Reduced Size Capacitive Defect EBG Resonators

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Abstract — **The concept of a capacitive defect in a periodic lattice is examined. An eigenvalue analysis has been performed to determine the resonant frequency of a capacitive section that forms a defect in an otherwise periodic lattice of metallic vias. This concept presented herein addresses one of the major concerns in a defect mode resonator scheme: the overall size of the structure. Theoretically by loading the cavity with a capacitive load, a size reduction up to a full order of magnitude can be achieved depending on the height of the capacitive post. Furthermore the Q remains relatively the same even with a substantial size reduction. However as a practical issue, the sensitivity of the resonant frequency limits the achievable reduction for a given set of fabrication tolerances. The sensitivity of the resonator frequency and the resonant quality factor of a capacitive defect resonator has been the focus of this study. In the evanescent defect EBG resonator presented herein, the second order resonance is not an integer multiple of the dominant resonant frequency thus resulting in a very clean spectrum. As an example of an application for this EBG resonator, multiple capacitive defects in a metallo-dielectric EBG substrate have been coupled to form a reduced size multipole filter.**

I. INTRODUCTION

Recently, the ability to create waveguide and resonant components by using vias in a substrate has been of interest [1]. In one attempt, a resonator has been created which uses the removal of a single rod in a periodic lattice of vias. The periodic lattice of vias, which prohibit propagation, is termed a bandgap and the resonance is termed a defect mode [2]. The periodic via concept uses the inductive nature of the confining sidewalls to constrict the energy and create a resonance. However, due to the multiple rows of vias needed to contain the energy for a high Q resonance, the size of the structure may become electrical large which may prevent the use of this technology in specific applications. In fact, the size is similar to the size of a traditional rectangular cavity, which limits its applicability. Therefore to combat this disadvantage a method of reducing the size of the structure is sought. To this end, instead of fully removing one of the periodic vias in a lattice, a defect can be created by reducing one of the post height in a periodic lattice as shown in figure 1. For a structure of similar size, the resonance that is created is significantly lower than that of a traditional defect structure. The amount of reduction can be up to an order of magnitude, but this depends on the tolerance of the fabrication method. Even with this reduction in size, the Q of the resonator is not sharply decreased. The size reduction achievable, the sacrifice in Q and the sensitivity of this resonator to fabrication errors are the focus of this investigation.

II. CAPACITIVE DEFECT EBG RESONATOR

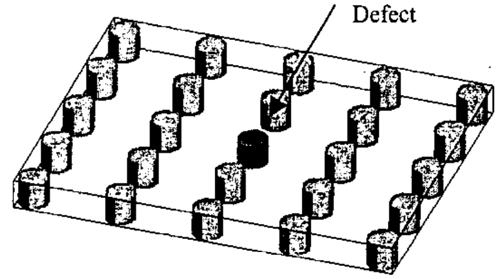

Fig. 1. Capacitive Defect Resonator in Periodic Lattice

Fig. 1 shows the structure of a capacitive post loaded resonator. In this work, loading a resonant defect cavity with a capacitive post creates a quasi-lumped element structure. This capacitive post provides a perturbation to the resonance of the cavity and lowers the frequency as much as one order of magnitude. Filters have been previously created by removing select inclusions in an otherwise periodic lattice of metallic rods [3]. In this work, however, the resonator is created not by removing the periodic inclusion, but by reducing one of the inclusion's height. The reduced-height post, which would otherwise go through the substrate to provide a metallic via between the two parallel plates, is made to provide a capacitive effect locally in the otherwise periodic substrate. The capacitance due to the close proximity of the top of the post and the metallized substrate substantially reduces the frequency of the resonance created by the defect. Most of the electric field is stored on the top of the defect post, while the magnetic field is

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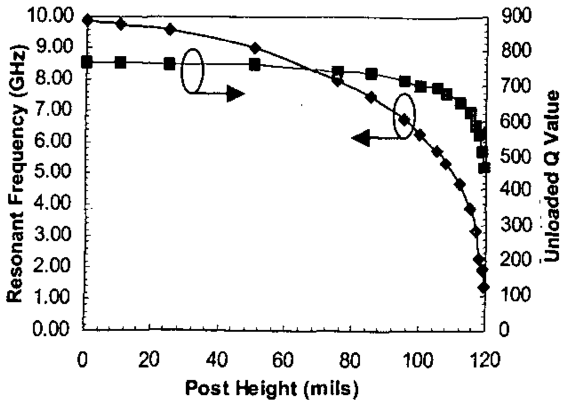

