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# An Adjustable Quasi-Optical Bandpass Filter—Part II: Practical Considerations

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*Abstract*—**This paper investigates the effects of using realistic grids on the performance of the adjustable quasi-optical bandpass filter presented in Part I. The theory given here is in excellent agreement with measurements performed on a three-grid filter in the 50–75-GHz band.**

## I. INTRODUCTION

IN PART I of this paper [1], an adjustable quasi-optical bandpass filter was described. The theory of operation and the design formulas reported were developed under the assumption that the wire-grid polarizers employed were ideal. To be more specific, let the field reflection and transmission coefficients for a plane wave at normal incidence on a parallel-wire grid be denoted, respectively, by $r_{||}$ and $t_{||}$ when the electric field is parallel to the wires, and $r_\perp$ and $t_\perp$ when it is perpendicular to the wires. In Part I of this paper it was assumed that $r_{||} = -1$, $t_{||} = 0$, $r_\perp = 0$, and $t_\perp = 1$. This would require the wires of the grids to have infinitesimal thickness and spacing. Thus in practice, such values of the $r$'s and $t$'s can only be achieved approximately. In this paper, the effects of using realistic grids on the performance of the filter are investigated.

## II. WIRE-GRID POLARIZERS

In this section, the values of $r_{||}$, $t_{||}$, $r_\perp$, and $t_\perp$ are given for two common types of grids. The grids will be assumed to be lossless, i.e.,

$$|r_{||}|^2 + |t_{||}|^2 = 1$$
$$|r_\perp|^2 + |t_\perp|^2 = 1 \tag{1}$$

and to have a thickness small compared to a wavelength, i.e.,

$$t_{||} = 1 + r_{||} \qquad t_\perp = 1 + r_\perp. \tag{2}$$

From (1) and (2), and from the fact that the grids are inductive for the parallel polarization and capacitive for the perpendicular polarization, the $r$'s and $t$'s can be written as functions of two positive real parameters $\psi_{||}$ and $\psi_\perp$ in the forms

$$r_{||} = -\cos\psi_{||} \exp(-j\psi_{||}) \tag{3}$$

$$t_{||} = j\sin\psi_{||} \exp(-j\psi_{||}) \tag{4}$$

$$r_\perp = -j\sin\psi_\perp \exp(-j\psi_\perp) \tag{5}$$

$$t_\perp = \cos\psi_\perp \exp(-j\psi_\perp). \tag{6}$$

The grids of interest for the filter are those which act as reasonably good polarizers, i.e., $|r_{||}|$, $|t_\perp| \simeq 1$ and $|t_{||}|$, $|r_\perp| \ll 1$. Thus the quality of a grid will be described by the two coefficients $|t_{||}|$ and $|r_\perp|$. The smaller these coefficients are, the better is the grid. Clearly, since $|t_{||}| = \sin\psi_{||}$ and $|r_\perp| = \sin\psi_\perp$, the magnitude and phase of any of the coefficients given in (3)–(6) can be calculated from $|t_{||}|$ and $|r_\perp|$. It is emphasized that this is only true since the grids are assumed to be lossless and thin in comparison to the wavelength.

Two common types of grids are shown in Fig. 1. The first grid, Fig. 1(a), consists of thin metallic strips of

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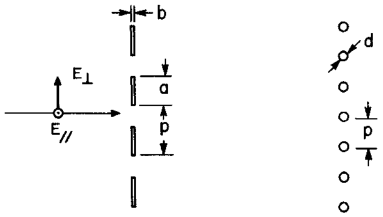

Fig. 1. Two common types of grids.

width $a$, thickness $b$, and period $p$. Under the assumptions that

$$b \ll a, \qquad (p - a) \tag{7}$$

$$p \ll \lambda \tag{8}$$

where $\lambda$ is the operating wavelength, it can be shown that at normal incidence [2], [3]

$$| t_{||} | \simeq \frac{2p}{\lambda} \log_e \csc \left(\frac{\pi a}{2p}\right) \tag{9}$$

$$| r_\perp | \simeq \frac{2p}{\lambda} \log_e \sec \left(\frac{\pi a}{2p}\right). \tag{10}$$

No restriction is assumed on the value of $a/p$. It is noted from (9) and (10) that

$$| t_{||}(a) | = | r_\perp(p - a) | . \tag{11}$$

This equation can also be deduced directly from Babinet's principle and is independent of condition (8). If $a = p/2$ then

$$| t_{||} = | r_\perp | \simeq \frac{p}{\lambda} \log_e 2. \tag{12}$$

In fact, if $a = p/2$, an exact expression for $t_{||}$ or $r_\perp$, independent of condition (8), is available in the literature [4], [5]. However, this is not of great importance here because condition (8) is required for the grid to act as a good polarizer.

