Dielectric Frequency-Selective Structures Incorporating Waveguide Gratings

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***Abstract*—In this paper, a frequency-selective structure based on guided-mode resonance effects in all-dielectric waveguide gratings is demonstrated theoretically and verified experimentally. Reflection (band-stop) filters with high efficiency, extended low-sideband reflection, and symmetric line shapes are designed by embedding gratings in layered antireflection structures. Reflection filter examples employing common dielectric materials illustrate linewidth control by grating modulation. An additional mechanism for linewidth control is demonstrated with phase-shifted gratings. Double-line reflection filters are obtained in structures containing two gratings with different grating periods. High-efficiency transmission (bandpass) filters are demonstrated using multilayer waveguide gratings in a high-reflectance thin-film configuration with a single grating in the center layer bordered by dielectric mirrors composed of high/low quarter-wave layers. Single-layer and multilayer waveguide gratings operating as reflection and transmission filters, respectively, were built and tested in the 4–20-GHz frequency range. The presence of guided-mode resonance notches and peaks is clearly established by the experimental results, and their spectral location and line shape is found to be in excellent agreement with the theoretical predictions.**

***Index Terms*—Bandpass filters, dielectric waveguides, frequency-selective surfaces, gratings, guide-mode resonance effect, periodic structures, waveguide filters.**

I. Introduction

DIELECTRIC waveguide gratings have been shown to possess resonance anomalies and unique frequency-selectivity properties that can be used to design reflection (band-stop) and transmission (bandpass) filters in the microwave-frequency [1]–[4] and optical-frequency [5]–[17] regions. This new type of filter, based on the guided-mode resonance phenomenon, combines principles of diffraction by periodic structures with waveguide theory and thin-film interference concepts to yield filters with high efficiency at a desired frequency and low sidebands extended over a sizable spectral range. In this paper, calculated characteristics of microwave waveguide-grating devices are presented, illustrating the variety of filtering devices that can be realized based on the guided-mode resonances. Reflection and transmission guided-mode resonance filters are fabricated and tested in the 4–20-GHz range with a close fit between the experimental and theoretical spectral response established.

A structure with multiple layers containing one or more gratings in separate layers can be used to obtain high-efficiency reflection or transmission filters depending on whether the thicknesses and dielectric constants are chosen to yield high transmission outside the stopband (i.e., antireflection (AR) design) or low transmission outside the passband (i.e., high-reflection (HR) design), respectively. The filter characteristics are tailored by adjusting the parameters of the device. Thus, the center frequency of the filter is determined principally by the grating period and influenced by the dielectric constants of the grating and layer thicknesses [7]. The sidebands can be made arbitrarily low and extended over a large frequency range by adding layers with dielectric constants and thicknesses obeying AR/HR conditions [9], [10]. The linewidth of the filter is determined by the difference between the dielectric constants of the materials within a grating period (i.e., grating modulation), by the difference between the average dielectric constant in the grating region and the dielectric constant of the surrounding medium, and by the fraction of the grating period occupied by the high dielectric-constant material (i.e., grating fill factor) [7]. Waveguide gratings with small grating modulation can generate filter linewidths comparable to those of YIG filters [18].

The principles of guided-mode resonance reflection and transmission filters will be discussed in Section II. Specific designs for microwave reflection and transmission filters are then described in Sections III and IV, respectively. Examples of single-layer and multilayer narrow-band and broad-band reflection and transmission filters using dielectric constants corresponding to practical materials are given with center frequencies in the spectral range of 8–16 GHz. The effect of spatial phase shifts of adjacent gratings on the filter linewidth is presented and multiline filters implemented with several gratings with different periods are introduced. Section V presents experimental verification of the theoretically predicted guided-mode resonances in waveguide gratings fabricated with commercially available inexpensive materials. A reflection filter exhibiting notches in the transmittance spectra at the guided-mode resonance frequencies is demonstrated with a single-layer Plexiglas grating, for both TE- and TM-polarized incident waves. Guided-mode resonance transmission peaks are obtained experimentally with a five-layer waveguide grating

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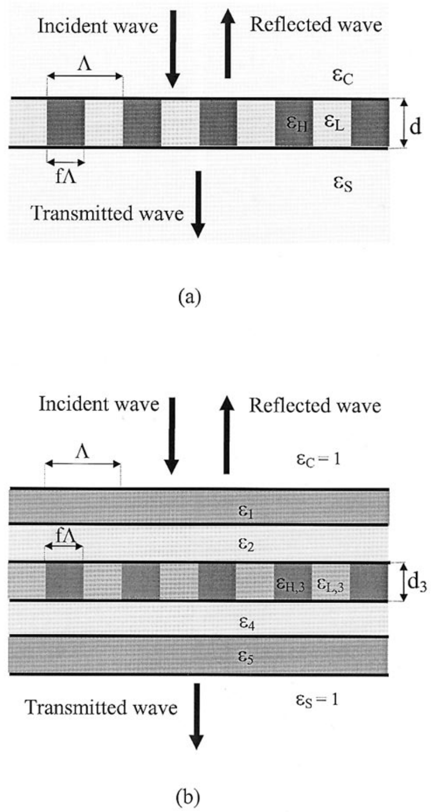

Fig. 1. (a) Single-layer and (b) multilayer square-wave profile waveguide grating under normal incidence. The grating period is denoted by Λ, fill factor by f, layer thicknesses by d, and dielectric constants by ε.

realized with G10 fiberglass. It is found that the resonance locations and other spectral characteristics measured for both reflection and transmission filters agree well with the theoretical predictions.

