STOPBAND STUBS BOOST REJECTION IN E-PLANE FILTERS

Simple additions to waveguide bandpass filters improve performance without complex construction.

METAL-insert E-plane waveguide filters are commonly used at millimeter-wave frequencies because they are relatively easy to design and construct. However, achieving low loss and good selectivity is a challenge using conventional designs. An improved, yet uncomplicated class of E-plane filters uses inductively coupled stopband stubs to boost performance.

E-plane integrated-circuit waveguide filters with all-metal inserts are often used in microwave and millimeter-wave systems.[1] These low-loss filters are easy to manufacture at low cost, and numerical design formulas[2] have been in close agreement with measurements[3] to 150 GHz. Additionally, improvements to early designs have increased bandpass separation and stopband attenuation.[4-5] Unfortunately, the moderate skirt selectivity of these filters, compared with dual-mode resonator designs, is still a disadvantage.[6-8]

Selectivity is improved by increasing the number of resonators in metal insert filters, but at the cost of higher insertion loss.[9] Dual-mode operation, effective for obtaining high rejection in many filter types, is not possible in metal-insert filters. However, improved skirt selectivity may be obtained by adding stopband circuits to provide attenuation peaks in the overall frequency response. Stopband circuits can be realized by mounting slot- or iris-coupled waveguide resonators on top of the filter[10] or by using two-path cutoff waveguide resonator filters.[11] Unfortunately, these structures employ parallel waveguides, making them unsuitable for E-plane integrated circuit fabrication.

An improved class of E-plane metal insert filters provides attenuation peaks in the frequency response using inductively coupled waveguide resonators (Fig. 1). The structure is fully compatible with millimeter-wave integrated circuitry and low-cost E-plane manufacturing processes.

FILTER DESIGN

An accurate computer-aided design technique is based on rigorous electromagnetic field theory. The method includes higher-order mode interactions and the effects of nonzero metal insert thickness. The ac-

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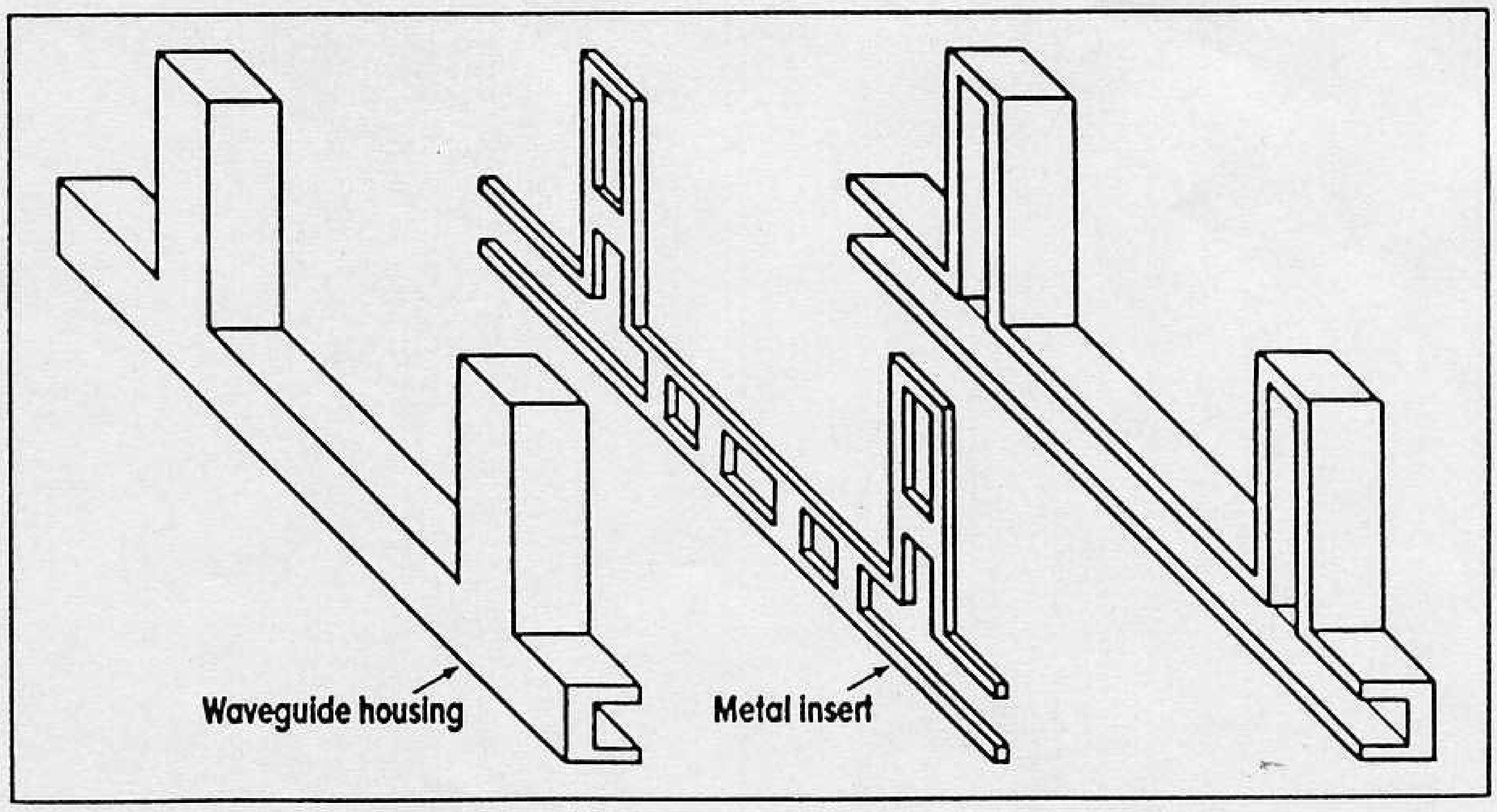

