Paper

Microstrip Filters with a Loaded Capacitance Containing a Light-Induced Plasma Region

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In this paper, we propose microstrip filters with a loaded capacitance of which frequency band can be changed by light-induced plasma in a silicon chip buried in part of a substrate. We analyze the frequency characteristics of the filters by using the $(FD)^2TD$ method.

Keywords: microstrip filter, loaded capacitance, plasma region, $(FD)^2TD$ method

1. Introduction

High-resistivity semiconductors have been expected to be used as substrate materials for microwave integrated circuits [(1)~(4)]. The light-illumination of which photon energy is larger than the bandgap energy of the semiconductor induces electron-hole plasma in a light-illuminated area. The small region filled with photo-excited electron-hole plasma, as distinct from the surrounding region, has a complex permittivity and hence modulates microwaves propagating through the area [(5)~(7)]. This property has been widely examined for the control of milli-meter-wave propagation along semiconductor waveguides with application to antennas, high-speed switches, phase shifters, modulators, and filters. We have proposed and studied microstrip filters of which resonator has light-induced plasma regions on its both ends [(8)]. However, this filter has a shortcoming that the insertion loss increases by light-illumination. In this study, we propose a new type of microstrip filters with a loaded capacitance containing a light-induced plasma region and investigate their filtering characteristics by using the $(FD)^2TD$ (Frequency Dependent Finite Difference Time Domain) method [(9)]. The proposed filter has a benefit that the deterioration of the insertion loss by light-illumination can be suppressed by setting the plasma region apart from the area where electromagnetic fields concentrate.

The FDTD (Finite Difference Time Domain) method was first proposed by K.S.Yee and has been applied by many investigators to the solution of various electromagnetic problems. In using this method, Maxwell's equations are discretized both in time and space. The FDTD method shows great promise in its flexibility in handling a wide variety of circuit configurations [(10)~(14)]. Broad-band pulses, if used as the initial condition for excitation, enable us to calculate the frequency-domain parameters over the entire frequency range of interest.

2. Analysis

The configuration of the microstrip filter with a loaded capacitance containing a light-induced plasma region is shown in Fig.1. The main part of the filter is printed on the bottom dielectric layer, on which the top dielectric layer is laminated. A thin rectangle of silicon chip, $L = 1.0$mm long and $W = 1.2$mm wide, buried into the top dielectric layer bridges two electrodes one of which is grounded as shown in Fig.1. Light beam illuminates the chip on the region with $1.0 \times 1.2\text{mm}^2$, inducing photo-excited plasma. Here, the thickness of the plasma t_p is assumed to be 0.2mm. In this analysis, the equipment of light beam emission is not taken into consideration for convenience of analysis. Light-illumination can change the filter characteristics because the loaded capacitance is varied through the light-induced plasma region. The parameters of the structure used in numerical calculations are as follows:
width of the microstrip conductor: 1.2mm,
thickness of the first substrate layer: 1.2mm,
thickness of the second dielectric layer: 0.3mm,
dielectric constant of the substrate: $\varepsilon_r = 4.4$,
length of the microstrip conductors: 12.0mm,
space between microstrip conductors: 0.8mm.

The relative complex permittivity of the semiconductor is given by

$$\varepsilon_r = \varepsilon_s - \sum_{i=e,h} \left[\frac{\omega_{pi}^2}{\omega^2+\nu_i^2} + j\frac{\nu_i}{\omega}\frac{\omega_{pi}^2}{\omega^2+\nu_i^2} \right] \cdots\cdots (1)$$

$$\omega_{pi} = \left[\frac{ne^2}{\varepsilon_0 m_i^*} \right]^{\frac{1}{2}} \quad (i = e, h) \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

where ω is the angular frequency of the electromagnetic fields, $e(= 1.60 \times 10^{-19}\text{C})$ the elementary charge,

