Dual-polarization large scan angle broadband thick metallic FSS

Negar Ehsan[1], Hung Loui[2], and Zoya Popović[1]

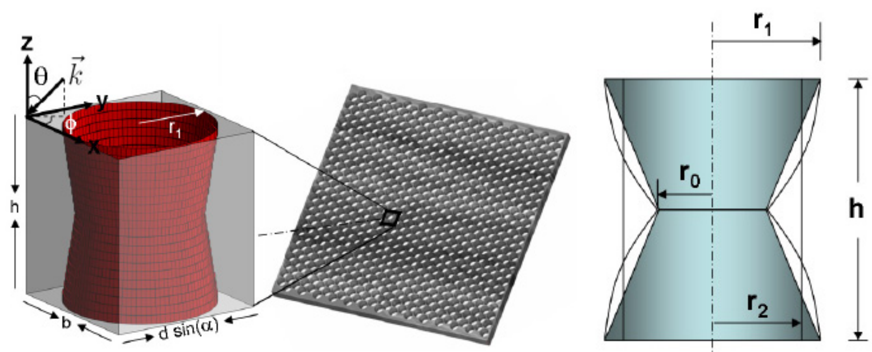
[1] Department of Electrical and Computer Engineering, University of Colorado, Boulder, CO, 80309

[2] Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185

Introduction

Over the past decades excellent work has been done in the area of analysis and design of a large variety of FSSs (Frequency Selective Surfaces), which are beautifully reviewed in [1] and [2]. A relatively small portion of this large body of work is devoted to thick metallic FSSs, which are useful when mechanical stability is required. It is also difficult to design an FSS that has equalized TE and TM responses, especially over a broad bandwidth. The added dimension of a thick FSS allows an additional design parameter that enables enhanced control of TE and TM responses.

This paper describes the design, fabrication, and characterization of a large scan angle FSS comprised of a periodic array of tapered holes as shown in Figure 1(a). The performances of three FSSs with different taper profiles and equal hexagonal lattices are compared. FSSs with cylindrical, linearly tapered, and cosine tapered holes (Figure 1(b)) show dramatically different TE and TM wide scan angle transmission responses for 18–27 GHz. Measurements are compared to simulation for a cosine tapered K-band thick metallic FSS which shows the widest bandwidth and largest scan angle for TE and TM transmission response.



(a) (b)

Figure 1: (a) A thick ($\lambda_0/2 = 9.24$ mm) FSS with tapered holes filled with paraffin wax ($\epsilon_r = 2.33$). (b) Geometry comparisons of a linear taper and cosine taper with $r_0 = 0.7r_1$ and a straight perforation with $r_2 = 0.9r_1$.

Design and Fabrication

A thick metallic K-band FSS is designed with a periodic array of cosine tapers. The thickness of the metal plate is $\lambda_0/2$ (9.24 mm) at 21 GHz. The radius of this taper as a function of thickness is given by

$$r(z) = r_1 \left(0.7 + 0.3 \left|\cos\left(\frac{\pi}{2} + \frac{\pi}{h} z\right)\right|\right) \qquad -\frac{h}{2} \leq z \leq \frac{h}{2} \tag{1}$$

and the cross-section is shown in Figure 1(b).

Each hole is a metallic waveguide that is analyzed using standard waveguide theory. The outer diameter of the cosine taper profile is chosen such that the cutoff frequency of the fundamental mode, TE_{11}, is 17.6 GHz when paraffin wax ($\epsilon_r = 2.33$) is used as the filling dielectric. The outer diameter (r_1) is found to be 3.264 mm and the inner diameter is set to 2.285 mm ($0.7r_1$). The lattice spacing is chosen to avoid grating lobes for all scan angles; for a hexagonal lattice this corresponds to $\lambda_0/\sqrt{3}$, which is 8.24 mm at 21 GHz. In the experimental model a square 25 cm^2 aluminum plate is machined using a custom designed end mill. The holes are filled with melted paraffin wax. When the paraffin wax hardens, the front and back of the plate are then planarized.