1. Stopband stubs are easily added to metal insert waveguide filters. The stubs improve skirt selectivity with little effect on passband performance.

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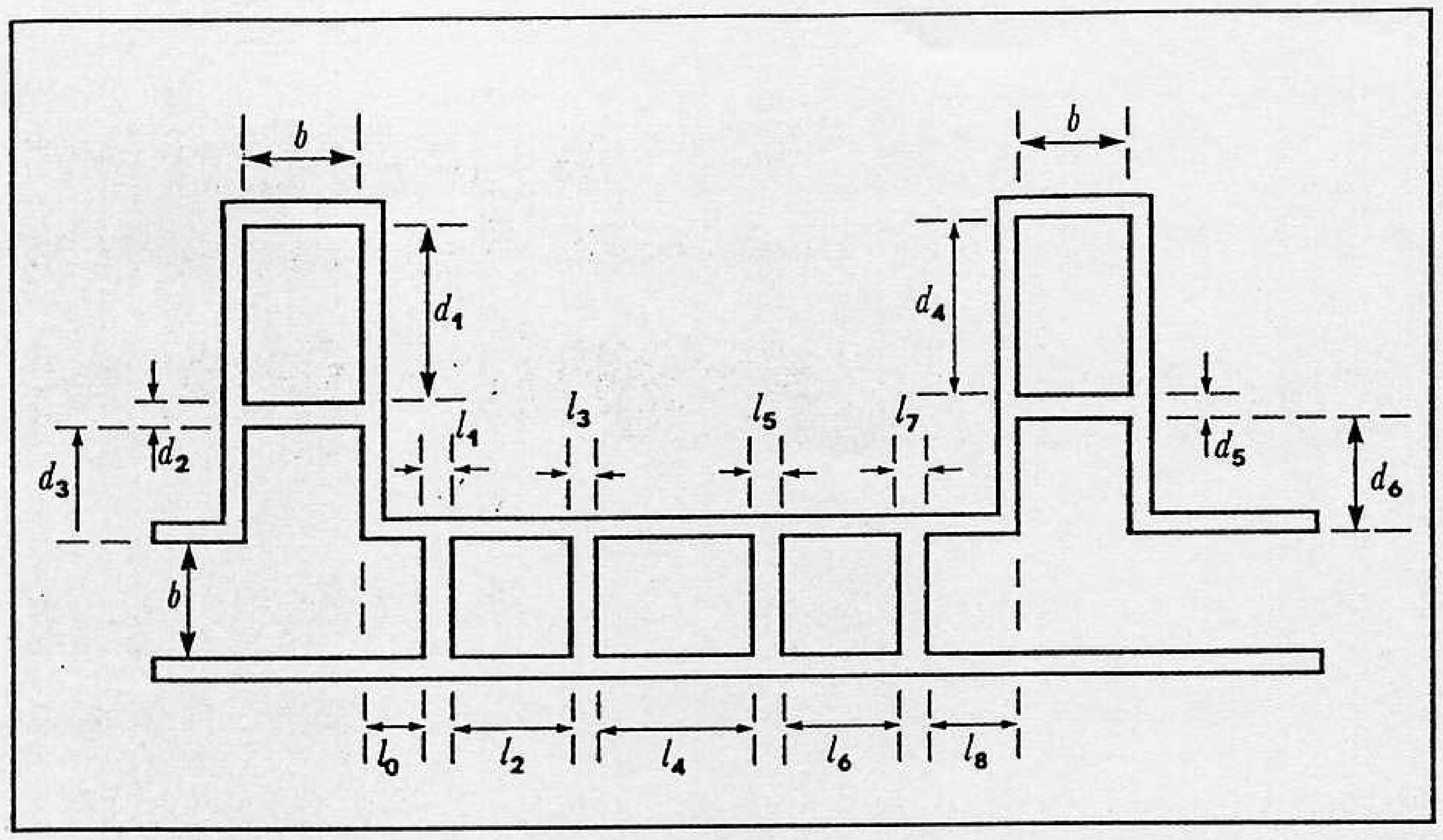

