STUDY OF OPTICALLY CONTROLLED MICROWAVE DEVICES

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ABSTRACT

By photo-excitation the complex dielectric constant of a semi conducting material can be modified to alter the propagation characteristics of the microwave signals. In this paper a theoretical as well as experimental study of optically controlled microwave phase shifters, attenuators, and antennas has been presented. It is shown that a 10dB variable attenuator at L band, and a variable phase shifter can be realized with as low an optical power as 50mW. Theoretical investigations of the photo-induced semiconductor antennas show that the radiation pattern of the antenna can be significantly modified by controlling the photo-illumination pattern, and a radiation efficiency of more than 50% can be achieved at millimeter wavelengths with moderate optical power.

INTRODUCTION

Optical control of microwave devices has been a subject of growing interest over last two decades [1, 2]. This is due to the rapid progress in the high power laser and photonic technology. The optical control of microwave devices has many advantages like, dynamic control, perfect isolation between the controlling and the controlled devices, fast response, immunity to EMI, monolithic integration etc. The basic phenomenon behind the operation of these devices is the photo-excitation. The photo-carriers modulate the complex dielectric constant of a semi-conducting material changing the propagation characteristics of the microwave signals. At low microwave frequencies the photo-carriers essentially modify the conductance of the material keeping the dielectric constant of the medium practically unaltered. However, at millimeter wavelengths, both the real and imaginary part of the dielectric constant get modified due to photo-excitation. It is then possible to develop optically controlled microwave components like the phase shifter, attenuators, slow wave structures etc using photo-excitation. In this paper we present a study of optically controlled phase shifters and attenuators in microstrip geometry at low microwave frequencies. Further we propose and investigate a novel device, the photo-induced semi-conductor antenna. This antenna shows a good promise for dynamic control of the radiation pattern at millimeter wavelengths.

THEORY

Let us consider the photo-excitation of a microstrip gap on a grounded semiconductor substrate. The gap is illuminated with an optical beam having photon energy greater than the band gap of the semiconductor. In general the dielectric constant of the photo-excited region is given as [2]

$$\varepsilon_r = \varepsilon_s - \frac{\omega_p^2}{\omega^2 + \gamma_c^2} - j\frac{\gamma_c}{\omega}\left(\frac{\omega_p^2}{\omega^2 + \gamma_c^2}\right) \tag{1}$$

Where $\omega_p = \sqrt{Nq^2/\varepsilon_0 m^*}$ is the plasma frequency of the photo-excited region, N is the photo-carrier density, q is the electronic charge, γ_c is the collision frequency, m^* is the effective carrier mass, ε_s is the dielectric constant of the intrinsic semiconducting material, and ω is the microwave frequency. For low microwave frequencies and low photo-excitation, $\omega \ll \gamma_c$, $\omega_p \ll \gamma_c$, and therefore the real part of the dielectric constant is almost ε_s. The imaginary part however plays a role and the photo-induced region behaves more like a variable conductance.

Let the microstrip gap be illuminated with a light beam of intensity I_{inc}. The intrinsic photo-carrier density has an exponential profile as a function of depth due to decay of the optical beam. However, the actual profile of the photo-carrier density is rather complicated due to diffusion of the carriers. Generally, the diffusion length is larger then the optical absorption length and the density profile is diffusion limited. The photo-excited region in the microstrip gap can be modeled as an effective resistance. Using resistance equivalence the effective resistance of the microstrip gap can be obtained as

$$R = \frac{L_g}{\sigma_{eff} W_g d_{eff}} \tag{2}$$

Where, the effective conductivity of the medium is given as

$$\sigma_{eff} = \sigma_{\max} \frac{L_g}{4L_a} (1 - e^{-L_g / L_a})^{1/2} \left[1 - \frac{L_a}{W_g} (1 - e^{-W_g / L_a}) \right] \tag{3}$$

$\sigma_{\max}$ is the maximum conductivity at the center of the gap and is a complicated function of the carrier diffusion length, L_a, the carrier life time, quantum efficiency, surface recombination velocity, optical absorption coefficient, carrier mobility, and optical intensity. The effective depth of the conducting channel is $\approx L_a$ for diffusion limited regime. L_g and W_g are the length and width of the gap respectively.

In addition to the channel resistance of the photo-excited region, the contact resistances have to be evaluated at microwave frequencies for complete characterization of the microstrip gap.

Once the microstrip gap is modeled correctly, optically controlled devices can be built around it. The realization of an attenuator is rather straight forward. The optically excited gap can behave like a variable attenuator. However, at high frequency the shunt capacitance across the photo conductance starts playing a role and even in dark condition there is microwave power transfer across the gap. The effectiveness of the photo-conductance reduces as the frequency increases. The variable attenuation then is possible only at lower end of the microwave spectrum where the gap capacitance has high reactance.

