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# BROADBAND MILLIMETER-WAVE E-PLANE BANDPASS FILTERS

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## ABSTRACT

A recently developed efficient CAD program has been extended to apply to superbroadband E-plane bandpass filters. An accurate method for estimating the starting values used in the CAD program is developed and incorporated for design. W-band and D-band filters with bandwidth over 10 percent designed by the new program are presented.

## INTRODUCTION

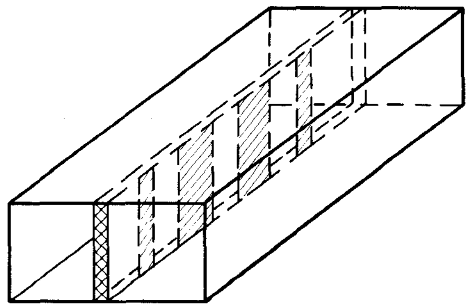
This paper reports an extremely cost effective yet accurate CAD program for a broadband E-plane filter. Most of the E-plane filters reported to date have a relatively narrow bandwidth.(1-3) For a wideband design, all the resonators must be very strongly coupled. Therefore, an accurate analysis procedure is needed which takes into account the interaction of not only the dominant, but also the higher order modes generated at the edge of the strips. The CAD algorithm in [3] theoretically meets these requirements because the analysis portion of the algorithm is mathematically exact and numerically very efficient. However, since there was no systematic scheme incorporated for providing starting values of the optimization routine, convergence was rather slow. It was found that this deficiency is especially noticeable for a wideband design. In the present paper, this CAD program is modified so that a standard impedance inverter technique is used for finding an initial guess. Since the equivalent circuit of the system used in arriving at the initial guess is based on the same analysis process as the one in [3]; the starting values for the filter are very close to the final values. Often no optimization is required.

The improved CAD program is used for designing E-plane bandpass filters with more than 10 percent bandwidth at D-band as well as lower frequency ranges. It is believed that the results obtained are unprecedented to the best knowledge of the authors.

## PROCEDURES

The analysis portion of the CAD program in [3] consists of three steps. In the first step, the generalized scattering matrix at one of the edges of the step is calculated exactly by the residue calculus technique. For instance, $S_{11}(m,p)$ is the amplitude of the reflected mth mode when the pth mode is incident. The second step is to compute the generalized S-matrix of a strip by combining the S-parameters derived in Step 1 for both edges of the strip. The third step is to combine generalized S-matrices of several strips. By these steps we obtain the generalized S-matrix of the entire filter structure (Figure 1). Notice that the use of the generalized S-matrix enables us to find the interactions between junctions due not only to the dominant mode, but also to all higher order modes. This is quite important for accurate design of wideband filters. The effect of higher order mode interactions becomes increasingly important in such filters in which the strips are narrow to make the resonators coupled strongly.

The improvement reported in this paper provides a good initial guess to the CAD program. The procedure is based on the formulation proposed by Rhodes(4) for a distributed step impedance low pass prototype. When the passband ripple $\epsilon$, the lower and upper bandedge frequencies $f_L$ and $f_H$, the out-of-band rejection L (dB) are



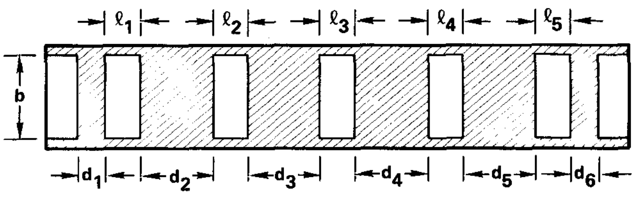



Figure 1. E-Plane Filter Structure



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specified, the procedure is as follows: (1) Determine the midband guide wavelength $\lambda_{go}$ by numerically solving[4]

$$\lambda_{gL} \sin(\pi\lambda_{go}/\lambda_{gL}) + \lambda_{gH} \sin(\pi\lambda_{go}/\lambda_{gH}) = 0 \qquad (1)$$

where $\lambda_{gL}$ and $\lambda_{gH}$ are the guide wavelength in the resonator section at $f_L$ and $f_H$; (2) Determine the number of resonators, N, by finding the minimum value of N for which the most severe constraints on the rejection L at the designated stopband frequency $f_s$ satisfies