Simulation and Experimental Results

An in-house MATLAB code, which is based on Floquet modes, waveguide modes, and mode-matching technique, is used to efficiently simulate the profiles shown in Figure 1(b). The code allows fast iteration when compared to commercial code such as Ansoft HFSS, which takes significantly longer when the structures are sufficiently segmented for correct modes [4]. The cosine tapered and linearly tapered profiles are analyzed as 31 straight circular waveguide sections each 0.298 mm thick. The outer and inner diameter of the linear taper are same as those for the cosine taper and the radius of the straight holes is $0.9r_1 = 2.94$ mm as shown Figure 1(b).

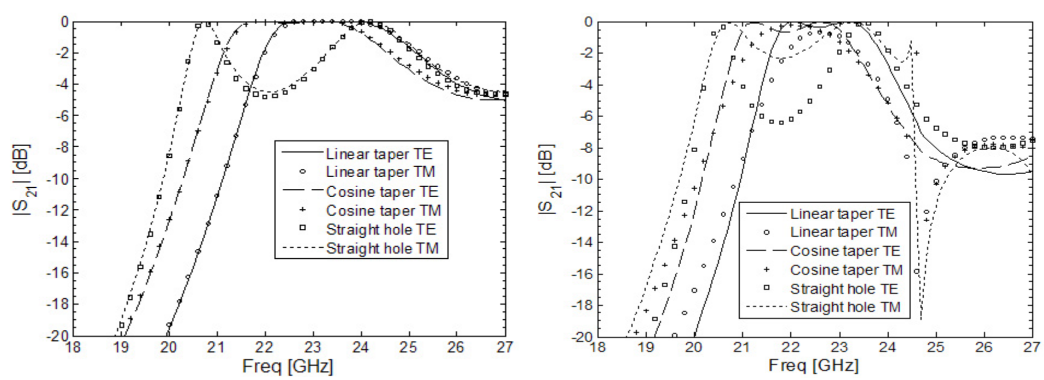


Figure 2: TE and TM transmission coefficient (S_{21}) as a function of frequency for thick FSS with hole profiles shown in Figure 1(b). The holes are filled with parafin wax. The plane of incidence is $\phi = 90°$, and the angle of incidence is $\theta = 15°$ (left), and $\theta = 45°$ (right).

In both TE and TM transmittance response of an FSS comprised of a periodic array of straight holes, multiple sharp resonances exist [3], which affect the usable bandwidth of transmission response at larger incident angles. The sharpness of the resonances depends on the Q-factor, which depends on the ratio of circular waveguide diameter and lattice dimensions. In order to reduce the sharpness of the resonances the Q-factor should be decreased. This can be done by using the linear taper profile shown in Figure 1(b). A total of 31 straight waveguide sections each 0.298 mm thick with $r_1 = 3.264$ mm are used for the linear taper. Figure 2 shows the simulated magnitude of the transmission coefficient ($|S_{21}|$) comparison between FSS created by straight holes, linear tapers, and cosine tapers for $\theta = 15°$ & $\theta = 45°$. As expected, the pass-band ripple between the two dominant resonance peaks in both TE and TM responses is reduced for both the linear and cosine tapers. Figure 2 also shows that in addition to reducing the pass-band ripple when compared to the straight hole, the cosine taper also produces a wider transmission bandwidth than the straight taper. This is due to the gradual change of cut-off frequencies of waveguide layers near the air-metal interfaces [4].

The fabricated FSS (periodic array of cosine tapered holes) is measured with a VNA and two open-ended rectangular waveguide probes, utilizing a straightforward procedure described in [3]. Figure 3 shows the simulated and measured magnitude and phase of transmission coefficient for both TE and TM polarizations when the angle of incidence is $\theta = 30°$. The reference plane is set at the front and back of the plate. This figure shows the close agreement between the simulated and measured results.

