# Millimeter-Wave Diplexers with Printed Circuit Elements

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*Abstract*—**A novel design of *W*-band (75–110 GHz) noncontiguous diplexers is described. The common port of the diplexer is fed by suspended probe transitions which are suitable for wide-band applications. The circuit is printed on a single substrate and easily assembled in a split-block housing. The measured insertion loss at the passbands is about 1 dB. The calculated frequency response of a diplexer is in good agreement with the measurement.**

## I. Introduction

Recent advances in the design of millimeter-wave channelized receivers have created a need for small, integrated high-performance diplexers and multiplexers [1]–[4]. However, the design information on these components is very limited. In [2], the authors have designed a diplexer consisting of two *E*-plane filters and a waveguide T-junction. Since the reactance of the T-junction varies relatively rapidly as a function of frequency, it is difficult to compensate for the reactance in order to design diplexers with wide-band performance using this scheme. In this paper, we will describe a novel design of a millimeter-wave noncontiguous diplexer that is capable of wide-band applications. Channel bandwidths as wide as 10 GHz can now be achieved with an insertion loss of about 1 dB at *W* band. In Section II, the diplexer structure is described and the design principle is discussed. Section III provides a brief discussion on the theoretical analysis for the diplexer. Section IV summarizes the results of both the theory and measurement. Good agreements are obtained.

## II. Diplexer Design

Fig. 1 shows a typical layout of the diplexer. It consists of two band-select filters and two waveguide-to-suspended-stripline probe transitions. The filters are *E*-plane filters [5]–[7] which can be bilateral, unilateral, or a combination of both. The complete circuit is fabricated on a single substrate, which is then cut to size and placed in a split-block housing.

The use of waveguide-to-suspended-stripline transitions at the common port of the diplexer makes is possible for wide-band applications. The idea stems from our experience in the design of suspended-stripline circuits at millimeter-wave frequencies, where a good transition has been designed to cover the full *W*-band (75–110 GHz). The design is a refinement of the work done by the other designers in this field [8].

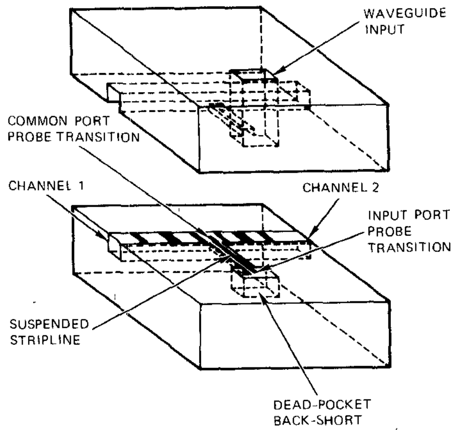

Fig. 1. Physical configuration of a diplexer.

There are two probe transitions, i.e., the input-port probe and the common-port probe. The input-port probe transition is very similar to the conventional coaxial-to-waveguide adaptor. One end of the suspended-strip probe is inserted into the broadside of the waveguide about one quarter-wavelength deep, and a waveguide backshort is located behind the probe to optimize the coupling. The other end of the probe is the common-port input to the diplexer and works in a similar way; however, this coupling structure is quite different. There are no waveguide backshorts but the bandpass filters. The transition works because at the passband of one channel, the other filter will reflect almost all the energy, and thus serves as a good short circuit. In this case, the loading effects of each filter at the short-circuit reference planes are required for the design of the transition and must be included in the net design of the diplexer to ensure good response. This requirement makes the *E*-plane filters an ideal candidate because of the existing accurate analytical modeling. High-performance *E*-plane filters have been designed up to 160 GHz using our modeling technique, and we have found excellent correlation between theory and measured data [7].