$$L = 10 \log\left\{1 + \epsilon^2 T_N^2\left[(\lambda_g/\lambda_{gL}) \sin(\pi\lambda_{go}/\lambda_g)/\sin(\pi\lambda_{go}/\lambda_{gL})\right]\right\} \qquad (2)$$

where $T_N$ is the Chebyshev polynomial and $\lambda_g$ is the guide wavelength at $f_s$; (3) Calculate the impedances $Z_n$ of distributed element and impedance inverter values $K_{n,n+1}$ according to the formula in [4]; (4) After an appropriate normalization of $Z_n$ and $K_{n,n+1}$, we finally determine the strip width to realize the required impedance inverter. It consists of a T-network with normalized shunt and series reactances $X_p$ and $X_s$ and transmission lines wtih electrical length $\phi/2$ connected on both sides of the T-network. $X_s$ and $X_p$ are functions of the strip width d and are given in [3]. Since these functions are not available explicitly, we developed a look-up table, stored it in the computer, and searched for a value of d that provided the required impedance value K and the angle for each impedance inverter. (5) Finally, the length of the jth resonator formed by the jth and (j+1)th strips is given by

$$\ell_j = \frac{\lambda_{go}}{2\pi}\left[\pi - \frac{1}{2}(\phi_j + \phi_{j+1})\right] \qquad (3)$$

## DESIGN AND MEASUREMENT

Table 1 shows specification for a D-band filter. The initial guess of dimensions for septums ($d_j$) and resonators ($\ell_j$) is derived by the theory above. When these values are used in the analysis portion of the CAD program, the response sufficiently meets the specifications; hence, no optimization was performed. The measured insertion loss of this filter is shown in Figure 2. Figure 3 is a photograph of a D-band filter.

## CONCLUSIONS

An accurate estimation method for the starting value of an E-plane filter design has been developed based on the distributed Chebyshev prototype filter synthesis. Several filters have been fabricated using these starting values and, if necessary, the refined values by the CAD program developed earlier. These filters, particularly those at D-band have performances unprecedented to date.

TABLE 1

D-BAND FILTER SPECIFICATIONS

| | |
|---|---|
| Ripple | 0.10 dB |
| Lower Band-Edge Frequency | 138.0 GHz |
| Upper Band-Edge Frequency | 154.0GHz |
| Lower Rejection dB | 20.0 at 130.0GHz |
| Upper Rejection dB | 20.0 at 162.0GHz |
| Relative Dielectric Constant | 2.2 |
| Substrate Thickness/Inches | 0.003 |
| Waveguide Width/Inches | 0.065 |
| No. of Resonators | 5 |

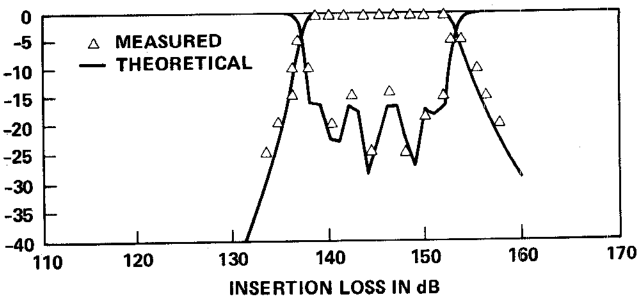


Figure 2. Measured Performance of D-Band Filter


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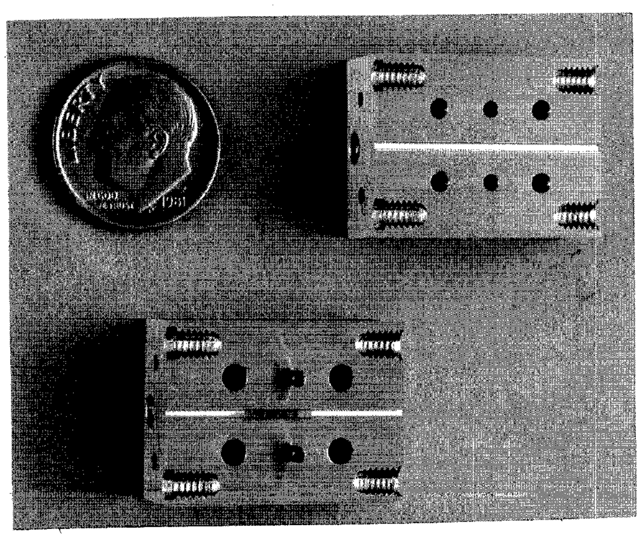

Figure 3. Photograph of a D-Band Filter