Narrow Ka Bandpass Filters Using Periodically Loaded Substrates

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Abstract — **High-K ceramics (TiO_2) are periodically embedded into a polymer based host material to create a filter utilizing the two-dimensional stopband of the periodic dielectric materials. The high-K ceramic rods (ε ~ 90) are periodically spaced in a commercially-available, Teflon-based host to create a material that will inhibit propagation in two-dimensions. The inhibition of energy is used to create a resonance (termed a defect resonance), which in turn serves as the basis to create a filter. 2 and 4 pole filters were designed using this technology. The filter comprises a narrow passband region residing within the material stopband (12.1GHz to 24.2GHz). An ~1% filter design *yielded measured insertion losses of 1.13dB and 1.69 dB @* 20.45GHz for 2 and 4 pole filters respectively, correlating to an unloaded Q of approximately 1100. Maximal discrepancy of 2% was achieved on all measures of filter performance.**

I. INTRODUCTION

Periodic materials, additionally referred to as Electromagnetic Bandgap materials, have been theorized to enable high-Q filtering for numerous years [1]. The theory stems from the fact that a resonator can be created by disturbing the periodicity in otherwise periodically alternating dielectrics. The alternating dielectric constants of the composite material can be utilized to inhibit energy propagation through a two-dimensional array. By disturbing the periodicity of the material (termed a defect in original bandgap work but restated as a "variant cell" according to recent MTT society guidelines), electromagnetic field can be localized inside of the material and a high-Q resonance can be created. Furthermore, a filter can be designed through multiple resonators coupled together by creating multiple aperiodic regions in the otherwise periodic substrate (illustrated in Figure 1). The coupled resonators must then be correctly externally coupled to create a usable passband. The first versions of these filters, demonstrated herein, are directly coupled poles with constant coupling coefficients. Adjusting the location of the poles can create more complex pass bands such as Chebychev or maximally flat filters. The focus of this paper is to illustrate high-quality filtering utilizing alternating periodic media designed with standard filter methodologies.

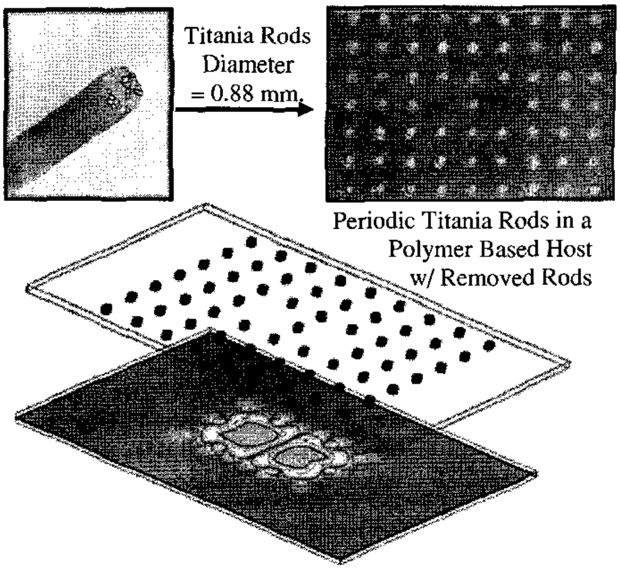

Fig. 1 – The schematic and fields within a periodically loaded substrate used to create a 2-pole filter. The E field (bottom) is contained within the periodically arranged rods creating resonances which can be used for filtering

Previously, high-Q planar resonators in two-dimensionally periodic materials have been developed by the current authors through various techniques. Resonators from alternating dielectric materials were designed and fabricated in Duroid/air [2], alumina/air [3], metal/polymer [4] and most recently Titania/polymer material composites [5]. The implementation of a filter from the resonators inside previous dielectric composites has proven difficult. Lack of repeatability of the resonant frequency has inhibited the extension of the resonators into narrowband filters. However, the Titania/Polymer composite material has proven repeatable and stable for the creation of resonators and filters. It is the purpose of this paper to illustrate the feasibility of creating a narrowband filter (~1.1 %) with a low insertion loss (1.15 dB) from an array of high dielectric inclusions in a low dielectric constant host.

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II. Composite Material Properties

The first step of the filter development requires analysis of field propagation through the periodic material. This is performed through previously developed two-dimensional plane wave expansion techniques [2-5]. To ensure the two-dimensional expansion accurately describes the fields within the periodic material, the material is sandwiched by two parallel metal plates, enforcing the correct polarization and field expansion in the material. The result of the analysis of the periodic material is the development of a dispersion diagram illustrating the frequency versus propagation vector relation for the material. In this manner, the stopband (also termed bandgap) region can be identified.