The filters may have any *E*-plane configuration, as defined earlier; however, because of the suspended-strip transition, we found it more convenient to make the filters and transitions on a single substrate. Furthermore, we have found that for the same filter specifications, the bilateral

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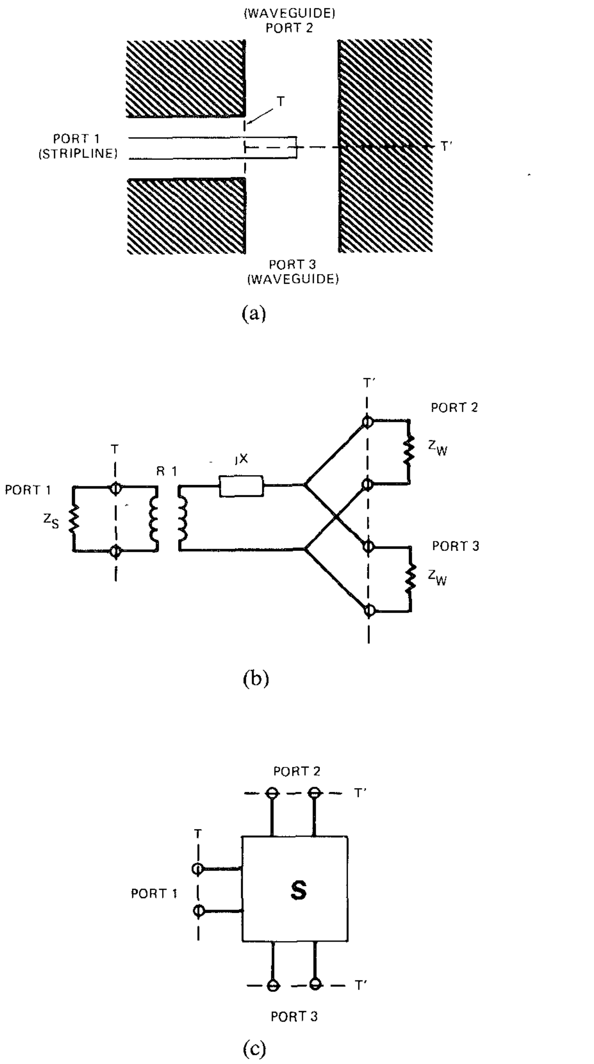



Fig. 2. (a) Stripline-to-waveguide T-junction, (b) the equivalent circuit, and (c) the $S$-matrix representation

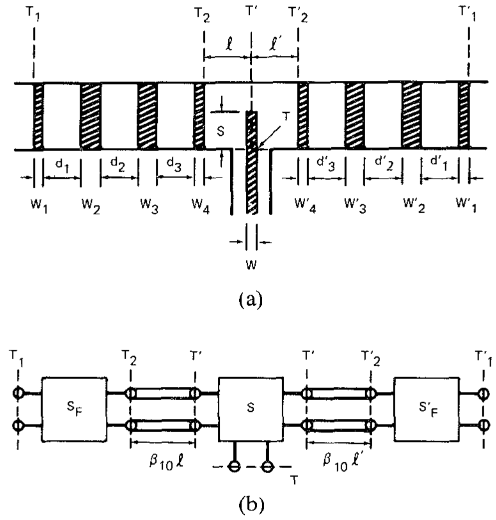



Fig. 3. (a) The printed-circuit part of the diplexer, and (b) the $S$-matrix network representation.

structure offers a loss performance comparable with, and sometimes superior to, that of the metal-insert structure. Note that the diplexer contains three parts: the upper and lower halves of the split block and the printed circuit. It is a very low-cost structure.

## III. Analysis

In a recent study [9], we analyzed a microstrip-to-waveguide transition using an approximate theory. The probe transition is considered as a monopole antenna radiating into the waveguide. Based on an assumed current distribution on the probe antenna, a variational expression has been derived in the spectral domain for the input impedance at the feed point. An equivalent circuit is then derived as shown in Fig. 2(b) for the transition in Fig. 2(a). The expressions for the turn ratio $R$ and the reactance $jx$ will be presented in [9].