2. The same waveguide height, *b*, is used for the bandpass section and the stopband stubs.

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curacy of this approach yields filters that do not require post-tuning elements such as screws or sliding shorts.

The theoretical treatment of the improved filter structure utilizes a selected-mode scattering matrix. Assuming an incident TE_{10} wave, the metal insert filter is analyzed using a set of longitudinal TE^x_{m0} modes. However, the E-plane T-junctions used in the filter require TE^x_{1n} modes.[12] In general, five field components of the TE^x_{mn} spectrum sufficiently describe the structure's electromagnetic behavior, provided that b is less than d_3 and d_6 (Fig. 2).

The electromagnetic field in each homogeneous subregion of the bandpass section (l_0 to l_8) is described as:

$$\mathbf{E} = \nabla \times (A_{hx}\mathbf{e}_x) \tag{1a}$$

$$\mathbf{H} = (j/\omega\mu)\, \nabla \times \nabla \times (A_{hx}\mathbf{e}_x) \tag{1b}$$

where:
$\mathbf{E}$ = electric field vector,
$\mathbf{H}$ = magnetic field vector,
$\mathbf{e}_x$ = unit x-vector,
$j = \sqrt{-1}$,
ω = radian frequency, and
μ = permeability.

The solution to Eq. 1 can be expressed in terms of corresponding Eigenfunctions:

$$A_{hx} = \sum_{m=1}^{M} \sum_{n=0}^{N} A_{mn} \sin(k_{xm}x) \times \cos(n\pi y/b) \times (1 + \delta_{on})^{-1/2} \times [V_{mn} \exp(-jk_{zmn}z) - R_{mn} \exp(+jk_{zmn}z)] \tag{2}$$

where:
A_{hx} = vector potential function,
M = number of TE^x_{1n} modes considered,
N = number of bandpass filter sections,
a = waveguide width,
b = waveguide height, and
δ_{on} = Kronecker delta function.

In Eq. 2, V_{mn} and R_{mn} are the amplitudes of forward and backward traveling waves, respectively, and k_{zmn} is the related propagation constant of the subregion. In sections containing a metal insert (l_1, l_3, etc.), k_{xm} is given as:

$$k_{xm} = 2m\pi/(a - t) \tag{3}$$

where:
t = insert thickness.

In waveguide sections that contain no metal insert, k_{xm} is expressed as:

$$k_{xm} = (2m - 1)\,\pi/a \tag{4}$$

The constant, A_{mn}, in Eq. 2 is used to normalize power to 1 W for propagating modes or j1 W for evanescent modes. Because the waveguide height used for the filter sections is equal to the waveguide height in the E-plane stopband stubs (d_1 to d_6), Eq. 2 can be applied to the stubs by interchanging the variables y and z.

