A Planar X-Band Electromagnetic Band-Gap (EBG) 3-Pole Filter

Hsiuan-ju Hsu, Michael J. Hill, John Papapolymerou, and Richard W. Ziolkowski

***Abstract*—A Duroid-based X-band electromagnetic band gap (EBG) Chebyshev 3-pole bandpass filter that is compatible with standard printed circuit board (PCB) fabrication techniques has been designed, fabricated, and tested. The filter consists of three EBG cavities in a multi-layer design. It provides a 5.95% bandwidth response at the resonant frequency $f_{res} = 9.72$ GHz with a corresponding insertion loss of 0.9 dB. Isolation is higher than 30 dB below 9 GHz and above 11 GHz.**

***Index Terms*—EBG resonators, high-Q cavity resonators and filters, .**

I. INTRODUCTION

An ELECTROMAGNETIC band-gap (EBG) structure has been used previously to replace a fully conducting side-wall (FCSW) structure as a single cavity resonator and to achieve a fixed [1] and a reconfigurable [2] X-band resonator with a Q of 450. The fixed EBG resonator cavity structure is used here for the first time as the basis of implementation of an X-Band Chebyshev 3-pole bandpass filter. Analogous metallic fence waveguides have been introduced for millimeter wave applications in [8] and have been used, for instance, as antenna feed lines. There are at least two main advantages of using this EBG implementation instead of a FCSW structure. One is that the requisite EBG structures can be fabricated on soft substrates by using inexpensive, standard printed circuit board (PCB) processing techniques. As a result, an EBG-based multi-pole filter can be easily incorporated in commercial products. The second advantage is that the dimensions of the cavities can be reconfigured as in [2], by switching on and off the metallic posts electrically or mechanically to achieve a different resonant frequency and, hence, realize a reconfigurable filter. In addition, this filter utilizes thinner substrates compared to other EBG designs [3], and can, thus, be implemented in typically thin semiconductor materials such as silicon and GaAs.

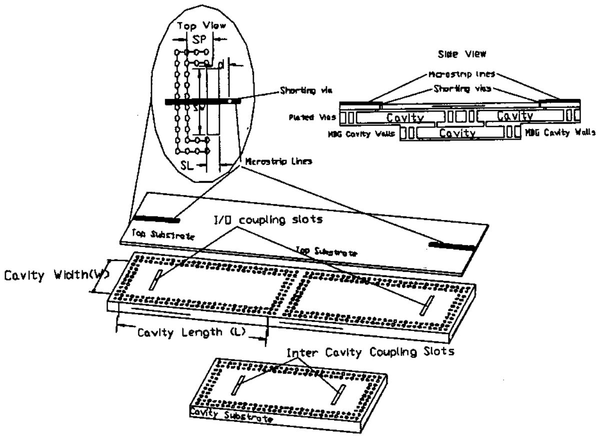

Fig. 1. EBG 3-pole filter structure, top and side views.

II. FILTER DESIGN

The desired X-Band EBG Chebyshev 3-pole bandpass filter is based on the equivalent circuit with four transformers given in [4]. With the choice of the resonant frequency $f_{res} = 10$ GHz, a 0.1 dB ripple and a $\Delta f/f_{res} = 5\%$ bandwidth (0.1 dB ripple bandwidth), the 3-pole Chebyshev bandpass network function with $n = 3$ is specified as [4]

$$N_{BP}(p) = \frac{H_{BP}p^3}{b_0p^6 + b_1p^5 + b_2p^4 + b_3p^3 + b_4p^2 + b_5p + b_6} \tag{1}$$

where H_{BP} is the amplitude of the network function and the coefficients $b_0 = b_6 = 1.0$, $b_1 = b_5 = 1.94$, $b_2 = b_4 = 5.63$, and $b_3 = 5.52$. The lowpass filter prototype values for this 3-pole filter can be found from [5]: $a_0 = a_4 = 1.0$, $a_1 = a_3 = 1.0315$, $a_2 = 1.1474$. The relations between the a and b coefficients are $b_1 = b_5 = (a_1 + a_3)/(a_1a_3)$, $b_2 = b_4 = 3 + (a_1 + a_2 + a_3)/(a_1a_2a_3)$, $b_3 = 2(1/a_1 + 1/a_3 + 1/(a_1a_2a_3))$. The inter-resonator coupling coefficients between the sections of this filter are also given by [5]

$$K_{ij} = \frac{\Delta f}{f_{res}} \frac{1}{\sqrt{a_ia_j}} \tag{2}$$

where $i, j = 1, 2, 3$. The coupling coefficient K_{12} is equal to K_{23} since $a_1 = a_3$. With these values, the corresponding inter-resonator coefficients are easily calculated to be $K_{12} = K_{23} = 0.046$. The external quality factor that controls the coupling between the feeding network and the input and output resonators of the filter can be found as [5]

$$Q_{ext,S.L} = \frac{f_{res}a_0a_1}{\Delta f} \tag{3}$$

where f_{res} is the resonant frequency, Δf the bandwidth, and a_0, a_1 the response coefficients. Using (3), Q_{ext} is found to be 20.63.

