

Microwave Multiplexers Using Complementary Filters

The authors describe a method for dealing with the problem of out-of-band mismatch among multiple filters

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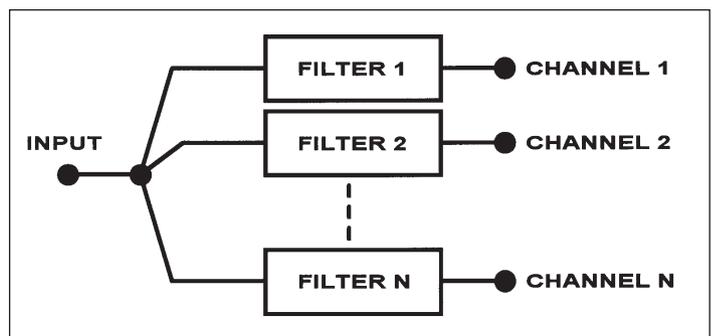
This paper describes the design procedure of a multiplexer using complementary filters. The technique described allows the design of matched structures over a large range of frequencies. The required conditions at the network which may be realizable with complementary filters are shown. The design procedure is developed for bandpass and bandstop complementary filters connected at a common junction for narrow band applications. A stripline structure was used to realize one diplexer. Experimental and theoretical results agree.

Multiplexers are devices that split a wide frequency band into a number of signal bands of different ranges. The separation of the desired frequency bands can be made using bandpass filters combined at a common input (Figure 1).

The main problem with this kind of topology is that the filters are reflective devices, whose performance is specified by good impedance matching between source and load in the pass-band, and a strong mismatch outside. If several of these filters are simply connected together, undesirable mutual interaction effects will appear, because the input impedance of the individual filters is not predictable outside their own passbands. This causes a drastic variation in the impedance presented to the external circuitry at each filter in its respective band. This mismatch degrades the performance of the system.

To avoid that problem, all the filters of the multiplexers are designed so that, at the operating frequencies of each individual filter, all other filters present an open circuit at the common junction.

One way to accomplish matched structures in

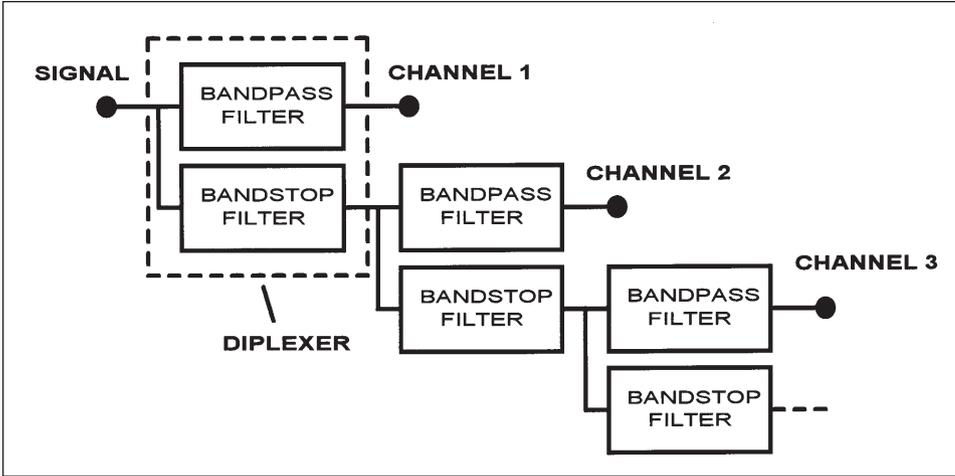


■ Figure 1. Multiplexer using bandpass filters combined at a common input.

a large range of frequencies is by using complementary filters. That means that the sum of the input impedances is real and constant for all frequencies. However, only minimum reactance and minimum susceptance networks may be made complementary [1]. When suitably designed bandpass and bandstop complementary filters are connected in parallel or series, they present a constant-resistance input impedance. This combination represents a diplexer, which is the basic building block of a multiplexer. The multiplexer consists of cascaded diplexers, each separating a particular band of frequencies (Figure 2).

Minimum reactance networks

The behavior of a network may be specified by one system function, which is defined as the ratio of the response or output variable to the excitation or input variable. Two types of system functions are of interest: the driving-point function and the transfer function. For a driving-point function, the input and output are measured at the same port. Therefore, any input or output impedance is a driving-point function.