Each waveguide T-junction may be regarded as a resonator having width = a, and height = length = b. The vector potential function of such a resonator is considered the superposition of cross-sectional

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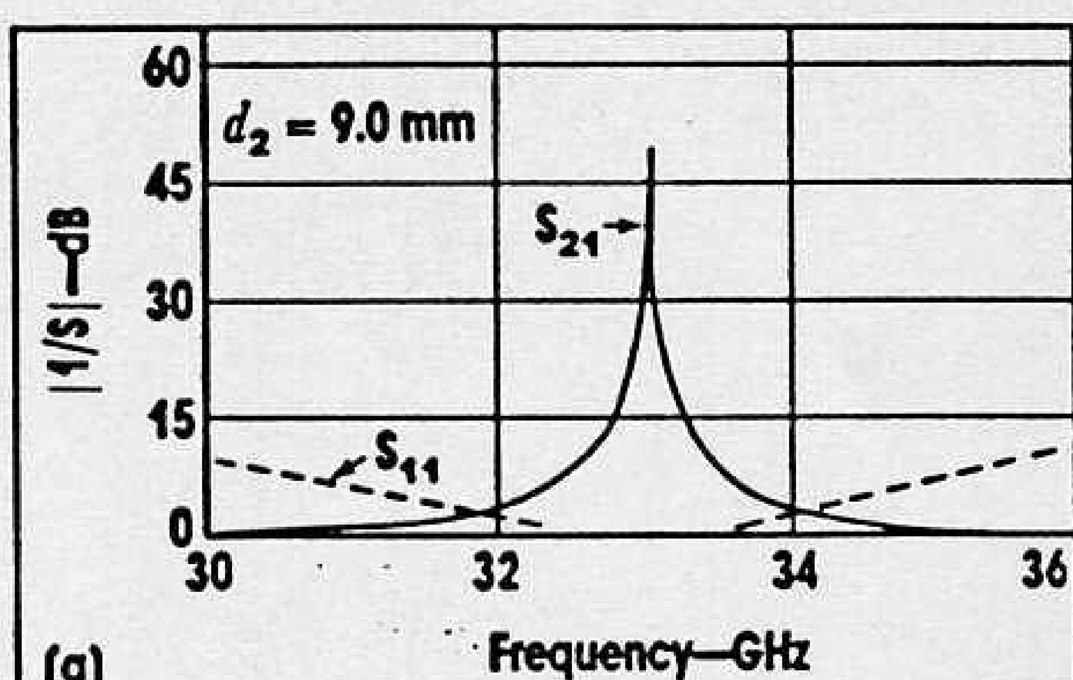

