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MILLIMETER WAVE PRINTED CIRCUIT SPURLINE FILTERS

C. Nguyen, C. Hsieh and D. W. Ball
Hughes Aircraft Company
Electron Dynamics Division
3100 West Lomita Boulevard
Torrance, CA 90509
(213) 517-6736

Abstract

This paper provides a new equivalent circuit model for a spurline filter section in an inhomogeneous coupled-line medium whose even and odd mode phase velocities are unequal. This equivalent circuit permits the exact filter synthesis to be performed easily. Millimeter-wave filters at 26 to 40 GHz and 75 to 110 GHz have been fabricated using the model, and experimental results are included which validate the equivalent circuit model.

Introduction

The spurline bandstop filter in homogeneous propagation medium was first introduced by Schiffman and Matthaei[1]. Bates[2] has adapted this technique and made it in microstrip form by assuming the same phase velocities for even and odd modes. This assumption is not true in practice for an inhomogeneous medium such as microstrip or suspended-substrate because the propagation is in the quasi-TEM mode. This paper presents an equivalent circuit of the spurline section taking into account the different even and odd mode phase velocities. This equivalent circuit allows exact filter synthesis to be performed easily.

Equivalent Circuit

The elements of the impedance matrix of a parallel-coupled transmission line in an inhomogeneous medium (Figure 1) are given below:

$$Z_{11} = Z_{22} = Z_{33} = Z_{44} = -j\frac{1}{2}\left[Z_{oe}\cot\theta_e + Z_{oo}\cot\theta_o\right]$$

$$Z_{12} = Z_{21} = Z_{34} = Z_{43} = -j\frac{1}{2}\left[Z_{oe}\cot\theta_e - Z_{oo}\cot\theta_o\right]$$

$$Z_{13} = Z_{31} = Z_{24} = Z_{42} = -j\frac{1}{2}\left[Z_{oe}\csc\theta_e - Z_{oo}\csc\theta_o\right]$$

$$Z_{14} = Z_{41} = Z_{23} = Z_{32} = -j\frac{1}{2}\left[Z_{oe}\csc\theta_e + Z_{oo}\csc\theta_o\right] \qquad (1)$$

where Z_{oe} and Z_{oo} are characteristic impedances; θ_e and θ_o are electrical lengths of even and odd modes, respectively. The termination conditions of a spurline section (Figure 2) are given by Equation (2) below:

$$V_A = V_1 = V_2, \qquad V_B = V_4$$

$$I_A = I_1 + I_2, \qquad I_B = -I_4$$

$$I_3 = 0 \qquad (2)$$

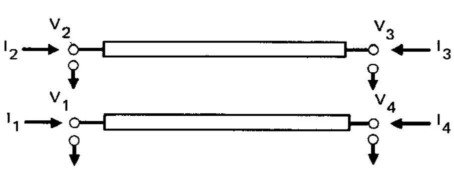

Figure 1 Parallel-coupled transmission lines.

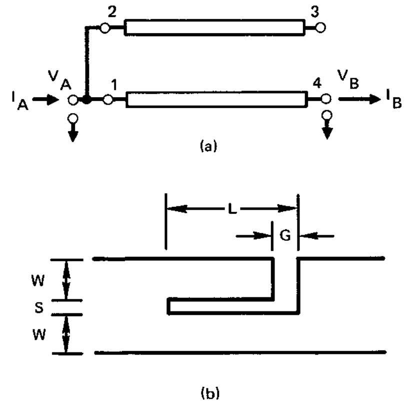

Figure 2 (a) Terminator conditions, (b) Spurline section.

After the termination conditions are applied to Equation (1), the four-port parallel-coupled transmission line network becomes a two-port spurline network. After some manipulations, the chain matrix of this two-port spurline network can be derived as:

$$\begin{bmatrix} V_A \\ I_A \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \frac{1}{2}j\left(Z_{oe}\sin\theta_e + Z_{oo}\tan\theta_o\cos\theta_e\right) \\ j2Y_{oe}\sin\theta_e & \cos\theta_e - \frac{Z_{oo}}{Z_{oe}}\sin\theta_e\tan\theta_o \end{bmatrix} \begin{bmatrix} V_B \\ I_B \end{bmatrix} \qquad (3)$$

or

$$\begin{bmatrix} V_A \\ I_A \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \frac{1}{2}j\,Z_{oe}\sin\theta_e \\ j2Y_{oe}\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} 1 & \frac{1}{2}j\,Z_{oo}\tan\theta_o \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_B \\ I_B \end{bmatrix} \qquad (4)$$

