236 KIEE International Transactions on EA, Vol. 4-C, No. 5, pp. 236~240, 2004

Transient Response of Optically-Controlled Microwave Pulse through Open-Ended Microstrip Lines

Yong K. Kim†, **Jin-Su Kim*** and **Kyoung-Su Park***

Abstract - In this paper we examine the reflection characteristics of dielectric microstrip lines with open-ended termination containing an optically induced plasma region, which are analyzed by the assumption that the plasma is distributed homogeneously in laser illumination. The characteristics impedances resulting from the presence of plasma are evaluated by the transmission line model. To estimate theoretically the characteristic response of identical systems in the time domain, the Fourier transformation method is evaluated. The reflection characteristics of time and frequency response in microwave systems have been calculated using an equivalent circuit model.

Keywords: microstrip lines, microwave, optical control, opto-electronics

1. Introduction

Research in the past has become increasingly focused on the applications of lightwave technology for the control, generation and measurement of microwaves [1-3]. At higher frequencies, either microstrip or dielectric waveguide structures have become more advantageous. Stripline configurations have taken on particular significance for the integration of electro-optic and microwave components [4-6].

Until now, there have been numerous literatures prepared concerning optically-controlled microwave circuits using microstrip lines or coplanar waveguides. Most of their analyses and experiments concentrated upon time domain characteristics for the purpose of high speed performance [6-7]. In this study, we analyze the reflection characteristics in the dielectric microstrip line optically induced plasma region. The frequency used in the microstrip transmission line in this paper is from 1 *GHz* to 128 *GHz*. The reflection characteristics are presented in the form of functions having frequency w and time t dependent variables.

We treat a microstrip line on a semiconductor substrate, one end of which is open-terminated and illuminated for optical injection of carriers. The microwave reflection characteristics of this line are theoretically investigated with respect to the illuminating light using an equivalent circuit model.

2. Dielectric Properties of Plasma

When a semiconductor material is illuminated with laser photon energy greater than the bandgap energy of the semiconductor, photons are absorbed, creating electron/hole pairs and resulting in a thin layer of plasma near the surface of the material. The presence of electron-hole plasma in the semiconductor produces modification of the conductive as well as the dielectric properties of the semiconductor material. The dielectric constant in the plasma-induced semiconductor material can be analyzed by the equation of motion of charge carriers in the semiconductor considering the classical electron-hole plasma theory as predicted by the Drude Lorentz equation [8]. One end of the strip is connected to an input/output port and the other end is open-terminated as shown in Fig. 1.

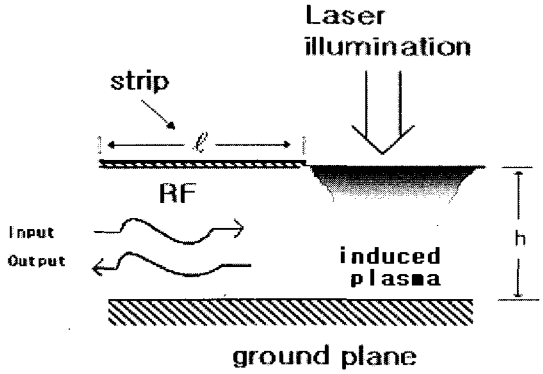


Fig. 1 The plasma induced microstrip line with an open-ended termination to be illuminated.

The laser illumination induces electron-hole pairs in the semiconductor near the open end of the strip. The density of the induced carrier is assumed to be exponentially

---

* Dept. of Electrical/Electronics, Information Engineering, Wonkwang University, Korea. (januskid@wonkwang. ac.kr, wallpass@wonkwang.ac.kr)

† Corresponding Author: Dept. of Electrical/Electronics, Information Engineering, Wonkwang University, Korea. (ykim@wonkwang.ac.kr)

Received May 28, 2004 ; Accepted June 27, 2004

distributed from the surface to the interior.

