AN OPTICALLY CONTROLLED MODULATOR USING A METAL STRIP GRATING ON A SILICON PLATE FOR MILLIMETER AND SUBMILLIMETER WAVELENGTHS

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ABSTRACT

An optically controlled modulator using a metal strip grating on a silicon plate with an external electric field applied between the strips, has been developed as a quasi-optical high-speed modulator for millimeter and submillimeter wavelengths. The experimental results obtained at 52 GHz to 60 GHz show that the maximum modulation frequency in the inductive metal strip modulator can be increased from 4 kHz to 37 kHz by applying only 13 volts (E ~ 150 V/cm) to the strips. A higher modulation frequenc is available for the metal strip modulator with a higher external electric field.

INTRODUCTION

Optical control of propagating waves in semiconductors is a potential method to modulate or switch millimeter and submillimeter waves, particularly in quasi-optical systems [1]. A low doped mono-crystal silicon (resistivity ~10 kΩ·cm) has been often used as the modulator because of its lower static insertion loss and a lower photon-energy (≥1.12 eV) to excite free carriers in it [2]. The high-resistivity silicon, however, has a lifetime of the free carriers of longer than several microseconds. This slow relaxation limits a modulation frequency to about 10 kHz or less [3]. In order to solve this problem, a modulator with metal strips has been proposed as a quasi-optical modulator for millimeter and submillimeter wavelengths.

Figure 1 is the conceptual drawing of the metal strip modulator. A laser light in optical waveguides on a silicon plate excites free carries at gaps between the metal strips and changes an effective refractive index n of the plate. Since a transmission property of the strip grating strongly depends on n [4], the transmittance and reflectance of the modulator are largely changed with light illumination. An external electric field between the strips will quickly sweep out the free carriers from the silicon plate, consequently increases the speed of modulation. In principle, a modulation frequency of several GHz is available for the metal strip modulator even though a high-resistivity silicon plate is used, because the maximum modulation frequency is limited not by a low inherent relaxation rate of free carriers in the silicon, but by a higher ratio of the saturation velocity of the carriers to the gap width. In this paper, the theoretical and experimental results obtained at the millimeter wavelengths are reported to show the feasibility of the metal strip modulator.

EQUIVALENT CIRCUIT

Modulation degrees of transmittance and reflectance in the metal strip (MS) modulator with a laser illumination have been estimated by using a simple transmission line model at the frequencies ranging from 40 GHz to 60 GHz. Figure 2 shows the equivalent circuit of the MS-modulator used for the calculation. The equivalent circuit includes a

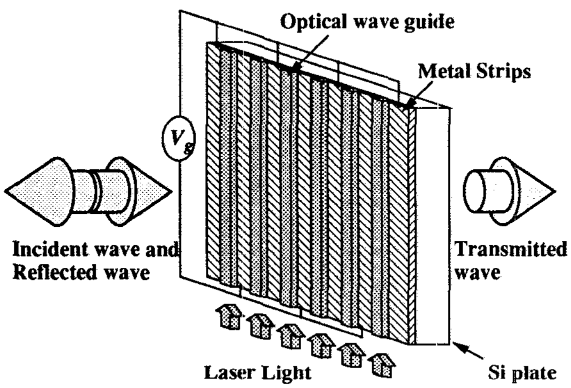

Fig. 1 Configuration of the MS-modulator.

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tuning silicon plate placed in parallel to the MS-modulator (refer to Fig. 3). In the MS-modulator, a uniform plasma layer with a depth d_p has been assumed to simplify the calculation. The complex refractive index n_p has been determined by Drude theory [2] as a function of a free carrier density N_c.

In Fig. 2, the impedance Z_m of the metal strip grating has been determined using the method of moments developed by Chiao [5]. $R(N_c)$ is given by $s/\sigma(N_c)d_p g$, where $\sigma(N_c) = e\mu N_c$ is the conductivity in the plasma layer, e is the electron charge, μ is the mobility of free carriers in silicon, and s and g are the pitch and the gap width of the metal strips, respectively. In the same figure, Z_o is the impedance of free space, and n_{Si} is the refractive index of the silicon plates with a thickness of 1 mm.