The dispersion diagram for a periodic composite of Titania rods in Duroid (Roger's Corp. 5880) with a period to diameter ratio of 0.251 is shown in figure 2. The stopband for this material is from 12.1 to 24.2 GHz which is significantly wider than the Alumina/Air composites that have previously been created due to the greater dielectric constant ratio ($\varepsilon_{INCLUSION}$ / ε_{HOST} = 40.9 for titania in a polymer vs. 9.8 for alumina in air). Also, the resulting material is electrically smaller for the titania/polymer composite relative to the alumina in air due to the higher dielectric constant. The bandstop region is the frequency range in which there are not eigenvalue solutions to the wave equation (corresponding to frequency) for any of the two dimensional propagation vectors along the Brillouin Zone (the irreducible set of propagation vectors representing all possible propagation vectors in the periodic array). At these frequencies, the electric and magnetic field evanesce inside of the material. A single variation in the periodic inclusions, such as the removal of one of the elements, creates a single resonance with a resonant frequency inside of the stopband, while multiple variations in the periodic array creates multiple coupled resonant modes. These modes are then used to create a narrow band filter that is within the stop band of the material. The passband region allows for propagation through the periodic material, which in the ideal case allows coupling between two ports only at a narrow band of frequencies. As a practical matter, the quality of the resonances controls the tradeoff between the bandwidth and the insertion loss as in all filters. Therefore the quality factor of the resonator is the topic of next section.

III. Resonator Properties

The resonance created in the periodic material can be viewed as nearly the inverse of a traditional dielectric resonator. In a standard dielectric resonator, the field is contained inside of the high dielectric region due to internal reflection from the interface of the boundary of the resonator. Alternatively, the resonator in the defect of the periodic material relies on multiple reflections from

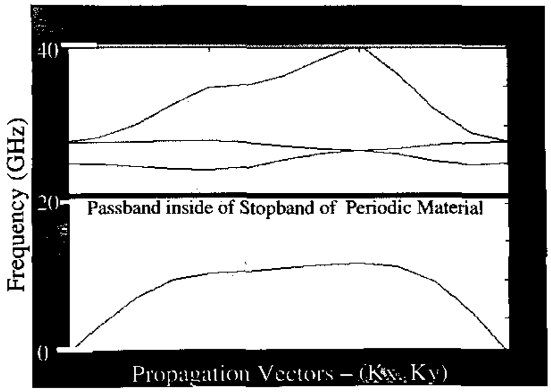

Fig. 2 – The dispersion diagram of titania rods with a radius of 0.88 mm periodically embedded inside of Duroid with a spacing of 3.5 mm

the surrounding periodic rods to localize the energy, in turn creating a resonance. The field in this type of resonator is predominantly in the low dielectric material rather than the high dielectric material, which would be the case in the traditional dielectric resonator. Therefore, the analogy of the inverse relation between the two applies.

As known, the performance of this resonance (specifically the unloaded Q) will dictate the performance of the filter which is comprised of said resonator. The resonator properties of a missing rod in a titania lattice in a Duroid host were dissected in a paper that is to be published in an upcoming special issue on metamaterials [5]. Therefore only the highlights relevant to the filter will be restated here. Since the material must be inserted in a parallel plate for the stopband calculated from the plane wave expansion to be valid, the metal loss tempers the expected Q values. For thin substrate (0.75 mm or less), the metal loss of the parallel plate dominates and the total unloaded Q is less than 500. The unloaded Q for a resonator in a relatively thick substrate (1mm and >) asymptotes with increasing height to the value of the Q of the field in the host material. For this particular material choice, the loss tangent of the Duroid is 9e-4 and the loss tangent of Titania inclusions is 5e-4. When figuring in the amount of energy stored in the host Duroid relative to the Titania (24%), this upper limit for the unloaded Q is ~ 1481. A host polymer with lower loss (polyethylene or polyurethane for example) would allow this upper limit to be significantly increased. More details of the breakdown in Q can be found in [5].

For the height of the substrate used in this filter (2.5 mm), the unloaded Q of the resonator is theoretically 1050. The measured unloaded Q of a single resonator was 73% of the theoretical value, at 760. We would expect this value to dictate the insertion loss to bandwidth tradeoff achievable for a given material.

IV. Filter Design

There are three main factors to designing the filters; designing the correct inter-resonator coupling, the external coupling, and the unloaded Q. The unloaded Q was previously determined as discussed in the previous section; therefore this section will focus on the inter-resonator coupling and the external coupling.