The second type of grid, Fig. 1(b), consists of circular metallic wires of diameter $d$ and period $p$. Under the assumptions that

$$d \ll p \tag{13}$$

$$p \ll \lambda \tag{14}$$

it can be shown that at normal incidence [6], [7]

$$| t_{||} | \simeq \frac{2p}{\lambda} \log_e \left(\frac{p}{\pi d}\right) \tag{15}$$

$$| r_\perp | \simeq \frac{\pi^2 d^2}{2\lambda p}. \tag{16}$$

It is to be noted that

$$| r_\perp | \ll | t_{||} | \tag{17}$$

which is a consequence of condition (13). Formulas are available in the literature for $t_{||}$ when condition (14) is not satisfied [6]–[10]. Also when neither condition (13) nor (14) is satisfied, $t_{||}$ is given in [11] and both $t_{||}$ and $r_\perp$ are given in [12].

A dense grating of thin circular wires is practical to use as an efficient polarizer at centimeter wavelengths. At millimeter wavelengths an array of thin strips is more easily manufactured, for example, by photoetching thin metallized Mylar sheets. In the infrared region, polarizers have been made by evaporation of metal on a plastic echelette grating [13]–[15], by photoetching techniques [16], by holographic techniques [17], and by ion-beam micromachining [18]. For example, a polarizer is described in [18] which has $| r_{||} |^2 > 99$ percent and $| t_\perp |^2 > 93$ percent at a wavelength of 10.6 $\mu$m.

## III. EFFECTS OF USING NONIDEAL POLARIZERS

The effects of using realistic grids with finite dimensions on the response of the filter are investigated in this section. It will be assumed that (1)–(6) hold. The results will be given in terms of $| t_{||} |$ and $| r_\perp |$. The method of analysis employed is essentially the same as that used by Hill and Cornbleet [19]. Thus only the results will be reported here. Basically, the method involves representing each grid and each spacing between grids as a 4-port network with two input ports and two output ports. Each port represents one component of polarization. A $4 \times 4$ matrix which is a generalization of the 2-port *transfer scattering matrix* [20], [21] is formed for each network. Such a matrix relates the incident and reflected wave amplitudes at the two input ports to those at the two output ports. The overall $4 \times 4$ transfer scattering matrix which describes the performance of the filter is then calculated by multiplying all the individual matrices together in the proper order.

Using the aforementioned method with $| t_{||} | = | r_\perp | = 0.1$, the frequency response of the 2-section filter of Fig. 4(b) of Part I is plotted in Fig. 2 for various values of $\theta$. In the figure, the frequency is normalized to $f_0$ which denotes the frequency at which the spacing between adjacent grids is equal to a quarter of a wavelength. The variation of $| t_{||} |$ and $| r_\perp |$ with frequency is neglected because the frequency does not vary appreciably over the

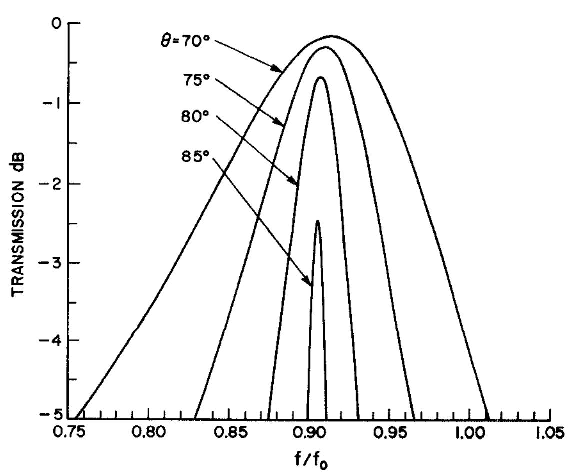

Fig. 2. Frequency response of a two-section filter with $| t_{||} | = | r_\perp | = 0.1$.

range of responses shown in the figure. This approximation is particularly appropriate if the filter has a narrow bandwidth and is operating at a higher order resonance.

