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APPLICATION OF GRATING-FILTER TECHNIQUES IN MICROSTRIP TO OBTAIN NARROWBAND MILLIMETER-WAVE BANDPASS FILTERS WITH LOW RADIATION LOSSES[1]

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SUMMARY

Microstrip lines are attractive for the lower millimeter-wave ranges, but use of relatively thick substrates would be desirable in order to minimize ohmic losses. On such substrates the usual types of microstrip bandpass filters (formed from, e.g., coupled line segments with open ends) tend to radiate strongly, giving poor performance. It has been found that a grating technique initially developed for use with dielectric waveguide can be adapted for microstrip, with some modifications. The grating technique yields narrowband mm-wave microstrip filters with little radiation and strong filter characteristics. Experimental filters have been designed and tested with good results.

INTRODUCTION

Radiation from sharp discontinuities (open ends in particular) tends to be the primary cause of losses in narrowband microstrip bandpass filters in the millimeter-wave (mm) range [1], [2]. Radiation could be suppressed by using thin enough substrates but that has the effect of increasing the ohmic losses of the microstrip resonators and little is gained overall. Some existing data [2] suggests filters with bandwidths as small as a couple of a percent would still be feasible in the lower mm-wave ranges if relatively thick substrates could be used without the radiation penalty. Shielded microstrip circuits may offer some improvement in this respect but lack the flexibility of inherently low-radiation designs. Also, waveguides modes inside the housing may detoriate the upper stopbands.

One filter structure that can be used with weakly guiding waveguides is the coupled-grating configuration [3], [4]. It was used to successfully realize narrowband bandpass filters in dielectric image guide which has an even stronger tendency to radiate than microstrip. It should therefore work with low radiation losses if realized in microstrip. However, in these filters "forward coupling" (due to the different odd- and even-mode velocities) is desired between the gratings. The "backward coupling" (due to the different odd- and even-mode impedances) is undesirable in this case. In most microstrip applications the roles of these coupling mechanisms have traditionally been reversed because forward coupling (in microstrip) is generally believed to be too weak to be usable. Nevertheless, we found that good filter properties can still be achieved, though some design modifications are necessary for microstrip applications. Because these filters do not suffer significantly from radiation on even electrically thick substrates, this technique yields narrowband mm-wave microstrip bandpass filters with relatively low losses. The main disadvantage of these filters is that they tend to be large measured in wavelengths. However, at mm-wavelengths (where their low-radiation characteristics are of most value) their overall size is reasonable for many applications.

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BANDPASS FILTER CONFIGURATION USING MICROSTRIP GRATINGS

Consider the part marked "G_1" of the microstrip structure shown in Fig. 1. Gratings such as G_1 (or other grating configurations) behave as bandstop filters, as is well known from the theory of periodic structures. It is generally convenient to design gratings so that the electrical lengths of the segments are all equal. Then the stopband center frequency is the frequency for which all the line segments are a quarter-wavelength long (ignoring fringing effects which is a good approximation since shallow notches are typically used. The notches in Fig. 1 have been exaggerated for clarity). The grating impedance ratio *r*, which is an important design parameter, is for microstrip gratings simply the ratio of the impedances of the narrow and wide line segments in the grating.

For *bandpass* filter applications gratings can be used in a parallel-coupled configuration, as for the gratings marked

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"G_{A1}" and "G_{A2}" in Fig. 1. At frequencies in the stopband of the gratings a wave entering, say, grating G_{A1} will not penetrate deep into that grating. Instead, the wave is reflected, and the reflected wave couples to grating G_{A2} via forward coupling and emerges out from G_{A2} causing *bandpass* behaviour, if the structure is properly designed [3]. On the other hand, at frequencies outside the grating stopband the reflected wave is weak, and if there is nothing else to cause reflections (say, if the gratings were infinitely long) a strong, absorptive attenuation is established between the input ports of the coupled gratings. In practical structures long gratings terminated in a distributed load can be used to simulate infinite gratings and give nearly idealized performance. We have found that in microstrip the use of notches on only one side of the coupled strips as shown in Fig. 1 (which keeps the spacing between the coupled lines constant) is convenient.

The whole structure in Fig. 1 forms a two-resonator bandpass filter. The first resonator is formed by gratings G_1 and G_{A1}, with a line length between equal to a multiple of a half wavelength at the resonant frequency. The second resonator is formed similarly from gratings G_2 and G_{A2}. The lengths of gratings G_1 and G_2 control the coupling of the resonators to the terminations while the spacing between G_{A1} and G_{A2} is a major factor in controlling the coupling between resonators. In the passband of the filter this structure behaves like a reactive-type filter. Over most of the stopband, however, attenuation is provided by the coupled gratings in the absorptive manner explained.

DESIGN CONSIDERATIONS OF MICROSTRIP GRATING FILTERS

The design procedure of [4] can be used with some modifications. It is feasible to synthesize the structure so that it will have some desired, prescribed passband shape and width. (The stopband characteristics are largely determined by the dissipative attenuation of the coupled gratings.) However, the design equations of [4] are not directly applicable because of the backward coupling of microstrip. We have modified these equations, and they can be found in [5] and [6].

