SCATTERING PARAMETERS OF INTERDIGITAL MICROSTRIP GAP UNDER LASER SPOT ILLUMINATION

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Abstract

This paper studies scattering characteristics of an optically controlled interdigital gap fabricated on the semiconductor microstrip line, and proposes the potential application of this gap to the microwave phase shifter with small variation in amplitude.

Experiments have been carried out by making interdigital gap on the silicon chip and using the semiconductor laser diode.

1. Introduction

When a semiconductor is illuminated with a laser which has a photon energy greater than its band gap, electron-hole pairs, called "plasma", are induced near the surface of the semiconductor, and cause a change of its complex permittivity[1]. As an application of this phenomenon, various kinds of optically controlled microwave devices have been proposed. But, the simultaneous change in micro-wave phase and amplitude during the laser illumination, prevents to give the quality for the practical use such as the phase shifter and the modulator.

This paper analyses the scattering characteristics of the laser-illuminated interdigital gap fabricated on the semiconductor microstrip line, and shows that this type of gap has superior characteristics over the commonly used single gap in respect of the effective extraction of phase shift of microwaves with keeping the small variation in its amplitude. For the theoretical analysis, the frequency-dependent finite-difference time-domain method ($(FD)^2TD$ method) is adopted.

Further, some experiments have been carried out to verify the theoretical predictions.

2. Theory

2.1 Model for analysis

Figure 1 shows the illustration of two types of microstrip gap, of which scattering parameters are controlled optically by using the photo-induced semiconductor plasma. Microstrip line with the width w=1.0mm and having zero thickness, is assumed to be

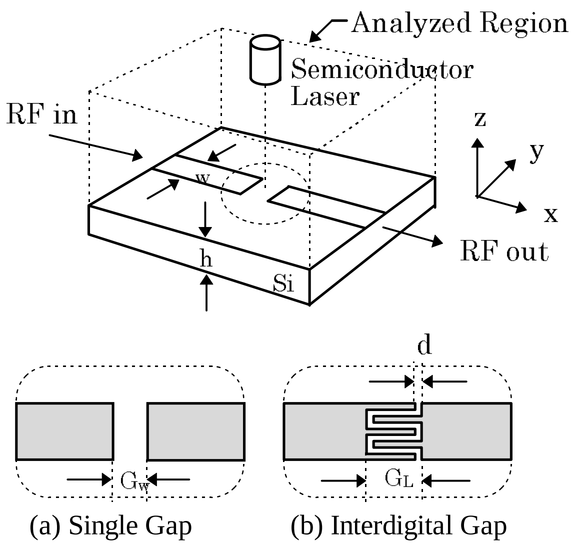

Fig.1 Illustration of the analyzed model.
(h=0.4mm,w=1.0mm, Single Gap: G_w=0.5mm, Interdigital Gap: G_L=1.0mm, d=0.1mm)

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made of a perfect conductor. The width of the single gap is G_W=0.5mm. Slit width and the coupling length of the interdigital gap are d=0.1mm and G_L=1.0mm, respectively. Silicon substrate with the thickness h=0.4mm and the relative permittivity ε_s=11.8 is adopted.

2.2 $(FD)^2TD$ method

The $(FD)^2TD$ method is capable to express the macroscopic transient electromagnetic interactions with three-dimensional geometry over a wide frequency range. In case of dispersive material like a semiconductor plasma, the constitutive equation expressed in the frequency domain is to be transformed into the time domain using the Fourier transformation theory.