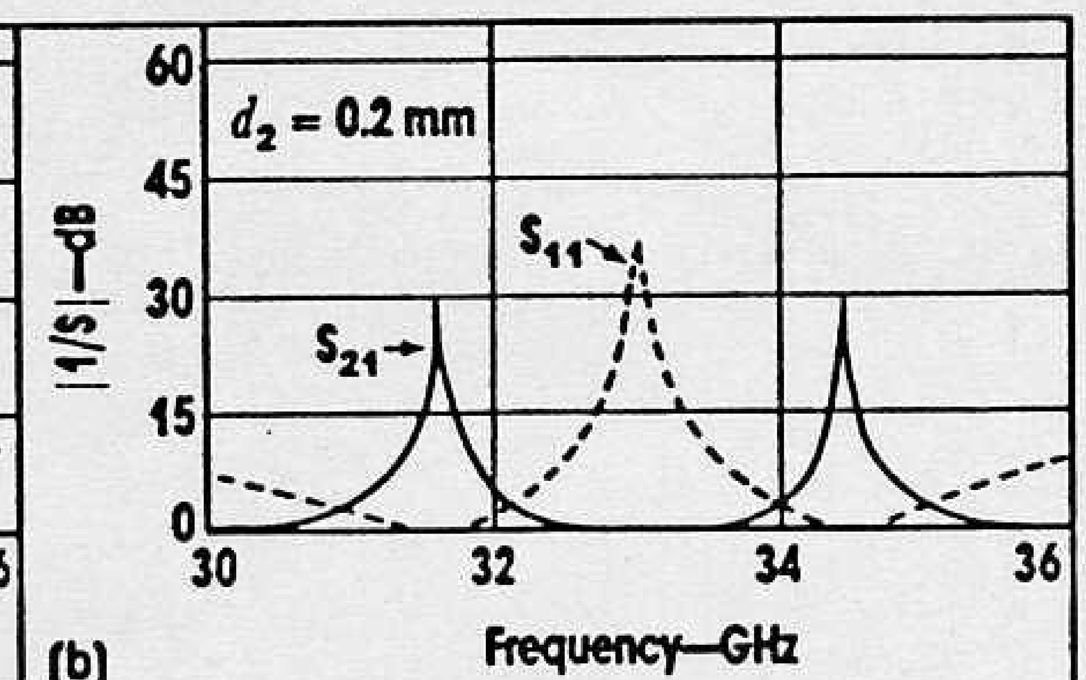

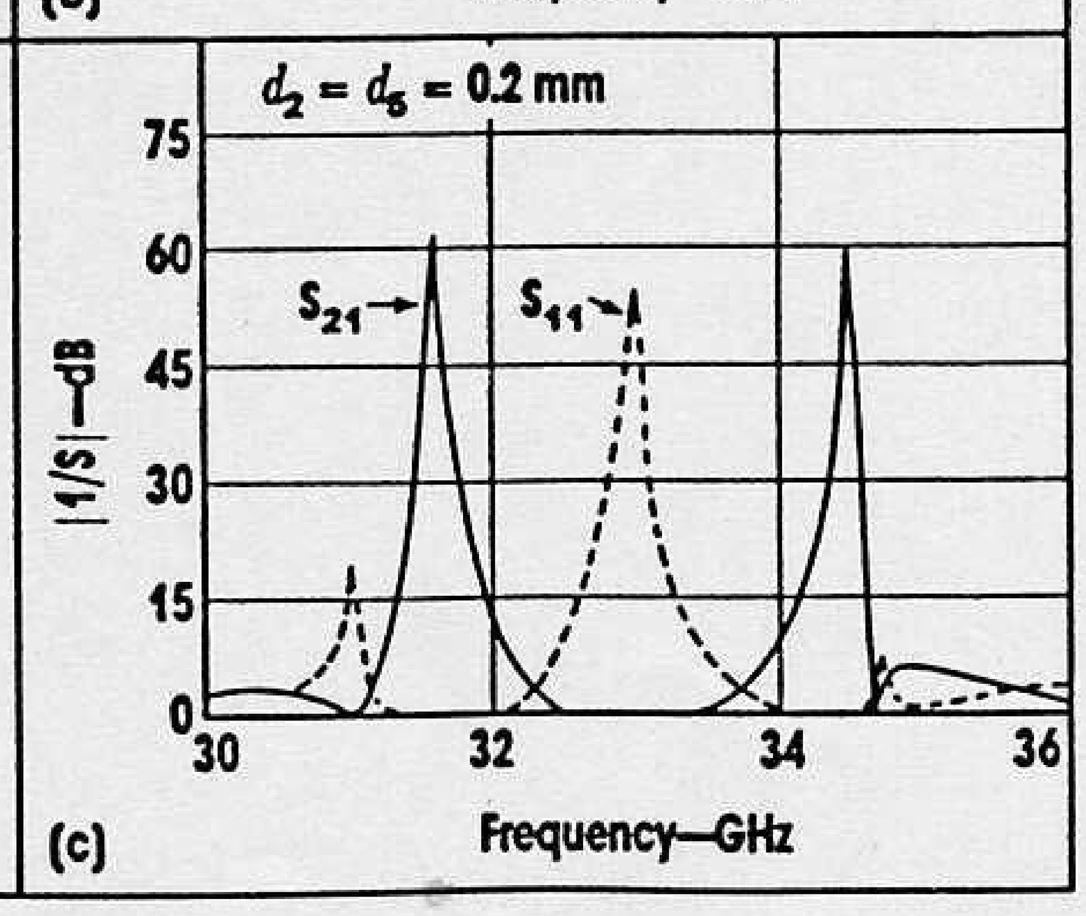

3. A 33-GHz E-plane stub with loose coupling has good stopband attenuation but high passband VSWR (a). A tightly coupled stub features two attenuation peaks with low VSWR in between (b). When two tightly coupled stubs are cascaded, attenuation reaches 60 dB (c).