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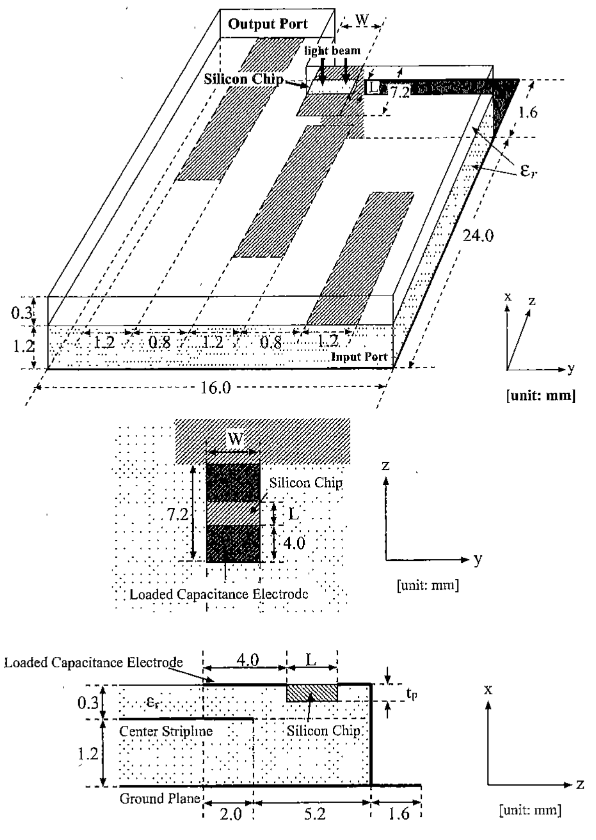


Fig. 1. Microstrip filters with a loaded capacitance containing a light-induced plasma region.

$\varepsilon_s(= 11.8)$ the permittivity of the semiconductor without plasma, $m_e(= 0.259m_0)$ the effective mass of an electron, $m_h(= 0.38m_0)$ the effective mass of a hole, $m_0(= 9.11 \times 10^{-31}\text{kg})$ the rest mass of an electron, $\nu_e(= 4.53 \times 10^{12}\text{s}^{-1})$ the collision angular frequency for electrons, $\nu_h(= 7.31 \times 10^{12}\text{s}^{-1})$ the collision angular frequency for holes and n the plasma density. We set the plasma density as $n = 1.0 \times 10^{22}/\text{m}^3$ that has been estimated from experiments [1] [4] [5] and is used commonly in numerical simulations.

In the analysis, we set up uniform grids with a difference $\Delta = 0.100$mm in space, and the time step $\Delta t = 2.22 \times 10^{-13}$sec. Three dimensions of the whole structure are $40\Delta \times 160\Delta \times 256\Delta$. We excite the input port at $z = 12\Delta$ with a Gaussian pulse in time. It is uniform on the transverse plane under the microstrip conductor and E_x is the only nonvanishing component of electric fields, expressed as

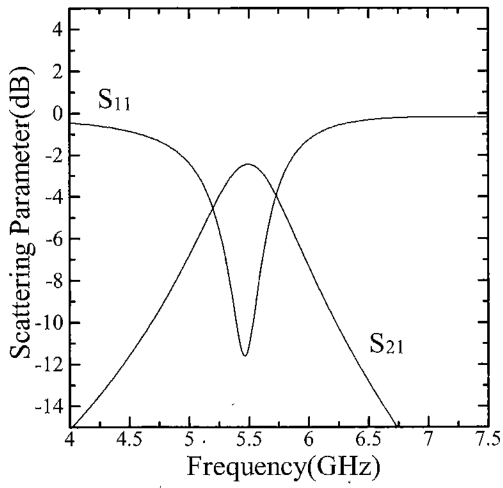
$$E_x(t) = -\frac{2(t-t_0)}{T^2} exp\left\{-\frac{(t-t_0)^2}{T^2}\right\} \quad \cdots\cdots \quad (3)$$

where $t_0 = 200\Delta t$ and $T = 60\Delta t$.