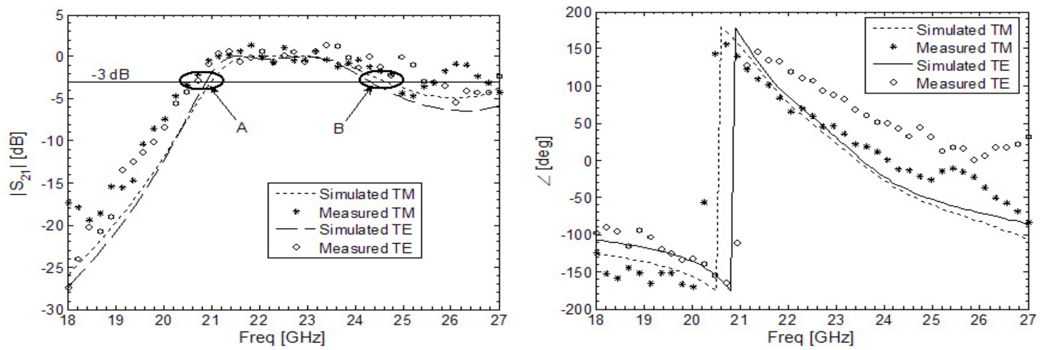


Figure 3: (Left) magnitude and (right) phase of transmittance of both TE and TM polarization for the incident angle of $\theta = 30°$. Ellipse A and ellipse B in the magnitude plot (left) represent the lower and higher side of 3 dB bandwidth.

This FSS is designed for incident angles up to $\theta = 75°$ off normal. However, an increase in incident angle decreases the transmission bandwidth. Figure 4 shows points A and B indicated in Figure 3 (left) — 3-dB low and high transmission bandwidth respectively — for simulated and measured TE and TM polarization of incidence angles up to $\theta = 75°$. Simulated and measured TE results match closely for all incident angles, but the measured 3-dB bandwidth is 200 MHz larger than the simulated result. For TM, as the incident angle increases above $\theta = 45°$ some resonances appear in the simulated transmission response which are not observable in the measured results.

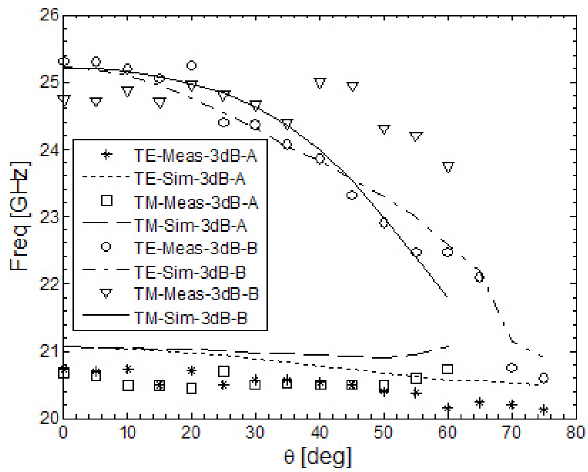


Figure 4: Ellipses A and B in Figure 3 show the low and high -3 dB points of the transmission band. This figure plots that transmission bandwidth as a function of incident angle θ.

Discussion

The thick periodic array of cosine tapers was designed with the in-house code as mentioned; since this code is based on the Extended General Scattering Matrices [4] other structures such as the Klopfenstein taper can be easily designed and fabricated for further performance comparisons. The fabricated plate will be measured through a more accurate measurement system, specifically, a focused Gaussian beam system. This system focuses the transmitted power to a specified spot size. It can also provide direct vector measurement for all four scattering parameters. The measurement system that were used (two open ended waveguide probes) was chosen due to its simplicity.

References

[1] T.K. Wu, *Frequency Selective Surface and Grid Array*, New York: J.Wiley & Sons, 1995.

[2] B.A. Munk, *Frequency Selective Surface Theory and Design*, New York: J. Wiley & Sons, 2000.

[3] H. Loui, E. Kuester, F. Lalezari, and Z. Popovic, "Thick FSSs for large scan angle applications," in *Proc. IEEE Antennas and Propagat. Society International Symposium*, vol. 2, Monterey, CA, June 2004, pp. 2171-2174.

[4] H. Loui, "Modal analysis and design of compound gratings and frequency selective surfaces," Ph.D. thesis, University of Colorado, Boulder, CO, U.S.A, 2006.