Preliminary MW and MMW Reflection and Transmission Measurements of a Silicon Wafer under Illumination of Light for Reflected Phased Array Antennas

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***Abstract* — At microwave frequencies, the antenna beam scanning is commonly realized using phased array antennas. Such approach is expensive and very time consuming. As the frequency increases into the millimeter region, the complexity and the cost makes the realization of phased array antenna even more complex, less desirable and very difficult. A preliminary study of implementing a low weight and a low cost antenna at Millimeter wave (MMW) frequency that can form and scan a beam is done. The antenna uses a semiconductor body, a MMW- and optical source. The optical source illuminates the semiconductor. In the semiconductor body the spatially varying density of charge carriers changes the relative dielectric constant of the semiconductor, such that it can reflect or transmit incident field from MMW source. Since the projection can be realized selectively a beam can be scan in the space.**

***Index Terms* — Semiconductor, reflected array, complex dielectric modulation, reflection, transmission**.

I. INTRODUCTION

A reflectarray, consisting of a very thin and flat reflecting surface illuminated by a feed, is a valid and attractive alternative to parabolic reflectors [1]-[3]. This is due to its easiness of fabrication and integration, low-profile, light weight, and low manufacturing cost. In general number of antenna elements (dipole, patch) is etched on substrate which forms the array. In this paper another approach is suggested. The antenna elements are projected on a semiconductor material by a light source. Different projection corresponds to different scan angle. The projection can be achieved using optical sources. The generated electron-hole pair changes the dielectric property of the material and it behaves more or less as a good reflector instead of insulator. This technique is called complex dielectric modulation. In order to understand the behavior of the semiconductor material under the illumination of the light, a silicon wafer is bounded between two waveguide and is illuminated with high power optical laser pulses. The optical source causes the change in the relative dielectric constant of material and since the propagation constant in the material depends on the generated electron-hole pair, a complete reflection can occur. The reflection and transmission of semiconductor material is modeled using S-T matrix. In order to validate the theoretical results measurements have been done. It is shown that there is a considerable change in the reflection and the transmission after the laser is turned on. This property of semiconductor material can be used to realize reflected phased array antenna. This paper is organized as follows: In section II the modeling of the reflection and transmission is given. In section III the theoretical results are presented. Measurement set up and measurement results are given in section IV. Finally section V gives the conclusions.

II. REFLECTION and TRANSMISSION

A. S-T Matrix

Fig. 1 shows the configuration of S-T matrix that relates the input-port to the output-port of a microwave network.

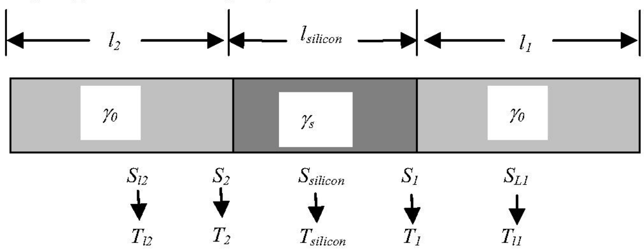


Fig. 1. Configuration of S-T matrix

The input reflection is related to the components of the *T*-matrix as follows

$$\Gamma_{in} = S_{11} = \frac{b_1}{a_1} = \frac{T_{12}}{T_{22}} \tag{1}$$

The T-matrix of the network is given as follows [4]

$$\begin{aligned} T_{l1} &= \begin{bmatrix} e^{-\gamma_0 l_1} & 0 \\ 0 & e^{\gamma_0 l_1} \end{bmatrix}, T_1 = \frac{1}{2\sqrt{\gamma_s \gamma_0}} \begin{bmatrix} \gamma_s + \gamma_0 & \gamma_s - \gamma_0 \\ \gamma_s - \gamma_0 & \gamma_s + \gamma_0 \end{bmatrix} \\ T_s &= \begin{bmatrix} e^{-\gamma_s l_s} & 0 \\ 0 & e^{\gamma_s l_s} \end{bmatrix}, T_2 = \frac{1}{2\sqrt{\gamma_s \gamma_0}} \begin{bmatrix} \gamma_s + \gamma_0 & \gamma_0 - \gamma_s \\ \gamma_0 - \gamma_s & \gamma_s + \gamma_0 \end{bmatrix} \end{aligned} \tag{2}$$

γ_s is the propagation constant in the silicon. γ_0 is the propagation constant in the air and is given by

$$\gamma_i = \begin{cases} j\sqrt{\omega^2 \mu \varepsilon_i - \left(\dfrac{\pi}{a}\right)^2} & if\ \omega^2 \mu \varepsilon_i > \left(\dfrac{\pi}{a}\right)^2 \\ \sqrt{\left(\dfrac{\pi}{a}\right)^2 - \omega^2 \mu \varepsilon_i} & otherwise \end{cases} \tag{3}$$

where a is the width of the waveguide. ω is the frequency of signal, ε_i is the permittivity, $\mu = \mu_0$ is permeability.

