A Tuneable, Switchable Dielectric Grating

Mark D. Bushbeck and Chi H. Chan

Abstract—**Electromagnetic scattering characteristics of dielectric gratings are examined numerically using the finite-element method. The gratings are created by introducing pressurized dielectric fluid into periodic tubes within a dielectric sheet. A structure is presented which has an extremely narrow stop-band (total power reflection) immediately adjacent to a pass-band (total transmission). It is shown that the critical bands can be shifted by changing the fluid pressure, at a cost of only slightly less than perfect pass-band transmission (97%), while the rejection band remains perfect (100%). Thus, a unique tuneable, switchable frequency selective surface can be easily realized.**

I. Introduction

In recent literature, various methods have been used to study the transmission and reflection characteristics of periodic dielectric gratings in the microwave and optical regions of the frequency spectrum [1]–[8]. An advantage of purely dielectric arrays over the conventional metallic screens is their low absorption loss [7]. In other applications, the use of lossy materials allows greater design flexibility and increased control over the scattering characteristics, including bandwidth [9].

We desired to further investigate the scattering properties of dielectric structures similar to those in [1]–[8] to explore how geometric and dielectric parameters affected the scattered fields. This was to constitute a basis by which to assess the feasibility of using such structures as switchable, tunable frequency selective surfaces.

For this study, the finite-element method (FEM) was applied in two dimensions [10]–[11]. Periodic boundary conditions were enforced along the gratings, while continuity of the tangential field components was enforced at the upper and lower material interfaces, as in [8]. The analysis focused upon the structures shown in Fig. 1, each consisting of a thick dielectric sheet containing shaped hollow passages arranged in a periodic pattern, injected with various dielectric fluids. In considering the structures for use as switchable gratings, we noted several possible modes of operation. In particular, there are two distinct avenues by which a periodic nature may be achieved: geometric or electrical periodicity. A hybrid mode incorporates both distinct modes simultaneously, as shown in Fig. 1(b).

For a grating with low pressure fluids, there is no bulging at the interface, and switching action is accomplished by altering the permittivity. When the injected fluid electrically matches the support structure, the grating is considered to be in the switched-off state, wherein a simple dielectric sheet remains. Injecting a fluid with a different permittivity restores the periodicity. This is considered to be the switched-on state.

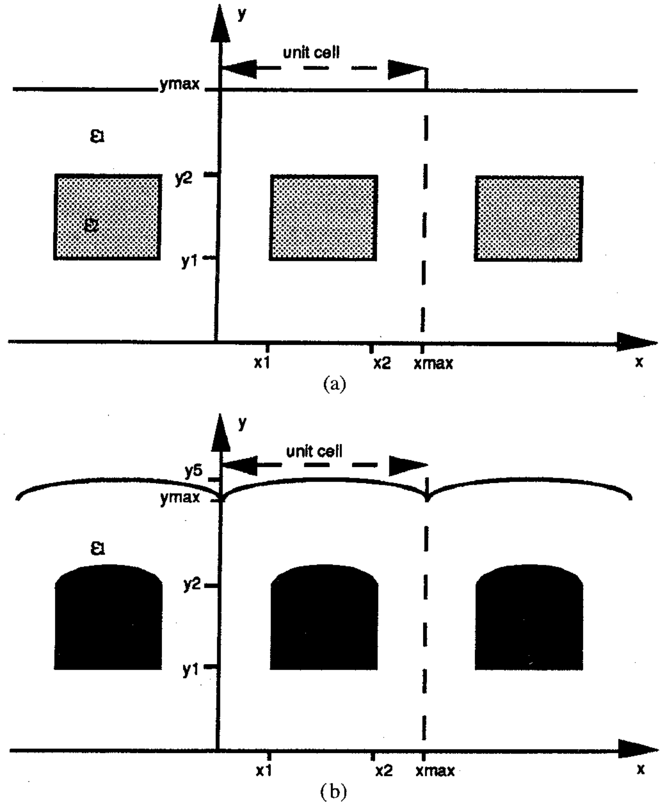

Fig. 1. (a) A periodic dielectric grating. (b) A pressurized periodic dielectric grating.

Generally, the gratings can be made of polypropylene, polyethylene, or similar low-loss plastics. For the lower interface, more rigid materials like fiberglass might be considered (which are easily bondable to plastics). Any number of dielectric fluids could be used, provided low enough viscosity to prevent unwanted bulging. Some lossy fluids might enable the gratings to have additional control over rejection frequencies and bandwidth.

II. Considerations

To validate our finite-element calculations, we compared our results with mode matching techniques [7] for the rectangular structures, and with a finite difference method [8] for various dielectric gratings with periodic sinusiodal interface profiles [11]. Other references [1]–[6] were used for further comparisons. In general, very good agreements were realized except

Manuscript received April 19, 1993.
The authors are with the Electromagnetics & Remote Sensing Laboratory, Department of Electrical Engineering, University of Washington, Seattle, WA 98195.
IEEE Log Number 9211887.

