DESIGN OF FREQUENCY-SELECTIVE SURFACES FORMED BY STRATIFIED DIELECTRIC LAYERS

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I. Introduction

Microwave frequency-selective surfaces (FSS) are often realized in microstrip technology where the element shape and spacing in an array of conducting patches or apertures within a conducting screen determine the selectivity of the configuration. Analyses to predict the reflection and transmission characteristics of such structures are presented in, e.g., [1-4]. Since at millimeter frequencies, dielectric structures offer the advantage of lower absorption loss compared to metallic screens, a periodic layer composed of alternating dielectric bars has been proposed in [5]. Although a 40 percent bandwidth for 90 percent transmission is obtained, the bandwidth for 90 percent reflection is extremely narrow (below 2.5 percent), thus severely limiting the application of this structure.

Therefore, this paper focuses on an alternative approach consisting of periodically stratified dielectric layers (Fig.1) to obtain the frequency selective properties. These structures are widely used in thin-film optics as anti-reflection or high-reflectance coatings and as edge filters [6,7]. At microwave and millimeter-wave frequencies, however, the number of layers must be limited in order to reduce losses, the weight of the constructed surface and the amount of material required.

This paper investigates the feasibility of this structure as a frequency-selective surface at millimeter waves. The response as a function of polarization, absorption loss and angle of incidence is optimized to obtain wider bandwidths for both transmission and reflection and, at the same time, to enhance the tolerance of incidence angle variation.

II.Theory

As in thin-film optics, the dielectric layers are arranged according to a sequence of alternate refractive indices (n_H, n_L, n_H, $n_L \cdots n_H$) with a number of 2N+1 layers (Fig. 1). The higher the ratio of n_H/n_L, the higher the reflection obtained with less number of layers. The high index is arranged outermost for maximum reflection for a given odd number of layers. The losses of the dielectric layers are considered by introducing the complex relative permittivity $\varepsilon=\varepsilon'(1-j\tan\delta)$.

For a given configuration and polarization of the incident wave, the overall behavior of the FSS is obtained by multiplying the normalized transmission matrices as applied in thin-film optics [7, 8]. The power reflection and transmission coefficients as well as the absorbtion losses are given by

$$R = r\,r^* = \left(\frac{p_0 - Y}{p_0 + Y}\right)\left(\frac{p_0 - Y}{p_0 + Y}\right)^* \tag{1}$$

$$T = p_0 \frac{1-R}{\mathrm{Re}\{BC^*\}} \tag{2}$$

$$A = 1 - R - T \tag{3}$$

where $Y=C/B$ and p_0 are the input admittance of the assembly and the admittance of the incident-wave region, respectively.

For given dielectric materials, optimization techniques such as DFP (Davidon-Fletcher-Powell) and BFGS (Broydon-Fletcher-Goldfarb-Shanon) algorithms [9] are used to minimize an error function

$$e(f,d) = \sum_{f\in\Omega_1} [R(f,d)-1]^2 + \sum_{f\in\Omega_2} [R(f,d)]^2 \tag{4}$$

with respect to the vector d of layer thicknesses. Ω_1 and Ω_2 are the desired frequency ranges of high reflection and high transmission, respectively.

III. Results

Dielectric materials from Roger's RT/duroid series [10] with RT/duroid 6010.5 as n_H ($\varepsilon'=10.5$, $\tan d\delta=0.0023$) and RT/duroid 5880 as n_L ($\varepsilon'=2.20$, $\tan\delta=0.0009$) are used as design examples. Without loosing generality, an incident angle is assumed to be $\theta=45°$.

Figs. 2 show the responses of an assembly consisting of a quarter-wave stack at the reference frequency *fo* ($\beta=\pi/2$ *for both high and low index layers at fo*) The transmission, reflection and absorption behavior of an incident TE (Fig. 2a) and TM wave (Fig. 2b) are plotted versus normalized frequency for a number of $2N+1=5$ layers. The 3dB bandwidths of reflection are 73 percent and 59 percent for TE and TM waves, respectively. Absorption and transmission peaks occur at the same frequencies, and the absorption trend increases with frequency. If $f/fo=0.32$ is chosen for transmission due to the low absorption loss at this frequency, then the 3dB *transmission* bandwidth for a TM wave (Fig. 2b) is very large, but only 16 percent for a TE wave (Fig. 2a). Fig.3 shows the influence of incident angle variation on the TE wave transmission response. It is demonstrated that quarter-wave stack structures only allow about ±3 degrees of incident angle variation.

