Optically Controlled Reflection Type RF Phase Shifter Using Rat-Race Coupler On Silicon Substrate

Avanish Bhadauria[1], Sonia Sharma[2]

[1]Central Electronics Engineering Research Institute (CEERI),
Council of scientific and Industrial Research (CSIR)
Pilani -333031, INDIA
Email:avanish@ceeri.ernet.in

[2]University Institute of Engineering and Technology
Kurukshetra University, Kurukshetra, INDIA

***ABSTRACT—* This paper presents an optically controlled reflection type RF phase shifter using microstrip rate race coupler fabricated on silicon substrate. Optically controlled reflection type RF phase shifter can be realized by creating an optically induced resistive termination by a laser spot at the open end of controlling ports in rat-race coupler. To simulate the transmission behavior of proposed structure, the optically induced load at the open end of the port has been modeled as a resistive termination. The simulation results show that the phase and amplitude of the output RF signal can be controlled by optical terminations at different intensities and can be used as an optically controlled RF phase shifter.**

***Keywords*—Optical control, Phase-shifter, Rat-race coupler**

I. INTRODUCTION

Phase shifters are important components in many microwave subsystems used for radar and communication. Current technology makes phase shifters very costly, and inhibits widespread adoption of devices such as phased-array antennas. There are several methods for designing digital phase shifters at microwave frequencies. One is to use the properties of ferromagnetic materials for obtaining switchable phase shift. The other important design for digital phase shifters uses semiconductor devices.

Reflection type phase shifters are one of the commonly used phase shifters which are widely used due to its wide-band performance. These phase shifters are used to provide both large as well as small phase shifts. Such phase shifters have several advantages like low complexity, easy to control and fabricate. The reflection-type phase shifter utilizes a 3-dB hybrid coupler and a pair of reflective termination circuits with impedance transformers. The most common type of reflection phase shifters is variable reactance reflection phase shifters. However, using bulk silicon processes, the low inductor/varactor values and the limited varactor capacitance range produce high losses and small phase control ranges.

In this paper, we propose an optically controlled reflection type phase-shifter based on rat-race coupler fabricated on silicon substrate shown in Figure 1. This technique offers high isolation between the controlling optical source and controlled microwave device, ultrafast response and high power handling capacity. Such optical control is based on the fact that when photons of energy greater than the band gap are incident on the surface; electron-hole pairs are created by light absorption. The electron-holes generated at the end of an open port forms an optically controlled load termination [1-2]. The phase shift between input and out ports depends on the reflection coefficient on controlling ports, which are linked to the load impedance created by optically induced resistive load as shown in Figure 2.

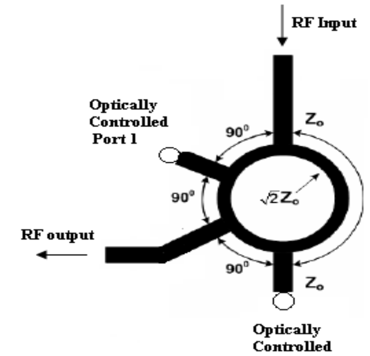

Figure 2: Optically controlled phase shifter using rat race coupler

II. OPTICALLY INDUCED LOAD

When an open end on the microstrip line fabricated on semiconductor substrate is illuminated by a laser spot, electron-hole plasma is created by light due absorption and spreads into the substrate due to carrier diffusion. The absorption or penetration depth of the illuminated radiation depends on the optical wavelength and substrate parameters. Such electron- hole plasma created at the end of the open microstrip line due to illumination by a laser spot leads to change in conductivity within the illuminated region in semiconducting substrate. The conductivity profile due to optical illumination can be expressed as [2]

$$\sigma_{op}(y) = e(\mu_n + \mu_p)\left(\frac{1}{hc}\right)(1-R)x$$
$$\frac{\alpha S \lambda_p \tau}{1-\alpha^2 L_a^2}\left[\exp(-\alpha y) - \frac{\alpha L_a{}^2 + v_s \tau}{L_a + v_s \tau}\exp\left(\frac{-y}{L_a}\right)\right]\frac{P}{A} \quad (1)$$

where, L_a is ambipolar diffusion length of charge carriers

$$L_a = \left[\frac{2\mu_n \mu_p \tau k_B T}{q(\mu_n + \mu_p)}\right]^{1/2} \quad (2)$$

Here, P is the incident power, A is illuminated area, τ is the carrier lifetime, μ_n and μ_p are the mobilities of electron and hole, e is the electronic charge, α is the wavelength dependent radiation absorption coefficient, R is surface reflectivity, h is Planck's constant, c is the velocity of light in free space, $S(\lambda)$ is relative spectral response of the semi-conductor exhibiting the peak response at optical wavelength λp (~850nm for Silicon).