The three-port transition junction can then be represented by a $3 \times 3$ scattering matrix. The $S$-parameters are derived from the equivalent circuit as

$$S_{11} = \frac{R^2(jx + Zw/2) - Zs}{R^2(jx + Zw/2) + Zs}$$

$$S_{22} = S_{33} = \frac{-R^2 Zw/2}{R^2(jx + Zw/2) + Zs}$$

$$S_{21} = S_{31} = S_{12} = S_{13} = \frac{R\sqrt{ZwZs}}{R^2(jx + Zw/2) + Zs}$$

$$S_{23} = S_{32} = \frac{jxR^2 + Zs}{R^2(jx + Zw/2) + Zs}.$$

We can now proceed to analyze the diplexer structure as shown in Fig. 3(a), where two channel filters have been connected to a common probe transition. The $S$-parameters for the $E$-plane filters are readily available from [5]. Taking into account the distance between the filters and the transition, we obtain the network representation in Fig. 3(b). The overall $S$-parameters for the diplexer are then obtained using the network combining technique described in the Appendix.

## IV. Results

The waveguide-to-suspended-strip transition is essential for the diplexer design. Therefore, we have tested numerous $W$-band transition circuits to find a good combination. Fig. 4 depicts the geometry and the dimensions of an operating $W$-band transition. The circuit is designed on an RT-5890 Duroid substrate whose dielectric constant is 2.0. We have analyzed, fabricated, and tested two such transitions connected back-to-back by a 1-in-long suspended stripline. The results are shown in Fig. 5 with good agreement between the theory and measurement. The return loss is better than 15 dB, and the measured insertion loss is

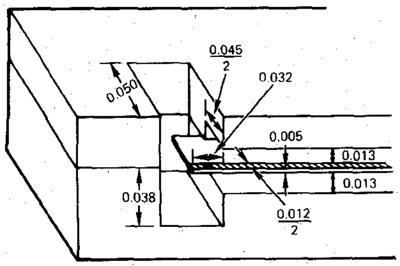



Fig. 4. Cross-section view of a *W*-band waveguide-to-suspended-strip transition in WR-10 waveguide.

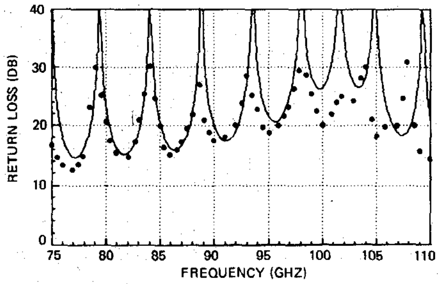



Fig. 5. Return loss of the probe transition at *W*-band (—— theory, • measurement).

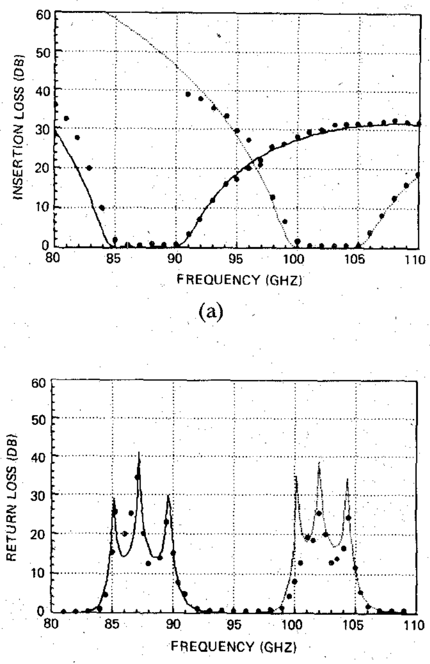



Fig. 6. (a) Insertion loss, and (b) return loss of *E*-plane filters (—— theory, • measurement).

