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Reconfigurable Array of Radiating Elements (RARE) Controlled by Light

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Physical Optics Corporation
Research and Development Division
20600 Gramercy Place, Suite 103
Torrance, California 90501

Principal Investigator:
Lev Sadovnik
(310) 320-3088

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A crucial question to be answered in the course of this investigation is how closely does the light-induced radiating element approximate a microstrip element. To find an answer to this question the following steps were taken during the reporting period.

1. A working focusing FLAPS antenna has been acquired from Malibu Research Inc.

2. Theoretical modeling of light-induced free carrier distribution in a silicon plate was performed. The theoretical model incorporated both surface and volume carrier recombination.

3. Based on the results of the theoretical modeling, characteristics of the light-induced microstrip silicon-dielectric-metal line were calculated and compared with characteristics of a regular dielectric-metal microstrip line.

These steps are described in detail as follows:

1. *FLAPS Antenna from Malibu Research Inc.*
   Figure 1 shows the 4" × 4" FLAPS microstrip antenna. This antenna is printed on a 0.010" Duroid with a copper ground plane. It has a focus at 12" at an angle of 35° for 94 GHz microwave radiation. The beamwidth is ≈12°. The real thickness of the dielectric plane, h, is 260 μm, the thickness of the top copper layer, t, is 13 μm.

   Figure 2 shows the typical reflecting element of this antenna. All crosses have the same width of microstrip lines, about 130 μm. The difference in the reflection coefficients is due to the variation in the length of the microstrip.

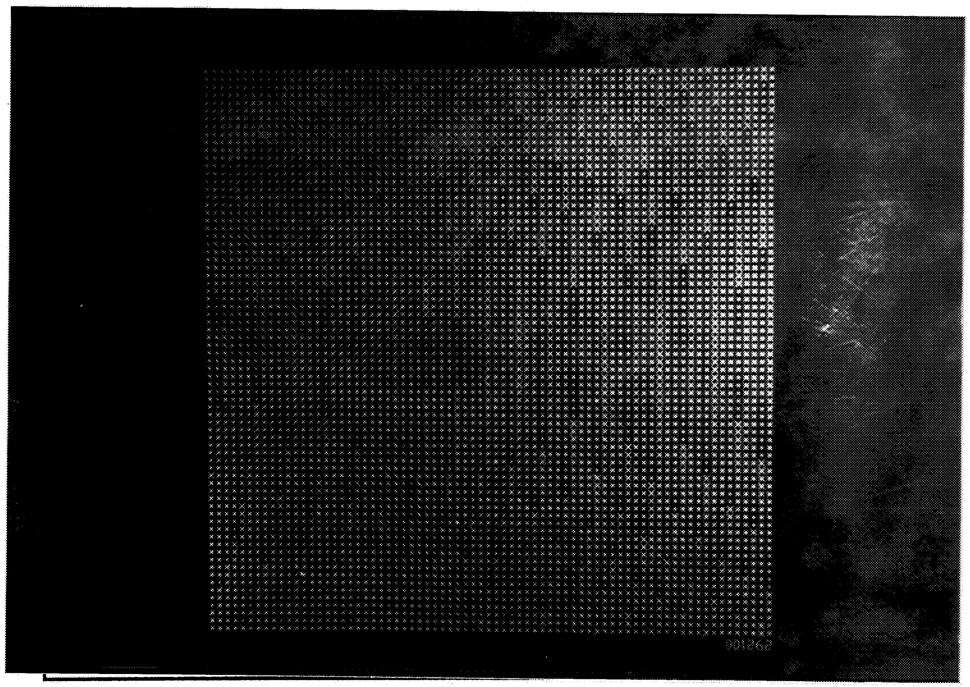


Figure 1
4" × 4" FLAPS microstrip antenna from Malibu Research Inc.