The optically illuminated spot on semiconductor can be considered as a cylindrical region filled with diffusion controlled conductivity profile and can be modeled as a resistive element and this optically created resistance can be evaluated by

$$R = \frac{1}{A}\int_0^d \frac{dy}{\sigma(y)} \quad (3)$$

Substitution of $\sigma(y)$ from Eq. 1 in Eq. 2 leads to following expression for resistance

$$R = \frac{(1-\alpha^2 L_a^2)hc}{(1-R)e(\mu_n + \mu_p)\alpha S \lambda_p \tau P} \times$$
$$\int_0^d \frac{dy}{\left[\exp(-\alpha y) - \frac{\alpha L_a{}^2 + v_s \tau}{L_a + v_s \tau}\exp\left(\frac{-y}{L_a}\right)\right]} \quad (4)$$

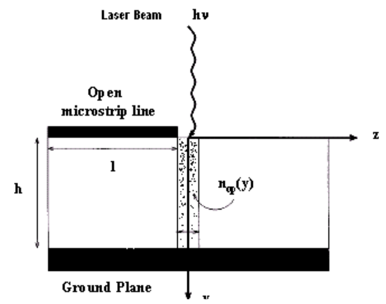

Figure 2: Formation of Optically induced load at the end of microstrip line

It is clear from the above expression that the optically generated resistance depends on the power levels and not on area of the spot.

For the silicon substrate within the wavelength range 500-900nm, where $\alpha L_a >> 1$ and $\alpha L_a >> v_s \tau / L_a$ the conductivity in Eq. 1 reduces to

$$\sigma(y) = \frac{(1-R)e(\mu_n + \mu_p)S \lambda_p \tau}{(1 + v_s \tau / L_a)hcL_a^2}\left(\frac{P}{A}\right)e^{-\frac{y}{La}} \quad (5)$$

and, hence, the expression for resistance is obtained as

$$R = \frac{(1 + v_s \tau / L_a)hcL_a^2}{(1-R)e(\mu_n + \mu_p)S \lambda_p \tau P}(e^{\frac{d}{La}} - 1) \quad (6)$$

Eq 5 clearly shows that the resistance obtained above is only controlled by diffusion mechanism of charge carriers. Optically induced resistance R shows the frequency independence as $\sigma(y)$ is frequency independent. Further, $\sigma(y)$ is also shown to be proportional to optical intensity implying that R is dependent only on the power level P and independent of spot diameter A. Experiment and simulation [2] show that the resistance decreases from several kilo-ohms in dark state to a few ohms with increase in optical intensity as shown in Table1.

Table 1

Modeled optically generated resistances illuminated by 650nm wavelength at different optical powers	
Power (mW)	Resistance (Ω)
5	280.38
10	140.19
15	93.46
20	70.09
25	56.07
30	46.73
35	40.05
40	35.04

The typical values of various parameters for silicon are : $L_a = 47\mu m$, $\alpha(650\ nm) = 3600\ cm^{-1}$, $\alpha(850\ nm) = 700\ cm^{-1}$, $\lambda p = 850$ nm, $v_s = 10^2 cm/s$, S (850 nm) =1.0, S (650nm) = 0.7, and $R = 0.3$ and τ can vary from 2μs to 200μs. For all the calculationsτ, the carrier life time was used as 18μs.