Fig. 2. Eigenvalue Solutions of the Capacitive Defect Resonator Showing Resonant Frequency and Unloaded Q

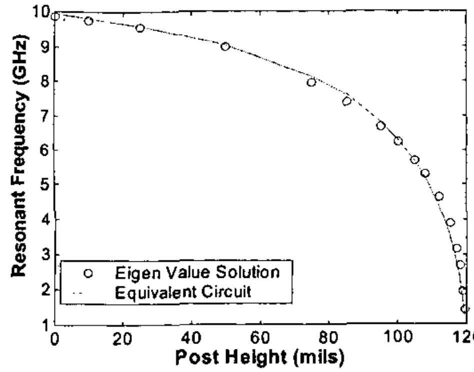

Fig. 3. Comparison of Eigenvalue Solutions to Equivalent Circuit Model

stored in the area surrounding the post. As a result the top of the post is referred to as the capacitive section while the region external to the post is referred to as the inductive section. The Q of this resonator is not sacrificed mainly because the currents induced are very similar to the ones excited in an unperturbed cavity. Since there is a magnetic field null at the center of the cavity with and without the perturbation, the post introduced at the center of the resonant cavity leaves the magnetic field relatively unchanged. The region surrounding the capacitive post, the primary inductive region, still has the full thickness of the substrate in which to store the magnetic field, thus maintaining the Q of an enclosed resonator. The magnetic field is directly related to ohmic losses, since the Q is proportional to the volume storage area for the field relative to the surface area for the currents. In the position of the defect, there is a strong electric field resulting in a high stored electric energy and standing charges associated with it. Though this region has a relatively small volume, it does not entirely sacrifice the Q because the currents are not affected. However this region stores electric field and the increased capacitance decreases the resonant frequency significantly. As a result a reduction in resonant frequency is achieved without a severe reduction in Q. To prove the concept, the resonators were designed and fabricated in 120 mil tall Duroid 5880©. These resonators can also be developed in either ceramics or micromachined silicon substrates for operation at any other frequencies above 1 GHz.

III. RESULTS AND DISCUSSION

A. Eigenvalue solution

An eigenvalue analysis was performed to determine the resonant frequency and the specific loss mechanisms limiting the performance of the resonator. Since there is no available closed form solution to the resonant frequency of the periodically formed resonator, the eigenvalue solution is used. Once the eigenvalue of a specific resonator is obtained, the lattice parameters and the inclusion can be linearly scaled to obtain the desired resonant frequency. Figure 2 shows that the resonant frequency approaches 1/5 of that of an unperturbed cavity when the post height goes to 99% of the substrate height, while Q reduces by less than 46%. Therefore a filter made by cascading a number of appropriately designed resonators could be five times smaller without a major reduction of the ratio of bandwidth to insertion loss.

To develop an equivalent circuit, Q of this resonator can be divided into two distinct sections, the capacitive and inductive regions. As the frequency is lowered and the dimensions of the resonator itself become much smaller than the size of the unperturbed cavity, the lumped element model for this resonator becomes more and more accurate since the field becomes more confined to the capacitive section. The electric field is contained mainly above the post. An equivalent circuit model was developed after the eigenvalue solutions were obtained. The total capacitance of this resonator is $C_{TOTAL}=C_{UNPERTURBED}+C_{POST}$ where $C_{UNPERTURBED}$ can be found by:

$$C_U=\frac{\omega_U^2}{L_U} \quad (1)$$

The capacitive section adds a capacitance value that is given by idealized formula for a parallel plate capacitor,

$$C_{post} = \frac{\varepsilon_r \varepsilon_0 A}{d} \quad (2)$$

Therefore the total resonant frequency can be approximated by

$$\omega \approx \frac{1}{\sqrt{L_U (C_U + C_{post})}} = \frac{1}{\sqrt{\omega_U^2 + L_U \frac{\varepsilon_r \varepsilon_0 A}{d}}} \quad (3)$$

By curve fitting we extracted the value C_u = 0.12 pF and L_u = 1.5 nH. The general agreement as shown on figure 3, verifies this equivalent circuit model for this resonator.