Originally, the complex permittivity of plasma is written as [1] :

$$\varepsilon(\omega) = \varepsilon_0\{\varepsilon_s + \chi_e(\omega) + \chi_h(\omega)\} \tag{1}$$

$$\chi_i(\omega) = \frac{\omega_{pi}^2}{\omega(j\nu_i - \omega)} \qquad (i = e, h) \tag{2}$$

$$\omega_{pi}^2 = \frac{n_p e^2}{\varepsilon_0 m_i^*} \tag{3}$$

where, $\chi_i(\omega)$: electric susceptibility
ε_0: permittivity of free space
ε_s: relative permittivity for $\omega \to 0$
ω_{pi}: plasma frequency — e : electron charge
ω: microwave frequency — m_i^*:effective mass
ν_i: collision frequency — n_p: plasma density

The constitutive relation in the frequency domain is given as:

$$\begin{aligned}\mathbf{D}(\omega) &= \varepsilon(\omega)\mathbf{E}(\omega)\\ &= \varepsilon_0(\varepsilon_s + \chi_e(\omega) + \chi_h(\omega))\mathbf{E}(\omega)\end{aligned} \tag{4}$$

By the Fourier transformation of the equation (4), the time domain formulation can be derived as follows[2,3].

$$\mathbf{D}(t) = \varepsilon_s\varepsilon_0\mathbf{E}(t) + \varepsilon_0\int_0^t \mathbf{E}(t-\tau)(\chi_e(\tau) + \chi_h(\tau))d\tau \tag{5}$$

$$\chi_i(t) = \frac{\omega_{pi}^2}{\nu_i}(1 - e^{-\nu_i t})U(t) \tag{6}$$

where $U(t)$ denotes the unit step function. Here, we let $t = n\Delta t$, and the equation (5) can be quantized as

$$\mathbf{D}^n = \varepsilon_s\varepsilon_0\mathbf{E}^n + \varepsilon_0\sum_{m=0}^{n-1}\mathbf{E}^{n-m}\int_{m\Delta t}^{(m+1)\Delta t}(\chi_e(\tau) + \chi_h(\tau))d\tau \tag{7}$$

Introducing the equation (7) into the quantized expression of Maxwell's equations, all the field components can be formulated. For instance, the equation (8) is the quantized formulation of E_y.

$$E_y^{n+1}(i, j+\frac{1}{2}, k) = \frac{\varepsilon_s + \Delta\chi_{0e} + \Delta\chi_{0h}}{\varepsilon_0 + \chi_{0e} + \chi_{0h}} E_y^n(i, j+\frac{1}{2}, k) + \frac{1}{\varepsilon_s + \chi_{0e} + \chi_{0h}}\left\{\sum_{m=1}^{n-1} E_y^{n-m}(i, j+\frac{1}{2}, k)(\Delta\chi_{0e} + \Delta\chi_{0h})\right\}$$
$$+ \frac{\Delta t}{\varepsilon_s + \chi_{0e} + \chi_{0h}}\left\{\frac{H_z^{n+\frac{1}{2}}(i+\frac{1}{2}, j+\frac{1}{2}, k) - H_z^{n+\frac{1}{2}}(i-\frac{1}{2}, j+\frac{1}{2}, k)}{\Delta x} - \frac{H_x^{n+\frac{1}{2}}(i, j+\frac{1}{2}, k+\frac{1}{2}) - H_x^{n+\frac{1}{2}}(i, j+\frac{1}{2}, k-\frac{1}{2})}{\Delta z}\right\} \tag{8}$$

To realize the realistic distribution of the optically induced plasma in the substrate region, the plasma density is defined as[4]:

$$n_P(x, y, z) = n_P(x_0, y_0, z_0)e^{-\frac{4}{\phi^2}\{(x-x_0)^2 + (y-y_0)^2\}} e^{-\frac{1}{t_P}|z-z_0|} \tag{9}$$

where, ϕ : diameter of the laser spot,
t_P: thickness of plasma, and
$n_P(x_0, y_0, z_0)$:surface plasma density at the center of the laser spot.

The field components are arranged on Yee's mesh[5], consisting of 210, 80 and 40 spatial cells in x, y and z directions. The size of smallest cell are $\Delta x = \Delta y = 0.05\ mm$ and $\Delta z = 0.025mm$. The time step is $\Delta t = 6.75 \times 10^{-14}(s)$. Calculations are made for a normally incident plane wave with a time behavior given by the derivative of a Gaussian pulse. To eliminate unwanted reflections, Mur's absorbing boundary condition of the first order approximation is adopted[6].