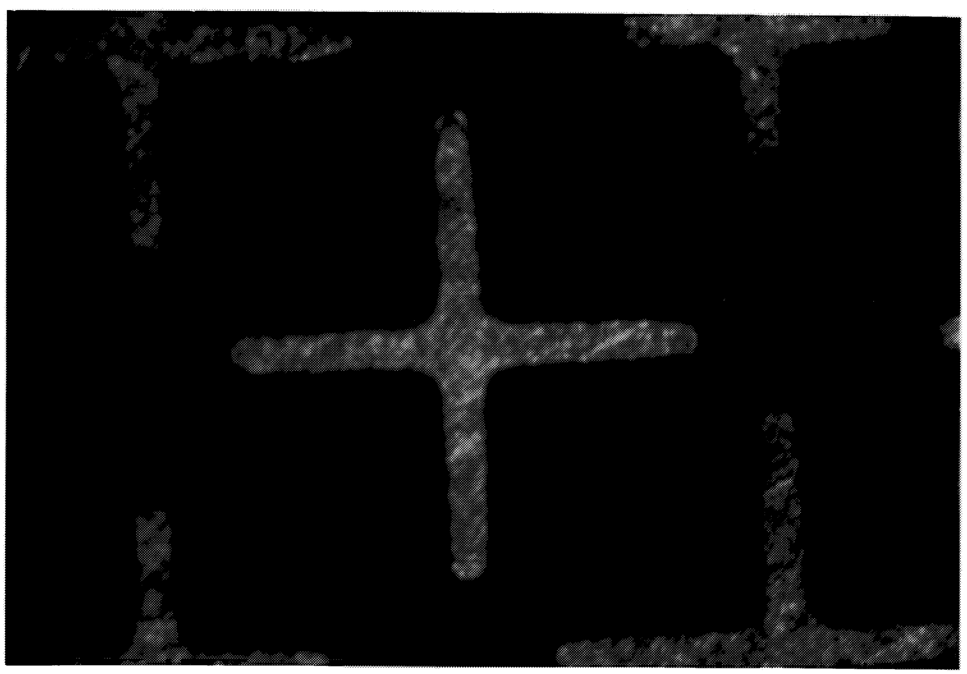


Figure 2
Element of the FLAPS microstrip antenna (magnified ~50x)

2. *Light-Induced Free Carrier Distribution in Thin Silicon Plate*

According to the Drude model, the dielectric constant at frequency ω has the form

$$\varepsilon = \varepsilon_\infty \left(1 - \frac{\omega_p^2}{\omega\left(\omega + i\tau^{-1}\right)} \right) \tag{1}$$

where ε_∞ is the high-frequency dielectric constant limit, ω_p is the plasma frequency, τ is the relaxation time. Generalization for two types of carriers with different ω_p and τ (as in the case of illuminated silicon) gives

$$\varepsilon = \varepsilon_\infty \left(1 - \frac{\omega_n^2}{\omega\left(\omega + i\tau_n^{-1}\right)} - \frac{\omega_p^2}{\omega\left(\omega + i\tau_p^{-1}\right)} \right) \tag{2}$$

where ω_n and ω_p are plasma frequencies for electrons and holes, and τ_n and τ_p are their momentum relaxation times.

$$\omega_n^2 = \frac{N_n\, q^2}{M_n\, \varepsilon_\infty}, \qquad \omega_p^2 = \frac{N_p\, q^2}{M_p\, \varepsilon_\infty},$$

$$\tau_n = \frac{\mu_n\, M_n}{q}, \qquad \tau_p = \frac{\mu_p\, M_p}{q},$$

N_n, N_p are electron and hole densities, μ_n and μ_p are their mobilities, and M_n and M_p are their effective masses.