Comparing Fig. 2 with Fig. 5 of Part I which was plotted under the assumption that the grids are ideal polarizers, one notes that realistic grids have the following effects on the response of the filter.

1) The resonance frequency is shifted from that at which the spacing between grids is $\lambda/4$.

2) The amount of frequency shift varies slightly as the angles between the wires of the different grids are changed.

3) The shape of the frequency response curve is not symmetric; in fact it will be shown later that the shape of the response of narrow-band multisection filters can be somewhat distorted.

4) The peak transmission of the filter is less than 100 percent.

Approximate formulas will now be given for the shift of the resonance frequency and the reduction in the peak transmission for the 2-section filter. For a greater generality, let $t_{\parallel}$ and $r_{\perp}$ be the coefficients of the two end grids and $t_{\parallel}'$ and $r_{\perp}'$ be those of the middle grid. The results are obtained by following the method of Hill and Cornbleet [19] described briefly in the preceding, and by using small-value approximations under the assumption that

$$|t_{\parallel}|, |t_{\parallel}'|, |r_{\perp}|, |r_{\perp}'| \ll 1. \tag{18}$$

Let $\delta f$ be the shift in the resonance frequency and $\delta\phi$ the corresponding shift in the electrical length between the grids. The frequency at the $m$th resonance is given by

$$f_m = (2m-1)f_0 + \delta f \tag{19}$$

and the corresponding electrical length by

$$\phi_m = (2m-1)\frac{\pi}{2} + \delta\phi. \tag{20}$$

Clearly,

$$\delta f/f_0 = \frac{2}{\pi}\delta\phi. \tag{21}$$

For the 2-section filter of Fig. 4(b) of Part I with angles $\theta_1 = -\theta_2 = \theta$, one obtains

$$\delta\phi \simeq -\tfrac{1}{2}|t_{\parallel}| + 2\cot^2\theta\,|r_{\perp}| - \csc^2\theta\,|r_{\perp}'| \tag{22}$$

which is independent of $|t_{\parallel}'|$ to a first order. In fact, the omitted terms in (22) are of cubic orders of the magnitudes of the $t$'s and $r$'s. For the 2-section filter of Fig. 4(a) of Part I with angles $\theta_1 = \theta_2 = \theta$, the term $\cos^2\theta\,|t_{\parallel}'|$ should be added to the right-hand side of (22).

The peak power transmission coefficient for either realization of the 2-section filter is

$$|t_2|^2 \simeq 1 - \tfrac{1}{2}\tan^2\theta\,|t_{\parallel}|^2 \tag{23a}$$

$$\simeq 2.17\tan^2\theta\,|t_{\parallel}|^2 \text{ dB} \tag{23b}$$

which is independent of $|t_{\parallel}'|$, $|r_{\perp}|$, and $|r_{\perp}'|$. The lost power is converted into cross-polarized waves propagating in the forward and reverse directions.

Equations (21)–(23), with $|t_{\parallel}| = |t_{\parallel}'| = |r_{\perp}| = |r_{\perp}'| = 0.1$, agree extremely well with the exact results shown in Fig. 2. The only exception is the loss for $\theta = 85°$ because the term $\tan^2\theta\,|t_{\parallel}|^2$ appearing in the right-hand side of (23) is too large for the approximations to hold.

The slight variation of $\delta f$ as $\theta$ is changed as indicated in Fig. 2 and (22) is an undesirable effect. However, (22) shows that this effect can be eliminated when the condition

$$|r_{\perp}'| = 2|r_{\perp}| \tag{24}$$

is fulfilled. In this case, (22) gives

$$\delta\phi \simeq -\tfrac{1}{2}|t_{\parallel}| - 2|r_{\perp}| \tag{25}$$

which is independent of $\theta$. To demonstrate this point, the frequency response of the 2-section filter of Fig. 4(b) of Part I is plotted in Fig. 3 for various values of $\theta$ and with $|t_{\parallel}| = 0.1$, $|t_{\parallel}'| = 0.2$, $|r_{\perp}| = 0.1$, and $|r_{\perp}'| = 2|r_{\perp}| = 0.2$. The particular value chosen for $|t_{\parallel}'|$ is unimportant since it does not affect the frequency shift. The figure shows that the center frequency of the filter is indeed independent of $\theta$. Such independence is not possible for the two-section filter realization shown in Fig. 4(a) of Part I because of the term $\cos\theta\,|t_{\parallel}'|$ which, as mentioned previously, should be added to the right-hand side of (22). This is a third advantage, added to the two mentioned in Section III of Part I, for the 2-section filter with angles $\theta_1 = -\theta_2 = \theta$ over that with angles $\theta_1 = \theta_2 = \theta$. It is appropriate, however, to notice that if only narrow bandwidths are involved, i.e., if $\theta \simeq 90°$, then

$$\delta\phi \simeq -\tfrac{1}{2}|t_{\parallel}| - |r_{\perp}'|, \qquad \theta \simeq 90° \tag{26}$$

for both cases.