B. Propagation Constant in Silicon Wafer

The propagation constant in the silicon is derived based on the derivation of equation (3) with some minor changes. The electrical property of semiconductor material under illumination of light will change. The propagation constant in a medium is given as [5]

$$\gamma_s = \sqrt{j\omega\mu\left(\sigma + j\omega\varepsilon\right)} \tag{4}$$

In order to determine the change in dielectric constant electron-hole plasma in Si is regarded as a gas of free carriers. The classical Drude model gives the following expression for the complex dielectric constant [6]

$$\varepsilon' = \varepsilon_r - \frac{Ne^2}{\varepsilon_0 m^*_{eh}} \frac{1}{\left(\omega^2 + \dfrac{1}{\tau}\right)}, \ \varepsilon'' = \frac{Ne^2}{\varepsilon_0 m^*_{eh}} \frac{1}{\left(\omega^3\tau + \dfrac{\omega}{\tau}\right)} \tag{5}$$

where ε_r is the relative dielectric constant, e is the magnitude of electronic charge, N is the concentration of electron-hole pairs, m^*_{eh} is the reduced optical effective mass of an electron-hole pair. τ is the relaxation time. It is shown that photons with energy greater than E_g (Bandgap energy) can be absorbed in semiconductor, thereby creating electron-hole pairs. If we assume that one absorbed photon at energy hv creates one electron-hole pair, then the generation rate of electron-hole pairs is [7]

$$g' = \frac{\alpha I_v}{hv}, \ \#/cm^3 - sec \tag{6}$$

where $I_v(x)$, energy/cm^2-sec, is the intensity of light source, $\alpha I_v(x)$ is the rate in which energy is absorbed per unit volume. α is the absorption coefficient in cm^{-1}. hv the photon energy in eV and is related to the wavelength of the optical source as follows

$$E = hv = \frac{1.24}{\lambda\,(in\,\mu m)} \tag{7}$$

The generated electron-hole during $\Delta\tau$ is given as

$$\delta n\left(t = \Delta\tau\right) = g'\Delta\tau, \ \#/cm^3 \tag{8}$$

Assuming that there are no spatial variation of the excess carrier concentration and that at time $t = 0$ the electron-hole pairs generated based on equation (9), then the time dependence of generated electron-hole pairs is given as [7]

$$\delta n(t) = \delta n(0) e^{-\frac{t}{\tau_{n0}}} \tag{9}$$

where τ_{n0} is the minority carrier hole life time. For semiconductor the conductivity is given as [8]

$$\sigma = N_n q_n \mu_n + N_p q_p \mu_p \tag{10}$$

where μ_n and μ_p are the mobility of electron and holes in cm^2/V-sec. N_n and N_p are the electron and hole concentration in cm^{-3}.

C. Reflection and Transmission

The overall T-matrix of the network is calculated by matrix multiplication and is given as

$$T_l = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = T_2 T_s T_l T_l \tag{11}$$

Using equations (2) and (12) the elements of the T-matrix needed for input reflection is given by

$$\begin{aligned} T_{12} &= \frac{1}{4\gamma_s\gamma_0}\left\{\left(\gamma_s^2 - \gamma_0^2\right)\left(e^{-\gamma_s l_s} - e^{\gamma_s l_s}\right)\right\} e^{\gamma_0 l_l} \\ T_{22} &= \frac{1}{4\gamma_s\gamma_0}\left\{\left(\gamma_s + \gamma_0\right)^2 e^{\gamma_s l_s} - \left(\gamma_s - \gamma_0\right)^2 e^{-\gamma_s l_s}\right\} e^{\gamma_0 l_l} \end{aligned} \tag{12}$$

Substituting equation (13) in (1) leads to an expression for the input reflection. The transmission coefficient is given as

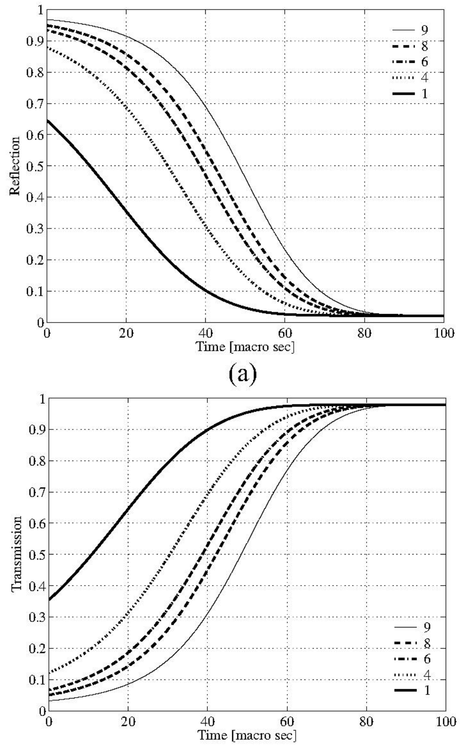
$$t = \frac{4\gamma_s\gamma_0}{T_{22}} \tag{13}$$