■ Figure 2. Multiplexer using cascaded complementary diplexers.

The input impedance of a linear network may be expressed as a rational function of two polynomials, $p(s)$ and $q(s)$. Both $p(s)$ and $q(s)$ may be written as a product of linear factors involving their roots, z_i and p_i , which are the zeros and poles of the function.

$$Z_{in}(s) = \frac{\prod_{i=1}^n (s - z_i)}{\prod_{i=1}^m (s - p_i)} \quad (1)$$

One basic property is that the driving-point impedances of linear, passive networks are positive real functions. This property is sufficient and necessary to ensure their realizability [2]. A rational function is a positive real function if it is analytic in the right half-plane, its real part is non-negative on the imaginary axis, and any poles on the imaginary axis are simple and have positive real residues.

For a given positive real function $Z(s)$, the poles can be removed at the origin, on the imaginary axis and at infinity, and the remainder function is positive and real. The positive real character of the function assures that any poles on the imaginary axis are simple and that the residues at these poles are real and positive. The corresponding terms of the partial-fraction expansion are realizable and the remaining portion of the function involving left half-plane poles is positive and real, and hence does not have its realizability impaired by the removal of the poles on an imaginary axis.

The same procedure cannot be made with the left half plane poles because subtracting them from the function can damage its positive real character, causing the remainder function not to be realizable. The impedance function is reduced to a form with no poles or zeroes on the imaginary axis. Therefore, no reactance function may be removed from the function without destroying its positive real character. In this case, the impedance function with no poles on the imaginary axis is known as

a minimum reactance function. Similarly, the admittance function with this property is a minimum susceptance function. The minimum reactance function is a special class of driving-point impedances that are positive and real, have no poles on the imaginary axis and have finite values for all real frequencies, including infinity [2]. The same is true for minimum susceptance functions.

Relationships between real, imaginary parts

In many synthesis applications, only one part of the network is prescribed. Relationships between the parts of a network function may be expressed

through the Hilbert transforms if the network function is analytic in the closed right-half side (including the imaginary axis) of the s -plane.

In our problem, $Z(s)$ is the input impedance, a driving-point function. Therefore, it does not have zeroes or poles in the right half-plane, but can have poles on the imaginary axis. If $Z(s)$ has a pole on the imaginary axis, $Z(s)$ will have one singularity there. Since $Z(s)$ needs to be analytic in the closed right half-plane, the impedance function is necessarily a minimum reactance function.

The input impedance may be written as:

$$Z(j\omega) = R(\omega) + jX(\omega) \quad (2)$$

where $R(\omega)$ and $X(\omega)$ respectively are, the real and the imaginary parts of the minimum reactance network. If:

$$\lim_{\omega \rightarrow \infty} Z(j\omega) = R(\infty) = \text{a finite real constant} \quad (3)$$

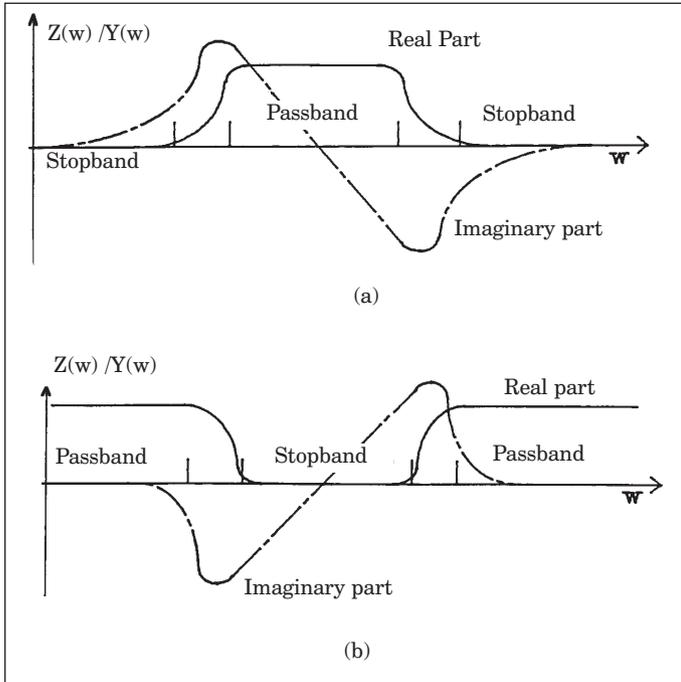
then the real and imaginary parts of minimum reactance and minimum susceptance networks are related by the following mathematical formulae, [3] :

$$X(\omega) = -\frac{1}{\pi} \int_{-\infty}^{\infty} \frac{R(u)}{\omega - u} du \quad (4)$$

$$R(\omega) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{X(u)}{\omega - u} du + R(\infty) \quad (5)$$