The most serious, harmful effect of the so-called backward coupling of microstrip lines (due to the differing odd- and even-mode impedances of the line segments) is that it limits the maximum attenuation available from a pair of coupled gratings. As was explained, the absorptive stopband of the filter occurs because when the gratings are not reflecting the power is transmitted off to distributed loads on the right. However, for microstrip coupled gratings this absorptive attenuation is weakened because of backward coupling. If the separation between the gratings is increased there is, of course, less coupling and the mode impedances differ less as do the mode velocities. However, while the maximum backward coupling is rapidly diminished for loose couplings, the needed amount of forward coupling can still be obtained if the coupling length is long enough. Because of this, satisfactory performance can be obtained by a proper choice of the parameters of the coupled gratings. In filter design this may translate to compromising between stopband attenuation and maximum available filter passband width (if a wide passband width is desired). For given gratings there is a unique grating spacing which will permit the maximum bandwidth [4]. In general, the larger the impedance ratio r of the gratings is, the larger that maximum possible bandwidth will be, but the lower the stopband attenuation will be (as a result of the presence of backward coupling). We have found in practice that filter bandwidths up to 3.5 percent with attenuations of about 20 dB or more per pair of coupled gratings are easily achievable. (The design bandwidths of our experimental filters have been less, but it has been found to be typical of these filters that the bandwidth of the actual filter turns out to be slightly larger than the design bandwidth.)

We also found that the curved input strips of the coupled gratings are beneficial in reducing unwanted backward coupling. (They were also found to be necessary in order to keep radiation at acceptable levels.) Because the coupling is continuously varied over a distance in the curved input strips, they tend to match the odd- and even-mode impedances by acting as tapered line transformers and therefore reduce backward coupling while preserving any forward coupling. Because of this, higher stopband attenuations are achieved at frequencies at which the length of the curved strips is an appreciable fraction of a wavelength. This is readily apparent in the calculated and measured responses in Figs. 2 and 4. In the low-frequency limit attenuation is not much improved, however, because the curved strips become short compared to wavelength.

EXPERIMENTAL RESULTS

We have designed, built and tested several grating filters. Here we will report on a two-resonator filter at 30 GHz and a four-resonator filter at 10 GHz. The substrate material used was Duriod with a dielectric constant of 2.20. The substrate thickness was 0.030 inch with 1-oz "RLC copper" for the four-resonator filter at 10 GHz, and 0.011 inch with 0.5-oz "RLC copper" for the 30-GHz filter, respectively. For computing frequency responses of these filters we have used both a program of our own (with parameters of coupled microstrips being computed using the equations from [7]) as well as the "Touchstone" software package.[2] The results using both methods have been very similar, though the metal thickness correction available in the Touchstone program gave improved results. In all cases the curved, coupled input strips of the coupled gratings have been treated by dividing them into small segments which then have been analyzed as being parallel and uniformly coupled. Fringing effects at the step discontinuities have been ignored in all calculations.

A 0.5-dB Chebyshev ripple prototype with 2.5% bandwidth was used for the 30-GHz, two-resonator filter. The filter was designed by methods discussed in [5] and [6]. The grating impedance ratio used in this filter was 1.15, and in the coupled gratings a spacing equal to one substrate thickness was used. The resulting strip pattern is approximately as shown in Fig. 1 except that the notches were much more shallow. The coupled gratings have 30 narrow segments (only the few first are shown in Fig. 1). In order to simulate infinitely long gratings, the portion covering the six last segments had distributed loss in the form of microwave absorbing material added next to the lines. A 50 Ω chip resistor was attached to the ends. The distributed load was modeled in computations as lossy, coupled microstrip lines. Theoretical responses computed using "Touchstone" are shown by the solid lines in Fig. 2.

A corresponding experimental filter was built and tested. The filter utilized K-connector "sparkplug" coax-to-microstrip launchers[3] which are rated for operation up to 40 GHz. Measured results are shown by dots in Fig. 2. These results include the launchers and some microstrip line, and their loss as measured on a reference line is shown by the dashed line in the inset of Fig. 2. After the loss of the reference line is subtracted from the measured passband loss, the loss of the filter alone is found to be only slightly higher (less than 0.3 dB difference) than predicted theoretically showing that these filters, indeed, radiate very little and can take advantage of the full potential Q of microstrip lines. Note also that the experimental filter has a slightly larger ripple than predicted theoretically which tends to increase the losses of the experimental filter.

A partial drawing of our four-resonator filter is shown in Fig. 3. The couplings of the first and last resonators to the terminations are via single gratings, but all inter-resonator couplings are arranged through pairs of parallel-coupled gratings. Thus, the filter has three pairs of coupled gratings. Since the attenuation per each pair is absorptive, their dB attenuations add, giving the filter very potent stopband characteristics. The filter was designed from a 0.2-dB Chebyshev ripple prototype with 2.9% bandwidth. The impedance ratio used in the coupled gratings is 1.16, and a spacing of 1.2 times the substrate thickness was used between them. The design procedure for this filter configuration is given in full detail [6]. Responses computed using "Touchstone" are shown by the solid lines in Fig. 4. It can be seen from the inset of Fig. 4 that the filter is slightly mistuned. This was determined to be due to metallization thickness effects which were ignored in the initial design.