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electromagnetic fields at the three openings.[13] Matching the resonator modes to those of the connected waveguides yields the modal scattering submatrices, S_{11} to S_{33}, for the T-junction.

The matrix S_{S11} contains the input reflection coefficients for the stub (sections d_1 to d_3). The overall two-port scattering matrix, S_G, of the T junction is described by:

$$S_{G11} = S_{G22} = S_{11} + S_{13}S_{S11}\,[U - S_{33}S_{S11}]^{-1}\,S_{31} \quad (5a)$$

$$S_{G21} = S_{G12} = S_{21} + S_{23}S_{S11}\,[U - S_{33}S_{S11}]^{-1}\,S_{31} \quad (5b)$$

where:

U = unit matrix.

The overall modal scattering matrix of the filter is obtained by cascading the two-port scattering matrices of each filter section.

In the computer analysis, solutions for T-junction and bifurcation discontinuities are calculated using M up to 35 and N up to 25. When combining cascaded scattering matrices, however, only the lowest five to seven modes are used. Compared to a full-mode analysis, this greatly reduces processing time while maintaining sufficient accuracy.

The design process begins by optimizing the bandpass filter and the stub sections separately. An evolution strategy is used to optimize and fine-tune the complete structure according to specified characteristics.

FILTER PERFORMANCE

Ka-band stopband filters were designed with $a = 2b = 7.112$ mm, $t = 0.19$ mm, $d_1 = 10.951$ mm, and $d_3 = 7.395$ mm. For loose coupling ($d_2 = 9.0$ mm), passband return loss is less than 10 dB at ±3 GHz from the stopband frequency (Fig. 3a). For the intended application, the stub must exhibit better return loss.

With tight coupling, d_2 is reduced to 0.20 mm, approximately the thickness of the metal insert. The frequency response of the tightly coupled Ka-band stub features two attenuation peaks, separated by a passband with improved return loss (Fig. 3b). When two such stopband filters are cascaded with 18-mm separation, the attenuation peaks reach 60 dB with better than 15-dB return loss over a 2-percent bandwidth (Fig. 3c).

An optimized Ka-band filter centered at 33 GHz has the following dimensions:

$a = 2b = 7.112$ mm
$t = 0.19$ mm
$d_1 = d_4 = 10.951$ mm
$d_2 = d_5 = 0.2$ mm
$d_3 = d_6 = 7.395$ mm
$l_0 = l_8 = 8.998$ mm
$l_1 = l_7 = 1.465$ mm
$l_2 = l_6 = 4.286$ mm
$l_3 = l_5 = 4.783$ mm
$l_4 = 4.296$ mm