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To implement the X-band Chebyshev 3-pole filter, three identical EBG resonant cavities were coupled together. This was accomplished using three layers of Duroid substrate. The circuit is shown in Fig. 1. Two magnetic coupling slots between the top layer and the middle layer couple energy from the input and output microstrip feed lines into the resonant cavities in layer 2. The geometry, size, and location of these slots determines the external Q, Q_{ext}. Magnetic coupling slots between the middle layer and bottom layer couple energy from these cavities into the lower level cavity. The latter slots determine the inter-cavity or inter-resonator coupling.

Because all of the resonant cavities are identical, the dimensions of one cavity determine the resonant frequency of the 3-pole filter. The resonant frequency of the TE_{101} mode can be found as [6]

$$f_{res} = \frac{c}{2\pi\sqrt{\varepsilon_r}}\sqrt{\left(\frac{\pi}{L}\right)^2 + \left(\frac{\pi}{W}\right)^2} \tag{4}$$

where L and W are, respectively, the effective length of and the effective width of the cavity, c is the speed of light, and ε_r is the relative permittivity. Thus, specification of f_{res} establishes the basic cavity dimensions.

It should be noted here that in a real system implementation all the cavities can be stacked one under the other, instead of having a back-to-back configuration as shown in Fig. 1, for real estate minimization. Access to and from the filter is achieved at different layers.

III. SIMULATIONS

The coupling slots are located approximately $L/4$ from the edge of the cavities to maximize the coupling [7]. To provide an electric short circuit at the center of the coupling slot, a shorting via was used. This broad-band shorting method was used in place of the narrow band $\lambda_g/4$ open-circuited stub that is commonly used to couple to single cavities of this type. With the desired Q_{ext} known, the requisite coupling slot sizes were determined by full-wave simulations.

All simulations of the response of the X-band filter were performed with ANSOFT's High Frequency Structure Simulator (HFSS), a finite element method based software tool. With simulations of the EBG resonant cavity, it was found that $f_{res} =$ 9.57 GHz. The slot geometry that provides the desired coupling Q_{ext} for the input and output cavities, was found by performing a parametric analysis on a single cavity, where the input/output slot size varied in each simulation. The Q_{ext} was evaluated from $Q_{ext} = 2Q_L = 2f_{res}/\Delta f$, until the desired value was achieved.

To determine the proper size of the cavity-to-cavity coupling slots (inter-resonator coupling), the response of a 2-pole filter with narrow input/output slots for low coupling was simulated. The latter allowed the filter response to be dominated by the inter-resonator coupling [5]. In particular, the coupling value, K_{12}, of the 2-pole filter can be found as

$$K_{12} = \frac{f_U^2 - f_L^2}{f_U^2 + f_L^2} \tag{5}$$

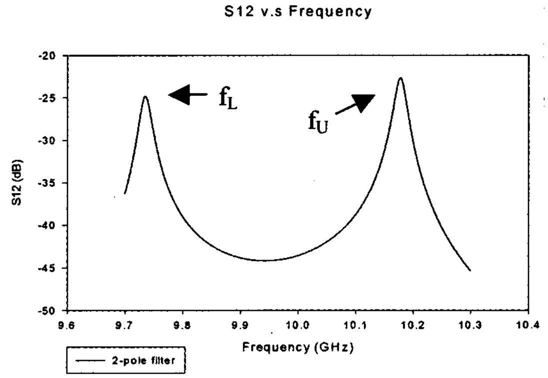

Fig. 2. Simulated results for the 2-pole filter used to determine the value of the inter-resonator coupling coefficients (Kij).

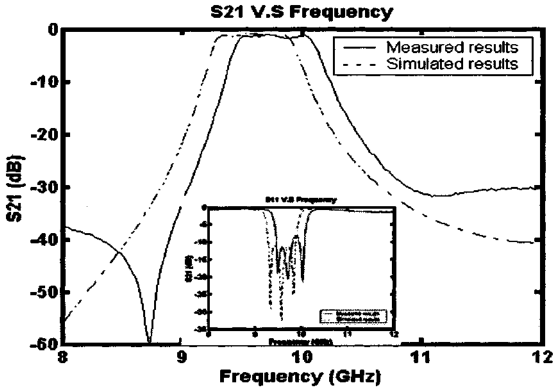

Fig. 3. Simulated and measured S_{11} and S_{21} parameters for the X-band EBG Chebyshev 3-pole filter.

where in the plot of the insertion loss versus frequency, f_U is the upper resonant frequency and f_L is the lower resonant frequency of the 2-pole filter response.