EXPERIMENTAL SETUP

Figure 3 shows the experimental setup of a MS-modulator with a tuning silicon plate. The power transmittances $|S_{21}|^2$ of the MS-modulator have been measured through a transmitting and a receiving horns connected to a Gunn diode oscillator and an HP-8562B spectrum analyzer, respectively. The frequency range is from 52 GHz to 60 GHz. Time responses of the modulator with a pulsed laser illumination have been measured using a Schottky-barrier diode (SBD) detector and an oscilloscope. The laser has a wavelength of 880 nm, a pulse energy of 2 μJ, a pulse width of 100 nsec, and a repetition rate of 1 kHz. This laser generates a thin plasma layer with a depth less than 30 μm at the surface of the silicon plate [6].

The MS-modulator has a metal strip grating fabricated on a silicon plate by evaporating aluminum. The strip grating has a dimensions of g = 1.7 mm and s = 0.87 mm. The silicon plate is 1 mm in thickness, and has a measured refractive index of 3.42 ± 0.05 at 50 GHz band and a resistivity of about 7 kΩ·cm. The metal strip voltage V_g was changed from zero to 15 V in DC. The laser beam has covered the entire grating surface. The tuning silicon plate is used to maximize the transmittance of the MS-modulator by adjusting a spacing between the plates.

In the experiments, both the strip configurations of inductive strips and capacitive strips were used and also a silicon plate without strips was tested for comparison.

MODULATION DEGREES

Figure 4 shows measured transmittances of three kinds of the modulators, the inductive metal strip (IMS)-, capacitive metal strip (CMS)-, and silicon (Si)-modulators, as a function of frequency from 52 GHz to 60 GHz. In this experiment, the tuning plate and laser illumination were not used. The theoretically calculated transmittances have been

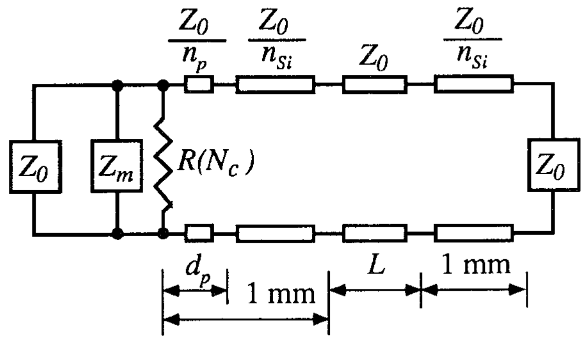

Fig. 2 Equivalent circuit of the MS-modulator with a tuning silicon plate.

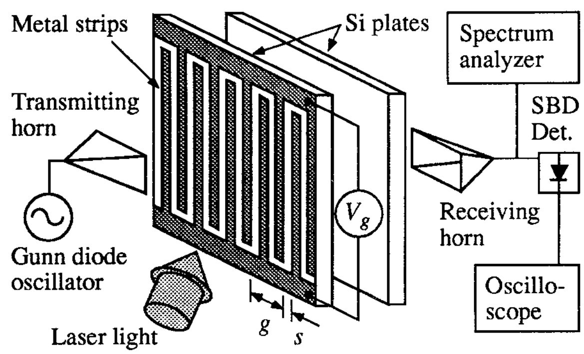

Fig. 3 Experimental setup.

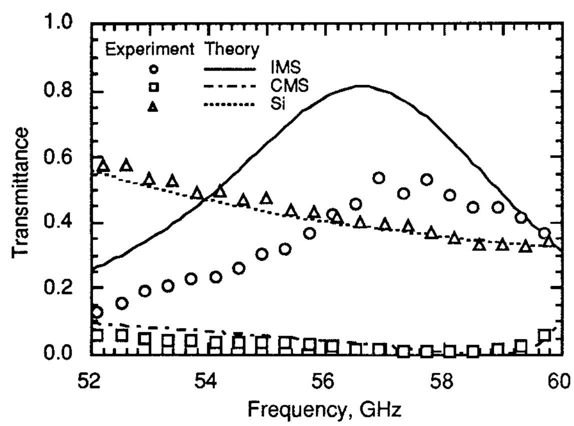

Fig. 4 Comparison of transmittances of the IMS-, CMS-, and Si-modulators without the tuning plate as a function of frequency.

indicated also in Fig. 4. From Fig. 4, it is seen that the IMS- and CMS- modulators have a peak and a dip in their transmission curves at around 57 GHz. Those are caused by a resonant effect [7]. The theory has well predicted the resonant effect in the MS-modulators, however, the measured transmittance of the IMS-modulator is 30 % smaller than the theoretical one at the peak value. This discrepancy between the theoretical and the experimental results could be caused by a larger rf loss in the inductive metal strips which has not been taken into account in the theoretical calculation.

