A Duroid-Based Planar EBG Cavity Resonator Filter With Improved Quality Factor

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

***Abstract*—A high-Q Duroid-based planar electromagnetic bandgap (EBG) cavity resonator/filter has been designed, fabricated, and tested. It was implemented in Rogers Duroid 5880 with standard board fabrication techniques. This filter provides a measured Q of 844 and a 0.91% bandwidth passband response at 10.63 GHz with a corresponding insertion loss of −2.76 dB.**

***Index Terms*—Cavity resonators, cavity resonator filters, electromagnetic bandgap structure, filters, high-Q resonator.**

I. Introduction

SEVERAL papers dealing with the design and realization of electromagnetic bandgap (EBG) cavity resonator filters have appeared recently [1]–[5]. There are at least two main advantages of using this EBG implementation instead of a fully conducting side wall (FCSW) structure. One is that the requisite EBG structures can be fabricated on soft or organic substrates by using inexpensive standard printed circuit board (PCB) processing techniques. As a result, an EBG-based cavity resonator filter can be incorporated in commercial products readily. 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 high-Q cavity resonator filter. This paper presents an EBG cavity resonator with the highest ever-reported unloaded quality factor, Q.

II. Simulations

All simulations of the performance of the EBG cavity resonator filter were performed with ANSOFT's high-frequency simulation software (HFSS) tools. To determine the reflection performance of the walls of the EBG cavity, a parallel-plate waveguide configuration with the EBG lattice centered in the middle of the guide was designed to allow variations in the spacing between the posts of the EBG lattice. To find the filter's bandwidth, insertion loss, and the unloaded quality factor Q_u the EBG cavity resonator filter was designed using two models. One was a strongly coupled EBG cavity resonator that was used to determine the bandwidth and insertion loss. The second was a weakly coupled EBG cavity resonator used to determine Q_u.

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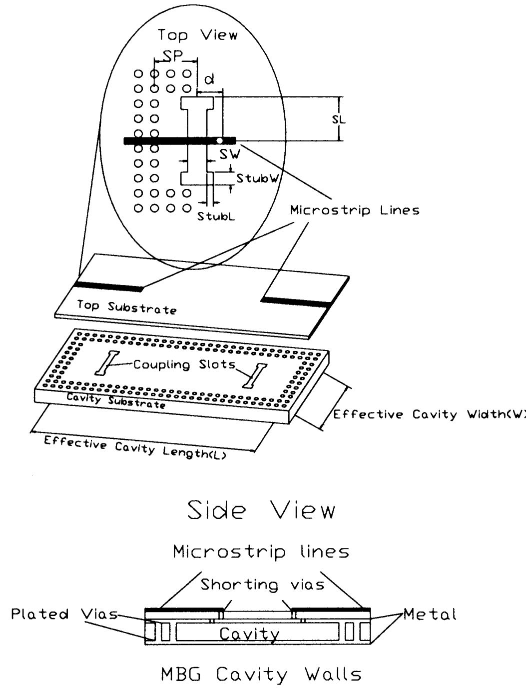

Fig. 1. EBG cavity resonator filter; top and side views.

III. Structure

The high-Q Duroid-based planar EBG cavity resonator filter is shown in Fig. 1. In order to make a stop-band in the EBG structure at the desired cavity resonant frequencies, the spacing and size of the cylindrical metallic posts were properly designed to achieve low electromagnetic (EM) field leakage. As shown in [1]–[4], 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. A square EBG lattice was found to be the most effective. The number of rows of posts used must produce a high-reflection cavity wall to minimize leakage and, hence, produce a high-quality factor Q.

