 GHz is in Fig. 2. Each line represents the waveform at every 5th unit cells from input port. Because no electrical attenuation and reflection are assumed, electrical wave at each unit cell has the same amplitude. On the other hand, it is found that the amplitude increases as the optical wave propagates along the waveguide, as is expected.

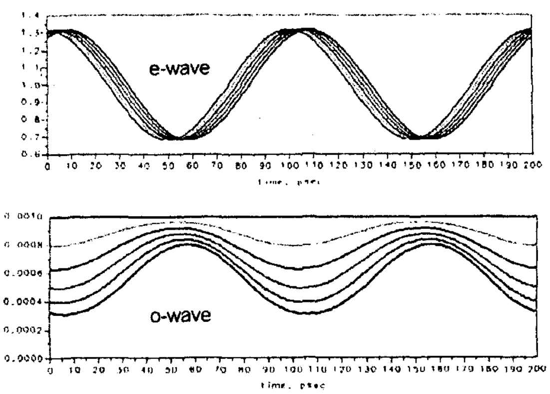

Fig. 2. Propagating waveform of electrical and optical waves at cascaded unit cells with lossless electrode,

Fig. 3 shows the electrical to optical frequency response for electrical wave with various velocities. It is found that the degradation of the electrical to optical response at 40GHz is less than 3dB in the impedance matched and lossless case. This indicates that the high frequency response of TWEAM is largely affected not only by velocity mismatching but also by impedance matching and electrical attenuation.

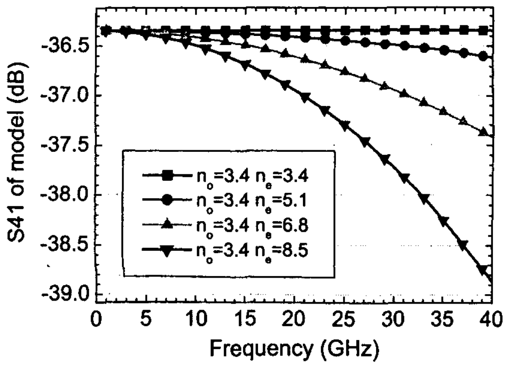

Fig.3. Simulated electrical to optical frequency response of lossless transmission line.

Fig. 4 shows simulated electrical to optical frequency responses compared with measured ones. The measurement was done with 40 Ω termination at port 2 and the loading effects were included in the simulation.

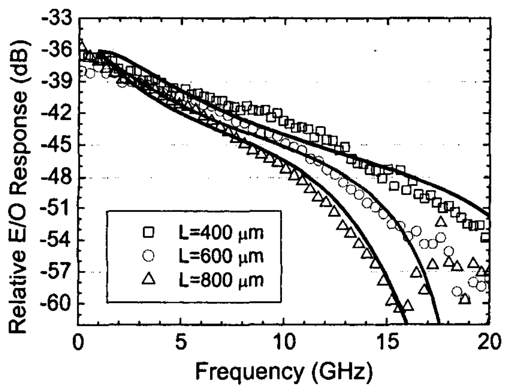

Fig. 4. Simulated and measured electrical to optical frequency response

IV. ESTIMATION OF TWEAM RESPONSE

In this section, frequency response of TWEAM is estimated using the proposed model. The circuit component values of R, L, C and R_S in reference [1] were used. The impedance of the structure is 20 Ω that is typical value and the refractive index is between 6 and 10, which is implying velocity mismatch.

Fig. 5 shows the estimated 3-dB frequency of lumped and traveling wave EAM. The reason that the 3dB frequency of TWEAM is always higher than that of lumped EAM is the impedance mismatching. The impedance of a lumped EAM with a shunt resistor decreases as the frequency goes up whereas TWEAM has constant characteristic impedance at the higher frequency. Therefore, the reflection of input microwave is high in a lumped EAM, which causes the decrease in 3dB frequency. The results are explained using the electrical to optical frequency response and microwave characteristics. It is also found that with appropriate impedance matching a TWEAM shorter than 200 μm must be used wide band application up to 60 GHz.

