# A Multilayer Microstrip Bandstop Filter for DCS

This article describes the design and construction of a filter that saves board space by using a multilayer topology

By Denis Jaisson Consultant

bandstop filter using multilayer microstrips was designed to operate around  $f_c = 1842.5$  MHz and reject unwanted carrier frequencies in the IF processing unit of a Digital Communication System (DCS). Its design involves a double layer microstrip resonator coupled to a microstrip line. This coupler was modeled and the filter's performance was predicted. The filter was then constructed and its performance measured. This article describes the design method and the results of those experimental measurements.

# Parallel stop for bandstop effect

Figure 1 shows a microstrip line with a parallel open stub, which brings about a stopband effect around some frequency  $f_c$ . In MICs, where space is restricted, one might prefer to have a somewhat more compact structure. One possibility is to rotate the open microstrip and place it on top of the access line, as shown in Figure 2, with an additional layer of substrate between them. Broadside coupling has been



Figure 2. Bandstop filter with multilayer microstrips.

used for obtaining tight coupling between microstrips, with a third cover layer for improved directivity [1]. Directivity is not critical in this case, and only two layers are



required. The structure in Figure 2 was selected for use as a bandstop filter. Using Malherbe's model [2] and first assuming a homogenous cross-section as in Figure 3 for this coupler, a simplified equivalent circuit was drawn. The behavior of the filter, namely its rejection bandwidth, was related to the coupler's parameters.

### Simple model: Homogeneous MCPW

Malherbe's static electrical equivalent circuit for a unit length of a homogeneous TEM coupler is shown in Figure 4. The model for the whole coupler, shown in Figure 5, consists of two transmission lines with a quarterwave length at  $f_c$ . Characteristic impedances normalized to 50 ohms are given by:



Figure 3. Cross-section of the filter showing its multilayer construction.

# **Microstrip Filters**



■ Figure 4a. Unit length equivalent circuit for the homogeneous TEM coupler.



Figure 4b. Equivalent circuit of the coupled lines for the homogeneous TEM coupler.



Figure 4c. Equivalent circuit of the filter for the homogenous TEM coupler.

$$\begin{split} & Z_1 = \frac{\sqrt{\varepsilon_r}}{c_0} \left( \frac{C_{12} + C_{22}}{C_{12}} \right) \text{and} \\ & Z_2 = \frac{\sqrt{\varepsilon_r}}{c_0} \left( \frac{C_{12} + C_{22}}{C_{11}C_{22} + C_{11}C_{12} + C_{22}C_{12}} \right) \end{split} \tag{1}$$

where  $c_0$  is the speed of light in free space. Voltage ratio of the ideal transformers is:

$$n = 1 + \frac{C_{22}}{C_{12}} \tag{2}$$

The left end of the top line is connected to that of the bottom line as in Figure 2, and its right end is left open. The circuit in Figure 4b is then further simplified to the one in Figure 4c. Parasitic effects brought about by the step in width and by the open end of the top strip are neglected. At a frequency  $f=f_c+\Delta f$  close to  $f_c$ , the input admittance of the 50 ohm loaded filter is:

$$Y_{in} \cong \frac{1}{Z_1^2} - j \frac{(n-1)^2}{Z_2} \left(\frac{2}{\pi}\right) \frac{f_c}{\Delta f}$$
 (3)

Neglecting losses, the transmission factor is given by [3]:

$$\left|S_{21}\right| = \sqrt{1 - \left|S_{11}\right|^2} \tag{4}$$

where:

$$S_{11} = \frac{1 - Y_{in}}{1 + Y_{in}} \tag{5}$$

From Equations (3), (4) and 5:

$$\left|S_{21}\right| = \pi \frac{Z_2}{\left(n-1\right)^2 Z_1} \left(\frac{\Delta f}{f_c}\right)$$
 (6)