According to simulations and experiments, two rows of posts for each cavity are sufficient [1]–[4]. The dimensions of the completed EBG cavity resonator filter design shown in Fig. 1 are given in Table I. The HFSS simulation results of the performance of the walls of the EBG cavity for normally incident waves are provided in Fig. 2. Based on the design frequency of 10 GHz ($\lambda_0 = 1181$ mils, $\lambda_m = 796$ mils), the distance between the centers of the posts of the two element deep square lattice: 372 mils = 0.47 λ_m, 186 mils = 0.235 λ_m, and 93 mils = 0.1175 λ_m, were examined. Typical EBG reflection behavior is apparent. The reflection coefficient at 10 GHz in these cases

TABLE I
EBG CAVITY RESONATOR DIMENSIONS

	Weakly coupled case	Strongly coupled case
Effective Cavity Length	715.4 mils	
Effective Cavity Width	217.3 mils	
EBG rows	2	
Center-to-center distance between vias	74.4mils	
Diameter of vias	31mils	
Stub W	4.9 mils	24.9 mils
Stub L	4.9 mils	19.7 mils
SL	78.7 mils	168.8 mils
SW	4.9 mils	11.7 mils
SP	185.6 mils	180.2 mils
d	53.5 mils	56.9 mils

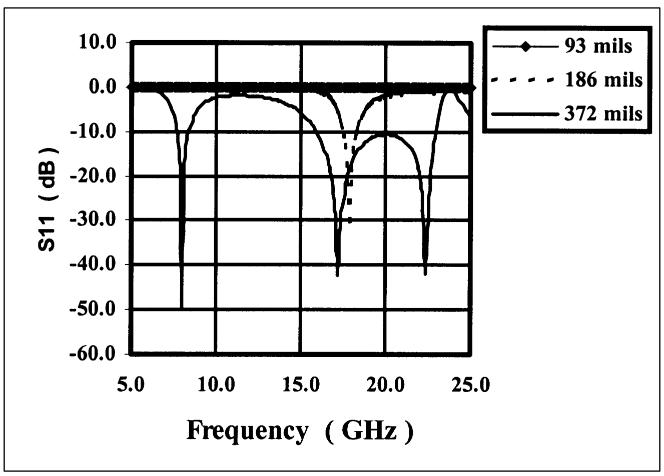

Fig. 2. Reflection coefficient of the walls of the EBG cavity resonator filter as a function of the frequency for different values of the distance between the centers of the posts in the two-element-deep square EBG lattice.

was 0.7614, 0.9976, and 0.9997, respectively. The smaller lattice spacing of the fabricated EBG cavity, 74.4 mils, was selected to ensure extremely good reflectivity even for the oblique incidence of the cavity modes.

The EBG cavity resonator filter requires two boards. The low-loss dielectric Duroid substrate, Rogers 5880 ($\epsilon_r = 2.2$, thickness $=$ 31 mils), was selected for use in the fabrication of the top board. The low-loss dielectric Duroid substrate, Rogers 5880 ($\epsilon_r = 2.2$, thickness $=$ 125 mils) was used for constructing the bottom board. The thicker board for the cavity section was selected based upon the predictions in [2] that thicker dielectric substrates would lead to a higher Q value for the cavity. The coupling slots were located approximately $L/4$ from the edge of the cavities to maximize the coupling, where L is the cavity length [6]. They are "dog bone" shaped to improve the coupling. To provide an electric short circuit at the center of the coupling slot, a shorting via was used.

IV. THEORY

The resonant frequency of the TE_{101} mode can be found as [7]

$$f_{res} = \frac{c}{2\pi\sqrt{\varepsilon_r}} \sqrt{\left(\frac{\pi}{L}\right)^2 + \left(\frac{\pi}{W}\right)^2} \tag{1}$$

where L and W are, respectively, the effective length and width of the cavity, c is the speed of light, and ε_r is the relative permittivity. Note that the higher order parallel-plate modes of the structure perpendicular to the boards occur far above the operating frequency range of the fabricated cavity; hence, they do not contribute to the performance of the cavity. The unloaded Q, Q_u of the cavity can be expressed as [7]

$$Q_u^{-1} = Q_c^{-1} + Q_d^{-1} \tag{2}$$

where Q_d is the quality factor with respect to the dielectric losses and Q_c is the quality factor related to lossy conducting walls. The quality factors Q_d and Q_c can be determined, respectively, from the following relations [7]:

$$Q_d^{-1} = \tan\delta \tag{3}$$

$$Q_c = \frac{(kLW)^3 H\eta}{2\pi^2 R_s (2W^3H + 2L^3H + W^3L + L^3W)} \tag{4}$$

where k is the wavenumber, H is the effective height of the cavity, η is the intrinsic impedance, and R_s is the effective surface resistance of the cavity walls.