MACH-ZEHNDER PHASE SHIFTER

The Mach-Zehnder interferometer geometry is commonly used in integrated optical devices to control the characteristics of light by a radio signal. Keeping the basic geometry same we essentially interchange the optical and the radio signals. That is, we control the characteristics of the microwave signals with the help of light. The problem however is rather complex in this situation. In case of optical Mach-Zehnder interferometer, since the dimensions of the wave guide are much larger, almost bulk-optics principles can be used to obtain the flow of light. On the other hand, for the proposed configuration, the impedance transformation concepts have to be properly used to get the microwave power flow. In fact the Mach Zehnder geometry is somewhat similar to a strongly coupled ring resonator. The power transfer from input to output therefore depends upon the resonance conditions of the loop formed by the two arms of the interferometer.

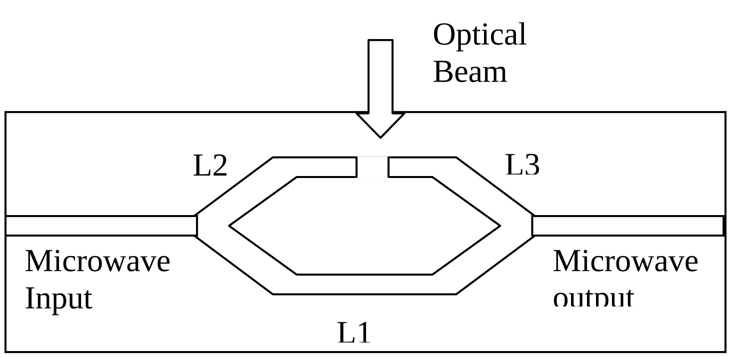
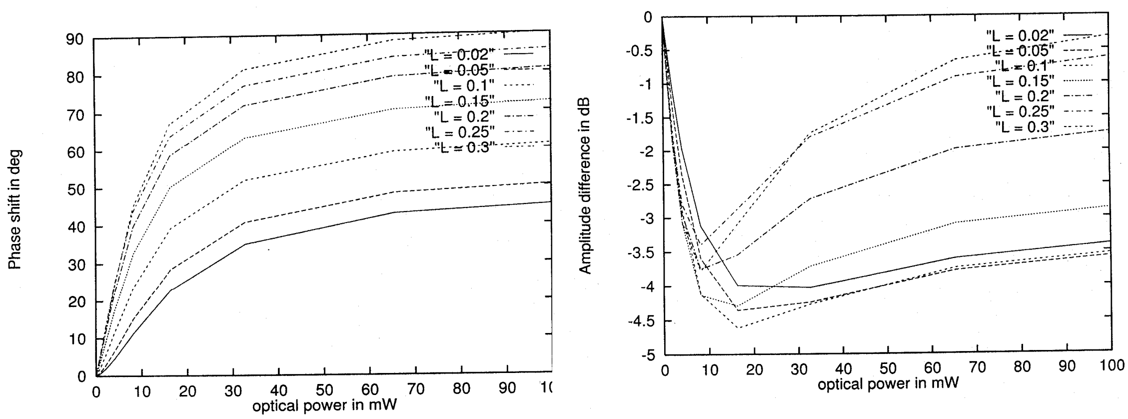


Fig. 1 Mach-Zehnder interferometer type optically controlled phase shifter. L=L1+L2.

A Mach-Zehnder optically controlled microwave phase shifter is shown in Fig. 1. The microwave signal is divided using a Y-junction into two parts. One of the parts is passed through an optically controlled microstrip gap while the other part is taken directly. The two parts are combined back through a Y-junction to get the output. By using transmission line models and impedance transformation the transmission coefficient of the interferometer is obtained.

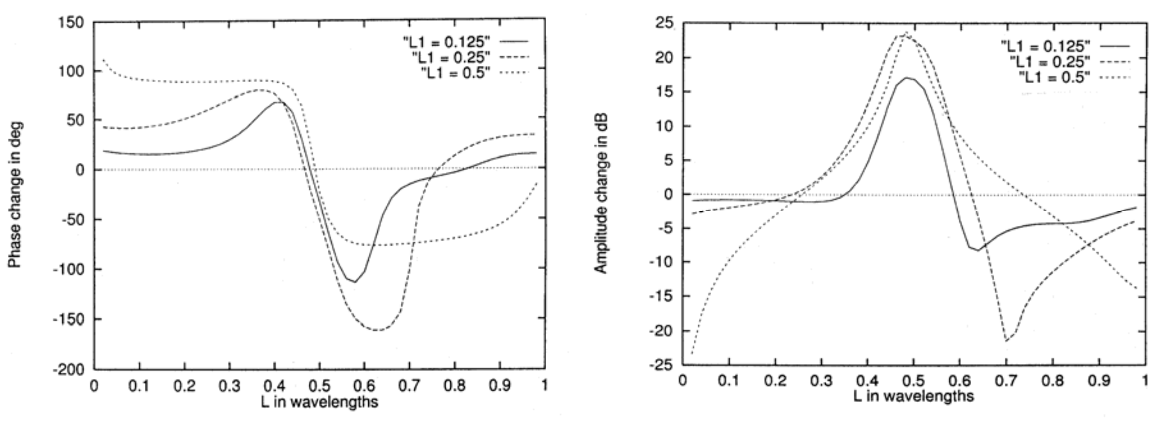
The analysis has been carried out for a microstrip geometry of 50 Ohm characteristic impedance on silicon substrate [3]. The length of the microstrip is taken to be 0.1mm. The phase shifter characteristics are investigated for various parameters like, the gap location in the interferometer, unequal arm lengths, gap width etc. It is seen that the phase shift and the insertion loss vary as a function of the gap location for given interferometer arm lengths. The best results are obtained for the centrally located gap.