The decomposed chain matrices in Equation (4) lead to the Exact equivalent circuit which is a transmission line with characteristic impedance $Z_{oe}/2$ and electrical length θ_e in series with a short-circuited stub with characteristic impedance $Z_{oo}/2$ and electrical length θ_o. Figure 3 is an illustration of this equivalent circuit. The impedance of the short-circuited series stub is infinity when $\theta_o = \pi/2$ or $\ell = v_{po}/4f$ and

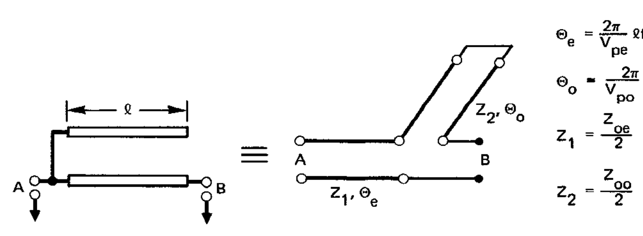

Figure 3 Equivalent Circuit of spurline section.

equals to zero when $\theta_o = \pi$ or $\ell = \nu_{po}/2f$, where ℓ is the physical length of the spurline, f is the frequency of interest and, ν_{po}, ν_{pe} are the phase velocities for even and odd modes, respectively. These infinity and zero impedance characteristics will provide the basis for bandstop and bandpass filters. In addition to regular circuit analysis, this equivalent circuit is particularly suitable for the exact filter synthesis as described by Schiffman and Matthaei.[1]

If the equal odd and even mode phase velocities are assumed and Kuroda's transformation applied to the equivalent circuit, the resultant circuit is the same as described in Bates' paper[2] and as shown in Figure 4.

Design Procedure and Experimental Results

The filter design procedure is outlined below.

1. From the filter specifications, determine the characteristic impedances of transmission lines in the filter by exact synthesis method as described by Schiffman and Matthaei[1].
2. For each spurline section, calculate $Z_{oe} = 2Z_1$, $Z_{oo} = 2Z_2$, where Z_1, Z_2 are the characteristic impedances for that section.
3. Determine ν_{po}, ν_{pe}, W and S by using a computer program based on J. Smith's paper[3].
4. Calculate the length of each spurline by:

$$L = \frac{\nu_{po}}{4f_o} - \Delta L \text{ For Bandstop Filter}$$

$$L = \frac{\nu_{po}}{2f_o} - \Delta L \text{ For Bandpass Filter}$$

$$\Delta L = \frac{\nu_{po}}{2\pi f_o} \tan^{-1}(2\pi f_o C_t Z_{oo}) \qquad (5)$$

$$C_t = 2C_{fe} + 2(C_{fo} - C_{fe}) = 2C_{fo}$$

where f_o is the center frequency of the filter. C_{fe}, C_{fo} are even and odd mode fringing capacitances and can be calculated from J. Smith's paper[3]. C_t is the toal end capacitance due to the gap G. ΔL is the effective length due to the gap G.

5. Use the exact equivalent circuit in Figure 3 to analyze and predict the filter response.

A single-section bandstop filter in Ka-band has been fabricated to validate the equivalent circuit model. The physical dimensions of the filter are shown in Figure 5. A

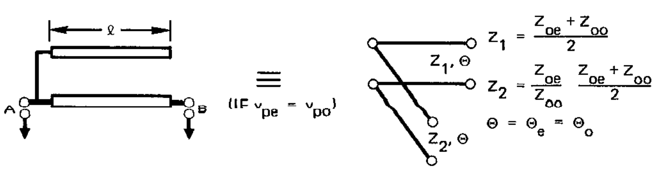

Figure 4 Equivalent circuit of spurline section with assumption $\nu_{pe} = \nu_{po}$.