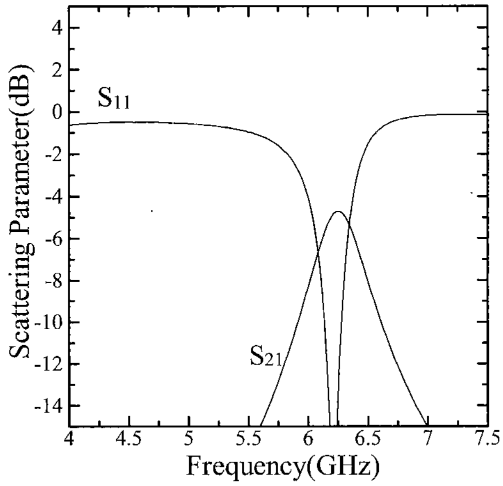
Scattering parameters S_{11} and S_{21} are given by

$$S_{11}(f) = \frac{V_{ref}(f, z_1) - V_{inc}(f, z_1)}{V_{inc}(f, z_1)} \quad \cdots\cdots\cdots\cdots \quad (4)$$

and



(a)$nt_p = 0.0/\text{cm}^2$



(b)$nt_p = 2.0 \times 10^{14}/\text{cm}^2$

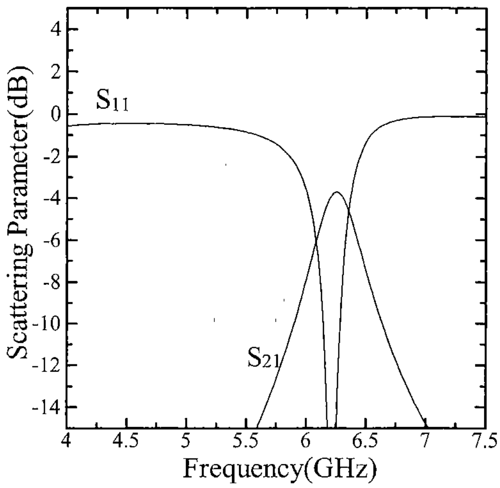
Fig. 2. Frequency characteristics of scattering parameters($L = 1.0$mm).

$$S_{21}(f) = \frac{V_{trs}(f, z_2)}{V_{inc}(f, z_1)}, \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (5)$$

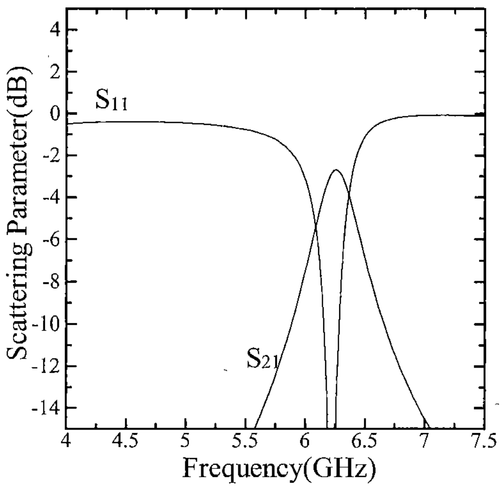
respectively, where V_{ref} is the Fourier transform of the voltage of reflected waves at an observation point in the input port,V_{inc} the Fourier transform of the voltage of incident waves at the same position,and V_{trs} the Fourier transform of the voltage of transmitted waves at an observation point in the output port.

Figure 2 shows the frequency characteristics of the scattering parameters when $nt_p = 0.0/\text{cm}^2$ in (a) and $2.0 \times 10^{14}/\text{cm}^2$ in (b), where the length L of a silicon chip is 1.0mm. This result indicates that the center frequency of pass band is shifted from 5.49GHz to 6.25GHz by light-illumination. On the other hand, the insertion loss increases from 2.45dB to 4.70dB when illuminated by light.