For multisection filters, it will be assumed that the two end grids are identical and, in general, different from the intermediate grids which, in turn, are assumed to be identical. Let $t_{\parallel}$ and $r_{\perp}$ be the coefficients of the two end grids and $t_{\parallel}'$ are $r_{\perp}'$ be those of the intermediate grids. It is not easy to obtain analytic results for multisection filters similar to those preceding, given for 2-section filters. However, from numerical results based on the method of Hill

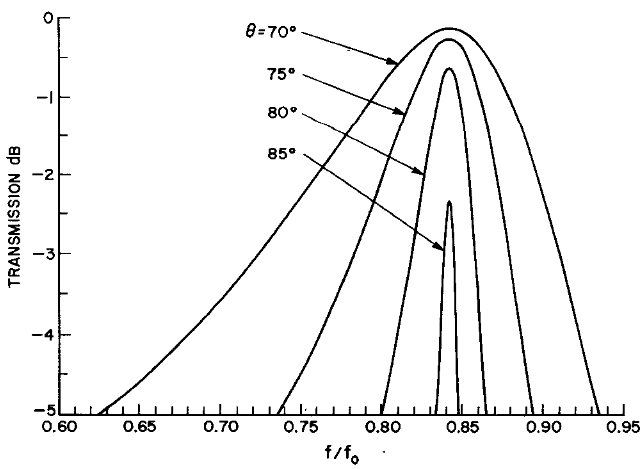


Fig. 3. Frequency response of a two-section filter with $|t_{\parallel}| = |r_{\perp}| = 0.1$ and $|t_{\parallel}'| = |r_{\perp}'| = 0.2$.