D. Theoretical Results

Using equations (1), (3)-(11) and (12)-(13) the reflection and transmission coefficient is determined. The operational frequency is 35 GHz. The dimensions of the waveguide are 3.5mm×7mm. The silicon wafer thickness is 0.3 mm. The wavelength of the optical pulse is considered to be 0.53 μm. At this wavelength the absorption coefficient for Silicon is α = 10^{4}cm^{-1}. It was attempted to use the data from the measurement set up which will be discussed in the next section. Fig. 2 shows the reflection and transmission as function of time. The parameter is the power density of the optical source in Mwatt/m^2. The considerable change in the dielectric constant results in the total reflection of the waves. A carrier lifetime of τ_n=25 μs is chosen. It is shown that as generation rate decreases input reflection also decreases.

III. MEASUREMENT RESULTS

Measurements have been done to validate the theoretical results. A silicon wafer with thickness of 0.3 mm is placed between two waveguides. Two wideband sensitive detectors and Tektronix Digital Scope TDS 784A are used to measure the reflection and transmission. A mirror and a lens are used to focus the laser light into the waveguide. The laser operates at a wavelength of 0.53 μm, with pulse duration of 30 ns and peak energy of 100 mJ.



(a)

(b)

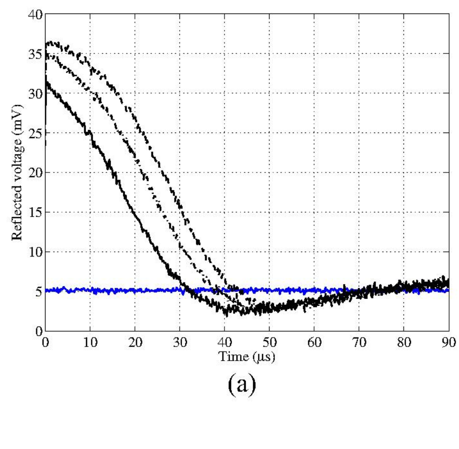
Fig. 2. (a) Reflection and (b) transmission of silicon material under illumination of optical source for different optical power density in Mwatt/m^2.

A. X-band

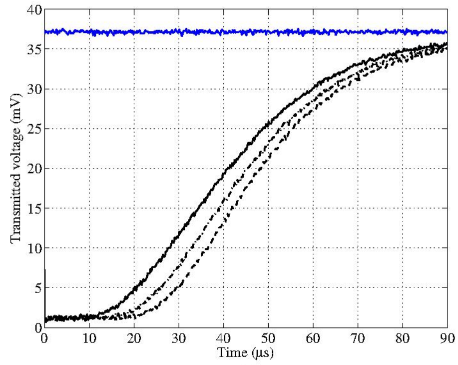
The measurement set-up at the x-band is the same as Ka-band which is shown in Fig. 3. A source at a frequency of 9.47 GHz is connected to the waveguides via a -20 dB wide-band coupler. Fig. 4 shows the reflection and the transmission before and after the laser is turned on for different laser power. Since the laser was not calibrated, the different power strength was not accurately known during the measurements. As the power of the laser pulse decreases, the reflection and transmission voltage decreases and increases respectively.

B. Ka-band

In this case the dimensions of the aperture of the waveguide are 3.5mm×7mm.



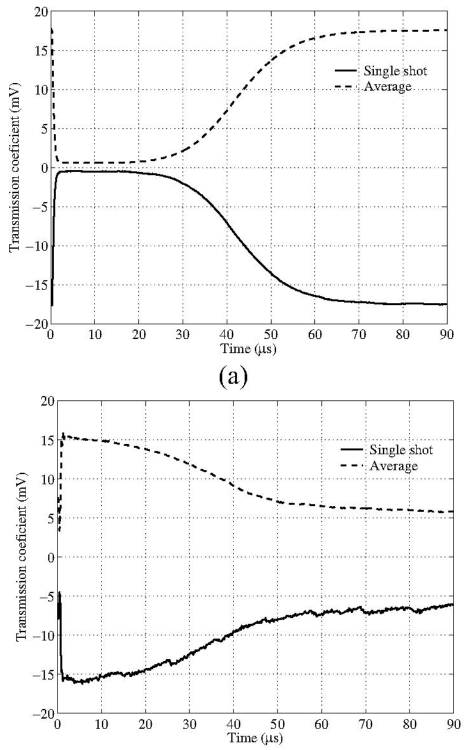
(a)



(b)

Fig. 4. Measured transmission (a) and reflection (b) at x-band after illuminating the silicon wafer with light. Laser is turn on at time 0 sec.