The passband response of the improved filter is similar to that of a

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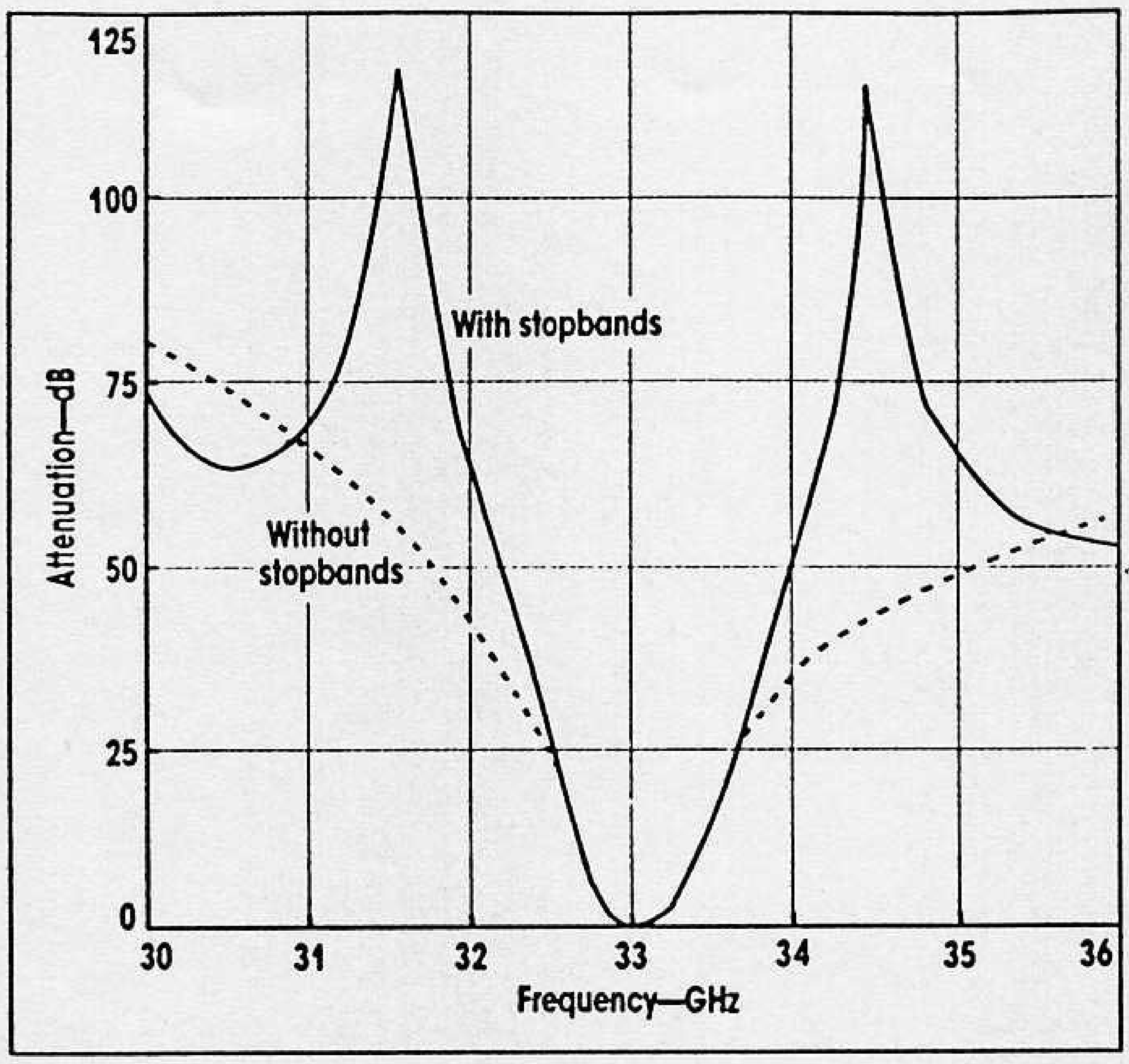
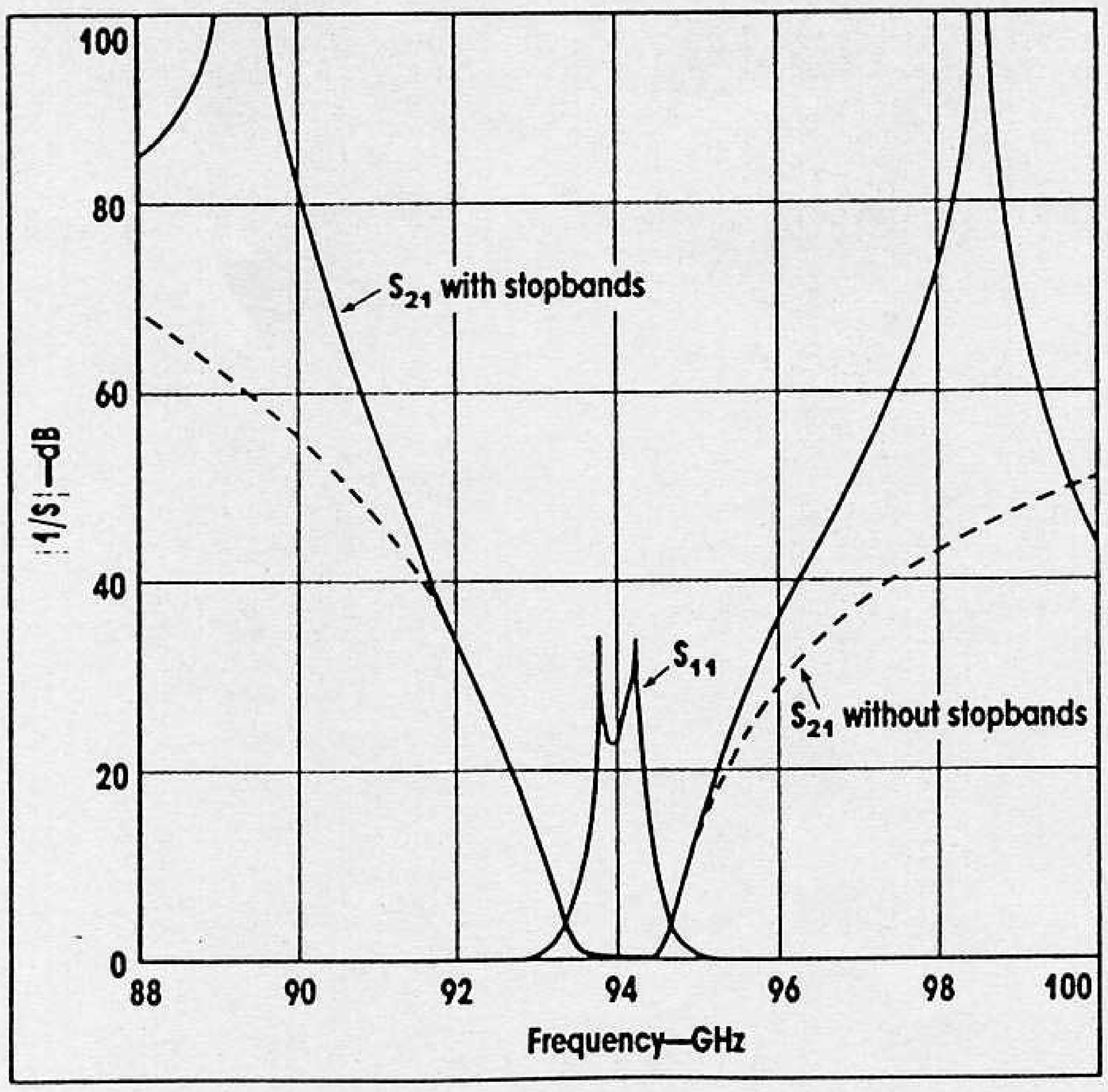