II. Principles of Waveguide-Grating Filters

The filtering properties of waveguide gratings originate in the guided-mode resonances that naturally occur in these structures. A simple waveguide grating with only one layer containing a planar rectangular grating is shown in Fig. 1(a). The grating is composed of dielectric materials (ε_H, ε_L) with the average dielectric constant being greater than the dielectric constants ε_C and ε_S of the surrounding media in order for this layer to constitute a waveguide. To maximize the efficiency of the device, a subwavelength grating period is chosen to admit only the zeroth diffraction orders propagating in reflection and transmission. A more general structure consisting of a stack of homogeneous and grating layers is the multilayer waveguide grating represented in Fig. 1(b).

To characterize waveguide-grating resonance filters, rigorous coupled-wave analysis [19] is used. Full solution of these equations yields the exact resonance frequency for a given angle of incidence as well as the diffraction efficiencies of the filters. Approximate values for the resonance frequency location and the free spectral range of the filters can be obtained with considerably less computation by solving the eigenvalue equation of the equivalent unmodulated slab waveguide corresponding to the

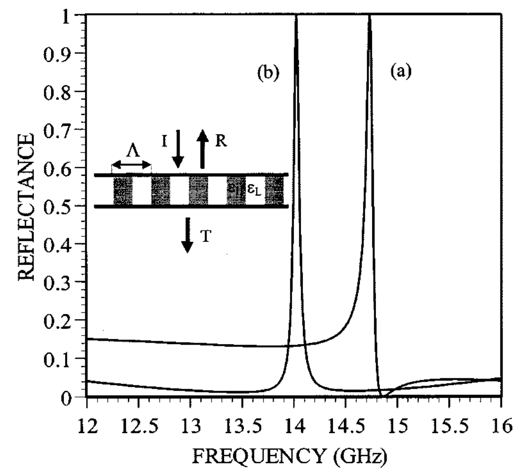

Fig. 2. Reflectance of a single-layer waveguide grating with grating period $\Lambda = 1.65$ cm and dielectric constants, $\varepsilon_H = 2.59$ (Plexiglas), $\varepsilon_L = 2.05$ (Teflon), and $\varepsilon_C = \varepsilon_S = 1.0$. The thickness is: (a) $d = 0.5$ cm and (b) $d = 0.7$ cm (half-wavelength).

waveguide grating [7], [9]. Additionally, resonance regime plots of incidence angle θ versus normalized resonance wavelength λ/Λ illustrate the $\theta - \lambda$ connection for the various diffraction orders [7], [16]. A filter design is polarization dependent; the TE and TM polarization states have different resonance locations, linewidths, and free spectral ranges. However, the principles and properties of the microwave waveguide filters presented in this paper are fundamentally similar regardless of polarization.

A typical TE-polarization (i.e., the electric vector normal to the plane of incidence of Fig. 1) reflectance spectrum for the device geometry of Fig. 1(a) is illustrated in Fig. 2. For the greater part of the spectrum, 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. At specific values of the frequency and incident angle, the diffractive element enables the incident electromagnetic wave to couple to the waveguide modes supportable by the structure. The periodic modulation of the guide makes the structure leaky, preventing sustained propagation of modes in the waveguide, but coupling the waves out into the substrate and cover. As the frequency is varied around the resonance, rapid variations in the phases of the reradiated waves occurs. The reradiated waves interfere with the directly reflected and transmitted fields to generate rapid variations in the intensity of the externally observable electromagnetic fields with respect to the frequency or angle of incidence of the incident wave. In particular, at the resonance frequency in Fig. 2, the forward-transmitted zeroth-order wave and the reradiated superimposed forward wave have equal amplitudes and are π radians out of phase, resulting in a transmission null and concomitant complete reflection, as shown in the figure. This paper focuses on the frequency dependence of the reflectance and transmittance of waveguide gratings for fixed angles of incidence.

The design of reflection filters based on the guided-mode resonance effect involves specifying the filter parameters such as the thickness and dielectric constant of each layer necessary to achieve symmetrical line shapes and reduced reflectance around the central wavelength. For the case of a single-layer waveguide grating, a symmetrical line-shape filter can be achieved by choosing the grating thickness to be near a multiple of half-wavelength (i.e., the resonance wavelength) in the layer and $\varepsilon_C = \varepsilon_S$ [8].

The sidebands can be substantially suppressed by adding homogeneous layers to form a multilayer waveguide grating, as shown in Fig. 1(b), and applying results from thin-film interference theory. A diffraction grating can be embedded into traditional AR designs provided the average dielectric constant of the layer remains unchanged, when substituting a homogeneous layer with a periodic one, thus reducing the reflectance in the sidebands to small values and over extended spectral ranges.

The basic guided-mode resonance effect has also been shown to enable transmission bandpass filters with high efficiency and a symmetrical response [10]. The basic element is a thin-film high/low (HL) dielectric-constant quarter-wave pair that is highly reflective in the absence of resonance effects. Low transmittance can be obtained by superimposing homogeneous quarter-wave layers of alternating HL dielectric materials, as in Fig. 1(b). A guided-mode bandpass filter results on replacing one or more of the homogeneous layers with gratings of equal average dielectric constant.