The plasma region ΔZ is assumed to have a uniform density of free carriers. The relative permittivity of plasma induced in a semiconductor is given by [7]

$$\begin{aligned}\varepsilon_p &= \varepsilon_s - \sum_{i=e,h} \frac{\omega_{pi}^2}{w^2+\gamma_i^2}(1+j\frac{\omega_i}{\omega}) \\ &= \varepsilon_{pr} - j\varepsilon_{pi} \qquad (1) \\ \omega_{pi}^2 &= \frac{N_p \times q^2}{\varepsilon_0 \times m^*} \qquad (i=e,h)\end{aligned}$$

where the subscripts *e* and *h* indicate the electron and hole and ε_s is the relative permittivity of materials. Also γ_i is collision frequency, w_{pi} is the plasma angular frequency, *q* is the electron charge, *m** is the effective mass, and N_p is the plasma density. The frequency and plasma dependence of the actual component of the dielectric constant of Eq. (1) is fairly weak, whereas the imaginary component of the dielectric constant shows a strong variation with frequency and density of plasma.

3. Optical Control of Reflection Characteristics

The optical controls of microwaves through discontinuities of microstrip lines have been actively studied, especially in the case of the reflection characteristics of waves in microstrip lines [6-7]. In most analyses of this type of device, with microwave switches having gaps of strips to be illuminated, only the conductance in the discontinuity of the line has been taken into consideration in the neglecting capacitance in *ON* state (large carrier density), while the conductance is neglected in *OFF* state (no carrier induced). Here we take both the capacitance and the conductance into account.

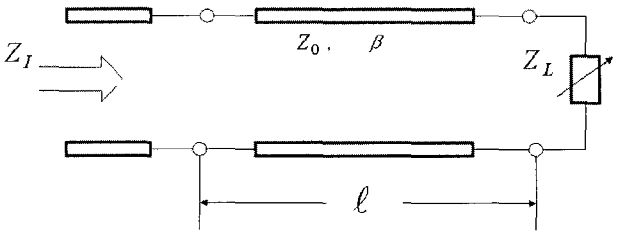


Fig. 2 Transmission line model of the microstrip line containing the equivalent terminal impedance. β is phase coefficient and *l* is the strip length.

We numerically evaluate the characteristics impedance and reflection characteristics of waves in this line with the transmission line model. The transmission line model of the microstrip line containing the equivalent terminal impedance is shown in Fig. 2.

The equivalent terminal impedance at the open end is represented as Z_L, and the transmission line model is expressed in Fig. 2 including Z_L and the characteristics impedance Z_o of the line [6]. The input impedance to a transmission line varies with the distance progressed along the line. The characteristics impedance Z_o is given generally

$$z_0 = \sqrt{\frac{R+jWL}{G+jWL}} \qquad (2)$$

where *R* is the resistive load and *G* is the load impedance at high radio frequencies. In most microstrip configurations, transmission loss is neglected due to the compactness of an entire circuit. The total attenuation of the line is insignificant due to the short line length. If the attenuation is primarily due to the dielectric loss, the dielectric constant ε becomes a complex quantity. Then, from Eq. (1),

$$\varepsilon_p = \varepsilon_0(\varepsilon_{pr} - \varepsilon_{pi}) \qquad (3)$$

we can derive the related equation with Maxwell's equation

$$\nabla \times \vec{H} = \vec{J} + jw\varepsilon\vec{E} = \vec{E}(\sigma + jw\varepsilon) = \vec{E}[jw(\varepsilon - j\frac{\sigma}{\omega})] \qquad (4)$$

$$\varepsilon_{eff} = \varepsilon(1+\frac{\sigma}{jw\varepsilon}) = \varepsilon_{pr} - \varepsilon_{pi}, \qquad \varepsilon_0\varepsilon_{pr} = \varepsilon \qquad (5)$$

$$\varepsilon_0\varepsilon_{pi} = \frac{\sigma}{\omega} \ \text{and} \ \sigma = \varepsilon_0\varepsilon_{pi}\omega \qquad [1/\Omega] \qquad (6)$$

The imaginary parts of the permittivity in Eq. (1), which are related to the conductivities, yield the conductance. The conductive is given by

$$\sigma = \sigma o(1+\omega^2\tau_e^2)^{-1} \ \text{where} \ \sigma o = Npq^2\tau_2/m^* \qquad [1/\Omega] \qquad (7)$$

where γ_i is the collision frequency and is related to the relaxation time of the carrier τ_i by $\gamma_i = 1/\tau_2$.

