Analysis and Applications of Dielectric Frequency-Selective Surfaces under Plane-Wave Excitation*

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1 Introduction

Planar structures consisting of multilayered periodic arrays, both dielectric[1] and metallic [2], have a frequency selective behavior. As a result, these structures may be used in a wide variety of active and passive devices operating in the microwave and optical frequency bands. In this paper we analyze multilayer dielectric frequency-selective surfaces (DFSS) using the formulation developed in [3] based in a vectorial modal method [4] for studying guidance and scattering by lossy all-dielectric guiding periodic structures. We show that ideal reflection (band-stop) filters with high efficiency can be designed by combining guided-mode resonance effects in DFSS with antireflection effects of thin-film structures, providing a symmetrical line shape with near-zero reflectivity over appreciable frequency bands adjacent to the resonance frequency. A reflection filter example employing common dielectric materials illustrates bandwidth control by grating modulation. Moreover, it is shown that the resonance frequency of the filter can be controlled by the angle of incidence. Finally, it is shown that double-band reflection filters can be obtained in structures containing two gratings with different grating periods, acting as a double-band filter at normal incidence with the center frequencies determined by the resonances of the individual single-layer waveguide gratings.

2 Principles of waveguide-grating reflection filters

To characterize waveguide-grating resonance filters, a vectorial modal method in combination with the generalized scattering matrix technique is used [3]. A very fast and efficient CAD tool has been developed for the analysis of the scattering of such structures, which allows to modify all the electrical and geometrical parameters, as the frequency, the grating period, the thickness, the polarization and the angle of incidence.

A simple DFSS with only one periodic layer is shown in Fig. 1. The periodic layer of period D is composed of two dielectric materials with relative permittivities ε_H and ε_L, and widths $l_H = l_L = D/2$, respectively, with the average dielectric constant being greater

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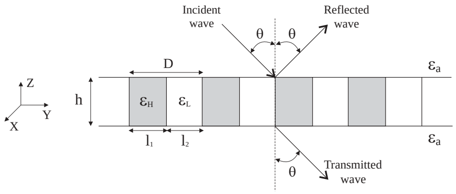

Figure 1: Diagram of a dielectric waveguide grating under plane-wave excitation

than the dielectric constant ε_a of the surrounding media in order for this layer to constitute a waveguide. The objective of this paper is to demonstrate the design of ideal reflection filters based on the guided-mode resonance filter principle in DFSS [1]. This involves determining the filter parameters such as the thickness and the relative permittivity of each layer necessary for obtaining the desired spectral response (i.e., symmetrical line shapes and low reflectivity around the central wavelength).

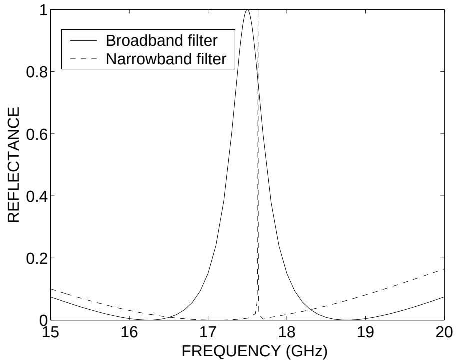

Figure 2: Spectral response of a reflection filter under normal TM plane-wave incidence. The relative permittivities are $\varepsilon_H = 6.13$, $\varepsilon_L = 3.7$ for the broad-band filter and $\varepsilon_H = 4.8$, $\varepsilon_L = 5.03$ for the narrow-band filter. $D = 11.95$ mm, $h = 2.95$ mm and $\varepsilon_a = 1.0$.

In a typical reflectance spectrum of a waveguide grating, it has been demonstrated that the zeroth-order grating has the reflectance and transmittance of a thin film with a dielectric constant equal to the average dielectric constant of the grating for the greater part of the spectrum. At specific values of the frequency and incident angle, the incident electromagnetic wave couples to the waveguide modes supportable by this guided structure. The approximate value for the resonance frequency location can be predicted imposing the phase-match condition for the equivalent unmodulated slab waveguide $k_0 \sin(\theta) = \beta_g - 2\pi/D$, where β_g is the propagation constant of the unmodulated waveguide in the y-direction and $2\pi/D$ is the wavevector provided by the grating. The periodic modulation of the guide makes the structure leaky, coupling the waves out of the grating, resulting in a transmission null or complete reflection.