Given the geometry specified by Table I, the theoretical value of Q_u was calculated to be 830 with the loss tangent equal to 0.0009. Note that the largest variations in this value are dependent on the actual values of the material parameters. For instance, according to the data sheet from Rogers, Inc., the loss tangent of this Duroid material is typically equal to 0.0009 at 10 GHz with a 2.22% error tolerance. Thus, the loss tangent could vary in the range from 0.00088 to 0.00092, with corresponding variations in the predicted Q_u. In particular, $Q_u =$ 844 when the loss tangent equals 0.00088.

V. FABRICATION

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.

VI. MEASUREMENT

Both the weakly coupled and the strongly coupled models of the EBG cavity resonator filter were fabricated and mounted on a SMA-launch microstrip fixture and were measured with an HP8510 network analyzer. The low-coupling model represents the case where a very small amount of energy is inserted into the resonator in order to accurately estimate or measure its quality factor. The influence of the external circuitry that can affect the Q_u measurements is thus minimized. On the other hand, in the high-coupling case the resonator is strongly coupled to the ex-

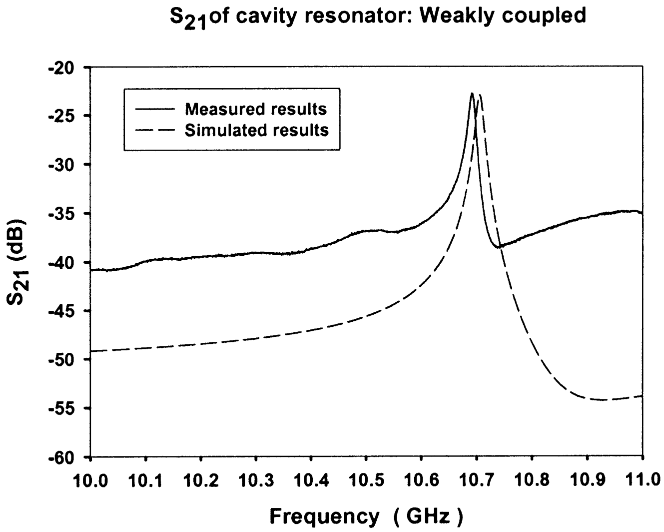

Fig. 3. Simulated and measured insertion loss of the cavity resonator with weakly coupled slots.

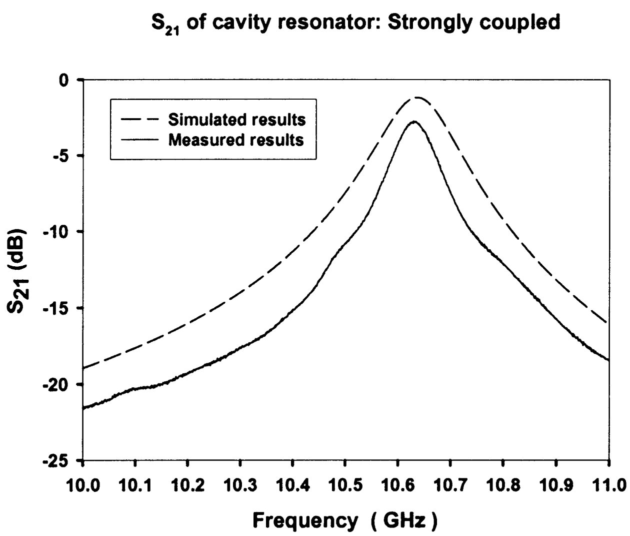

Fig. 4. Simulated and measured insertion loss of the cavity resonator with strongly coupled slots.

ternal circuitry for minimization of the insertion loss. Operation of the resonator more as a filter is achieved in this case. It is important to note that most practical filter implementations would utilize several of these high-Q EBG resonators to achieve a desired frequency response as was accomplished in [4].