III. Reflection Filters

A typical single-layer reflection filter with air as cover and substrate ($\varepsilon_C = \varepsilon_S = 1.0$) has the calculated response shown in Fig. 2. The grating materials have dielectric constants $\varepsilon_H = 2.59$ and $\varepsilon_L = 2.05$ (corresponding approximately to the parameters of Plexiglas and Teflon, respectively) and a grating period $\Lambda = 1.65$ cm. As shown in Fig. 2(a), arbitrary thicknesses of the grating layer yield reflectance curves with asymmetrical line shape. Using a thickness of a half-wavelength, determined by the resonance frequency $\nu \sim 14$ GHz, a symmetrical diffraction efficiency with small sideband reflection [see Fig. 2(b)] in the spectral range of 12–16 GHz results. Adding two more layers with dielectric constants $\varepsilon_2 = 6.13$ (E-glass) and $\varepsilon_3 = 2.59$ (Plexiglas), approximately satisfying the three-layer AR condition $\varepsilon_{1,\text{eff}}^2 \varepsilon_3^2/\varepsilon_2^2 = 1$, and with quarter-wave thicknesses of the three layers, a high-efficiency filter is realized with a broad low-reflectance response (Fig. 3). For TE polarization $R < 1\%$ (-20 dB) in the range of 12–16 GHz and $R < 0.1\%$ (-30 dB) in the range of 13.0–14.9 GHz. A change in grating period shifts the resonance wavelength approximately linearly within the low-reflectance spectral region with insignificant changes in the filter line shape or sideband reflectance. A grating period $\Lambda = 1.3$ cm generates the TE and TM polarization spectral response illustrated in Fig. 3. The TM and TE resonances typically have similar sideband reflectance, but different frequency location, linewidth, and line shape. Thus, this structure is more robust parametrically than the single-layer waveguide grating since a slight change in one grating parameter has a reduced effect on the filter response. Almost identical filter characteristics can be obtained with the grating being contained in the second or third layer, provided that the AR condition is satisfied [9]. Multiple-layer filters allow for a greater flexibility in the choice of dielectric constants to achieve desired filter parameters as well as an increased control over the passband and the angular aperture of the filter.

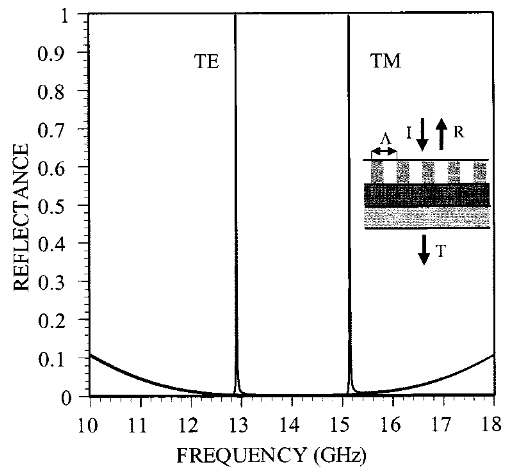

Fig. 3. Spectral response of a triple-layer guided-mode resonance reflection filter for TE (electric-field vector normal to the page) and TM polarization of the incident wave. The parameters are: $\Lambda = 1.3$ cm, $\varepsilon_{H,1} = 2.59$ (Plexiglas), $\varepsilon_{L,1} = 2.05$ (Teflon), $\varepsilon_2 = 6.13$ (E-glass), $\varepsilon_3 = 2.59, \varepsilon_C = \varepsilon_S = 1.0, d_1 =$ 0.35 cm, $d_2 = 0.22$ cm, and $d_3 = 0.33$ cm. The resonance peak frequencies are $\nu = 12.91$ GHz and $\nu = 15.15$ GHz, for TE and TM polarizations, respectively.

An important goal in filter design is spectral linewidth control. The linewidth of guided-mode resonance reflection filters has been shown to increase with the modulation of the grating and the dielectric-constant difference between the grating and substrate [7]. The increase with modulation is due to increased leakage of the waveguide grating about the resonance wavelength. A guided-mode resonance response with symmetrical line shape can be approximated by a Lorentzian function with the center frequency determined by the phase-matching condition of the external field to the waveguide mode and with the linewidth proportional to the waveguide coupling loss [12]. Therefore, an increased leakage of the grating generates a larger linewidth of the guided-mode resonance filter. A higher dielectric constant of the grating region leads to increased confinement of the modes in the associated unmodulated waveguide, thus resulting in a broadening of the linewidth [7]. The influence of the modulation on the bandwidth is illustrated in Fig. 4 by two examples of simple single-layer filters of fixed thickness ($d = 0.67$ cm) and grating period ($\Lambda = 1.61$ cm) at central frequencies close to 14 GHz. A narrow-band filter response [see Fig. 4(a)] is obtained with the grating made of Plexiglas ($\varepsilon_H = 2.59$) and polystyrene ($\varepsilon_L = 2.54$) resulting in a modulation of $\Delta\varepsilon = \varepsilon_H - \varepsilon_L = 0.05$, a central frequency $\nu \sim 13.74$ GHz, and a linewidth (full width at half maximum) $\Delta\nu \sim 1.5$ MHz. A larger modulation achieved with alternating bars of glass laminate ($\varepsilon_H = 3.0$) and Teflon ($\varepsilon_L = 2.05$) yields a modulation of $\Delta\varepsilon = 0.95$, a center wavelength $\nu \sim 14$ GHz, and a filter linewidth $\Delta\nu \sim 162.4$ MHz. The sideband reflectance of these filters can be reduced by adding layers with AR design, as demonstrated by the previous three-layer example.