As the distribution of carriers within the slab under illumination is nonuniform, the dielectric constant is a function the coordinate. If illumination of the slab's surface is uniform, we can consider a one-dimensional distribution along the z-direction (Figure 3), so that

$$\varepsilon(z) = \varepsilon_0 \left(1 - \frac{N_n\, q^2}{M_n\, \varepsilon_\infty\, \omega^2} - \frac{N_p\, q^2}{M_p\, \varepsilon_\infty\, \omega^2} \right) \tag{3}$$

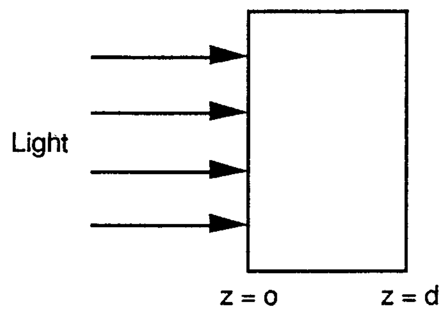


Figure 3
Schematic diagram of an illuminated silicon slab.

To calculate the distribution of the dielectric function $\varepsilon(z)$ using Eq. (3), we need to calculate the carrier distributions $N_p(z)$ and $N_n(z)$. Assuming that, because of electroneutrality, $N_p = N_n$, and allowing volume and surface recombination, as well as diffusion, one can obtain an expression for carrier concentration distribution

$$N_p(z) = N_n(z) = N(z) = \frac{g(0) \cdot \tau_r}{\alpha^2 L^2 - 1}\left[\left(A_1 \exp\left(-\frac{z}{L}\right) + B_1 \exp\left(\frac{z}{L}\right) - \exp(\alpha z)\right)\right] + N_0 \quad (4)$$

where $g(0)$ is the generation rate at $z = 0$, $g(0) = \dfrac{\alpha \cdot \Phi}{\hbar\omega}$,
τ_r is the bulk carrier lifetime,
α is the light absorption coefficient,
L is the ambipolar diffusion length, $L = \sqrt{D \cdot \tau_r}$,
D is the ambipolar diffusion coefficient, $D = 2D_n D_p/(D_n + D_p)$,
D_n and D_p are the diffusion coefficients for electrons and holes,
Φ is the intensity of illuminating light,
$h\omega$ is the photon energy,
N_0 is the equilibrium carrier concentration,

$$A_1 = \frac{1}{2C_1}\left[(S_1 + \alpha D)\left(\frac{D}{L} + S_2\right)\exp\left(\frac{d}{L}\right) + (S_2 - \alpha D)\left(\frac{D}{L} - S_1\right)\exp(-\alpha d)\right] \quad (5)$$

$$A_2 = \frac{1}{2C_1}\left[(S_1 + \alpha D)\left(\frac{D}{L} - S_2\right)\exp\left(-\frac{d}{L}\right) + (S_2 - \alpha D)\left(\frac{D}{L} + S_1\right)\exp(-\alpha d)\right] \quad (6)$$

$$C_1 = \left(S_1 S_2 + \frac{D}{\tau_r}\right)\sinh\left(\frac{d}{L}\right) + (S_1 + S_2)\frac{D}{L}\cos\left(\frac{d}{L}\right), \quad (7)$$

S_1 and S_2 are surface recombination rates at the face and rear surface, respectively.

All results were calculated for the following parameters:

$f = 94 \cdot 10^9$ Hz,
$\alpha = 8 \cdot 10^3\ cm^{-1}$
$h\omega = 2.41$ eV (for $\lambda = .515\ \mu m$)
$D_n = 37.6\ cm^2/s$
$D_p = 13\ cm^2/s$
$\varepsilon_\infty = 11.8$
$m_n = 0.26\ m_e$
$m_p = 0.39\ m_e$
$m_e = 9.1 \cdot 10^{-31}$ kg
$q = 1.6 \cdot 10^{-19}$ C
$\mu_n = 1300\ cm^2/Vs$
$\mu_p = 600\ cm^2/Vs$
$N_0 = 10^{12}\ cm^{-3}$
$\Phi = 0.4\ W \cdot cm^{-2}$
$S_1 = S_2 = 1 \cdot 10^2$ cm/s
$\tau_r = 10^{-3}$ s

The results of our calculations are exhibited in Figures 4 and 5.