The first formula shows how to compute the imaginary component of the input impedance of a minimum reactance network, if the real component is known. Similarly, if the imaginary part is specified over all frequencies, the real part is determined completely to be an additive constant.

One advantage of these relationships is that the specified component of the minimum reactance function can be given merely as a graph. If the real input impedance



■ **Figure 3. Input impedance/admittance of minimum-reactance/susceptance networks, (a) bandpass filter and (b) bandstop filter.**

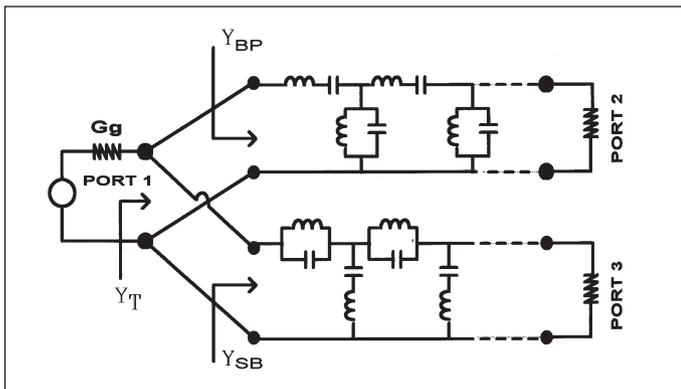
is constant over a band of frequencies and falls to zero and remains zero outside the passband, equation (4) may be used to show that the imaginary part has the following shape:

- A negative slope in the passband,
- A change of slope in the transition band and
- A positive slope in the stop band.

Figure 3 [1] shows the behavior of the input impedances (or admittances) of minimum reactance (or susceptance) networks of bandpass and bandstop filters.

Complementary multiplexers

The design of complementary multiplexers is based on the construction and connection of diplexers in cas-



■ **Figure 4. Parallel-connected diplexers using complementary filters.**

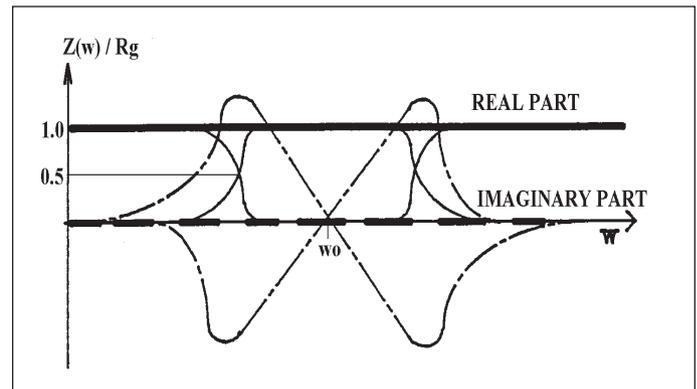
cade. The diplexer consists of a bandpass filter and a bandstop filter arranged so that they have the same cut-off frequencies and are tuned to the same center frequency. Each diplexer separates a band of frequencies around the center frequency of the filters from the remaining frequencies. The bandpass and bandstop filters of each diplexer are designed to be complementary. The filters are interconnected to produce a constant-resistance input impedance at all frequencies. If the filters are connected in series, the sum of their input impedance should be constant and equal to the generator resistance. If the filters are connected in parallel, the sum of their admittances should be constant and equal to the generator conductance. The filters must be of minimum reactance for the series connection and minimum susceptance for the parallel connection. Figure 4 shows a diplexer using bandpass and bandstop complementary filters, connected in parallel [4].