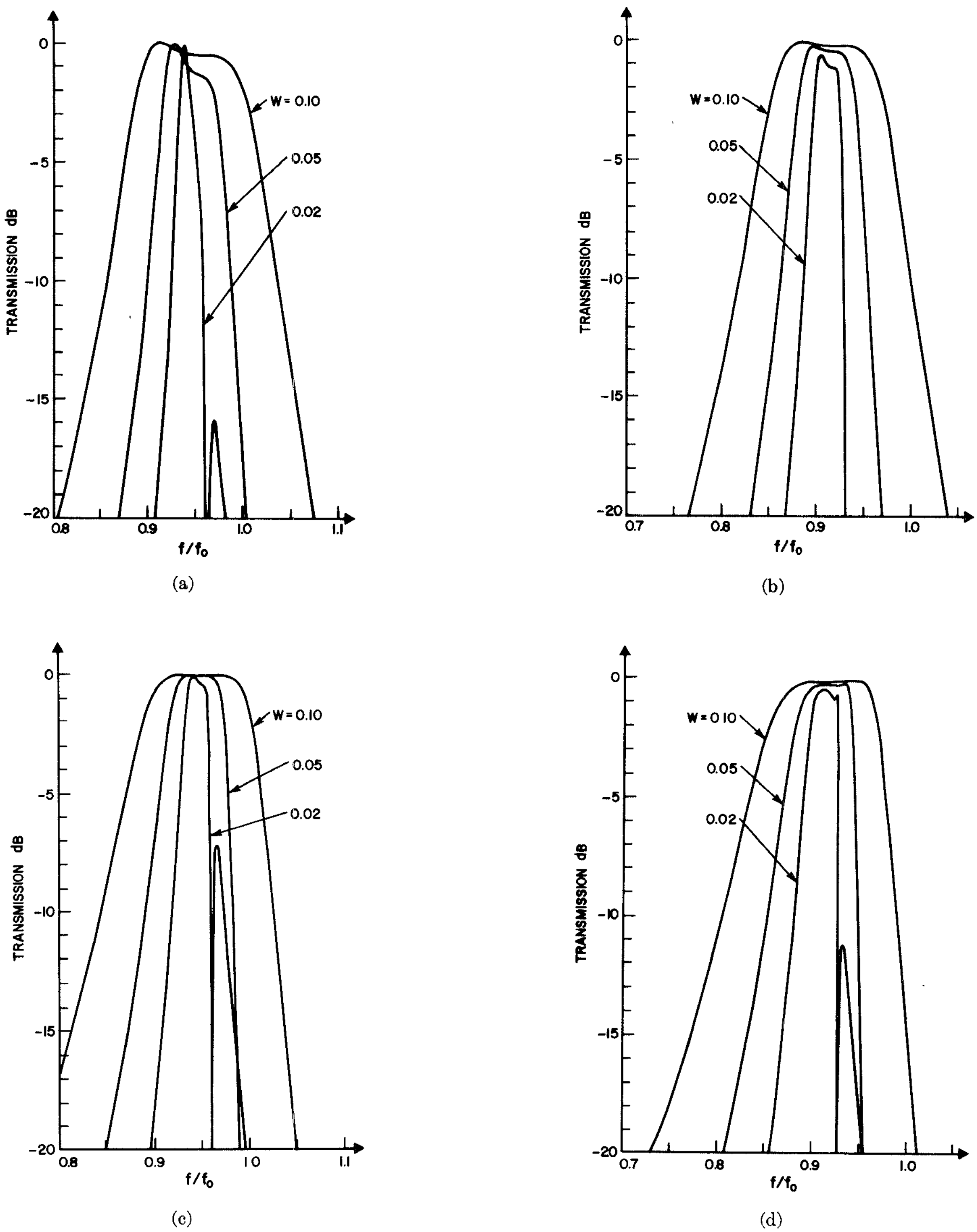


Fig. 4. Frequency responses of a 4-section filter under four different conditions. (a) Angles = $(\theta_1,\theta_2,-\theta_2,-\theta_1)$ and $|t_\parallel| = |t_\parallel'| = |r_\perp| = |r_\perp'| = 0.05$. (b) Angles = $(\theta_1,\theta_2,-\theta_2,-\theta_1)$ and $|t_\parallel| = |r_\perp'| = 0.1$, $|t_\parallel'| = |r_\perp| = 0.05$. (c) Angles = $(\theta_1,-\theta_2,\theta_2,-\theta_1)$ and $|t_\parallel| = |t_\parallel'| = |r_\perp| = |r_\perp'| = 0.05$. (d) Angles = $(\theta_1,-\theta_2,\theta_2,-\theta_1)$ and $|t_\parallel| = |r_\perp'| = 0.1$, $|t_\parallel'| = |r_\perp| = 0.05$.

and Cornbleet [19] described at the beginning of this section, one can reach the following conclusions.

1) For multisection filters with narrow bandwidths, (26) of the 2-section filter can still be used to calculate the approximate shift in the resonance frequency.

2) To make the frequency shift independent of the values of the $\theta$'s, then one must have

$$|t_\parallel'| = \tfrac{1}{2}|t_\parallel|, \qquad |r_\perp'| = 2|r_\perp|. \tag{27}$$

As an example, three responses of a 4-section filter under four different conditions are given in Fig. 4. The three responses are of the maximally flat type with 1-dB relative bandwidths $w = 0.1$ ($\theta_1 = 65.00°$, $\theta_2 = 82.40°$), $w = 0.05$ ($\theta_1 = 72.18°$, $\theta_2 = 86.11°$), and $w = 0.02$ ($\theta_1 = 78.67°$,

$\theta_2 = 88.42°$). The values of $\theta_1$ and $\theta_2$ (see Fig. 6 of Part I) which are necessary to plot the responses were calculated from (18) of Part I assuming perfect grids. Both Figs. 4(a) and 4(b) have the angles of the four sections in the order $\theta_1$, $\theta_2$, $-\theta_2$, $-\theta_1$. This arrangement makes the input and output polarizations parallel to each other. The same effect is obtained by having the angles in the order $\theta_1$, $-\theta_2$, $\theta_2$, $-\theta_1$. This case is represented in Fig. 4(c) and 4(d). In Fig. 4(a) and 4(c) all the grids are identical with $|t_{\parallel}| = |t_{\parallel}'| = |r_{\perp}| = |r_{\perp}'| = 0.05$. In Fig. 4(b) and 4(d), $|t_{\parallel}| = 0.1$, $|t_{\parallel}'| = \frac{1}{2}|t_{\parallel}| = 0.05$, $|r_{\perp}| = 0.05$, and $|r_{\perp}'| = 2|r_{\perp}| = 0.1$, i.e., (27) is satisfied. It is evident from a comparison of Fig. 4(a) and 4(b) that fulfillment of (27) not only eliminates the shift in the resonance frequency for different $w$'s, but also reduces the distortion of the response curves. It is interesting that this remains true even though all the grids used for Fig. 4(b) are slightly worse polarizers, i.e., have larger $|t_{\parallel}|$'s and $|r_{\perp}|$'s, than those used for Fig. 4(a).