By the transmission line model (in Fig. 2), the input impedance Z_{IN} can be deduced from Z_L,, Z_o and other parameters;

$$Z_{IN} = \frac{z_0[R + j(z_0 \tan\beta l - \frac{1}{\omega C})]}{[(z_0 + \frac{\tan\beta l}{\omega C}) + jR]} \qquad (8)$$

where β is phase coefficient, C is capacitance per unit length [$C = \varepsilon(a/l)$], and assuming input termination reflects some of the energy originally sent down the line except for the completely matched condition. The reflection characteristics as well as amplitude in time and frequency are calculated by Z_l and the characteristic impedance of the transmission model. The reflection coefficient in the input termination is then given by

$$\rho_{in}(w) = \frac{z_{\text{in}}(w) - z_0(w)}{z_{in}(w) + z_0(w)} \tag{9}$$

Fig. 3 shows the reflection coefficients in 1 *GHz* and 128 *GHz* when the input signal has the unit impulse function. The microwave signal is input to the port and the reflected signal is calculated through a directional coupler connected to the same port. The input microwave is almost totally reflected in the dark state, and increasing the frequency reduces amplitude of the reflection. The reduction of the reflection amplitude is continually diminished from 16 *GHz*.

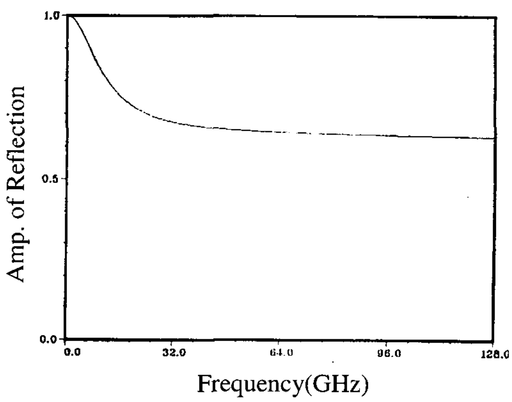


Fig. 3. Calculated reflection coefficient characteristics with $\varepsilon_s = 11.8$, $m_e^* = 0.259^*m_o$, $m_h^* = 0.380^*m_o$, $\gamma_e = 4.52^*10^{12}$, $\gamma_h = 7.71^*10^{12}$, and $N_p = 1.0^*10^{21}/m^3$.

Supposing that equivalent terminal impedance at the open end can be expressed as Z_L, the characteristics response of systems in the time domain can be evaluated by the Fourier transformation method. The Fourier transformation is defined as [9]

$$F(w) = \int_{-\infty}^{\infty} f(t)e^{-jwt}\,dt \tag{10}$$

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} f(w)e^{jwt}\,dw \tag{11}$$

These two relations couple the time and frequency dependent responses for liner microwave circuits.

Consider the pulse-modulated sinusoid when amplitude modulating carrier ω_o shifts angular frequency ω to ($\omega - \omega_o$),

$$F_0(w) = \int_{-\infty}^{\infty} \rho_{in}(t)e^{j(w0-w)t}\,dt = F_0(w - w_0) \tag{12}$$

the frequency dependence of the reflection coefficient evaluates the carrier frequency ω_0 and the plasma density. The characteristics response for the pulse modulated signal is given by

$$O(w) = \rho_{in}(w)e(w) \tag{13}$$

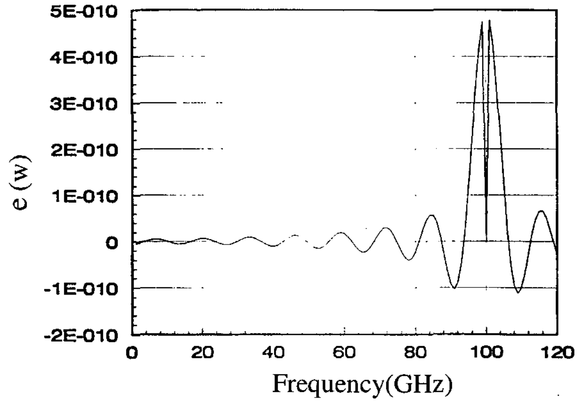


Fig. 4 Characteristics response in the frequency reflection coefficient.