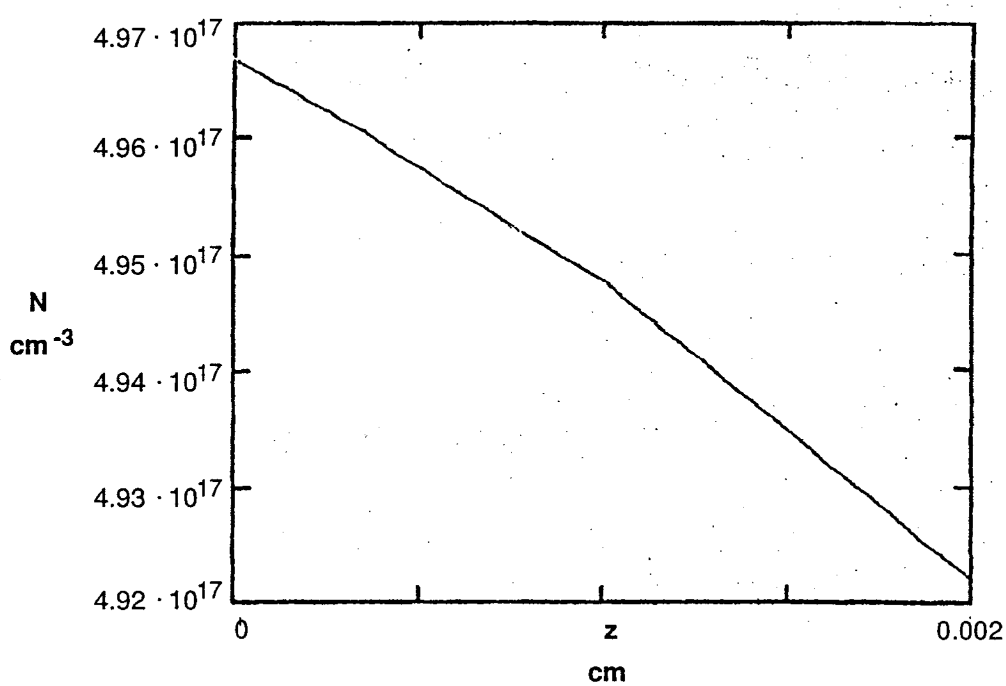
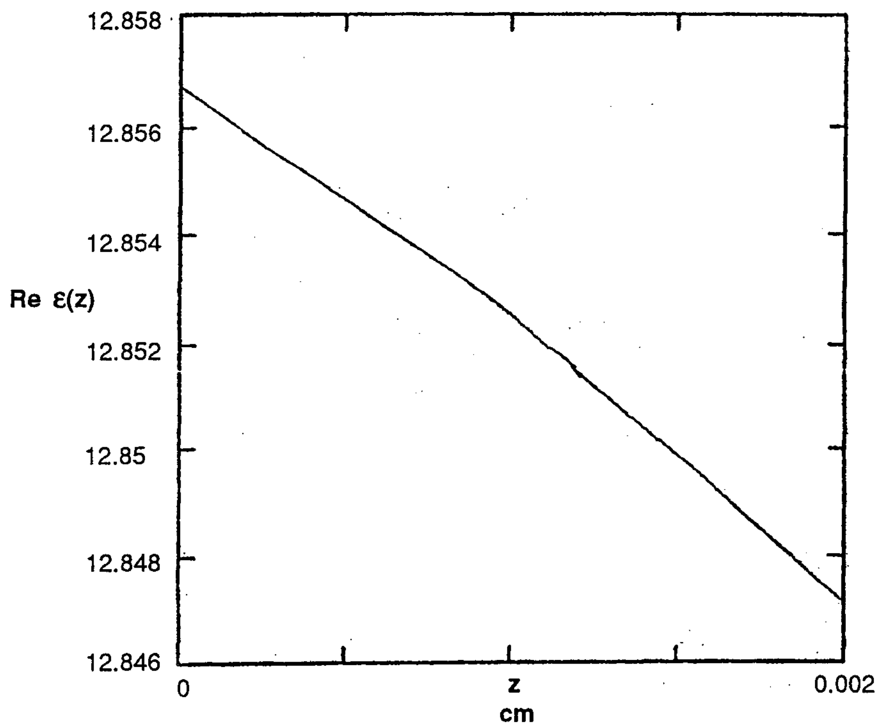
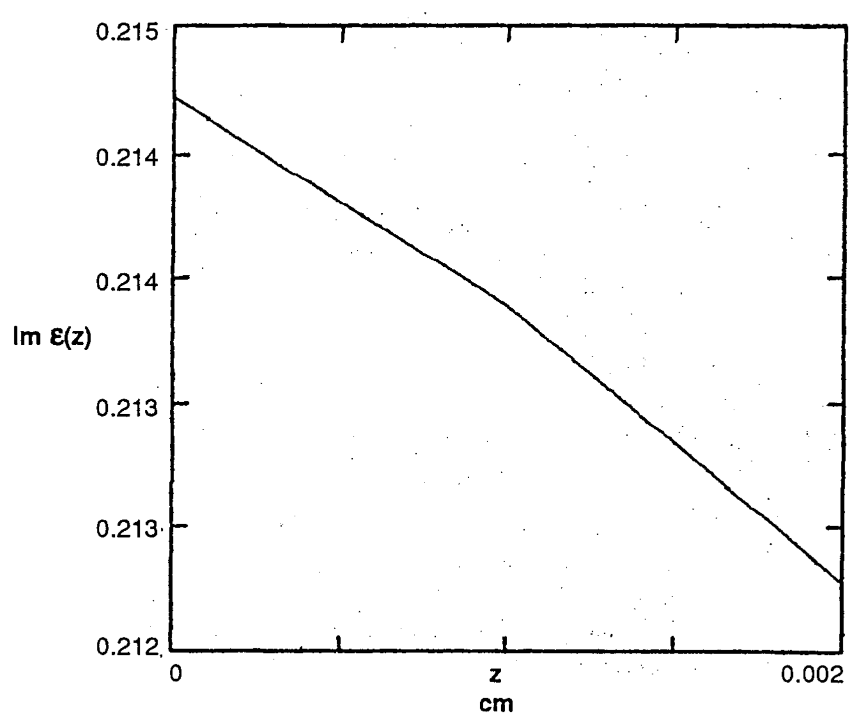