An important advantage in the microwave spectral region is provided by the possibility of placing a grating in air and using air as the low dielectric-constant medium ($\varepsilon_L = 1.0$) as well as

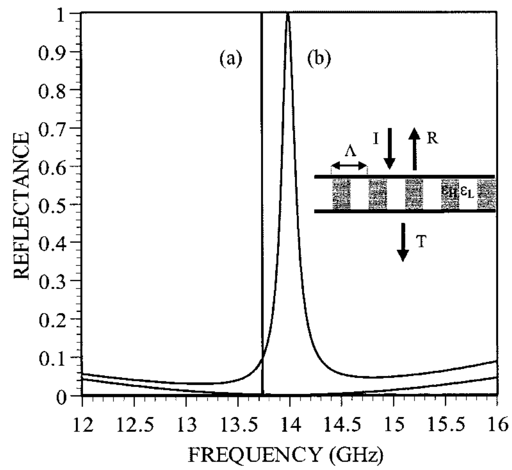

Fig. 4. Single-layer guided-mode resonance reflection filters with: (a) narrow-line (center frequency: $\nu \sim 13.7$ GHz, linewidth: $\Delta\nu = 1.56$ MHz) and (b) broad-band response (center frequency: $\nu \sim 14.0$ GHz, linewidth: $\Delta\nu = 163$ MHz). The dielectric constants are $\varepsilon_H = 2.59$ (Plexiglas) and $\varepsilon_L = 2.54$ (polystyrene) for the narrow-line filter and $\varepsilon_H = 3.0$ (glass laminate) and $\varepsilon_L = 2.05$ (Teflon) for the broad-band filter. Both structures have a grating period: $\Lambda = 1.61$ cm, a thickness: $d = 0.67$ cm, and air as cover and substrate medium: $\varepsilon_C = \varepsilon_S = 1.0$.

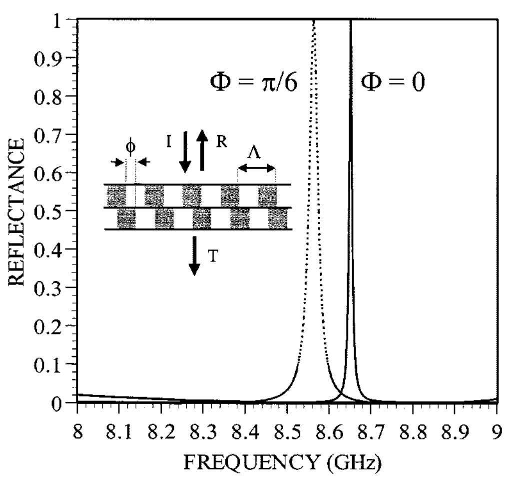

Fig. 5. Single-layer response of a guided-mode resonance filter in air ($\varepsilon_C = \varepsilon_S = 1.0$) with Plexiglas as the high dielectric-constant medium ($\varepsilon_H = 2.59$) and air as a low-dielectric medium ($\varepsilon_L = 1.0$). The period is $\Lambda = 3.0$ cm and thickness $d = 2.58$ cm. The dotted curve shows the reflectance of the two-layer structure obtained by shifting half of the grating by $\pi/6$ with respect to the other half, as shown in the inset.

the surrounding medium ($\varepsilon_C = \varepsilon_S = 1$). Fig. 5 (with $\Phi = 0$) shows a single-layer waveguide-grating filter made of Plexiglas bars ($\varepsilon = 2.59$) in air. This periodic set of rectangular bars has a large modulation as well as a large dielectric-constant difference between the grating region and the substrate. The grating with a period of $\Lambda = 3.0$ cm generates a resonance at the frequency $\nu = 8.65$ GHz with a bandwidth $\Delta\nu = 8$ MHz. Larger or smaller bandwidths can be obtained with larger or smaller dielectric constant materials, respectively.

The linewidths of guided-mode resonance filters are limited by the available low-loss microwave materials with the highest dielectric constants. Further increase in linewidth can be accomplished with spatially phase-shifted gratings obtained by translating one-half of the grating with respect to the other. Fig. 5 ($\Phi = \pi/6$) illustrates the spectral response of such a two-layer structure with $\pi/6$ shifted gratings. The resonance is broadened to $\Delta\nu = 24.4$ MHz and slightly shifted in frequency. Other values of the phase shift lead to a split-peak resonance caused by the different coupling conditions of the $+1$ and -1 diffracted orders to the waveguide modes of the device. At a certain value of the phase shift that depends on the waveguide-grating parameters (in this case $\pi/6$), the two peaks merge into a broadened reflectance peak. Considering a weakly modulated corrugated waveguide, Avrutsky *et al.* found that, for a particular spatial phase shift, the reflected wave was nearly extinguished [17].

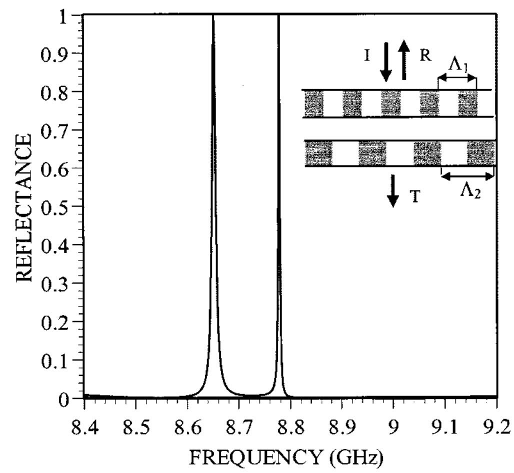

Fig. 6. Dual-line reflection filter response. The structure has three layers with two gratings in the first and third layers. The parameters are: $\Lambda_1 = 2.95$ cm, $\Lambda_2 = 3.0$ cm, $\varepsilon_{H,1} = \varepsilon_{H,3} = 2.59, \varepsilon_{L,1} = \varepsilon_2 = \varepsilon_{L,3} = \varepsilon_C = \varepsilon_S = 1.0$, $d_1 = d_3 = 2.58$ cm, and $d_2 = 5.2$ cm. Guided-mode resonance peaks are at frequencies $\nu_1 = 8.65$ GHz and $\nu_2 = 8.78$ GHz.