Define bandwidth  $B = 2 \Delta f/f_c$  where  $|S_{21}| \le |S_{21}|_{max}$ , and assume B<1. From Equations (1), (2) and (6):

$$B = \frac{2}{\pi} \left( \frac{C_{22}^{2}}{C_{11}C_{22} + C_{11}C_{12} + C_{22}C_{12}} \right) \left| S_{21} \right|_{\text{max}}$$
(7)

By looking at Equation (7) it appears that for a given  $|S_{21}|_{\text{max}}$ , *B* is larger if  $C_{11}$  and  $C_{12}$  are small, and  $C_{22}$  is large. Consequently, top and bottom strips in Figure 2 were respectively widened and narrowed where they were coupled to each other.

The model in Figure 4c helps to relate B qualitatively to the parameters of the coupler. It cannot predict  $f_c$  and B accurately for the filter in Figure 2, because CS is not homogeneous. Moreover, it does not account for discontinuities. A more sophisticated model is therefore required.

# Non-homogeneous coupler

The unit length quasi-static equivalent circuit of the coupler in Figure 2 is given in Figure 5 [4]. Capacitances are computed in terms of the geometry of CS, substrate relative permittivity  $\varepsilon_r$  and potentials  $V_1$  and  $V_2$  of the

# **Microstrip Filters**



**Figure 5. Non-homogeneous coupler.** 

top and bottom conductors, using a finite element method [5]:

- 1)  $C_{ii}$  is computed for:  $V_1=1$  (8) (all other conductors are grounded)
- 2) Setting  $V_1 = V_2 = 1$  yields a capacitance  $C_3$ , so that:

$$C_{12}(\varepsilon_r) = \frac{1}{2} \left( C_1(\varepsilon_r) + C_2(\varepsilon_r) - C_3 \right)$$
(9)

Symmetry of *CS* about plane x=0 is taken advantage of, by treating this plane as a magnetic wall, and discretizing only half of *CS* into finite elements. Inductances in Figure 5 are given in terms of capacitances by removing the substrate ( $\varepsilon_r=1$ ).

The following formulae have been derived in a previous paper [6]:

$$\frac{1}{L_{12}} = c_0^2 C_{12} \left( 1 \right) \left( \frac{C_1(1)C_2(1)}{C_{12}^2(1)} - 1 \right)$$
(10)

and:

$$L_1 = L_{12} \frac{C_2(1)}{C_{12}(1)}, \ L_2 = L_{12} \frac{C_1(1)}{C_{12}(1)}$$
(11)



■ Figure 6. Touchstone network for the filter.



**Figure 7. Top view of the filter.** 

where  $c_0$  is the speed of light in a vacuum. The  $C_{ij}(1)$  are obtained in the same way as the  $C_{ij}(\varepsilon_r)$  for  $\varepsilon_r = 1$ .

The coupler in Figure 2 was modeled into a network of ten of the cells in Figure 5 connected in series. Unit length capacitances and inductances were multiplied by one tenth of total coupled length l. A short Fortran program was written, which:

- 1) Computes capacitances under the voltage conditions in Equations (8) and (9),
- 2) Computes inductances according to Equations (10) and (11),
- 3) Automatically updates an HP EEsof Touchstone<sup>TM</sup> circuit file for length l to be optimised at  $f_c$ .

The Touchstone network for the filter is shown in Figure 6. The resonator open end is modeled as two microstrip open end effects (MLEF). The one MLEF accounts for the fringing capacitance to the ground-plane, with width  $w_2$ -w' (top view in Figure 7). The other one, with width w', accounts for the fringing capacitance to the dielectric covered 50 ohm output line. The latter MLEF is connected through an ideal transformer, because the MLEF model of Touchstone is referenced to ground.