## IV. EXPERIMENT

In this section, an experiment on a 2-section filter in the 50–75-GHz band is described. The three grids employed in the filter were of the thin strip type shown in Fig. 1(a). The strips, which were made of copper, had a width $a = 0.076$ mm (0.003 in), a thickness $b = 0.018$ mm (0.0007 in), and were spaced at a period $p = 0.203$ mm (0.008 in). They were photoetched on a metallized 0.004-mm (0.00015-in)-thick Mylar sheet. The grids were stretched over three aluminum rings having an opening of approximately 15 cm (6 in). The rings holding the two end grids were fixed together so that their wires are parallel while the ring holding the middle grid was allowed to rotate with the help of two ball bearings fixing it to the end rings. Thus the filter was of the type shown in Fig. 4(b) of Part I. The spacing of the grids was $s = 1.016$ cm (0.400 in).

A schematic diagram of the experiment is shown in Fig. 5. Two standard conical horns with approximately 2-cm diameters and two polystyrene lenses with 30-cm diameters and 30-cm focal lengths were used. The lenses were slightly misaligned to prevent multireflections. The beam was about 15 cm in diameter at the 20-dB points. The waveguide-to-waveguide insertion loss of the horn-lens combination without the filter was about 3 dB. The dynamic range of the measuring system exceeded 20 dB and the accuracy was approximately ±0.1 dB.

The fourth ($s = 7\lambda/4$) and fifth ($s = 9\lambda/4$) resonances of the filter occurred in the 50–75-GHz band. Assuming perfect grids, and with $s = 1.016$ cm, the resonances occur, respectively, at 51.67 and 66.44 GHz. From the dimensions of the preceding grids given and from (9) and (10), one obtains $|t_{\parallel}| = 0.041 \equiv -28$ dB and $|r_{\perp}| = 0.013 \equiv -38$ dB at the first frequency, and $|t_{\parallel}| = 0.053 \equiv -26$ dB and $|r_{\perp}| = 0.017 \equiv -36$ dB at the second frequency. From these numbers and from (21) and (22) with $|r_{\perp}'| = |r_{\perp}|$, the frequency shifts for $\theta = 60°$ and 75° are, respectively, $-0.14$ and $-0.15$ GHz at the first frequency and $-0.18$ and $-0.20$ GHz at the second frequency. The

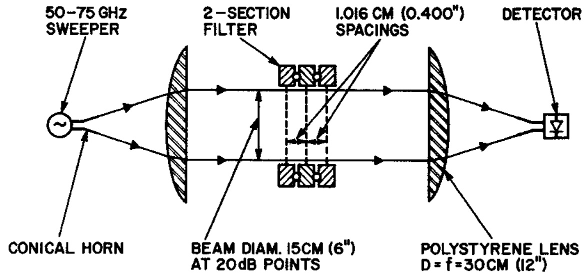


Fig. 5. Experimental schematic.

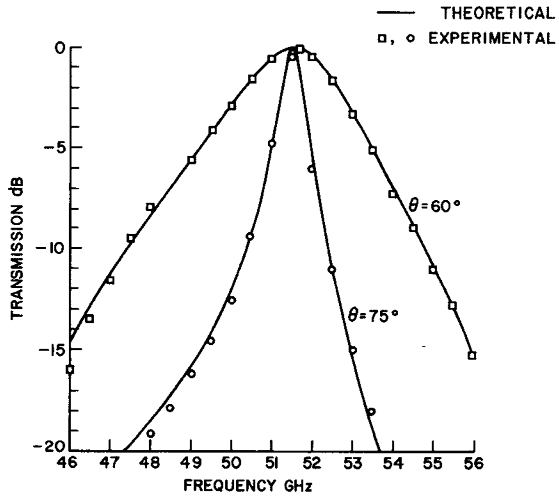


Fig. 6. Comparison of the experimental results and the theory at the fourth resonance of the two-section filter.