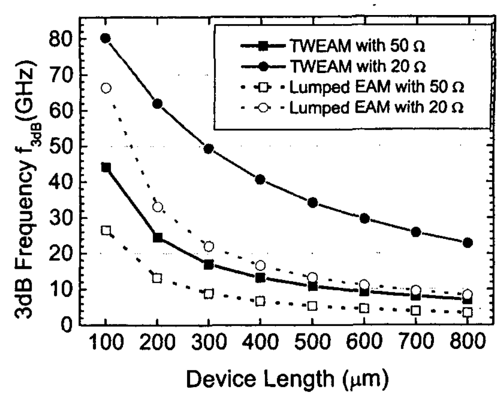

Fig. 5. Estimated 3-dB frequency of lumped and TWEAM

The photocurrent effects on electrical to optical frequency response of TWEAM are investigated considering the microwave characteristics. Fig. 6 shows the 3 dB frequency as a function of input optical power for a 200 μm-long TWEAM with 50 Ω termination. No optical power saturation and no optical coupling loss are assumed in the simulation.

Because the photocurrent path is parallel with intrinsic capacitor, it changes the admittance of unit cell at low frequency. With high input optical power the increase of admittance causes the decrease of characteristic impedance as shown in Fig. 7. The electrical to optical response is suppressed at low frequency due to impedance mismatch. This results in wide band response with high input optical power.

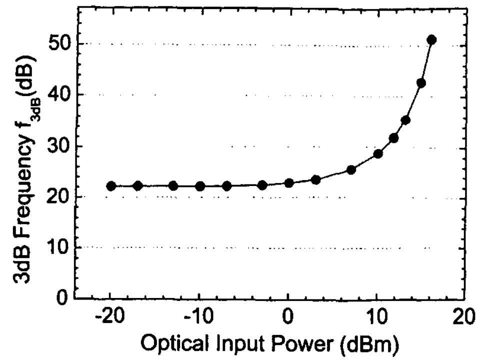

Fig.6. Estimated 3-dB frequency for various input optical powers

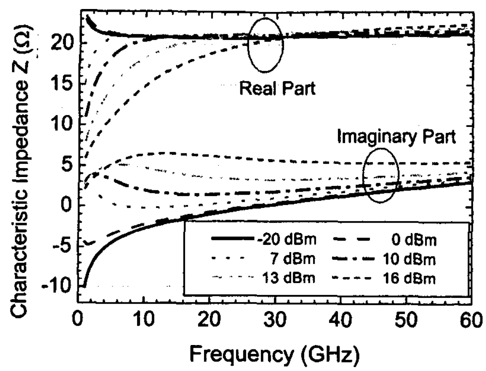

Fig. 7. Characteristic impedance for various input optical powers

V. CONCLUSION

A circuit model of TWEAM including both the electrical and the optical feature is proposed for the first time. The absorption is straightforwardly realized using non-linear circuit components. The model is verified by fitting the measured response of fabricated TWEAM. The model can be used in commercially available circuit simulators. Moreover it is applicable to large signal operation with proper model parameter extraction.

High frequency electrical to optical response was estimated for various lengths of TWEAM and input optical power. The frequency response was explained with microwave characteristic impedance. It is found that with properly impedance matched TWEAM could have better performance than a lumped EAM with the same length.

REFERENCES

[1] G. L. Li, C. K. Sun, S. A. Pappert, W. X. Chen and P. K. L. Yu, "Ultrahigh-speed traveling-wave electroabsorption modulator – design and analysis," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-47, no. 7, pp. 1177-1183, July 1999.

[2] Jiyoun Lim, Myunghun Shin, Jeha Kim, Jeong Soo Kim, Kwang Eui Pyun and Songcheol Hong, "Velocity-mismatching effect on extinction characteristics of traveling wave electroabsorption modulator," *Jpn. J. Appl. Phys.*, vol. 40, part1, no. 4B, pp. 2735-2737, April 2001.

[3] R. E. Collin, *Foundations for Microwave Engineering*, New York: McGraw-Hill, 1966