A typical time-response in the IMS-modulator with a pulsed laser illumination for $V_g = 0$ V at 57 GHz is shown in Fig. 5. The dip in the curve indicates that the transmittance of the modulator has decreased by 6 %. From Fig. 5, a recovery time t_r of the IMS-modulator has been estimated to be 114 μsec. This long recovery time results from slow relaxation of the free carriers in the high-resistivity silicon.

Figure 6 compares the maximum modulation degrees M for the IMS-, CMS-, and Si-modulators at $V_g = 0$ V at the frequencies between 52 GHz and 60 GHz. The maximum modulation degree M is defined as a ratio of the maximum change of transmission power to the transmission power. Theoretical results calculated by using the equivalent circuit have been indicated also in Fig. 6. In the calculations, the parameters, $N_c = 7.4\text{x}10^{13}/\text{cm}^3$ and $d_p = 30$ μm, have been used. This carrier density would theoretically be produced by a laser pulse energy of 1.4 μJ which agrees with an experimental value of 2 μJ.

In the experimental results shown in Fig. 6, the modulation degree M of the Si-modulator is about 2 % and is almost constant in the measured frequency region. In contrast to the Si-modulator, due to the resonant effect, the IMS- and CMS-modulators have a peak (6.8 %) and a dip (almost zero) at 58 GHz. This fact shows that the resonant effect in the IMS-modulator has increased the modulation degree by three times or more compared to the Si-modulator. The theory has well predicted these effects in the experiments.

TIME RESPONSES

Figure 7 shows the measured time-responses of the IMS-modulator for different metal voltages V_g of 0, 1.7, 4.3, and 13 V at 57 GHz. When V_g increases from zero to 13 V, the recovery time t_r decreases from 114 μsec to 12 μsec. Those experimental results show that the maximum modulation frequency (=0.44/t_r) of the IMS-modulator can be increased from 4 kHz to 37 kHz by applying V_g of only 13 V to the metal strips. Similar experimental results have been obtained for the CMS-modulator.

Figure 8 shows the measured maximum modulation degrees M and the recovery times t_r for the IMS-modulators with and without the tuning silicon plate as a function of V_g at 57 GHz. In Fig. 8, M and t_r have been normalized to the measured ones at $V_g = 0$ V which are (6 %, 114 μsec) and (3%, 37 μsec) for the modulators with and without the tuning plate, respectively. As V_g increases, the recovery times

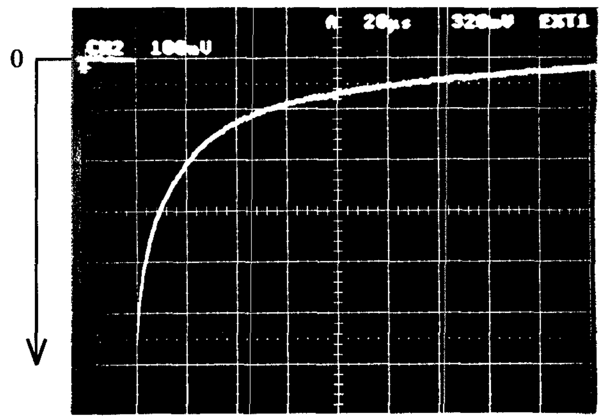

Fig. 5 Oscilloscope trace of the ac-component of the transmission signal for the IMS-modulator, measured for $V_g = 0$ V at 57 GHz.

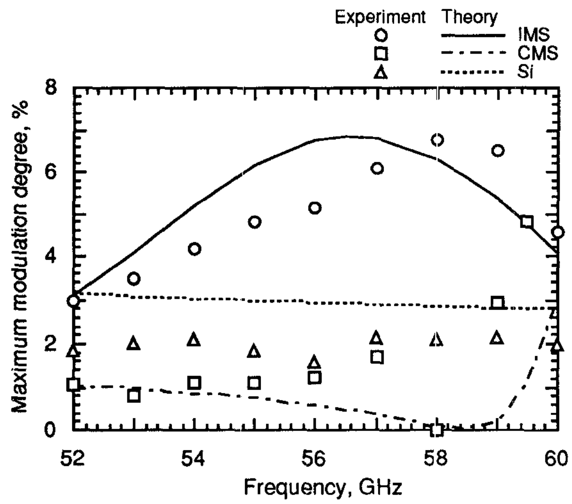

Fig. 6 Comparison of the maximum modulation degrees of the IMS-, CMS-, and Si-modulators as a function of frequency.