1051–8207/93$03.00

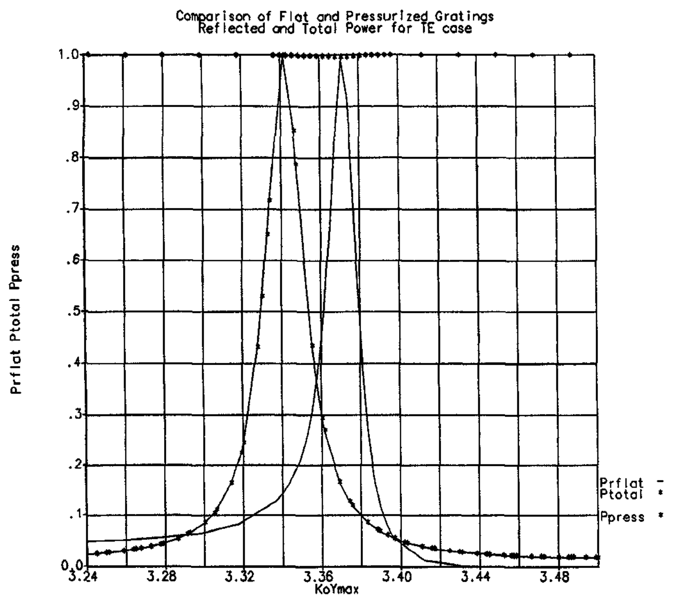

Fig. 2. Selecetive rejection, TE case.

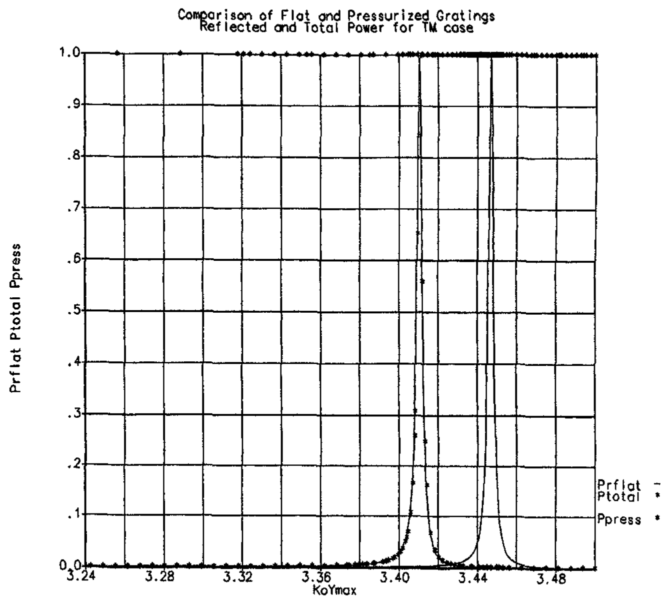

Fig. 3. Selective rejection, TM case.

that mode 1, a propagating mode, is mistakenly omitted in [8, p. 1030]. We have also performed extensive convergence studies of the finite-element method. Interested readers are referred to [11] for detailed discussions of validation and convergence. Power conservation is included in the results section. While empirical data is not currently available for the structures presented herein, the authors agree that such data would be useful for verification of the analytical results, and hope to include measured data in subsequent work.

Refer to the rectangular grating geometry shown in Fig. 1(a). The ratio of the unit cell height to width ($Y_{\max}/X_{\max}$) was kept equal to one, as well as the ratios y_1/x_1 and y_2/x_2. The other physical constraints were that $y_1 = Y_{\max}/3$ and $y_2 = 2^*Y_{\max}/3$. The analysis was conducted at an incident angle of 45°. The relative permittivity of the substrate ε_{r1} was 1.44, and that of the injected fluid ε_{r2} was 2.56 (values typically used in the literature).

Next, refer to the pressurized grating geometry shown in Fig. 1(b). In the analysis, only the upper surface was allowed to expand, since in real applications, this is often the case. These gratings are usually mounted on a surface, or the interfaces are made of materials with different mechanical properties. The surface was allowed to protrude by 16.67%, so that the bulging at the center of the cell was equal to 1/6 of the initial height. This corresponds to a 1 millimeter (mm) bulge for a 6-mm cell with 2-mm interfaces and 4-mm walls. The parameters were otherwise the same as those for the square grating.

III. Results

In this section, we present results for the new tuneable and switchable structures. Computed data is shown for both the flat and pressurized gratings in free space (with flat lower surfaces). Reflected and total power is depicted for both the TE and TM polarizations.

A. The Transverse Electric Case

Fig. 2 shows the reflected power for the TE case as functions of normalized wavelength for each grating. The total power calculated is also included. This is for a horizontally directed electric field, perpendicular to the plane of the page. Only the zero order modes ($m = 0$) are presented since, for the region shown in the figure, only these modal powers are non zero. For a look at the higher order modes, the interested reader is referred to [11].