In general, an arbitrary waveguide-grating geometry results in a resonance response with an asymmetrical line shape. For the case of a single-layer waveguide grating we can achieve a symmetrical line-shape filter at normal incidence by choosing the grating thickness to be near a multiple of half-wavelength (i.e., the resonance wavelength) in the layer. Obviously,

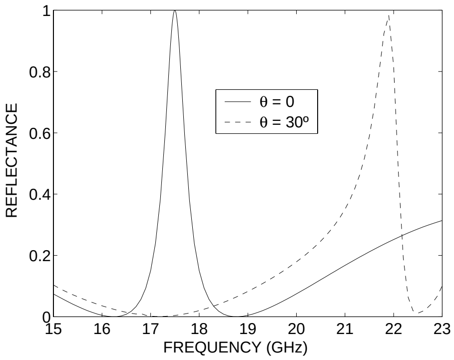

Figure 3: Effect of the angle of incidence on the reflection response.

when a single-layer waveguide grating designed for normal incidence is excited with a wave at a different angle of incidence, the reflectance spectrum is no more symmetric. Another effect of changing the angle of incidence is that the resonance frequency is shifted to higher frequencies. This displacement can be predicted through the phase-match condition. The bandwidth of guided-mode resonance reflection filters has been shown to increase with the modulation of the dielectric permittivity of the grating. This fact is due to increased leakage of the waveguide grating about the resonance frequency.

3 Reflection filters

A typical single-layer symmetrical reflection filter under TM normal plane wave incidence is shown in Fig. 2 (continuous line) . The grating period is $D = 11.95$ mm, and the grating materials have relative permittivities $\varepsilon_H = 6.13$ and $\varepsilon_L = 3.7$, $\varepsilon_a = 1.0$, and widths $l_H = l_L = D/2$. The periodic grating has thickness $h = 3.95$ mm, corresponding to a half wavelength at the resonance frequency of 17.5 GHz, with a bandwidth (full width at half maximum) $\Delta f \sim 500$ MHz. This reflection filter shows a symmetrical reflectance spectrum with small sideband reflection (see Fig. 2) in the band of $15 - 20$ GHz. In the same figure it is also shown the influence of the modulation on the bandwidth, where it is represented with dash line the reflection response at normal incidence of a waveguide grating with identical thickness and period, but with a lower modulation of the relative permittivity of the grating. A narrower-band filter response (dash line) is achieved with dielectric materials of relative permittivities $\varepsilon_H = 4.8$ and $\varepsilon_L = 5.03$, resulting in a bandwidth $\Delta f \sim 5$ MHz at a center frequency of 17.63 GHz. The effect of changing the angle of incidence of the incident plane-wave is illustrated in Fig. 3, where it is represented the spectral response of the reflection filter of Fig. 2 designed for normal incidence (continuous line) and compared with that corresponding to an angle of incidence of $\theta = 30^\circ$ (dash line). In this case, we can appreciate the asymmetry of the spectral response, as well as the displacement of the resonance frequency, which has shifted from 17.5 GHz to 21.8 GHz.

The method developed can also analyze multilayers with different periods. Finally, we have analyzed a multilayered periodic structure with two grating layers with dielectric materials of relative permittivities $\varepsilon_{1H} = \varepsilon_{3H} = 2.56$ and $\varepsilon_{1L} = \varepsilon_{3L} = 1.0$ of different period ($D_1 = 30.0$ mm and $D_2 = 29.0$ mm) and widths $h_1 = h_3 = 25.8$ mm, separated by an air layer of width $h_2 = 52.0$ mm under TE normal plane-wave excitation. This structure can

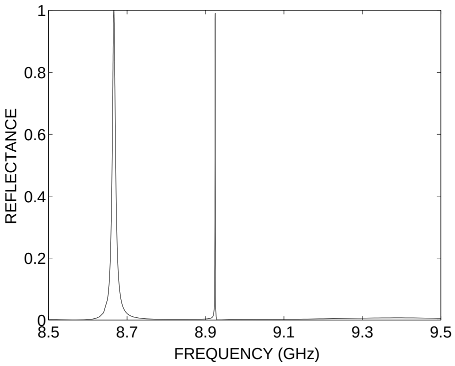

Figure 4: Double-band reflection filter

act as a double-band filter at normal incidence with the center frequencies determined by the resonances of the individual single-layer waveguide gratings. In Fig. 4 it is shown the reflection response of this structure, exhibiting two reflection peaks with a frequency difference between them of 258.4 MHz, which can be adjusted by changing the periods of the gratings. Choosing a smaller grating period difference and adding more waveguide gratings of successive slightly different periods can provide a bandwidth-broadening mechanism.

4 Conclusions

An ideal reflection (band-stop) filter with high efficiency and symmetrical shape under TM normal plane-wave excitation is theoretically demonstrated using a periodic dielectric grating. It is shown that the resonance frequency and the bandwidth of the filter can be controlled by the angle of incidence and the grating modulation, respectively. Finally, a double-band reflection filter under TE normal plane-wave excitation is obtained in a structure containing two gratings with different grating periods.

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