New possibilities emerge by use of structures with gratings of different periods in successive layers. For instance, a device with two gratings of slightly different periods in the three-layer geometry shown in the inset of Fig. 6 can act as a double-line filter at normal incidence with the center frequencies determined by the resonances of the individual single-layer waveguide gratings. The buffer layer placed between the two gratings should be thick enough to weaken the coupling between the evanescent waves of the two gratings. Fig. 6 shows the response of a three-layer device using two Plexiglas/air gratings of different periods separated by an air-gap buffer. The difference between the two grating periods is $\Delta\Lambda = 0.05$ cm, exhibiting nearly 100% reflection peaks with a frequency difference between them of 126.6 MHz (corresponding to a wavelength difference of 0.05 cm). The frequency difference between the two peaks can be adjusted by changing the periods of the gratings. For small grating period difference, resulting in partly overlapping resonance peaks, this approach can also provide yet another linewidth-broadening mechanism. However, this may also lead to a distorted filter line shape.

IV. TRANSMISSION FILTERS

Transmission filters can be obtained by superimposing the resonance of a waveguide grating on the high-reflectance

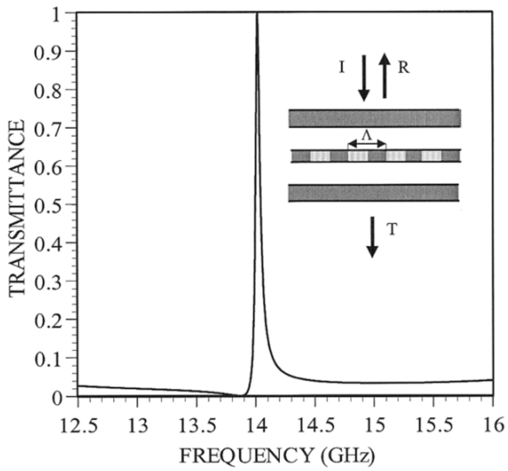

Fig. 7. Guided-mode resonance transmission filter spectral response with the structure illustrated in the inset. The peak frequency is $\nu \sim 14$ GHz. The filter parameters are: $\Lambda = 1.58$ cm, $\varepsilon_{H,3} = 6.13$ (E-glass), $\varepsilon_{L,3} = 3.7$ (silica), $\varepsilon_1 = \varepsilon_5 = 6.13$, $\varepsilon_2 = \varepsilon_4 = \varepsilon_C = \varepsilon_S = 1.0$, $d_1 = d_5 = 0.22$ cm, $d_2 = d_4 = 0.53$ cm, and $d_3 = 0.24$ cm.

response of a homogeneous multilayer structure [10], [13]. This is achieved by replacing one or more high dielectric-constant layers of the high/low homogeneous quarter-wave stack with gratings of approximately equal average dielectric constant to maintain the low off-resonance transmittance of the device. The resonances that were used to generate reflection filters are now forced by the HR design to produce transmission filters. A higher difference between dielectric constants of the successive layers determines a larger width of the low-transmittance spectral region affecting the free spectral range of the filter. An increased ratio between high and low average dielectric constants of the quarter-wave stack also implies fewer layers to achieve the same sideband transmittance. Since materials with relatively high dielectric constants are available at microwave frequencies and air can be used effectively as the low-dielectric constant medium, high-efficiency transmission filters with few layers and low sideband transmittance can be designed. Single-grating transmission filters can be obtained with a dielectric multilayer mirror on each side of the grating [13]. Fig. 7 shows an example of a five-layer transmission filter at $\nu \sim 14$ GHz with the structure illustrated in the inset using E-glass ($\varepsilon = 6.13$) and silica ($\varepsilon = 3.7$) as grating materials. All layers are quarter-wave thick at the frequency $\nu = 14$ GHz to obtain a high reflectance at frequencies away from resonance. The filter bandwidth is $\Delta\nu = 45$ MHz. As in the case of reflection filters, the bandwidth of the transmission filters can be made narrower or broader by forming the grating with materials having a smaller or higher difference between the dielectric constants within a period of a waveguide grating. The filter range of guided-mode resonance transmission filters is limited by peaks due to other resonating modes and by the range of the high-reflectance spectral region of the multilayer structure. For example, with the response of Fig. 7, the waveguide supports three TE modes with the peak at 14 GHz caused by coupling of the evanescent diffracted waves to the TE_2 waveguide mode. The filter range is limited by the TE_1 resonance at 11.94 GHz and by a Rayleigh anomaly (produced by the onset of higher order diffracted waves) at 18.98 GHz. Arbitrarily small sideband transmittance can be achieved with an increase in the number of quarter-wave homogeneous layers. However, as the structure thickness increases, additional modes can propagate in the equivalent homogeneous multilayer waveguide, thereby decreasing the filter range.