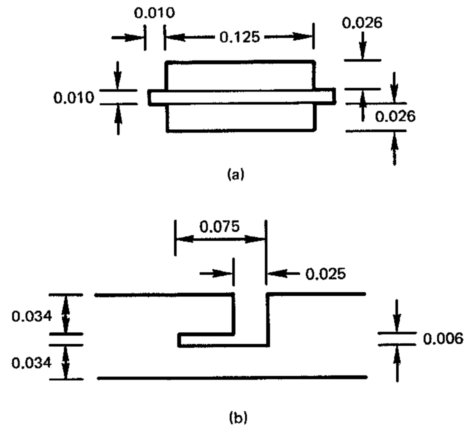

Figure 5 (a) Suspended substrate dimensions, (b) Spurline circuit board dimensions.

remarkable consistency exists between the measured and predicted responses as shown in Figure 6. Similar consistency can also be obtained by two-section W-band bandstop filter as shown in Figures 7 and 8. To minimize the discontinuity, these

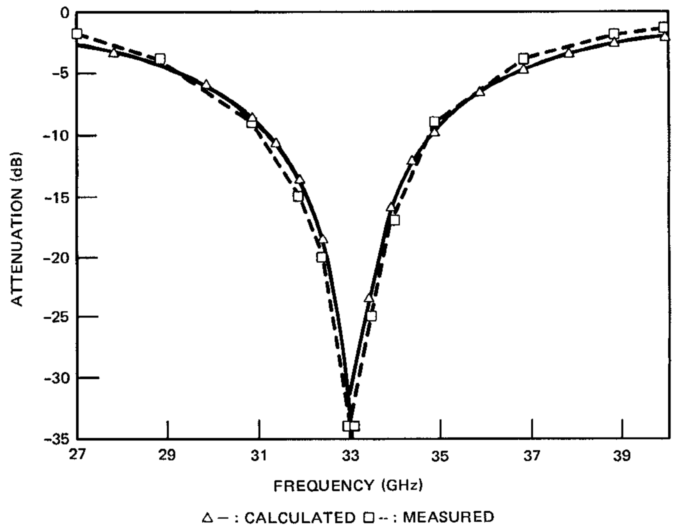

Figure 6 Single-section Ka-band filter response.

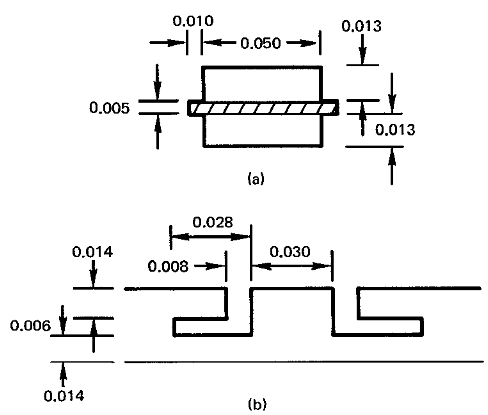

Figure 7 (a) Suspended substrate dimensions, (b) Spurline circuit board dimensions.

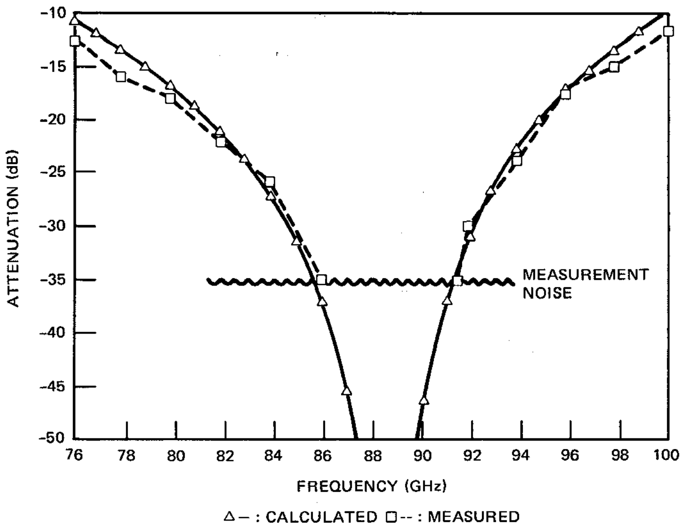

Figure 8 Two-section W-band filter response.

filters have been computer-optimized to fit in the same width of transmission lines. Also, good wideband transitions between suspended substrate and waveguide have been designed to make these measurements. Figures 9 and 10 are photographs of these two filters.