Since the networks are minimum susceptance, the input admittances of the individual filters have the general form given in Figure 3. The input admittance of the diplexer is approximately the superposition of the input admittances of the individual filters. The design of the diplexer requires that the cutoff frequencies of each filter have to be adjusted so that the real part of the input admittance is approximately 0.5 mhos (normalized) for each filter. The normalized input admittance of the diplexer is shown in Figure 5. To provide a constant resistance input impedance for all frequencies, the imaginary components of the input admittances of the filters are conjugates of each other [1, 4].

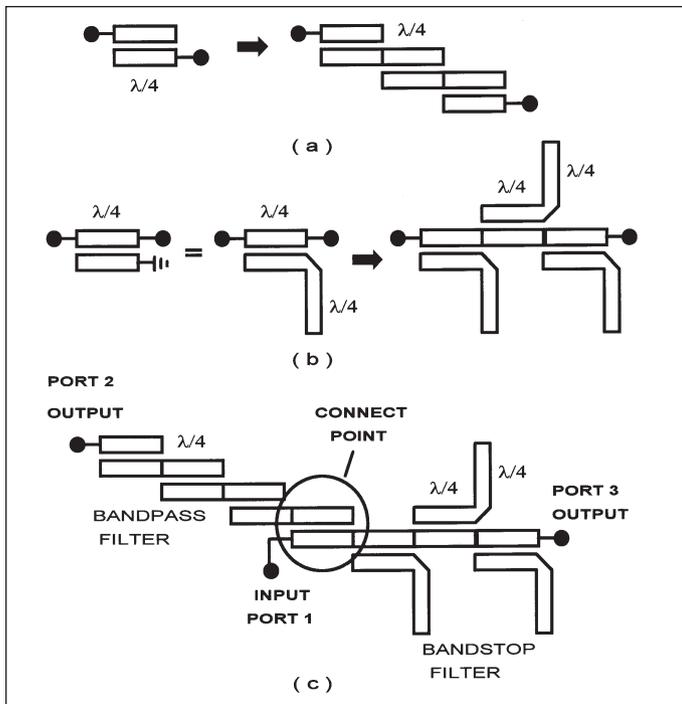
Parallel connected complementary diplexer design

The multiplexer design can be understood by implementing a single diplexer. Each diplexer is responsible for separating one frequency band or channel. Since each diplexer provides a constant resistance input impedance, it's possible to replace the load resistance of the bandstop filter with another diplexer without affecting the performance of the system. In this way, several diplexers may be cascaded to separate the desired number of channels.

One topology of filters attractive for narrow channel diplexers are filters using quarter wave length parallel



■ **Figure 5. Normalized input impedance of the complementary diplexer.**



■ **Figure 6. (a) Interdigital bandpass filter, (b) parallel-coupled-resonator bandstop filter, (c) layout of complementary diplexer.**

coupled resonators. These filters can be designed with accuracy, giving a compact structure and easy realization for moderate bandwidth [5]. For the large bandwidth, the spacings between resonators become too close, making it impractical.

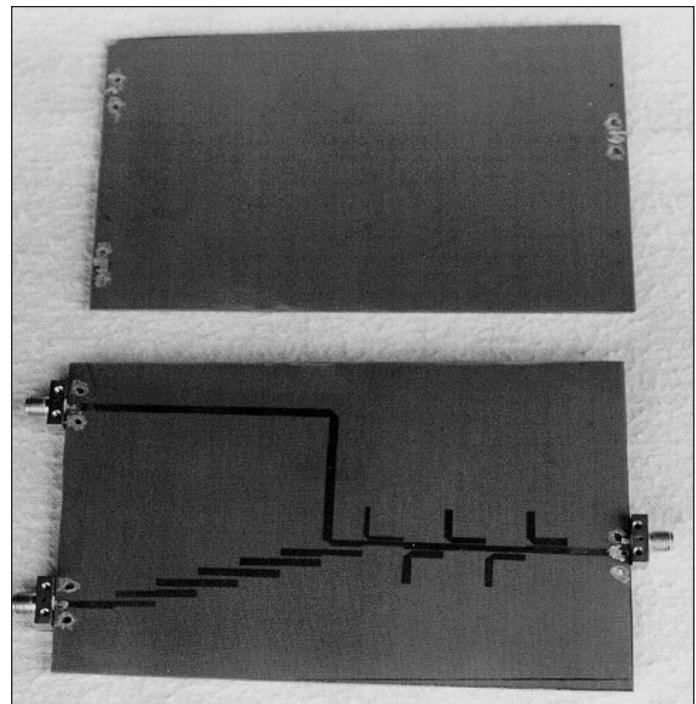
Figure 6 shows the layout of the multiplexer, composed of an interdigital bandpass filter and a parallel-coupled-resonator bandstop filter. The design of the filters is based on a cascade combination of quarter wave length parallel coupled resonators. For the interdigital bandpass filter, the input and output ports for each resonator are made in different lines on opposed sides, and the remaining terminals are open circuits. In the case of the bandstop filter, the input and output ports of each resonator are made in the same line, while the terminals of the other line are open and short circuits. At the narrow bandwidth, it is possible to replace the short circuits with open circuit quarter wave length stubs without disrupting the performance of the filter.