#### Experiment

The bandstop filter in Figure 2 was designed for  $f_c = 1842.5$  MHz on an FR4 substrate, with relative per-

mittivity  $\varepsilon_r$ =4.7 and substrate height h=1.165 mm. Conductor thickness t=18 µm was neglected. Width w'=1.57 mm of the dielectric covered 50 ohm output line was obtained for an air filled microstrip line with impedance [7]:

$$\sqrt{\varepsilon_r}(Z_0) = \frac{1}{c_0 C(1)} = 108 \,\Omega \tag{12}$$

where  $c_0$  is the speed of light in a vacuum and C(1) is the unit length



Figure 8. Filter measurement results.

capacitance of the air filled line. A B=6.6 percent 20 dB rejection bandwidth was predicted around  $f_c$  for  $w_1=0.5$  mm,  $w_2=5$  mm and l=19.44 mm (Figure 7).

The following values were obtained for the circuit in Figure 5 (ignoring conductor thickness):

$C_{11}(\epsilon_r) = 0.192 \text{ pF/mm}$	$L_{11}$ =0.274 nH/mm
$C_{22}(\varepsilon_r) = 0.116 \text{ pF/mm}$	$L_{22}$ =0.546 nH/mm
$C_{12}(\varepsilon_r) = 0.0681 \text{ pF/mm}$	$L_{12}$ =0.161 nH/mm

Figure 8 shows measured  $|S_{21}|$  and  $|S_{11}|$  over a wide frequency range  $(|S_{21}| \cong |S_{11}|$  by a half dB up to  $f_c$ ). A minimum  $|S_{21}| = -27$  dB was measured at  $f_m = 1836.8$  MHz, which is 0.3 percent off design  $f_c$ . Rejection is more than 20 dB over B = 6.3 percent. Transmission loss is less than half a dB up to 794 MHz, where  $|S_{11}|, |S_{22}| = -11$  dB.  $|S_{11}|, |S_{22}| < -20$  dB for f < 410 MHz.

# Conclusion

A bandstop filter has been presented which can be easily "thrown" onto a microstrip line. Where spurious carrier frequencies are a problem, this filter will knock them down by 20 dB or so. Although its performance is not nearly as good as a structure with more poles, its narrow shape does not require any change in the housing of the system where it is integrated.

Permittivity  $\varepsilon_r$  of FR4, as this material is commonly manufactured, is known to suffer a larger spread than that of substrates which were first introduced for microwave applications such as filters, where low tolerance on  $\varepsilon_r$ is important. However, a good agreement was observed between simulated and measured values of  $f_c$ . Full wave modeling of the filter with a 3D electromagnetic simulator, combined with an accurate measurement of  $\varepsilon_r$ , would give a better idea about the accuracy of the model in Figure 6.

# Acknowledgement

This project was funded by the Cost Reduction Program at Ericsson Radio Systems AB in Kista, Sweden.

# **Bibliography**

1. D. Jaisson, "Broadside-Coupled Structure Features Easy MIC Integration," *Microwaves* & *RF*, Volume 32, No. 3, March 93, pp 88-96.

2. J.A.G. Malherbe, *Microwave Transmission Line Filters*, Artech House, 1979.

3. R.E. Collin, *Foundations for Microwave Engineering*, McGraw-Hill, 1966.

4. M.K. Krage, G.I.Haddad, "Characteristics of Coupled Microstrip Transmission Lines-I: Coupled-Mode Formulation of Inhomogeneous Lines," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-18, No. 4, April 70.

5. P.P. Silvester and R.L. Ferrari, *Finite Elements for Electrical Engineers*, Cambridge University Press, 1983.

6. D. Jaisson, "Microstrip-Coplanar Waveguide Coupler, Application to an Attenuator," *Microwave Journal*, Vol. 38, No. 9, Sept. 1995, pp 120-130.

7. D. Jaisson, "Design Microstrip Components with a Dielectric Cover," *Microwaves & RF*, Vol. 32, No. 2, Feb. 93, pp 71-80.

# Author information

Denis Jaisson is a microwave and RF design consultant. He can be reached by mail at 27, rue Pierret, 92200 Neuilly-sur-Seine, France. He can also be reached by email at: jaisson@usa.net.