B. Measurement Results

Resonators with 50-mil and 100-mil post heights are realized and measured. The S-parameters are shown in Fig. 4 and Fig. 5. The lattice period is 275 mils by 354 mils. Using the equation $Q_u = Q_L/(1-S_{21})$, the quality factor of resonator can be extracted. It is found to be close to the eigenvalue solution in the table below.

Post Height (mil)	Eigen solution	Extracted Qu
50	763	653
100	699	602

Figure 4 shows the response of resonator with 50-mil post height. Originally we designed for 50-mil post which gives a resonant frequency of 9 GHz. However due to the fabrication tolerances a 6-mil air gap (measured by

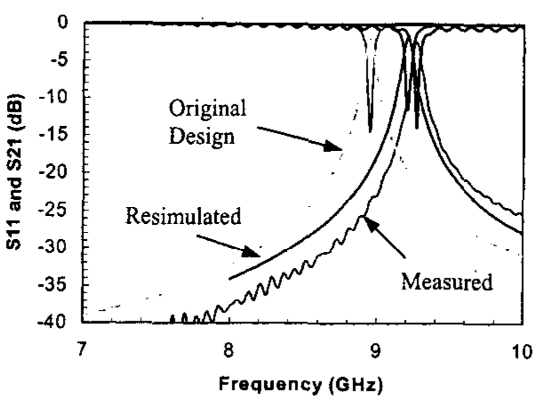

Fig. 4. S-parameters of Capacitive Defect Resonator With a 50-mil Post

caliper) exists between the capacitive post and substrate. Incorporating the air gap in the simulation, the computed response agrees very well with the measurement. As seen

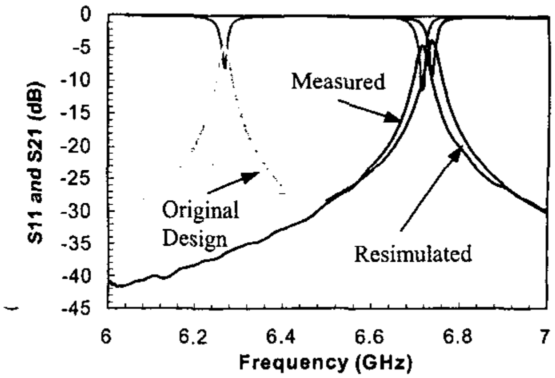

Fig. 5. S-parameters of Capacitive Defect Resonator With a 100-mil Post

in figure 4, the measured resonant frequency is 9.27 GHz. For the 100-mil post height resonator, we measured the actual post height to be 98 mils and an air gap to be 6 mils. So the frequency goes from designed 6.26 GHz to measured 6.72 GHz in Fig. 5.

For this proof of concept, the frequency shifts down by 8% for 50-mil post and by 30% for 100-mil post. The resonators were built in Duroid, which limits the effectiveness of the size reduction. However more advanced techniques could realize the full reductions shown possible in Fig. 2. Under better fabrication conditions, the frequency reduces to less than 20% of that of a resonator without post. Or equivalently, the size can be reduced to one fifth of original dimension. Practically though the amount of size reduction depends on the tolerance of the fabrication technique. Since capacitance grows with increased epsilon, more reduction in size is possible. Ceramic materials may be used for example. Alumina (permittivity = 9.8, loss tangent = 0.0001) would provide f=2.973 GHz and Q=1524 under the same dimensions used above.