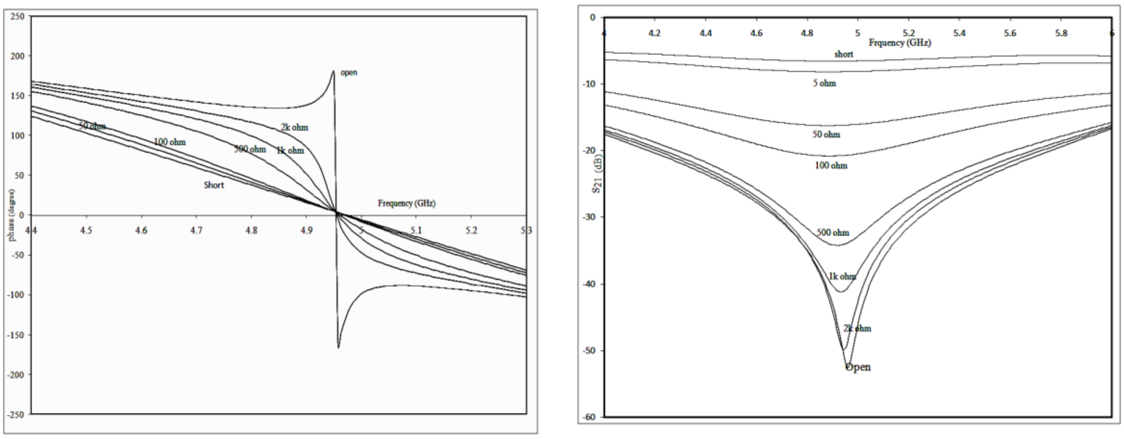

Figure 3: Simulated results for output phase and magnitude of S_{21} by terminating port 2 with different optically load

III. OPTICALLY CONTROLLED RAT-RACE COUPLER

The proposed optically controlled rat-race coupler as shown in Figure 2 consists of input and output ports with two controlling ports and circular coupling ring. The phase shift between input port and out port depends on the reflection coefficient on controlling ports, which are linked to the optically induced load impedance. A rat-race coupler divides the input signal into two signals 180^o out of phase. These signals reflect from a pair of reflective loads, and combine in phase at the phase shifter output. The phase of the reflection-type phase shifter can be controlled by varying the impedance of the reflective load Z_l . The reflection coefficient can be expressed as Reflection coefficient can be expressed as

$$\Gamma = \frac{Z_l - Z_0}{Z_l + Z_0} \qquad (7)$$

If Z_l varies from Z_{min} to Z_{max}, the phase shift achieved is given by

$$\Delta\varphi = 2\left[\arctan\left(\frac{Z_{max}}{Z_0}\right) - \arctan\left(\frac{Z_{min}}{Z_0}\right)\right] \qquad (8)$$

And, hence, the magnitude and phase of the output signal can be controlled by varying the illumination level. For our simulation the rate coupler has been designed at 5 GHz frequency on silicon substrate of 300 micron thickness. The inner radius of coupler ring is 5.3 mm and outer radius 5.4 mm with the width of circular ring 100 micron. The 50 ohm input arm has been chosen as 6.9 mm with the width of 0.239 mm. The length of output arm is chosen as 13.8 mm. The Metal thickness in the design was chosen as 2 micron.

IV. RESULTS AND DISCUSSION

Optically induced resistive loads at different optical power levels have been estimated by modeling as discussed in section II based on earlier work [2]. The optically induced resistive loads at different optical power levels are shown in Table 1. It can be seen that by increasing optical intensity from few mW to hundreds of mW the modeled resistance decreases from several mega-ohms to almost short circuit. To study the RF transmission behavior of the structure under optical control, the simulation has been carried out using Mentor graphics IE3D V15 software. The MODUA platform was used to terminate the control port 2 by a modeled optically induced load at different power levels.The simulation results show that in absence of illumination (dark condition), when the port is open, the phase at the output port 180 degree out from the input port. As we start to increase the incident optical power the equivalent resistance keep decreasing. This leads to change in output phase and at a very high illumination level (~200 mW) equivalent resistance attains the value of few ohms and gets almost short circuited, which leads to maximum phase change of 180 degree as shown in Figure 3. The results also show that at very high optical illumination (correspond to a short circuit or zero resistance) at the port 2, the magnitude of transmission parameter at the output port remains constant but a large shift in phase can be seen(~180 degree change in phase) at the frequency of interest.

V. CONCLUSION

We have proposed a new type of phase shifter based on race coupler. Due to ultrafast response and high isolation between controlling optical signal and controlled RF signal, the device can be use for ultrafast microwave signal processing. Further, It can also be as an optically controlled reflection at type variable attenuator using different level of illumination. This type of phase shifter has the advantage of being easy to realize in planar technologies with a ultrafast response.

REFERENCES

[1] B.Boyer, J Haider, A Vilcot and M. Bouthinon, “Tunable Microwave Load Based on Biased Photoinduced Plasma in Silicon”, *IEEE Trans. Microwave Theory Tech*. 45, 1362 (1997).

[2]A. Bhadauria, Nasimuddin, A.K. Verma, E.K. Sharma, and B.R. Singh, Optically controlled microstrip load and stub on silicon substrate, Microwave And Optical Technology Letters, Vol. 39 (2003), 271–276