TABLE I
DIMENSIONS FOR A *W*-BAND DIPLEXER (ALL UNITS IN MILS)

| | $W_1 = W_4$ | $W_2 = W_3$ | $d_1 = d_3$ | $d_2$ | $\ell$ | W | S |
|---|---|---|---|---|---|---|---|
| Filter 1 | 3.0 | 20.9 | 63.4 | 64.4 | 27 | | |
| Filter 2 | 8.7 | 37.4 | 45.2 | 44.9 | 27 | | |
| Probe | | | | | | 12 | 32 |

better than 0.7 dB (not shown) over the *W*-band frequencies.

The *E*-plane filters are designed using the procedures described in [5]–[7]. As an example, we have designed two 3-cavity bilateral *E*-plane filters having 5-GHz bandwidths centered at 87.5 and 102.5 GHz, with passband ripples of 0.2 and 0.1 dB, respectively. The dimensions of the filters are listed in Table I for a dielectric substrate of 5-mil thick. Both the theoretical and experimental results are shown in Fig. 6 for comparison. The measured insertion loss is less than 1 dB in the passband of both filters. In the analyses, we have also obtained the short-circuit reference location for each filter at the passband frequencies of the other filter. Based on this information, the relative locations of the filters with respect to the probe are then adjusted to yield a complete diplexer.

Fig. 7 is the picture of a complete diplexer. The *E*-plane filters and the transitions are fabricated on a single 5-mil substrate using chemical etching. The circuit is then cut and placed in the split-block housing. The diplexer was evaluated over the frequencies of interest and its performance is shown in Fig. 8. A close agreement is found between the theoretical and experimental data. In the passband of the channels, the return loss is more than 10 dB, and more typically 15 dB. The measured insertion loss is typically 1 dB. Notice that each channel very much preserves the characteristics of the corresponding filter, except that the upper-end rejection of the lower channel has a slight improvement.

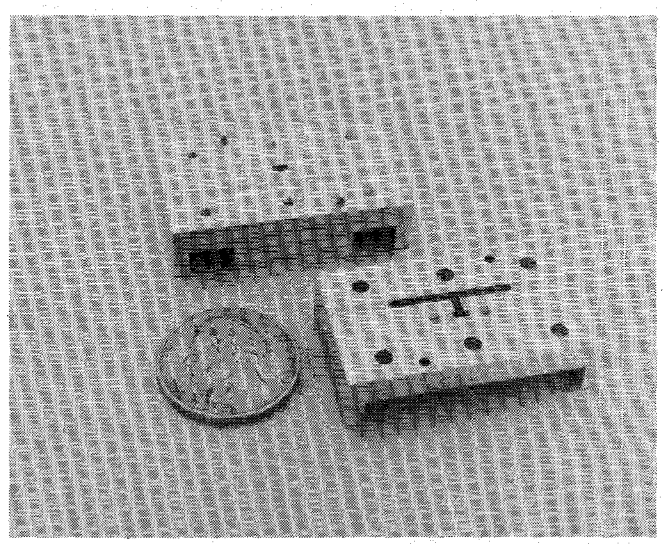
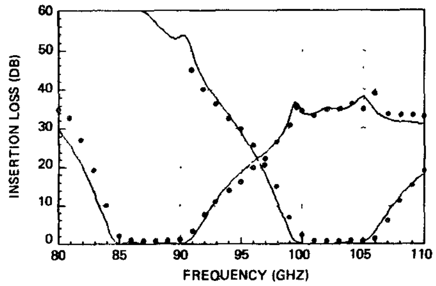
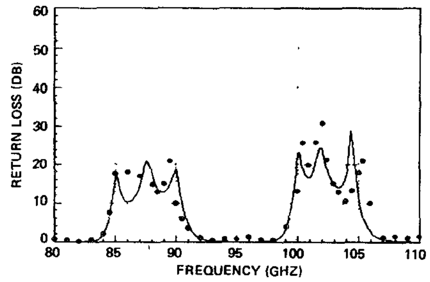


Fig. 7. Photograph of a completed *W*-band diplexer.