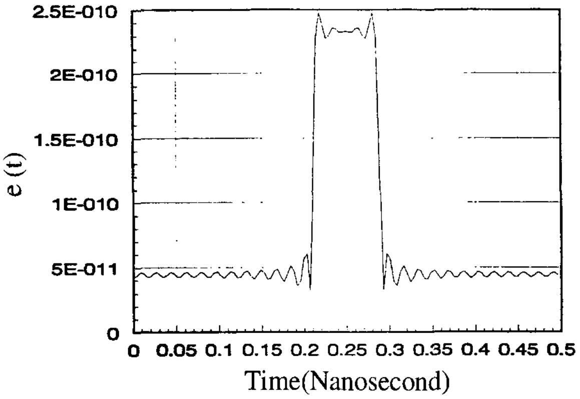


Fig. 5 Transient response in time domain of optically-controlled microwave pulse.

Fig. 4 depicts the characteristics response in frequency-domain when the input signal is the pulse modulated sinusoid signal. This result shows the maximum peak of frequency in $e(w)$ at about 16 *GHz*. Here, we used the input signal at 1 *GHz* and 128 *GHz* with variable carrier frequency ranging from 1*GHz* to 100 *GHz*. Fig. 5 indicates that the characteristics in time domain to the input signal are shifted to the angular frequency. Compared with the reflection characteristics of the unit impulse signal, the effect of the shifted sinusoid signal depicts the real and imaginary parts of the input termination reflected coefficient at the open end of the line. Fig. 6 indicates the evaluated amplitude and characteristics of the reflected microwave, showing the reflection characteristics when the input signal has shifted to sinusoid signal *vs.* frequency domain.

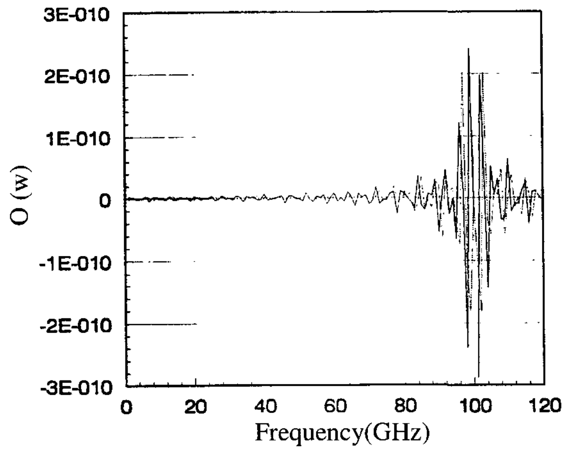


Fig. 6 Characteristics response to optically-controlled microwave pulse with shifted signal.

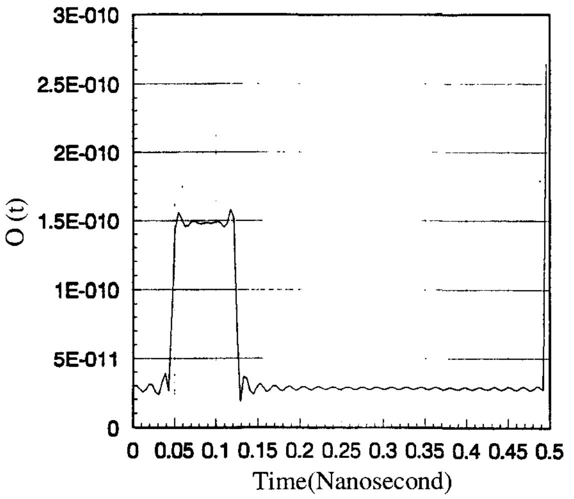


Fig. 7 Transient response in time domain of optically-controlled microwave pulse by shifted signal.