New avenues for design of guided-mode resonance transmission filters are opened by structures containing highly modulated thick gratings ($d \sim \lambda$), with asymmetric fill factors ($f \neq 0.5$). Such devices can yield high-efficiency transmission filters with yet fewer layers [3], [4]. However, due to the high modulation of the grating, the average dielectric-constant approximation employed in the design of high-reflectance structures does not hold as well. Therefore, unlike the previous transmission filter example, the physical parameters of the layers are more efficiently determined by an elaborate search procedure such as genetic algorithm optimization [3].

V. Experimental Results

The filtering properties of waveguide gratings based on guided-mode resonances are experimentally demonstrated with single-layer and multilayer devices designed to operate as reflection or transmission filters. Spectral measurements of the waveguide-grating transmittance are made in an anechoic chamber with the setup illustrated in Fig. 8. A plano-convex Teflon lens, with a diameter $D = 35.6$ cm and focal length $f_l = 121.9$ cm, is positioned with the flat side toward the transmitter horn antenna, at a distance from the transmitter equal to the lens focal length. Thus, an approximately planar wavefront is incident on the waveguide grating. A second microwave lens, identical to the first, focuses the transmitted zeroth-order diffracted wave on the receiver horn antenna located in the focal plane of the lens. The transmitted power is measured in the spectral range of 4–20 GHz in increments of 2.5 MHz, thus acquiring 6400 data points. The transmittance of the guided-mode resonance filter is obtained by normalizing the microwave power measured with the setup of Fig. 8 with the power received without the filter. The raw measured data contains rapidly varying oscillations due to interference effects caused by multiple reflections between components in the path of the beam. Therefore, to obtain a smoother experimental response and to compare the data with the theoretical predicted spectral characteristics, each filter transmittance value is replaced with the average transmittance of 20 neighboring frequency points.

A. Reflection Filters

A single-layer guided-mode resonance device has been fabricated with rectangular Plexiglas bars in air forming a grating with period $\Lambda = 3.0$ cm, fill factor $f = 0.5$, and thickness $d = 0.87$ cm. The spectral response of this device, measured with the setup of Fig. 8, exhibits a reflection peak at the waveguide-grating resonance frequency corresponding to a sharp notch in the high-transmittance region. Fig. 9 compares the calculated response using rigorous coupled-wave analysis with the experimentally measured frequency dependence of the transmittance for a TE-polarized incident wave. The dielectric constant and

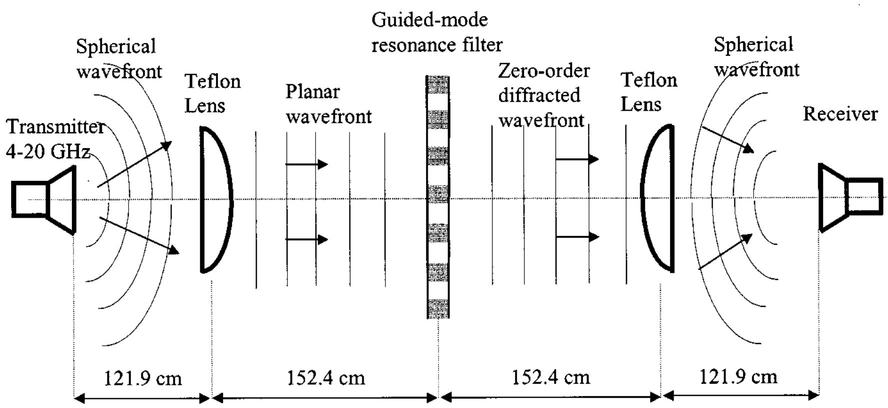

Fig. 8. Experimental setup in an anechoic chamber for transmittance measurements of waveguide gratings in the spectral range of 4–20 GHz. The dimensions of the filters are 91.4 cm (along the grating vector) by 61.0 cm.

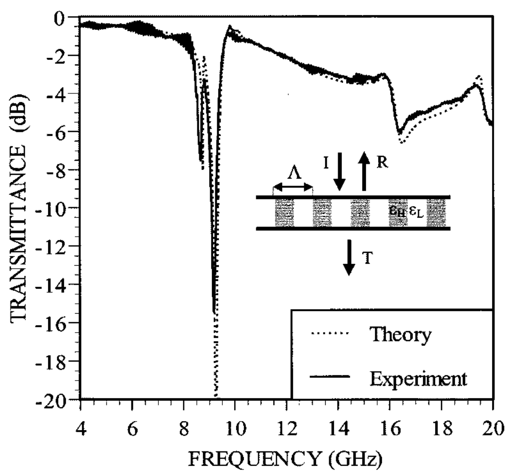

Fig. 9. Calculated and measured transmittance notches due to guided-mode resonances occurring in a single-layer Plexiglas/air waveguide grating for a TE-polarized incident wave. The grating period is $\Lambda = 3.0$ cm, the fill factor $f = 0.5$, the thickness $d = 0.87$ cm, and the dielectric constants are $\varepsilon_H = 2.59$, $\varepsilon_L = \varepsilon_C = \varepsilon_S = 1.0$. The calculated plot was obtained with a loss tangent $\tan\delta = 0.0067$, and an incident angle $\theta = 1°$.