C. Sensitivity Analysis

The sensitivity of the resonant frequency is crucial to the realization of resonators and as such is studied herein. Though the resonant frequency may be as low as desired by reducing the gap between the capacitive post and top plate, the repeatability becomes an issue as the capacitance increases. For an effective filter implementation, the resonant frequency must be repeatable, since this is a basic assumption in filter development. The sensitivity of the resonator is shown in figure 6. The basic assumption in many filter designs is that the peaks of transmission

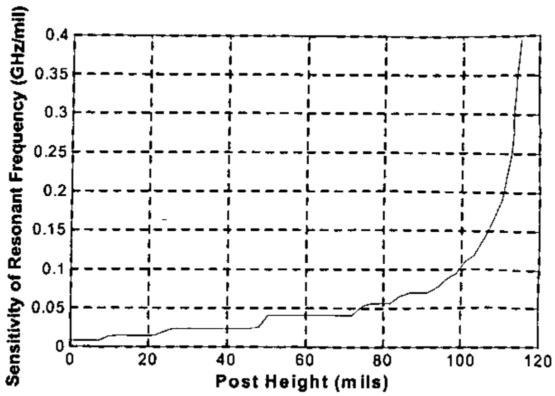

Fig. 6. Sensitivity of Resonant Frequency to the Post Height

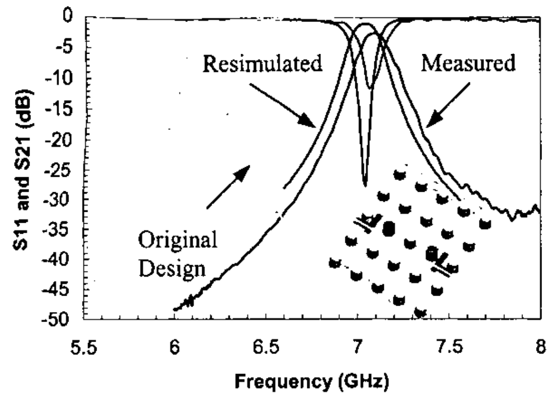

Fig. 7. S-parameters of Two Capacitive Defect CPW Fed Filter With a 100-mil Post

response are solely due to the coupling mechanism between resonators, assuming that all the resonators resonant at the center frequency. For example, in the implementation of a 1%, two-pole filter, the separation between the resonant peaks should be less than one percent when the resonators are weakly externally coupled. From Fig. 6 we see that when the post height is 100 mil, a one-mil variation in post height gives a 0.1 GHz frequency shift, which is on the same order of the bandwidth of a 10 GHz, 1% filter. Therefore 1-mil tolerance would effectively ruin the desired filter response.

IV. Example Application of Resonator

Once the resonator's performance has been determined, multiple defects must be coupled to form a multipole filter. The effect of the capacitive post is three fold. It decreases the resonant frequency of the resonator; therefore for a given frequency of operation it shrinks the overall size of the filter. In addition, the bandwidth of the filter can be adjusted by varying the depth of the posts. Thirdly an intriguing and beneficial result of utilizing the defect post is that the resulting resonator is free from any spurious modes in the bandgap.

In the filter that was realized in this study, the external transition is made from a shorted CPW line, as in [3]. This CPW line excites the inductive section of the resonator through the magnetic field built up at the location of the short. By adjusting the length of the slot, the amount of magnetic field from the slot, coupled to the inductive section of the resonator, is controlled. As a result, a critically coupled filter can be obtained.

A 2-pole filter is created by placing two defect posts 90% through the substrate two periods away from each other. Using the posts as a defect rather than just removing the post completely reduces the resonant frequency from 9.86 GHz to 7.2 GHz. The rod diameters were chosen to provide a 2% bandwidth. The resulting filter response is shown in figure 7. The bandwidth is 1.97%. There is a slight mismatch from external coupling in the measurement results. When this mismatch is accounted for in the simulation, it adds 0.5 dB to the insertion loss. Therefore the difference between the simulated and measured is 0.7 dB, which may come from the loss in the connectors or the feed lines.

V. Conclusion

This work has shown that the concept of a capacitive post defect can be used to create relatively small resonators. The Q of the resonator is not drastically affected, while the resonant frequency can be reduced by a factor of almost five. The limitations on this effect have been explored, however with more advanced fabrication technology we would push the size reduction to a full order of magnitude. The various resonator parameters that affect performance have been described and filter designs have been implemented. Advanced, reduced size diplexers and filters are currently being designed, fabricated and tested.

Acknowledgement

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