2.3 Scattering Parameters of Microstrip Gaps

The amplitude $|S_{21}|$ and the phase shift $\Delta\theta$ of the transmission parameters are derived theoretically for both gaps when the laser spot with the diameter ϕ is focused onto these gaps. The numerical results are evaluated on the basis of ϕ =0.5mm and t_P=0.025mm at the microwave frequency of 10GHz.

Figure 2 shows the numerically estimated results of the single gap. It is apparent from this figure that both parameters, $|S_{21}|$ and $\Delta\theta$, increase simultaneously with the increase of plasma density n_P. These characteristics for single gap is not available as an amplitude modulator and a phase shifter applications. However, in the case of interdigital gap as shown in figure 3, the variation in $|S_{21}|$ is suppressed comparing with the single gap of figure 2. But interestingly, the only $\Delta\theta$ changes with the same trend during the illumination. For instance, the $\Delta\theta$ changes 48° but the $|S_{21}|$ varies almost within 1dB when the plasma density increases from 0 to 10^{22} /m^3. Especially, when the plasma density switches digitally from 0 to 10^{22} /m^3 the phase can be switched from 0 to 48° without any variation in $|S_{21}|$, because the $|S_{21}|$ keeps the same constant value of -3.0dB at n_p=0 and $n_p=10^{22}$/m^3. These results indicate that the interdigital gap has a great potential to an application of an optically controlled phase shifter and modulator.

3. Experiment

3.1 Experimental Setup

Experiments have been carried out at the frequency range up to 3GHz using an experimental setup as shown in figure 4. A microstrip line has been fabricated on a 10mm×10mm×0.4mm silicon chip with high resistivity of about 5000Ω·cm. This silicon chip was fixed on the glass epoxy substrate with the thickness of h=1.6mm. The interdigital microstrip gap with the coupling length of G_L=5.0mm and the slit width of d=0.3mm was made by etching a 3mm width copper tape. The silicon surface around the gap was illuminated by a semiconductor laser with wavelength of 830nm and the optical power of 40mW. The vector network analyzer HP8714B was used to measure the $|S_{21}|$ and the $\Delta\theta$.

3.2 Experimental Results

Figure 5 shows the frequency response of the $|S_{21}|$ and the $\Delta\theta$. The drive current of the laser diode is I_d=100mA (≈40mW optical power) for the case of illumination. When the microwave frequency is 1350MHz, the $|S_{21}|$ remains the same value with and without illuminations. But the only $\Delta\theta$ increases up to 21.8° during illumination.

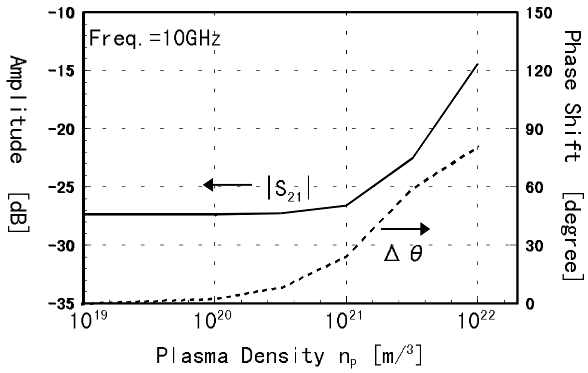

Fig.2 Calculated transmission parameters of the single microstrip gap versus the plasma density n_P.

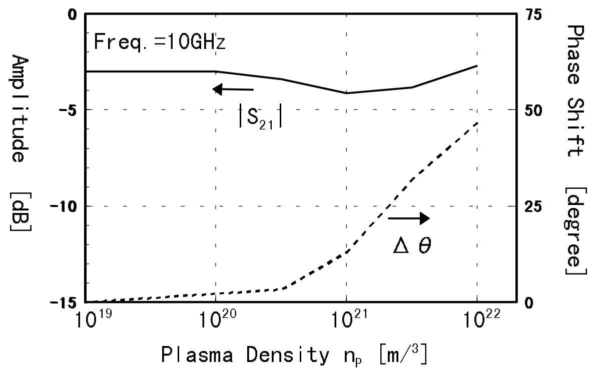

Fig.3 Calculated transmission parameters of the interdigital microstrip gap versus the plasma density n_P.