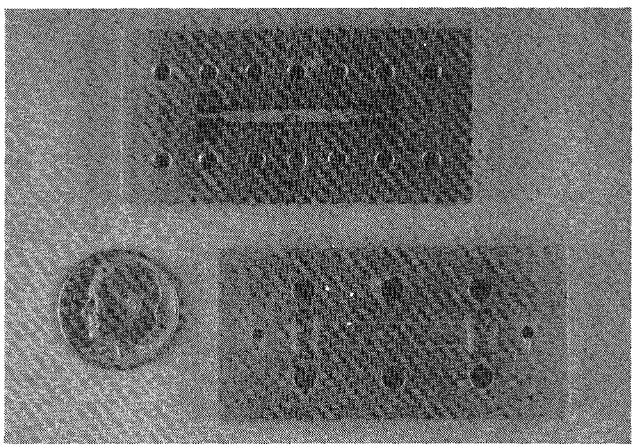

Figure 9 One-section Ka-Band bandstop filter.

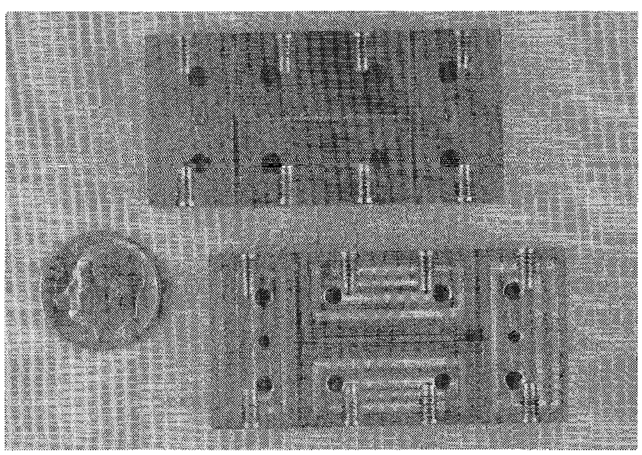

Figure 10 Two-section W-Band bandstop filter.

Discussion

The chain matrix in Equation (3) can also be decomposed as follows:

$$\begin{bmatrix} V_A \\ I_A \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ jY_2 \tan\theta_e & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_e & jZ_1 \sin\theta_e \\ jY_1 \sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} V_B \\ I_B \end{bmatrix} \qquad (6)$$

where

$$Z_1 = \frac{Z_{oe}}{2}\left[1 + \frac{Z_{oo}}{Z_{oe}}\left|\frac{\tan\theta_o}{\tan\theta_e}\right|\right]$$

$$Z_2 = \frac{Z_{oe}}{2}\left[1 + \frac{Z_{oe}}{Z_{oo}}\left|\frac{\tan\theta_e}{\tan\theta_o}\right|\right]$$

This means one can have an equivalent circuit of an open-circuit stub with characteristic impedance Z_1 and electrical length θ_e in shunt with a transmission line of characteristic impedance Z_2 and the same electrical length. Figure 11 shows this equivalent circuit. Because the characteristic impedances Z_1, Z_2 are functions of frequency, this equivalent circuit is not convenient for circuit analysis and filter synthesis. Bates' equivalent circuit can also be obtained by equaling the odd and even phase velocities.

Conclusion

A full analysis of spurline filters in inhomogeneous medium (homogeneous medium is a special case) has been presented, allowing filters to be exactly designed - a definite advantage compared to single-ridge fin-line bandstop filters whose full analysis has not been available in the literature. Also, the less radiation characteristic of spurline filters compared to the conventional shunt stubs and parallel-coupled lines bandstop filters makes them more useful than conventional ones. The exact equivalent circuit model allows one to design spurline filters in microwave frequency regions as well as in millimeter-wave regions.

References

1. Schiffman, B.M., and Matthaei, G.L. "Exact Design of Bandstop Microwave Filters," IEEE Trans MTT-12, pp. 6-15, January 1964.

2. Bates, R.N., "Design of Microstrip Spurline Bandstop Filters," IEE Journal on Microwaves, Optics and Acoustics, Vol. 1, Nr. 6, pp. 209-214, November 1977.

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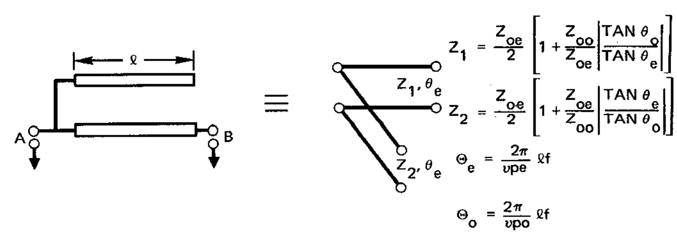

Figure 11 Equivalent circuit of spurline section.