Fig. 2 and 3 show the phase shift and the insertion loss for different optical powers and arm lengths.



(a) (b)

Fig. 2 : Phase shift (a) and insertion loss (b) as function of optical power for different arm lengths.



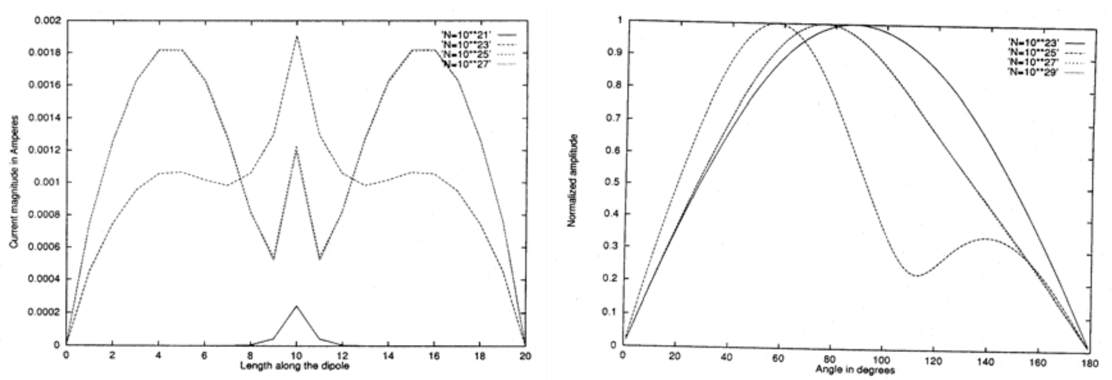
(a) (b)

Fig. 3: Phase shift (a) and insertion loss (b) as a function of arm length

OPTICALLY INDUCED SEMICONDUCTOR ANTENNA

An antenna can be optically created by shining light in appropriate pattern on a semiconductor substrate. Since the photo-conductivity is proportional to the light intensity, the conductivity profile on the antenna

can be controlled by controlling the illumination pattern. With linear illumination pattern a strip of high conductivity is created on the semiconductor substrate which when excited with a microwave signal, acts like an antenna. It can be noted that in this case there is no permanent radiating structure and the structure is created as and when required by optical illumination.
The linear photo-induced antennas have been investigated using the Method of Moments (MoM) and Sommerfeld's spectral domain approach [4]. The current distribution for a given conductivity (optical illumination) profile are obtained. Once the complex current distribution is known, the input impedance and the far-field radiation pattern of the antenna is calculated using Fourier transform. Fig.4 shows the far-field radiation patterns of a linear antenna for uniform and logarithmically tapered illumination patterns along the length of the antenna. It can be seen that the radiation pattern is similar to a Hertz dipole for low illumination but as the optical intensity changes, the radiation patterns vary according the illumination pattern.



(a) (b)

Fig. 4 Radiation pattern of a linear photo-induced antenna with (a) uniform illumination (b) logarithmically tapered illumination, for different peak illumination intensities.

Since the photo-induced semiconductor antennas essentially fall in the category of resistive antennas, the radiation efficiency is one of the important aspect of this antenna. Since we know the input impedance of the antenna, we can compute the power supplied to the antenna. From the knowledge of the conductivity profile and the current distribution along the antenna, the Ohmic loss in the antenna and the radiation efficiency is computed. It can be shown that for a photo carrier density of 10^{23} /m^3 an efficiency greater than 50% can be achieved. It should be pointed out here that if the carrier density is too large, the efficiency is good but then the antenna becomes more like a conductor antenna and its special features are lost. One has to make a compromise between the efficiency and the dynamic control of the radiation pattern.
The photo-carrier density depends crucially upon the carrier life time and the diffusion length. As the diffusion length increases the optical power requirement increases. Also the optical power is proportional to the size of the antenna. The photo-induced antennas therefore are more promising at millimeter wavelengths

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