Experimental results

A diplexer of the following specifications was designed and tested.

- Central frequency = 5.0 GHz
- Fractional bandwidth = 10 percent
- Ripple = 0.1 dB
- Resonators/filter = 5

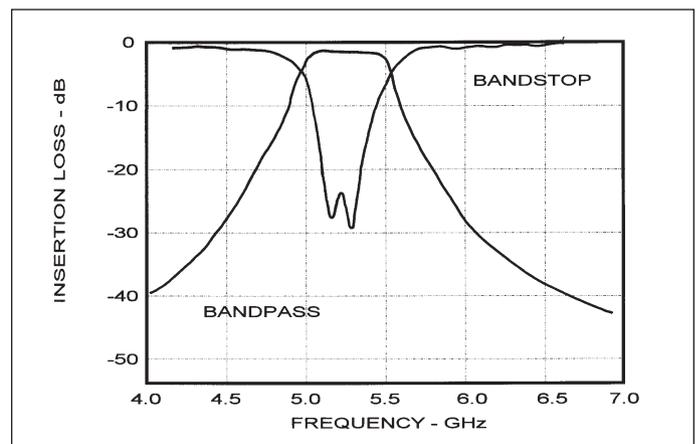
The structure of transmission chosen was the edge-coupled stripline. It consists of two conducting strips placed side by side and sandwiched between two dielec-



■ **Figure 7. Photograph of the complementary diplexer.**

tric sheets with conductive plating outer sides. The design of the filters initially was realized by applying the exact synthesis theory followed by numerical techniques. A computer-aided optimization process was used to tune the filters.

The diplexers were built using dielectric sheets with $\epsilon_r = 2.17$ with ground planes having 3.048 mm spacing. A photograph of the diplexer is shown in Figure 7. The performance of the diplexer is shown in Figure 8. The insertion loss in the bandpass was approximately 1.5 dB and the crossovers occurred at 4.5 dB down from the band-center attenuation. Stopband attenuation of more than 25 dB, around 80 percent of the bandwidth, was achieved. The measurements indicate a displacement of 6 percent at the center frequency and a bandwidth equal that specified. The measured and calculated results are shown in Table 1.



■ **Figure 8. Insertion loss plot.**

Specification	Theoretical	Measured
Central Frequency	5.0 GHz	5.3 GHz
Bandwidth	500.0 MHz – 10 %	500.0 MHz – 9.4%
Insertion Losses		Bandpass Filter: 1.5 dB Bandstop Filter: 25 dB

■ **Table 1. Theoretical and measured results.**

Conclusion

A design process has been presented for bandpass channel multiplexers where each channel is composed of two complementary filters. The design process was used to realize a diplexer in stripline. Agreement between the theoretical and experimental results was observed, proving the efficiency of the complementary filters for the isolation of each channel. ■

References

1. L. Young, *Advances in Microwaves*, Academic Press, New York, 1967.
2. Norman Balabanian, Theodore A. Bickart, *Electrical Network Theory*, John Wiley & Sons, Inc., 1969.
3. Harry Y-F. Lam, *Analog and Digital Filters*, Design and Realization, Prentice-Hall, 1980.

4. Harold L. Schumacher, *Understanding Filters and Multiplexers*, MSDH, 1983.

5. G. Matthaei, L. Young, E.M.T. Jones, *Microwave Filters, Impedance Networks and Coupling Structures*, Arctech House, 1980.

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