The HFSS simulation results of the insertion loss for the 2-pole filter are shown in Fig. 2. Several simulations were run for different slot geometries and a plot of K versus slot size was produced. Based on this plot, a value of $K_{12} = 0.046$ can be achieved for a slot length of 280 mils and a width of 20 mils.

In order to make a stop-band in the EBG structure at the desired cavity frequencies, the spacing and size of the cylindrical metallic posts were properly designed to achieve low leakage. As shown in [1], [2], the gap between the metallic posts in the EBG walls needs to be shorter than $0.5\lambda_g$ at the highest frequency of interest. The number of rows of posts used must produce a high reflection cavity wall to minimize leakage and provide a low insertion loss. According to simulations and experiments, two rows of posts for each cavity is sufficient [1], [2]. The dimensions of the final X-Band EBG Chebyshev 3-pole filter were determined by assembling the filter with the slot parameters found from the single and two-pole filter results. The entire 3-pole filter was then simulated and results are shown in Fig. 3. The dimensions of the completed 3-pole filter are shown in Table I.

TABLE I
THE EBG CHEBYCHEV 3-POLE FILTER DIMENSIONS

<table>
<tr><td>Cavity Length</td><td>784 mils</td><td>Via Spacing</td><td>47.3 mils</td></tr>
<tr><td>Cavity Width</td><td>464 mils</td><td>MBG rows</td><td>2</td></tr>
<tr><td>d</td><td>45 mils</td><td>Via Diameter</td><td>31 mils</td></tr>
<tr><td colspan="2">SL 1(slot length between top and middle boards)</td><td colspan="2">406.8 mils</td></tr>
<tr><td colspan="2">SW 1(slot width between middle and bottom boards)</td><td colspan="2">36 mils</td></tr>
<tr><td colspan="2">SL2 (slot length between middle and bottom boards)</td><td colspan="2">280 mils</td></tr>
<tr><td colspan="2">SW2 (slot width between middle and bottom boards)</td><td colspan="2">20 mils</td></tr>
</table>

TABLE II
COMPARISON OF SIMULATED AND MEASURED RESULTS FOR THE X-BAND EBG CHEBYCHEV 3-POLE FILTER

Parameter	Simulated	Measured
f_{res}	9.57 GHz	9.72 GHz
Bandwidth	568 MHz	580 MHz
Insertion Loss	0.8 dB	0.9 dB
Ripple	0.34 dB	0.7 dB
Isolation (7% off f_{res})	26.3	30 dB

IV. FABRICATION

The low dielectric constant Duroid substrate, Rogers 5880 ($\varepsilon_r = 2.2$, thickness = 31 mils), was selected for use in the fabrication of the X-Band EBG filter design because of its low dielectric loss characteristics ($1/Qd = \tan\delta = 0.0009$). For a single cavity of this size, the total loss is dominated by the metal loss [2]. It is, therefore, expected that the total loss of the three-pole filter will also be dominated by conductor losses. Rogers 5880 was also selected due to its frequent use in commercial applications.

Standard PCB techniques were applied to fabricate the blind and buried vias required by our design. The vias were first constructed by drilling holes in the substrates. Copper was then plated on the surface of the holes and their edges. Next, the circuit pattern was wet-etched. The bonding surface was then coated with solder, and the boards were thermally fused together, leaving a highly conductive and oxidation-free bond.

V. RESULTS

The X-band EBG Chebyshev 3-pole filter was mounted on a SMA-launch microstrip fixture and was measured with an HP8510 network analyzer. The S-parameter data with the fixture losses de-embedded is shown in Fig. 3. The insertions loss was measured to be 0.9 dB, while the bandwidth was 580 MHz. The attenuation reached a value of 30 dB at 9.06 GHz and 10.99 GHz, a 7% and 13% deviation from the center frequency, respectively. Measured results agreed very well with simulations, as can be seen in Table II. The small differences are due to fabrication tolerances and numerical errors of the simulation tool.

VI. CONCLUSION

An X-Band EBG Chebyshev 3-pole filter was designed and simulated with HFSS. A multi-layer Duroid realization of this filter was fabricated using standard PCB techniques, and its performance was measured. Very good agreement between simulated and measured results was found for the filter parameters. These results indicate that this type of structure can be readily used to implement low cost, high performance, multi-pole filters on planar printed wiring boards and eventually on semiconductor substrates by using micromachining techniques.

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