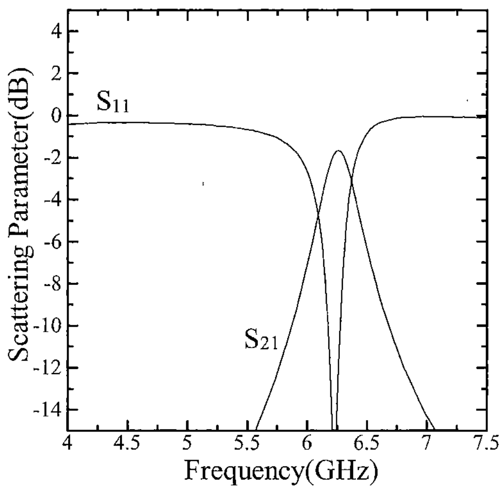
Next, we change the length L of a silicon chip in order to suppress insertion losses. Figure 3 shows the frequency characteristics of the scattering parameters when $L = 0.8$mm in (a) and 0.6mm in (b) and 0.4mm in (c), where $nt_p = 2.0 \times 10^{14}/\text{cm}^2$. It is found that the



(a)$L = 0.8$mm



(b)$L = 0.6$mm



(c)$L = 0.4$mm

Fig. 3. Frequency characteristics of scattering parameters($nt_p = 2.0 \times 10^{14}/\text{cm}^2$).

center frequency of pass band is about 6.25GHz in any cases, while the insertion loss changes from 3.70dB($L = 0.8$mm) to 1.69dB($L = 0.4$mm). These results indicate that we can suppress the insertion loss largely, without reducing the frequency shift, by reducing the length L of a silicon chip. This is because the material loss can be reduced by decreasing the Length L while the total length of the loaded capacitance does not change regardless of L. It is also expected that the switching speed can be improved as the electrode gap L becomes narrower.

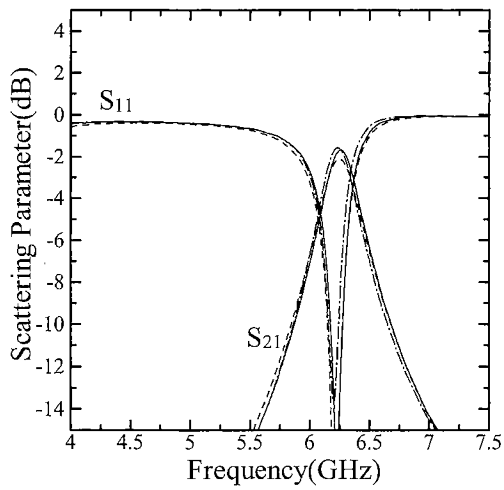


Fig. 4. Frequency characteristics of scattering parameters($nt_p = 2.0 \times 10^{14}/\text{cm}^2$, $L = 0.4$mm).

Finally, we consider to suppress insertion losses of the microstrip filter shown in Fig.1 when light is illuminated. Fig.4. shows the frequency characteristics of the scattering parameters, when $nt_p = 2.0 \times 10^{14}/\text{cm}^2$ and $L = 0.4$mm, with the width W of the electrodes and the silicon chip as a parameter: $W = 0.8$mm for the dashed line, 1.2mm for the solid line and 1.6mm for the dash-dotted line. It is found that the insertion loss is reduced monotonously as the loaded capacitance electrode broadens and lowest when $W = 1.6$mm. The narrowing electrode of loaded capacitance enhances the edge effect more and more. This, in turn, increases dissipative losses in the induced plasma region. Hence, we have a higher Q factor, as shown in Fig.4, for a narrow electrode of loaded capacitance. It seems possible to suppress the insertion losses by optimizing other parameters of the structure, such as the interval between microstrip lines, the length of electrodes, and so on.

3. Conclusion

In this paper,we have proposed a new type of microstrip filters with a loaded capacitance containing a light-induced plasma region and investigate its filter characteristics through $(\text{FD})^2$TD simulations. It has been shown that the pass band of frequencies can be controlled by light-illumination and that the insertion loss is reduced by narrowing the gap buried with the silicon chip. The present filter configuration is also expected to have, the advantage that the switching speed can be improved as the silicon chip bridging the loaded capacitance electrodes becomes narrower.

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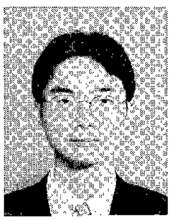

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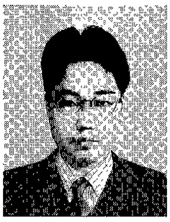

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