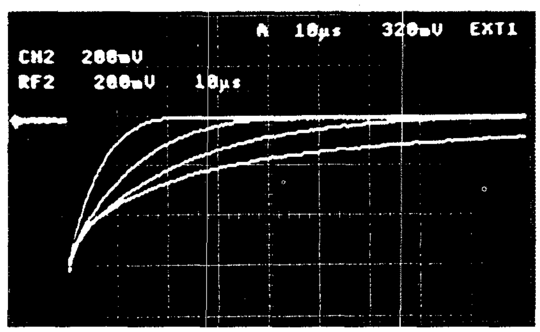

Fig. 7 Oscilloscope traces of the ac-components of the transmission signals for the IMS-modulator measured for different metal strip voltages V_g of 0, 1.7, 4.3, and 13 V at 57 GHz. The lowest trace is for $V_g = 0$ V.

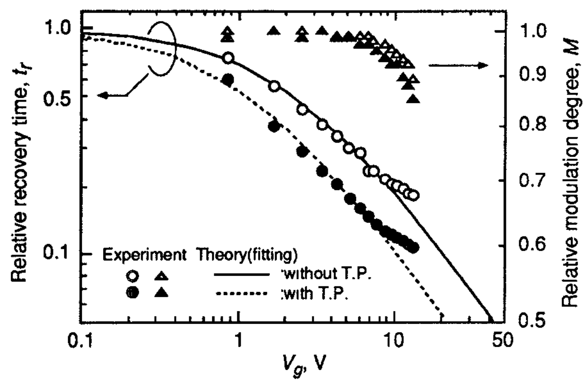

Fig. 8 Measured normalized maximum modulation degrees M and recovery times t_r for IMS-modulators with and without the tuning silicon plate as a function of the metal strip voltage V_g at 57 GHz. The solid and dashed curves are the theoretical fits to the measured recovery times. T.P. means the tuning plate.

of both the modulators quickly decrease and are less than a half of the initial values at V_g of only 2 V. In contrast to the recovery time, the modulation degrees are almost unity at V_g up to 10 V, and at further V_g start to decrease.

In Fig. 8, the solid and dashed curves are the theoretical fits to the measured recovery times, assuming $t_r = (1/t_0+V_g/\xi)^{-1}$, where t_0 is the recovery time measured at $V_g = 0$ and ξ is a fitting constant to the experimental results. The good agreements between the theoretical and experimental results indicate that our assumption on the relationship between t_r and V_g is valid. For V_g greater than 9 V, the measured recovery times for both the modulators deviate from the theoretical ones. These deviations may be caused by decrease of the carrier mobility in silicon due to a higher electric field at the gaps.

To support the above discussions, we have assumed that an effective relaxation rate γ_e of the carriers in the IMS-modulator is expressed by $\gamma_e = \gamma_i + \mu V_g/s^2$, where γ_i is the initial relaxation rate, μ is the carrier mobility, and s is the gap width. Using the following values: $\gamma_i = 10^5$/sec, μ = 0.21 m^2/V·sec, s = 0.87 mm, γ_e is estimated to be 2.8×10^6/sec at $V_g = 10$ V. This value of γ_e is comparable to a carrier generation rate [1] during the 100 nsec laser pulse in our experimental conditions. This higher γ_e could be a reason why the modulation degrees decrease at V_g greater than 10 V.

In the experiments, the maximum voltage of V_g was limited to about 13 V due to a small DC resistance of about 65 Ω in the metal strip gaps. A larger V_g where the free carriers have a saturation velocity (~ 10^5 m/sec) in silicon could be available for a MS-modulator with a Schottky-barrier structure between meal strips and a silicon plate.

CONCLUSION

The metal strip grating on a silicon plate has been fabricated and tested as an optically controlled quasi-optical modulator for millimeter and submillimeter wavelengths. Two specific features of the metal strip modulator have been demonstrated in the millimeter wave frequency region. One of them is a higher modulation efficiency and the other is an externally controllable time-response speed of modulation. The experimental results show that the time-response speed of the metal strip modulator can be increased more than 500 % by applying only 13 V to the metal strips. Those results show that the metal strip modulator is a potential high-speed modulator at millimeter and submillimeter wavelengths.

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