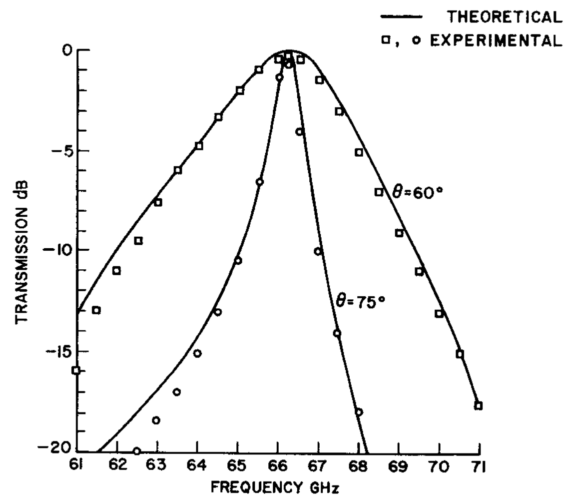


Fig. 7. Comparison of the experimental results and the theory at the fifth resonance of the two-section filter.

amount of loss predicted by (23) is less than 0.1 dB for any of the preceding cases mentioned.

The experimental results for the two aforementioned resonances are plotted in Figs. 6 and 7 for $\theta = 60°$ (squares) and $\theta = 75°$ (circles). In each figure, the solid lines represent the responses calculated by the method mentioned in Section III. The transmission and reflection coefficients of the grids were calculated from the preceding grid dimensions given with the help of Section II. The variation of these coefficients with frequency was taken into account.

The figures show that the solid curves are in excellent agreement with the measurements. However, the losses of 0.5 dB and 0.7 dB occurring at resonance for $\theta = 75°$ in Figs. 6 and 7, respectively, are larger than those predicted by the theory (less than 0.1 dB). The difference is attributed to ohmic losses in the grids which were neglected in the theory.

## ACKNOWLEDGMENT

The author wishes to thank F. A. Pelow for assistance in performing the experiment.

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# Short Papers

## Reduction of the Attenuation Constant of Microstrip

I. J. ALBREY AND M. W. GUNN

*Abstract*—**Modifications to a normal microstrip transmission line are proposed, with the aim of reducing the attenuation constant of the line. The results of a computer analysis of a structure containing multilayers of dielectric show that significant reductions in attenuation appear possible.**

### INTRODUCTION

The advent of solid-state microwave devices has given great impetus to the development of microwave integrated circuits, which are based on a microstrip structure consisting of conducting strips separated from a ground plane by a substrate material with a high dielectric constant. Methods for the calculation of characteristic impedance, capacitance, and wavelength of such structures were established in the 1950's [1], but the first accurate calculations did not appear until the 1960's [2]. This two-conductor structure can be effectively shielded by enclosure in an appropriately large metal container, but as pointed out by Brenner [3], such transmission lines are beset with problems of inhomogeneity of the substrate, narrow strip widths for typical characteristic impedance levels (up to say 150 Ω), and high attenuation. The suspended substrate transmission line, which largely overcomes such difficulties, has thus become popular.

This short paper reports some results of an investigation into possible methods of reducing the attenuation of microstrip. It is proposed that the attenuation constant of a normal suspended substrate transmission line can be reduced by removing the substrate from the immediate vicinity of the conducting strip. The investigation was prompted by work on the use of loading in the form of a "shell" of dielectric to reduce the attenuation of a coaxial cable [4].

Such a modified structure would have the general form shown in Fig. 1 where dielectric $\epsilon_2^*$ is to be regarded as the substrate material that was originally in contact with the center conducting strip, but has now been removed a finite distance from the strip. The other regions consist of low-loss low dielectric constant material ($\epsilon_1^*$ and $\epsilon_4^*$ are air), and $\epsilon_3^*$ supports the center strip.

### METHOD OF ANALYSIS

This multilayered structure has been analyzed on the assumption that a TEM field pattern exists. For this to be valid, the wavelength must be much greater than the transverse dimensions of the line, and so a frequency of 1 GHz ($\lambda_0$ equals wavelength in air-filled line = 30 cm) is chosen. Several methods of analysis are available, the variational approach [5] being chosen because of its direct nature and its accuracy, particularly in the calculation of attenuation. The method is based on a variational technique using Green's functions and considers the center conductor to be infinitely thin.

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