Diplexers having wider channel passbands can also be built in a similar manner. For example, Fig. 9 shows the performance of a diplexer having a 10-GHz passband for both channels. A 10-GHz guard band is placed between the two channels. The input return loss in the passband of the channels is more than 12 dB, and the insertion loss about 1 dB.

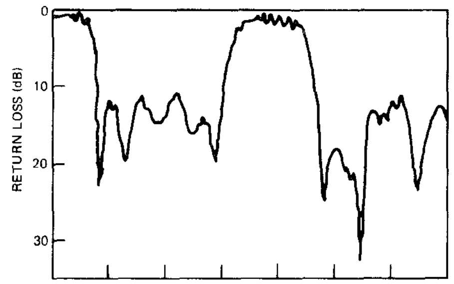



(a)

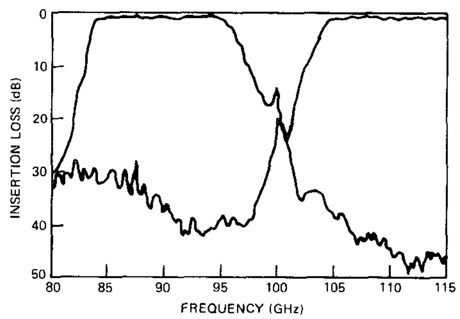



(b)

Fig. 8. The (a) insertion loss and (b) return loss of a diplexer shown in Fig. 7 (—— theory, ● measurement).




(a)




(b)

Fig. 9. The measured (a) return loss (b) insertion loss of a diplexer with 10-GHz channel bandwidths.

## V. Conclusion

The combination of the $E$-plane filters and a unique suspended probe transition imbedded at the common port has resulted in the design of high-performance and low-cost diplexers with wide channel bandwidths. The complete circuit is printed on a single substrate and is easily assembled in a split-block housing. This makes it highly reproducible using photolithographic techniques. Typical $W$-band diplexers exhibit about 1-dB insertion loss over the channel passbands.

Combining the probe-transition analysis program with the $E$-plane filter analysis program, we have calculated the frequency response of a diplexer in good agreement with the measurement.

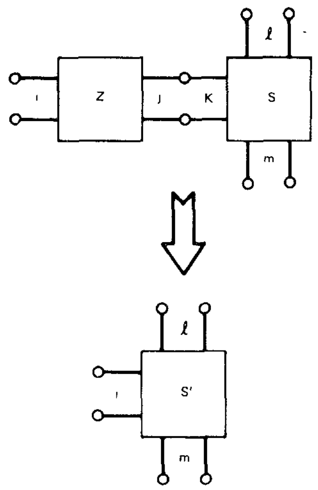



Fig. 10. The network combination scheme for a two-port and a three-port network.

## Appendix

Refer to Fig. 10. Port $j$ of a 2-port network $Z$ is connected to port $k$ of a 3-port network $S$. The result is a 3-port network $S'$ with the following elements:

$$S'_{ii} = Z_{ii}FZ_{ij}S_{kk}Z_{ji}$$
$$S'_{ll} = S_{ll} + FS_{lk}Z_{jj}S_{kl}$$
$$S'_{mm} = S_{mm} + FS_{mk}Z_{jj}S_{km}$$
$$S'_{ml} = S_{ml} + FS_{mk}Z_{jj}S_{kl}$$
$$S'_{lm} = S_{lm} + FS_{lk}Z_{jj}S_{ml}$$
$$S'_{il} = FZ_{ij}S_{kl}$$
$$S'_{im} = FZ_{ij}S_{km}$$
$$S'_{li} = FS_{lk}Z_{ji}$$
$$S'_{mi} = FS_{mk}Z_{ji}$$

where

$$F = \frac{1}{1 - S_{kk}Z_{jj}}.$$

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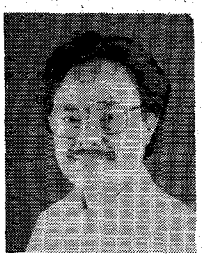

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