Fig. 5 shows the transmission and the reflection of the silicon wafer before and after the laser is turned on. The Figures display single- and averaged measurement over 16 laser pulses. The average measurement is inverted. Note that in both cases a complete reflection occurs after the laser is turned on. An on/off ratio of 20 dB is measured. Fig. 6 shows the comparison between the theoretical and measurement results.



(a)

(b)

Fig. 5. measured (a) reflection and (b) transmission pulse at Ka-band after illuminating the silicon wafer with a laser. The laser is turn on at time 0 sec.

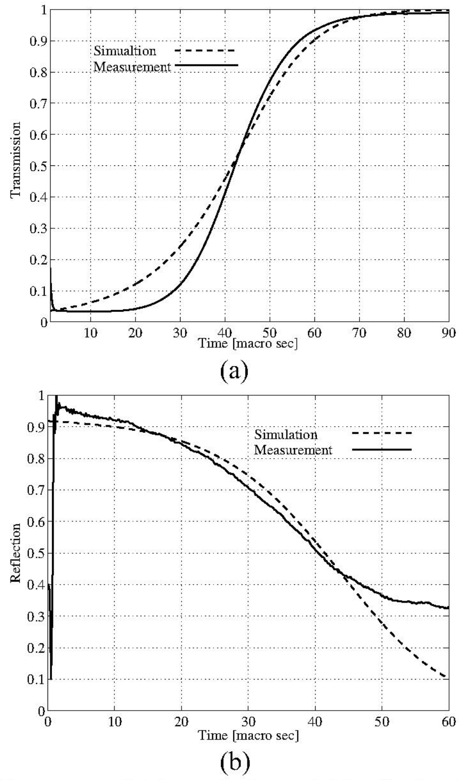


Fig. 6. Comparison (a) transmission and (b) reflection between the measurement and simulation results

The theoretical- and measurement results given in this paper show that this feature of semiconductor material can be used to form and scan beam in the MW or MMW band.

V. CONCLUSION

This paper introduced a technique for realization of reflected phased array antennas. A piece of silicon wafer with thickness of 0.3mm is bounded between the two media in a closed waveguide structure is illuminated with a optical pulsed laser. The measurement results show that there is considerable change in the reflection and transmission of the silicon wafer after turning on the laser. The measurement results are modeled using S-T model. There is a good agreement between the simulation and measurement results. The duration in which the beam can be scanned at a certain point depends heavily on the carrier life time of electron-hole pairs generated in the material.

ACKNOLEDGEMENT

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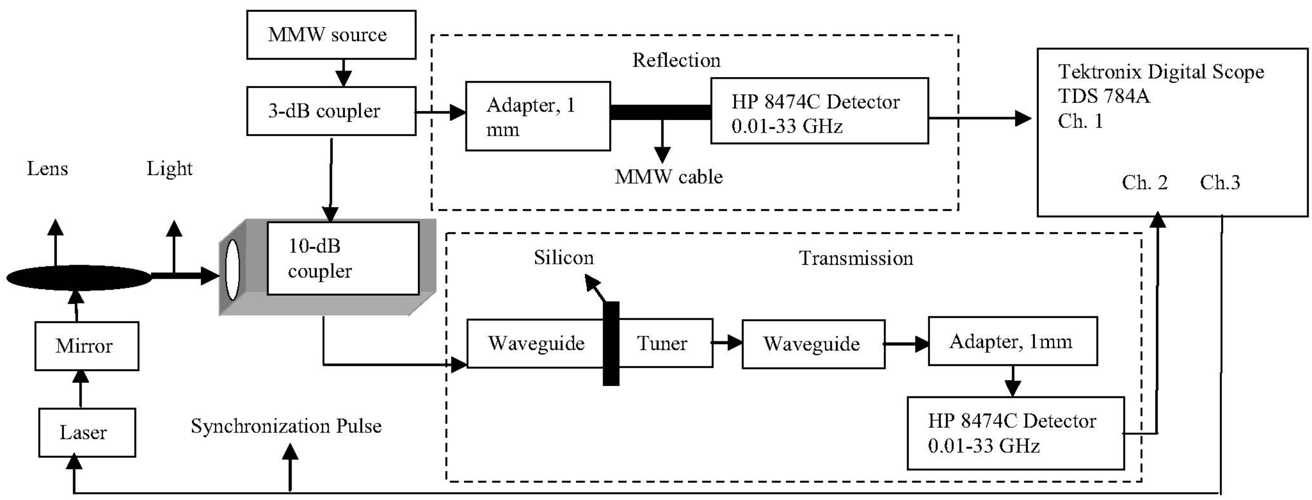

Fig. 3. Reflection- and transmission measurement set up at Ka-band