4. Adding two stopband stubs to a 33-GHz metal insert filter improves selectivity without degrading passband characteristics.



5. Improved selectivity and low VSWR are provided by a 94-GHz bandpass filter with stopband stubs. The stubs increase VSWR from 1.11 to only 1.15.

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passband filter without stopband stubs (Fig. 4). However, the stopband stubs greatly improve skirt selectivity. In certain frequency ranges, interactions between stubs and the bandpass filter reduce out-of-band attenuation. However, these effects occur only at attenuation levels above 50 dB, as specified in the optimization process.

An optimized W-band filter centered at 94 GHz has the following dimensions:

$a = 2b = 2.54$ mm
$t = 0.05$ mm
$d_1 = d_4 = 3.799$ mm
$d_2 = d_5 = 0.066$ mm
$d_3 = d_6 = 2.529$ mm
$l_0 = l_8 = 3.495$ mm
$l_1 = l_7 = 0.599$ mm
$l_2 = l_6 = 1.441$ mm
$l_3 = l_5 = 1.832$ mm
$l_4 = 1.443$ mm

For this filter, an effort was made to maintain better than 20-dB return loss in the passband (Fig. 5). Adding stopband stubs to the bandpass filter increased VSWR from 1.11 to only 1.15.

On an enhanced personal computer, the program used to design these filters requires about 10 min. to compute the frequency response of each set of input parameters. The filters are relatively easy to design and manufacture for applications beyond 100 GHz. Additionally, stopband stubs can be used to improve the performance of millimeter-wave diplexers, mixers, and frequency multipliers that employ E-plane construction. ••

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