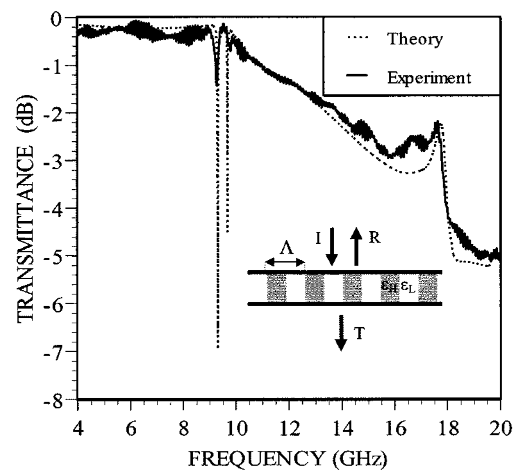

Fig. 10. Theoretical and experimental transmittance of the single-layer Plexiglas/air waveguide grating of Fig. 9 for a TM-polarized incident wave.

loss tangent used in calculations are $\varepsilon = 2.59$, and $\tan\delta = 0.0067$, respectively [20]. Assuming an incident angle of the plane waves on the structure, $\theta = 1°$, the two notches in the transmittance curve observed in the experimental data at frequencies 8.70 and 9.20 GHz are closely matched by the theoretical calculations that yield resonance frequencies 8.74 and 9.24 GHz, respectively. The splitting of the guided-mode resonance, visible in Fig. 9, is due to asymmetry arising in coupling of the $+1$ and -1 evanescent diffracted orders to the leaky modes of the waveguide as the angle of incidence shifts away from zero. Thus, at nonnormal incidence, the resonances corresponding to the $+1$ and -1 diffracted orders occur at different frequencies. The coupling efficiencies of the incident wave to the corresponding leaky modes with opposite directions of propagation are different, causing unequal linewidths and transmittance values in the resonance notches.

The theoretical and experimental spectral response of the same Plexiglas structure, under identical experimental conditions, is shown in Fig. 10 for a TM-polarized incident wave. A TM-polarization guided-mode resonance was measured at the frequency of 9.30 GHz, in excellent agreement with the theoretically calculated value of 9.29 GHz.

In both polarization cases, the measured transmittance values at resonance are higher than the theoretical predictions. This can be explained in part by the imperfect collimation of the microwave beam with a divergence that exceeds the angular aperture of the device. The angular components of a diverging beam generate guided-mode resonances at slightly different frequencies, thus contributing to the decrease of the filter efficiency. The discrepancy between the theoretical and experimental resonance transmittance is more pronounced in the case of TM polarization, which is due, in part, to the narrower linewidth and angular aperture in comparison with the TE guided-mode resonances. Thus, the calculated angular widths (at -3 dB) of the transmittance notches are $\Delta\theta_{\rm TE} = 7.3°$ for the TE-polarization case and $\Delta\theta_{\rm TM} = 0.25°$ for the TM-polarization case. The guided-mode resonance frequency varies with changes in geometrical parameters or dielectric constants of the waveguide gratings. Therefore, variations of the dielectric constants and

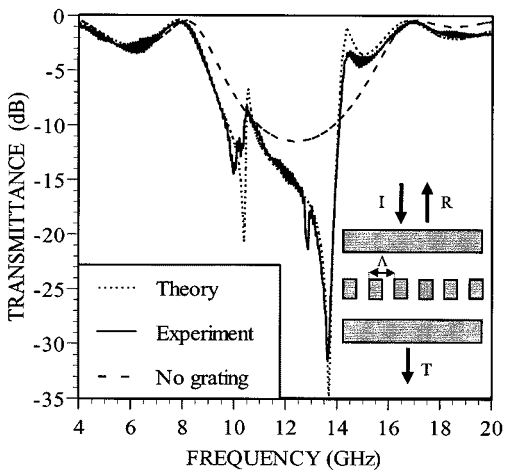

Fig. 11. Theoretical and experimental spectral response of a G10 fiberglass and air waveguide grating exhibiting guided-mode resonance peaks. The parameters of the structure are: $\Lambda = 2.03$ cm, $f = 0.5$, $d_1 = d_3 = d_5 = 0.31$ cm, $d_2 = d_4 = 0.62$ cm, $\varepsilon_{H,3} = \varepsilon_1 = \varepsilon_5 = 4.49$, and $\varepsilon_{L,3} = \varepsilon_2 = \varepsilon_4 = \varepsilon_C = \varepsilon_S = 1.0$. A value for the loss tangent $\tan\delta = 0.01$ was used in calculations. The dashed curve represents the transmittance of a structure identical to the one presented in the inset, but with the grating replaced by a homogeneous layer with dielectric constant $\varepsilon = 2.75$.

geometrical parameters (thicknesses, grating period, fill factor) across the device may also contribute to decrease in filter efficiency. Yet another factor that can affect the filter efficiency and lead to deviations from the theoretical data is the interaction of the nonplanar incident wave with a limited number of grating periods (12 periods) of this waveguide grating while the theory assumes an infinite structure and infinite number of periods.