By reducing the ripple in the transmit passband region, the bandwidth and, at the same time, the tolerance of the incidence angle variation can be improved. As a design example, optimization techniques are used to obtain high reflection at $1.0\le f/fo\le 1.4$ and high transmission at $0.4\le f/fo\le 0.8$ *for* $2N+1=5$ *layers and* $\theta=45°$. The optimized values are $\beta_1=\beta_5=0.314$, $\beta_2=\beta_4=2.120$, $\beta_3=1.347$ which, assuming 40GHz operation, translate into the following substrate thicknesses: $d_1=d_5=0.51$mm, $d_2=d_4=7.6$mm, $d_3=2.21$mm. Figa. 4a *and* 4b *show the* reflection, transmission and absorption characteristics for the TE- and TM-wave cases, respectively. A 3dB transmission bandwidth of 50 percent is achieved. The influence of incident angle variation for the optimized structure is demonstrated in Fig. 5. Compared with the quarter-wave solution of Fig. 3, the permissible tolerance margin of the optimized FSS has been significantly enhanced.

IV. Conclusion

The characteristics of frequency-selective surfaces formed by stratified dielectric layers are investigated. It is demonstrated that the structure is well suited for millimeter-wave operation and that by optimizing the frequency response with respect to polarization, absorption loss and incidence angle, wider bandwidths and enhanced incident-angle tolerances can be achieved. A design example is given for *operation at* 40 GHz.

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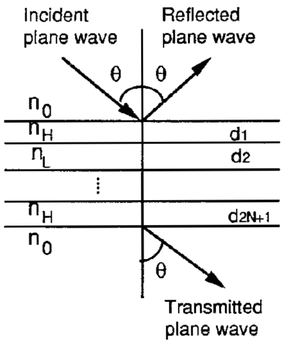
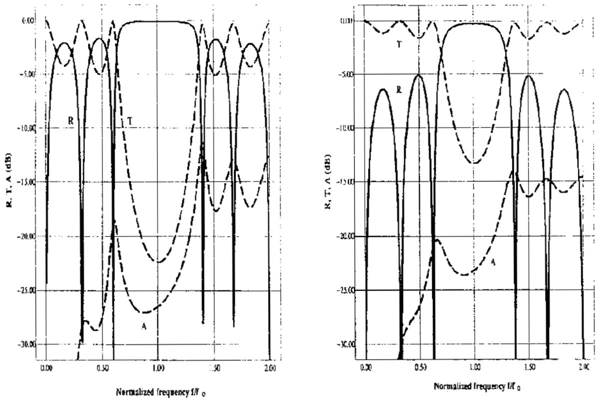


Fig.1 Frequency selective surface composed of stratified dielectric layers.



a **b**

Fig.2 Frequency response of quarter-wave stacked five-layer FSS with θ=45°. a) TE wave; b) TM wave.

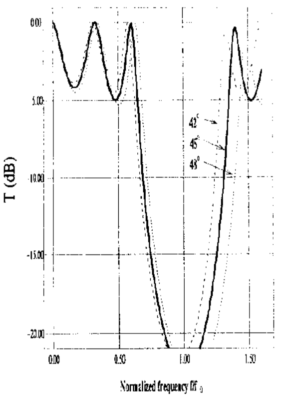


Fig.3 Variation of transmission coefficient with incident angle (TE-wave case).

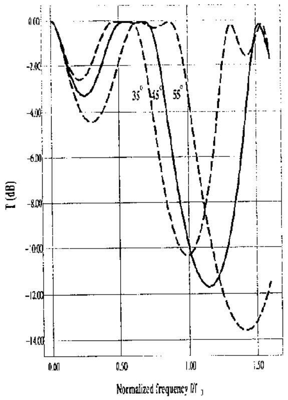
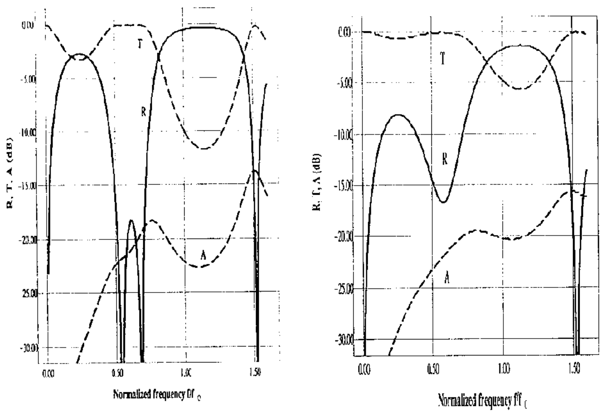


Fig.5 Variation of transmission with incident angle for optimized FSS (TE-wave case).



a b

Fig.4 Frequency response of optimized five-layer FSS with θ=45°. a) TE wave; b) TM wave.