It represents the frequency characteristics with carrier density N_p at the open end of the line. The frequencies used in this paper are used from 1 *GHz* to 128*GHz* and the carrier frequency ω_o is used at 100 *GHz*. The central frequency of the pulse modulated signal in this Fig., $f_0(w)$, shifts about 16 *GHz* higher. Fig. 7 displays the characteristics of transiently responded signal in time pulse as a result of shift. In these theoretical calculations both the conductance and the capacitance have been considered using the equivalent model in open-ended terminated microstrips.

4. Conclusion

The reflection characteristics in a microstrip line with microwave pulse have been studied with respect to light illumination at the open end of the strip. We have emphasized the transient responses of optically-controlled time characteristics in the presence of the electron-hole plasma region. The reflection characteristics have been calculated for the frequency range from 1GHz to 128GHz. The maximum peak of frequency for sinusoidal input in the induced plasma region has occurred at 16GHz. The estimated values may possibly apply to the optically-tuned reflection type filter.

Acknowledgements

This work has been supported by KESRI (R-2003-B-274), which is funded by MOCIE (Ministry of Commerce, Industry and Energy).

References

[1] H. Matusiewicz, “A novel sample introduction system for microwave-induced plasma optical emission spectrometry”, *Spectrochimica Acta Part B* #57, pp. 485-494, 2002.

[2] H. Matusiewicz, “Design consideration and preliminary characterization of a microwave-induced plasma atomic emission spectrometry system”, *Chem. Anal*, #40, pp. 667-674, 1995.

[3] Ki Young Kim, Heung-Sil Tae, and Jeong-Hae Lee, “Application of Davidenko’s Method to Rigorous Analysis of Leaky Modes in Circular Dielectric Rod waveguides”, *KIEE International Transactions on Electrophysics and Applications*, vol. 3-C, #5, pp. 199-206, October 2004.

[4] Yong-tae Kim, et. al, “A Tight Coupling Microstrip Directional Coupler with High Directivity Performance using FE Calculations”, *KIEE International Transactions on Electrophysics and Applications*, vol. 11-C, #4, pp. 150-154, December 2001.

[5] Yong-Tae Kim, Jun-Seok Park, and Hyeong-Seok Kim, “Efficient Calculation of a Step Discontinuity for Shielded-Microstrip using Vector Finite Element and Mode Matching Method”, *KIEE International Transactions on Electrophysics and Applications*, vol. 2-C, #5, pp. 268-272, October 2002.

[6] Makoto, T and Arokiaswami, “Optical control of millimeter waves in the semiconductor waveguide”, *Trans. IEICE*, Vol. E76-C, #2, pp. 175-182, February 1993.

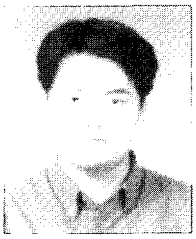
[7] Hitoshi S. and Makoto T., "Reflection characteristics of optically-controlled microwaves through open-ended microstrip lines", *Trans. IEICE*, Vol. E76-C, #2, pp. 301-304, February 1993.
[8] C. A. Balanis, *Advanced Engineering Electrimagnetics*, 2nd Edition, John Wiley & Sons, 1996.
[9] Alan Jeffrey, *Table of Integrals, Series, and Products*, 6th Edition, Academic Press 1995.

Jin-Su Kim

He received his B.S. degree in the Division of Computer and Information Engineering from Wonkwang University, Iksan, Korea in 2004. At present he is working as a M.S. student at Wonkwang University. His current research work is focused on Electronic Materials in the Information & Telecommunications field.
Tel : +82-63-850-6695

Yong K. Kim

He received his Ph.D. degree in Electrical Engineering at North Carolina State University. His research interests are Fiber Optics Sensing, Photorefractive Fiber and Crystal Devices.
Tel : +82-63-850-6695



Kyoung-Su Park

He received his B.S. degree in the Division of Computer and Information Engineering from Wonkwang University, Iksan, Korea in 2004. At present he is working as a M.S. student at Wonkwang University. His current research work is focused on Electronic Materials in the Information & Telecommunications field.
Tel: +82-63-850-6695