[2]Available from EEsof, Westlake Village, CA

[3]Available from Wiltron, Morgan Hill, CA 95037-2809

Corresponding measured results are shown by the dashed lines in Fig. 4. It should be noticed that the measured result again includes the losses of the input lines and connectors. Their contribution is about 1.0 dB, so the measured response of the filter alone is in excellent agreement with the computed one. In the stopband it was found that the attenuation was limited primarily by cross talk between different parts of the filter rather than by reaching the limit indicated possible by the theoretical calculations (see Fig. 4). To get the response shown in Fig. 4 the coax-microstrip transitions were shielded with conductive covers and absorbing material was used between the gratings G_1 and G_{B2} in Fig. 3 (as well as between gratings G_4 and G_{B3}) and between gratings G_{A2} and G_{C3}. In the passband the additional loss due to them was measured to be only about 0.2 dB over that shown in the inset of Fig. 4. However, even without any shielding the minimum stopband attenuation was measured to be better than 50 dB at all frequencies in the band 0.5 to 18 GHz, except at 11.3 GHz where there was a glitch where the attenuation dropped to 40 dB. Thus, the stopband performance of these filters is relatively strong even if no shielding inserts are used.

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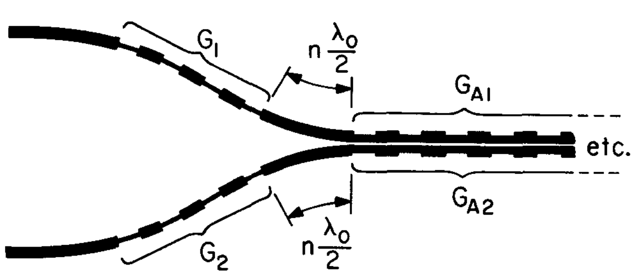

Fig. 1. The strip pattern of a two-resonator filter. The notch depth of the gratings has been greatly exaggerated. The coupled gratings continue to the right, only part is shown here.

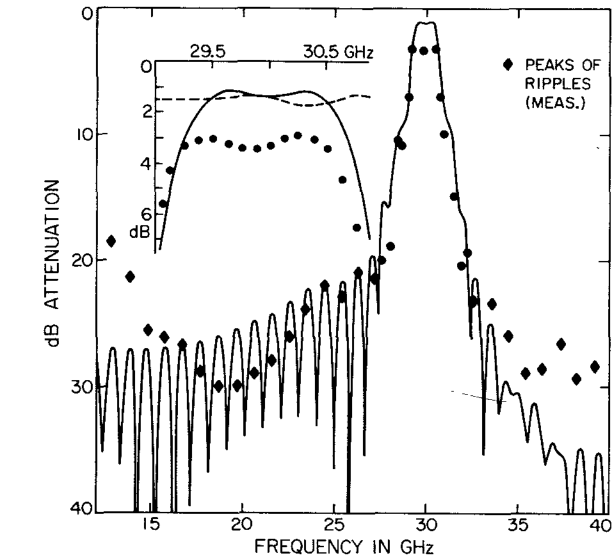

Fig. 2. A computed response for the 30-GHz, two-resonator filter shown in Fig. 1. The dots indicate measured results, and the dashed line indicates the measured loss of the relatively lengthy input lines of the filter.

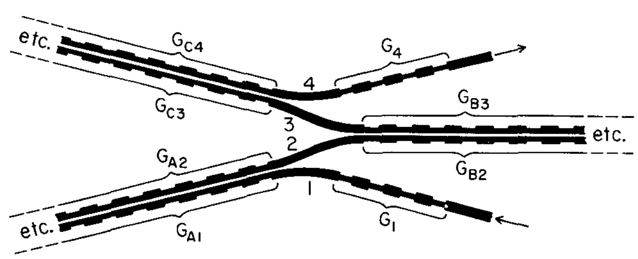

Fig. 3. A partial drawing of the four-resonator filter. The notch depth has been exaggerated.

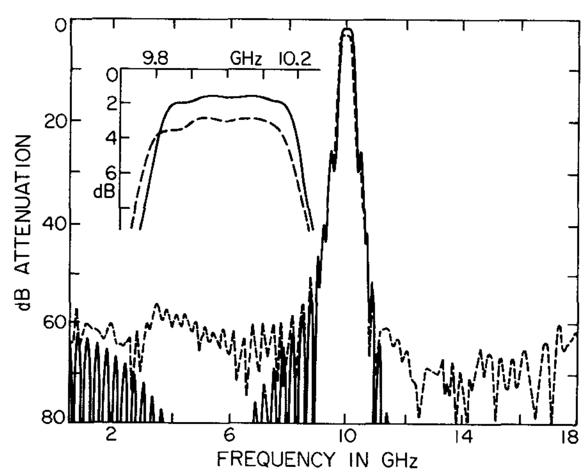

Fig. 4. Computed (—) and measured (---) responses for the four-resonator filter shown in Fig. 3. The measured data includes the loss of extra lengths of line.