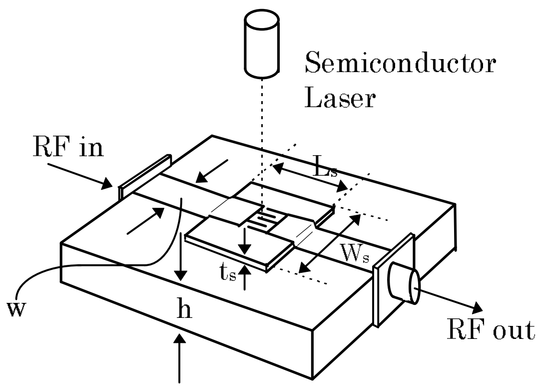

Fig.4 Experimental Setup.
(h=1.6mm, w=3.0mm, G_L=5.0mm, d=0.3mm, Silicon: $L_s=W_s$=10.0mm, t_s=0.4mm, ε_s=11.8, Semiconductor Laser: 830nm, 40mW)

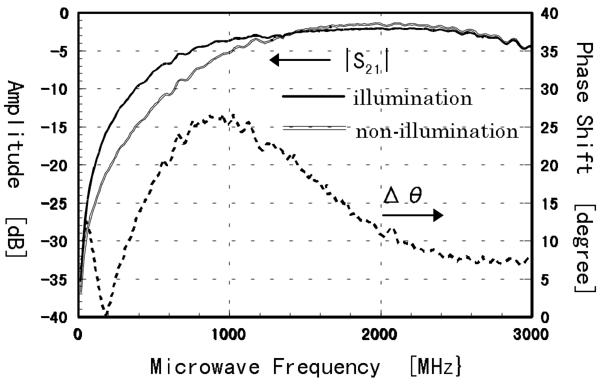

Fig.5 Measured frequency characteristics of the transmission parameters on the interdigital microstrip gap.

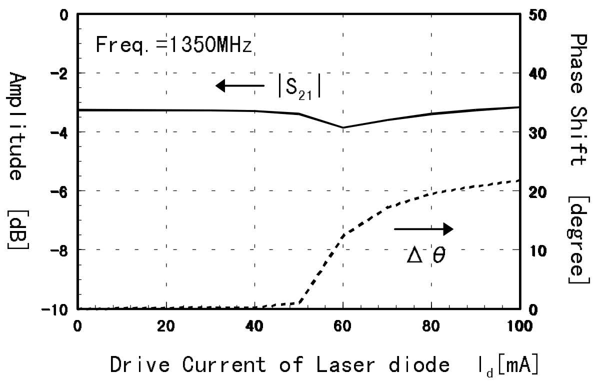

Fig.6 Measured transmission parameters of the interdigital microstrip gap versus the drive current of semiconductor laser diode I_d.

To study these results in detail, figure 6 presents the relationship between the drive current of the laser diode I_d and the transmission parameters of the $|S_{21}|$ and the $\Delta\theta$. The variation in $|S_{21}|$ is suppressed within 1.2dB under laser illumination, while the $\Delta\theta$ increases monotonously to 21.8°. Due to the insufficient setup in structural parameters and its fabrication, the observed phase shift $\Delta\theta$ is unexpectedly small. But, as the drive current is directly proportional to the plasma density, these results are phenomenologically agreed with theoretical ones as discussed in figure 3.

4. Conclusion

We have demonstrated the scattering characteristics of a microstrip line containing an optically controlled interdigital gap, both theoretically and experimentally. As a result, it became clear that this type of gap is effective enough to extract the microwave phase shift $\Delta\theta$ with small variation in amplitude $|S_{21}|$. Therefore, the interdigital gap structure, proposed here, is considered to be useful for applications to an optically controlled phase shifter and modulator.

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