Figure 4
Distribution of the carrier density N along the depth z of the illuminated silicon plate.



(a)



(b)

Figure 5
Distribution of the real (a) and imaginary (b) parts of permittivity of the illuminated silicon plate as a function of depth.

These figures show that for a plate of thickness about 25 μm and having the parameters defined above, the variations in the carrier density and permittivity with depth are very small (less, than 1.5%). It allows us to approximate this distribution by a uniform value. With this approximation, the thin illuminated silicon plate will have a volume electrical conductivity:

$$\sigma = Nq\left(\mu_e + \mu_p\right) = 5 \cdot 10^{17}\text{cm}^{-3} \cdot 1.6 \cdot 10^{-19}\text{C} \cdot (1300 + 600)\text{cm}^2 / \text{V} \cdot \text{s} \; = \; 1.52 \cdot 10^{1} \cdot \text{ohm}^{-1}\text{cm}^{-1}$$

3. *Characteristics of the Light Induced Microstrip Line*

Although all elements of the FLAPS antenna have a cross shape we will analyze only the characteristic of a microstrip line. The cross-shape elements in real antennas are used to generate the millimeter waves radiation with both polarizations.

The schematic of the microstrip line is shown in Figure 6. We assume that this line consists of a dielectric layer with permittivity ε and with the tangent of the dielectric losses tan δ. This layer has a solid bottom metallic electrode and a strip top electrode with a width w and a thickness t. In the proposed antenna this upper electrode will be imitated by a thin silicon plate. As shown above, under illumination by light, a conductive strip can be created.