B. Transmission Filters

The concept of transmission guided-mode resonance filters discussed in Section IV is demonstrated with five-layer waveguide gratings employing G10 fiberglass as the high dielectric-constant material and air as the low dielectric-constant medium, for both the homogeneous layers as well as for the grating layer. The devices, with the cross section illustrated in the inset of Fig. 11, consist of a grating formed with rectangular bars of G10 fiberglass equally spaced in air and homogeneous G10 sheets placed on each side of the grating as shown. The thicknesses of the G10 sheets and air gaps between the grating and the G10 sheets are chosen to be equal to a quarter-wavelength at the central frequency of the filter, thus providing the low transmittance sidebands required for a transmission filter design. The waveguide grating with the response illustrated in Fig. 11 has G10 sheet thickness, $d = 0.317$ cm with ± 0.03-cm variation according to manufacturer's specification. This thickness is equal to a quarter-wavelength at the frequency $\nu = 11.14$ GHz (for a refractive index of G10 fiberglass $n = 2.12$ [21]). The high-reflectance design is accomplished with air-gap thicknesses between the grating and the G10 homogeneous sheets twice as thick as the G10 layers. The grating period ($\Lambda = 2.0 \pm 0.05$ cm) is selected to generate a guided-mode resonance within the high-reflectance spectral range of the structure. Fig. 11 demonstrates an excellent agreement between the theoretically calculated transmittance for a TE polarized incident wave and the spectral response measured with the experimental setup shown in Fig. 8. A TM-polarization guided-mode resonance peak, predicted theoretically at $\nu = 13.87$ GHz to exhibit significantly smaller linewidth and angular aperture, was not observed experimentally. The grating period used in the calculation of Fig. 11 ($\Lambda = 2.03$ cm) is the average value determined through measurement on the waveguide grating after assembly. A thickness of the fiberglass layer $d = 0.31$ cm and a loss tangent value $\tan\delta = 0.01$ were used to yield the close fit between the theory and measurements. Guided-mode resonance transmission peaks are determined experimentally (after smoothing the curve by averaging over 20 neighboring points) at frequencies $\nu = 10.50$ GHz and $\nu = 14.51$ GHz; the theoretically predicted values are $\nu = 10.50$ GHz, and $\nu = 14.34$ GHz, respectively. Transmission notches accompanying each guided-mode resonance peak are measured at frequencies and with transmittance values close to the theoretical predictions. The split notch visible in the experimental data is caused by a small nonzero angle of incidence on the device, which has not been accounted for in the theoretical calculations given for normal incidence. The lower experimental peak transmittances compared to the calculated values can be attributed, in part (as in the reflection filter case), to the phase curvature of the incident beam, to the sensitivity of the resonance frequencies to waveguide grating parameter variations across the device, and to the finite-size effect (the microwave beam covers 18 periods here) of the device.

The presence of guided-mode transmission resonances is emphasized by comparison of the G10 waveguide grating spectral response with the transmittance of an identical structure with the grating replaced by a homogeneous layer with dielectric constant equal to the average dielectric constant of the grating (Fig. 11). The spectral response of the structure containing only homogeneous layers (dashed curve) possesses a high-reflectance spectral region similar to the transmittance curve of the waveguide grating, except for the peaks and notches due to the guided-mode resonances.

VI. Conclusion

Resonances in all-dielectric waveguide gratings can be used to implement reflection and transmission filters in the microwave spectral range. By merging concepts of diffraction, waveguides, and thin-film electromagnetics, a wide variety of reflection and transmission filters can be designed with specified filter characteristics, including center frequency, linewidth, and sidebands.

In this paper, it is theoretically shown that reflection and transmission filters with high efficiency and low sidebands can be obtained by embedding a grating in an AR or HR design, respectively. Calculated reflection filter examples using practical materials illustrate how the linewidth can be controlled by modifying the grating modulation and the sideband reflection can be reduced by improving the AR design of a waveguide grating with additional homogeneous layers. Phase-shifted gratings are introduced as a new method to increase the linewidth of a guided-mode resonance reflection filter with specified materials and layer thicknesses. Double-line reflection filters are presented using structures with two gratings in separate layers with a central homogenous layer. The two resonance wavelengths can be tuned independently by an appropriate choice of the grating periods. Transmission filters with high peak response are demonstrated in multilayer waveguide gratings with a grating in the central layer and adjacent quarter-wave-thick homogeneous layers. Generally, transmission filters require more layers than reflection filters to obtain a similar sideband response.

Spectral measurements of the transmittance of single and multilayer waveguide gratings in the 4–20-GHz range confirm the theoretical models used to describe guided-mode resonance filters. A reflection filter consisting of a single-layer waveguide grating with Plexiglas and air as the high and low dielectric-constant materials was fabricated and tested, yielding a close fit with the calculated spectral measurements for both TE and TM polarizations. Guided-mode resonance transmission peaks are experimentally found for a TE-polarized incident wave in a five-layer G10 fiberglass/air structure at frequencies that are in excellent agreement with the theoretical predictions. These results are found with a finite-size microwave beam covering relatively few periods.

Losses in the waveguide gratings through bulk absorption and scattering significantly affect the efficiency of the device, dampening the transmission notches in the case of reflection filters, and the transmittance peaks in the case of guided-mode resonance transmission filters. Yet another factor limiting the filtering efficiency is the sensitivity of the center frequency of the guided-mode resonance filters to changes in the physical parameters of the device. Therefore, high-efficiency guided-mode resonance filters can be achieved in materials with lower losses, higher degrees of homogeneity, and with structures possessing improved uniformity in grating period, fill factor, and thickness. Such microwave materials with low-loss and high dielectric constants are available and provide increased flexibility in the realization of waveguide-grating filters. Microwave guided-mode resonance filters can be fabricated with ordinary machine tools due to the relatively large grating periods appropriate at these large wavelengths.

Guided-mode resonance filters generate narrow linewidths like YIG filters, but at a comparatively lower cost. Potential applications for these all-dielectric (no metallic components) structures include passive interference reduction for satellite ground stations and as a first-stage aperture filter in a phase-array antenna.

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