The sharp transitions near $K_o Y_{\max} = 3.36$ are interestingly very narrow banded. Notice that immediately after the stop band, there is a wide range of frequencies for which there is total transmission and nearly total transmission for the relaxed and pressurized gratings, respectively. This results in an extremely effective frequency selective behavior.

As the graph shows, there is a slight lowering of the rejected frequency when the cell is bulged. This results in a slightly less efficient transmission above the stop band, and somewhat better transmission below. The effect makes the overall response more symmetric about the rejected frequency at a cost of losing the total transmission region.

B. The Transverse Magnetic Case

Finally, results are shown for the same relaxed and pressurized gratings under illumination from a TM wave. Fig. 3 shows the reflected power for each case, and the total power.

Notice how much more symmetric the response is about the rejected frequency when compared with the TE case. Although pressurization alters the overall envelope much less here than previously, note that there is a similar lowering of the rejected frequency. Also notice that the stop band locations are different for each polarization.

IV. Conclusion

The FEM is effective for finding the scattering properties of periodic dielectric gratings. It can provide accurate results for gratings with arbitrary yet well-defined periodic profiles. The method in [11] applies equally well for either polarization, and is easily applied to multilayered dielectrics.

It was shown that the critical frequencies for total reflection from a dielectric array could be physically altered in a controllable way. Specifically, it was shown that the stop band could be frequency shifted, with a slight modification of the response envelope. The TM pass band for the flat grating was naturally more symmetric about the rejection frequency, and thus was not as affected by pressurization as the TE pass band envelope. One might also notice that the rejection bandwidth, as might be defined by the half power points, is significantly wider for the TE case than for the TM case. Finally, the stop band location was different for each polarization, which may be taken advantage of in certain applications.

Thus, it seems that the feasibility of using periodic dielectric arrays as tunable, switchable frequency selective gratings is quite promising. These structures are versatile and easily realizable. The rejection bands can be modulated by either physical or electrical means. Further, advantage may be taken of the similarities or the differences in response due to polarization.

Similar studies are intended to be topics of future correspondence. Investigations are underway to study the effects of using electrically or magnetically lossy fluids and substrates. Other studies will further assess the effects of various metallic boundaries.

References

[1] H. L. Bertoni, and T. Tamir, "Analysis of periodic thin-film structures with rectangular profiles," *Optics Commun.*, vol. 10, no. 1, pp. 91–94, Jan. 1974.

[2] M. G. Mohram and T. K. Gaylord, "Diffraction analysis of dielectric surface-relief gratings," *J. Opt. Soc. Amer.*, vol. 72, no. 10, pp. 1385–1392, Oct. 1982.

[3] K. Knop, "Rigorous diffraction theory for transmission phase gratings with deep rectangular grooves," *J. Opt. Soc. Amer.*, vol. 68, no. 9, pp. 1206–1210, Sept. 1978.

[4] M. G. Moharam and T. K. Gaylord, "Rigorous coupled-wave analysis of planar-grating diffraction," *J. Opt. Soc. Amer.*, vol. 71, no. 7, pp. 811–818, July 1981.

[5] ——, "Rigorous coupled-wave analysis of grating diffraction: E-mode polarization and losses," *J. Opt. Soc. Amer.*, vol. 73, no. 4, pp. 451–455, Apr. 1983.

[6] ——, "Three-dimensional vector coupled-wave analysis of planar-grating diffraction," *J. Opt. Soc. Amer.*, vol. 73, no. 9, pp. 1105–1112, Sept. 1983.

[7] H. L. Bertoni, L.-H. S. Cheo, and T. Tamir, "Frequency-selective reflection and transmission by a periodic dielectric layer," *IEEE Trans. Antennas Propagat.*, vol. 37, no. 1, pp. 78–83, Jan. 1989.

[8] M. K. Moaveni, "Plane wave diffraction by dielectric gratings, finite-difference formulation," *IEEE Trans. Antennas Propagat.*, vol. 37, no. 8, pp. 1026–1031, Aug. 1989.

[9] R. C. Hall, R. Mittra, and K. M. Mitzner, "Scattering from finite thickness resistive strip gratings," *IEEE Trans. Antennas Propagat.*, vol. 36, no. 4, pp. 504–510, Apr. 1988.

[10] S. D. Gedney, J. F. Lee, and R. Mittra, "A combined FEM/MOM approach to analyze the plane wave diffraction by arbitrary gratings," *IEEE Microwave Theory Tech.*, vol. 40, no. 2, pp. 363–370, Feb. 1992.

[11] M. D. Bushbeck, "Applications of the finite element method: analysis of the electromagnetic scattering characteristics of periodic dielectric arrays," Masters Thesis, Univ. of Washington, Seattle, June 12, 1992.