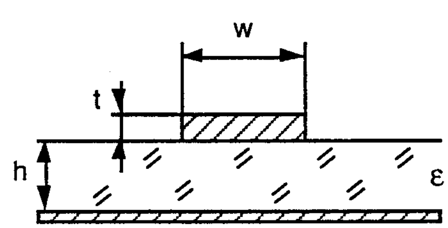


Figure 6
Schematic of a microstrip line.

To compare the parameters of the proposed line with those of a regular line, we used, as a first approach, the same sizes of electrodes and the same dielectric material. This material (0.010" Duroid) has a real thickness 260 μm, $\varepsilon = 2.2$ and $\tan\delta = 0.001$ at 94 GHz [1]. We used the value of $w = 130$ μm as measured in the sample from Malibu Research, Inc. The final aim of our calculation was to compare the electric and dielectric losses in the regular and in the proposed configurations. In the first approximation we didn't pay attention to the changes in the field distribution and to any additional losses caused by the presence of an additional dielectric layer in the form of the non-illuminated silicon on the top of the proposed line. The influence of this layer must be included in next approximations.

The thickness of the upper metal strip in our sample is 13 μm. In our calculation we assumed the thickness of the silicon layer to be 26 μm. Silicon plates of such thickness are now commercially available, for example from Virginia Semiconductor, Inc. (Fredericksburg, VA).

The assumed layer is thicker than the skin layer r_s in the illuminated silicon at 94 GHz. $r_s = \sqrt{\frac{2}{\pi\mu\omega\sigma}}$, where $\mu = 1.252 \cdot 10^{-7}$ is the magnetic permittivity, σ is the electrical conductivity, and $\omega = 2\pi f$, where f is the frequency of the millimeter wave.

For illuminated silicon $r_s = 7.7$ μm, and for copper it is only 0.133 μm.

The effective electrical resistance of the skin layer R_s is equal

$$R_s = \sqrt{\frac{\omega\mu}{\sigma}}$$

$R_s = 2 \cdot 10^{-6}$ ohm for copper and $R_s = 6.9 \cdot 10^{-2}$ ohm for silicon.

The following set of formulas [2] was used assuming $w/h < 1$ and $w/h > \frac{1}{2\pi}$

$$\frac{w'}{h} = \frac{w}{h} + \frac{1.25}{\pi} \cdot \frac{t}{h}\left(1 + \ln\frac{2h}{t}\right)$$ – dimensionless geometric parameter,

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} F\left(\frac{w}{h}\right) - \frac{\varepsilon_r - 1}{4.6} \cdot \frac{t/h}{\sqrt{w/h}}$$ – effective dielectric constant in low-frequency approximation

where

$$F\left(\frac{w}{h}\right) = (1+12\ h/w)^{-\frac{1}{2}} + 0.04(1-w/h)^2;$$

$$Z_o = \frac{\eta_o}{2\pi\sqrt{\varepsilon_e}}\ln\left(\frac{8h}{w'} + 0.25\frac{w'}{h}\right)$$ - characteristic impedance, where

$\eta_o = 377$ ohm is the characteristic impedance of free space.

$$\alpha_c = 1.38\frac{R_s}{hZ_o}\ \frac{32-(w'/h)^2}{32+(w'/h)^2}\Lambda$$ is the attenuation constant due to the resisttivity of the top electrode (db/unit length),

where

$$\Lambda = 1 + \frac{h}{w'}\left(1 - \frac{1.25}{\pi}\cdot\frac{t}{w} + \frac{1.25}{\pi}\ln\left(\frac{2h}{t}\right)\right)$$

$$\alpha_d = 27.3\frac{\varepsilon_r}{\sqrt{\varepsilon_e}}\cdot\frac{\varepsilon_e - 1}{\varepsilon_r - 1}\cdot\frac{\tan\ \delta}{\lambda_o}$$ – attenuation constant due to dielectric losses,

where λ_o is the wavelength of the millimeter wave in the free space.