The S-parameter data was collected in both cases. The results are shown in Figs. 3 and 4. The fixture losses were de-embedded from these measurements since they would not be present in an integrated design. The minimum measured S_{21} value is limited by the noise floor of the network analyzer. A comparison of the simulated and measured results for the EBG cavity resonator filter is shown in Table II. Quite favorable agreement between these results was obtained.

TABLE II
COMPARISONS OF THE THEORETICAL, SIMULATED, AND MEASURED RESULTS FOR THE EBG CAVITY RESONATOR FILTER

	Simulated results	Measured results	Difference
f_{res}	10.635 GHz	10.628GHz	-0.0658%
Bandwidth	1.379% 147 MHz	0.911% 97 MHz	50 MHz
Insertion loss (S_{21})	1.202 dB	2.763 dB	+1.561dB
Unloaded Q	844	842.6	-0.17%

The value of the unloaded quality factor Q_u was extracted from the measured external quality factor Q_{external} and the loaded quality factor Q_{loaded} [6] with the following equations:

$$Q_{\mathrm{loaded}} = \frac{f_0}{\Delta f} \tag{5}$$

$$Q_{\mathrm{external}} = 10^{-[S_{21}(\mathrm{dB})/20]} Q_{\mathrm{loaded}} \tag{6}$$

$$Q_u^{-1} = Q_{\mathrm{loaded}}^{-1} - Q_{\mathrm{external}}^{-1}. \tag{7}$$

The measured value of Q_u was 842 ($\Delta f = 13.686$ MHz and $S_{21} = -22.7615$ dB). This result is very close to the predicted theoretical value, 844, associated with the low value of the loss tangent for Duroid 5880. The measured operating frequency 10.628 GHz was 0.066% different from the predicetd value 10.635 GHz. The measured insertion loss -2.76 dB was larger than the simulated value -1.20 dB; but, correspondingly, the measured bandwidth 0.91% or 97 MHz was (50 MHz) smaller than the predicted value 1.38% or 147 MHz. The difference between them is most likely due to fabrication issues (especially the bonding of the two substrates), but is well within reasonable tolerances. We should note that the fabrication issues have a more pronounced effect on the resonator with the strongly coupled slots than the weakly coupled one.

VII. CONCLUSION

A high-Q Duroid-based planar EBG cavity resonator filter demonstrating an unloaded Q of 844 was designed, simulated, fabricated, and tested. When configured as a simple, single pole filter, this device resonated at 10.63 GHz with a 0.91% bandwidth and with an insertion loss equal to -2.76 dB. The improvement in the unloaded value of the quality factor from previous cases reported in [1]–[4] and for a related structure in [5] resulted, as predicted in [2], from the increase in the height of the EBG cavity. To the best of the authors' knowledge, this is the highest Q ever reported for such a kind of PCB based cavity resonator. Generally, the measured results agree well with the theoretical and simulated results. This particular resonator can be used for the development of very narrowband, low-loss filters for wireless communication systems. As in [4], a more desirable frequency response and an improved insertion loss can be achieved by using this novel high-Q resonator in a multipole filter design. Typically, the design equations used in a multipole filter design assume resonators with infinite Qs. Therefore, the use of these enhanced high-Q resonators may allow the realized filter response to match more closely the anticipated result. In particular, the high-Q EBG cavity resonator can be used immediately to improve further the three-pole filter design given in [4]. The assembly and bonding of these resonators will play a primary role in ensuring a superior performance in any specific application.

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