Q is the quality factor:

$$\frac{1}{Q} = \frac{1}{Q_o} + \frac{1}{Q_r}$$, where

$$Q_o = \frac{8.68\ \pi\ \sqrt{\varepsilon_e(f)}}{\lambda_o(\alpha_c + \alpha_d)}$$ is the quality factor due to the dielectric losses and conductive losses in the microstrip line,

$$Q_r = \frac{Z_o(f)}{480\ \pi\ (h/\lambda_o)^2 R}$$ is the quality factor due to radiaton from the microstrip line.

In these formulas

$$\varepsilon_e(f) = \left(\frac{\sqrt{\varepsilon_r} - \sqrt{\varepsilon_e}}{1 + 4\,F^{-1.5}} + \sqrt{\varepsilon_e} \right)^2 \text{ – effective dielectric permittivity,}$$

where

$$F = \frac{4h}{\lambda_o} \sqrt{\varepsilon_r - 1} \left\{ 0.5 + \left[1 + 2\log\left(1 + \frac{w}{h} \right) \right]^2 \right\}$$

$$Z_o(f) = Z_o \frac{\varepsilon_e(f) - 1}{\varepsilon_e - 1} \sqrt{\frac{\varepsilon_e}{\varepsilon_e(f)}}$$

$$R = \frac{\varepsilon_e(f) + 1}{\varepsilon_e(f)} - \frac{[\varepsilon_e(f) - 1]^2}{2[\varepsilon(f)]^{3/2}} \ln \frac{\sqrt{\varepsilon_e(f)} + 1}{\sqrt{\varepsilon_e(f)} - 1} \; .$$

The results of the calculations are shown in Table 1.

Table 1 Parameters of Microstrip Lines

Type and size of top electrode	Electrical conductivity of the top electrode material $ohm^{-1} \cdot cm^{-1}$	Resistivity of the skin-layer R_s, ohm	Attenuation due to the conductivity of the top electrode, α_c db/cm	Attenuation due to dielectric losses, α_d, db/cm	Quality Factor (conductivity + dielectric losses) Q_o	Quality Factor (radiation factor)
Cu, t = 13 μm	$5 \cdot 10^5$	$8.43 \cdot 10^2$	0.19	0.08	400	10.7
Cu, t = 26 μm	$5 \cdot 10^5$	$8.43 \cdot 10^2$	0.16	0.08	454	10.3
Illuminated Si, t= 26 μm	$1.53 \cdot 10^1$	4.7	9.07	0.08	11.9	10.3

Although a microstrip line with a silicon top electrode has larger conductive losses, due to lower electrical conductivity, than the line with a copper electrode, the value of the conductive loss is about the same as the value of radiative loss.

Close values of quality factors Q_0 and Q_r for this line gives reason to expect that the proposed optically controlled MMW beamsteering and beamforming antenna can operate with relatively small intrinsic losses under a reasonable light flux.

REFERENCES

1. Handbook of Microwave and Optical Elements, V. 1, Ed. by Kai Chang, John Wiley & Sons, 1989.

2. I. J. Bahl and P. Bhartia, "Microwave Solid State Circuit Design," Wiley, N.Y., 1988.

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Lev Sadovnik

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Physical Optics Corporation, R&D Division
20600 Gramercy Place, Building 100
Torrance, California 90501

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13. ABSTRACT *(Maximum 200 words)*
The parameters of a silicon-dielectric-metal microstrip line were compared with those of a metal-dielectric-metal microstrip line from an actual FLAPS antenna. The proposed structure has higher losses; this is caused by the electrical conductivity of the illuminated silicon electrode being lower than is the case with a line using a copper top electrode. However, the value of these conductive losses is on the same order as the radiative losses in the microstrip line used in FLAPS antenna. These results point to the feasibility of using the proposed type of a microstrip line in a light-controlled reconfigurable MMW antenna with reasonable energy losses and with a reasonable light flux.

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