A. Inter-resonator Coupling - The inter-resonator coupling is a function of the containment of the field within the defect (a.k.a. aperiodic region) resonator. The field in the resonator is shown in figure 1 to be only partially contained in the defect region. The overlap of the fields in the resonant modes creates coupling between the two resonators. One heuristic way of looking at this resonator is envisioning a resonator created by boundary conditions imposed from a surrounding two-dimensional bandstop filter. The surrounding periodic material is, in essence, the same as a traditional one-dimensional bandstop filter except that it blocks energy propagation in two-dimensions. The greater the impedance mismatches between each section of the filters, the larger the attenuation into the filter. The larger the attenuation, the more localized the energy and the less the field evanesces into the surrounding periodic material. Therefore the coupling between adjacent resonators is reduced with a greater impedance mismatch. This is another way of stating that the higher the dielectric contrast ratio between the two materials, the less the coupling coefficient characterizing the two adjacent resonators will be. The period to diameter ratio of the inclusions can be adjusted to alter the coupling coefficient to suit the needs of a specific application. By creating weak external coupling to the coupled resonators the coupling coefficient can be extracted. In the example presented as verification, an approximately 1.25 % filter was desired and therefore the coupling coefficient, k, was designed to be 0.0089 as defined by the equation:

$$k_{12} = \frac{f_e^2 - f_o^2}{f_e^2 + f_o^2} \tag{1}$$

f_e and f_o represent the even and odd resonances of the coupled resonators, respectively.

B. External Coupling to Substrate – To determine the unloaded Q, weak coupling ($Q_{EXT} > 1000$) was purposefully designed which enables the accurate determination of the unloaded Q of the resonator and therefore the inherent loss inside the resonator itself. For weaker coupling, the coupling mechanism may reside external to the defect region and rely on coupling to the evanescent fields in the periodic portion of the substrate. However, to create a usable passband, a much lower external Q ($Q_{EXT} < 100$) is necessary. A means to strongly couple to the resonators without significantly perturbing the resonators was needed for the formation of the filters.

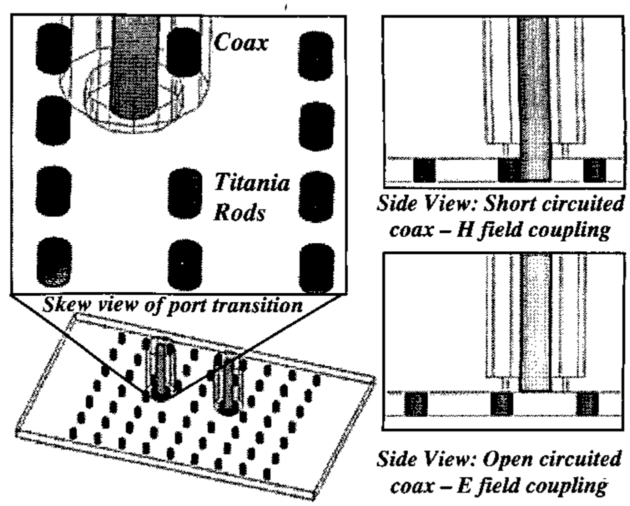

Fig. 3 – Views of the coax port transition to the filter in the substrate. Both E field coupling (top right) or H field coupling (bottom right) can be utilized for external coupling to the resonators.

The location of the external ports was utilized to control the external Q of the resonator. The closer to the defect, the lower is the external Q and vice versa. However, the titania/polymer material constrains the energy inside of the defect region to an extent that it is difficult to get an appreciable amount of coupling with the probe external to the defect region. In more moderate dielectric constant contrasts (such as Alumina/Air composite materials), this is not the case and a wide range of external coupling can be achieved. For the Titania/Duroid filter, the probe must be located over the defect region itself.

There were two techniques used to couple energy into the defect resonator. These two techniques are highlighted in figure 3. The first coupling technique is to "short" the coaxial center pin by soldering it through the substrate to the other side of the parallel plate. The "shorted" center pin creates magnetic field coupling to the resonator. Alternatively, the coaxial probe can have an "open" center pin which is attached to the face of the substrate without protruding into the substrate. The fringing electric field from the open coax will match to the electric fields in the resonant mode in the substrate. Either coupling mechanism can be used, however judicious choice of this mechanism allows for a simpler, less sensitive implementation. By analyzing the field solution of a full wave simulation, the electric field varied more gradually in the defect region than did the magnetic field. Therefore, the E-field probe was utilized because it minimized the sensitivity on the fabrication tolerance. The correct external coupling was created with the center of the coax spaced .88 mm from the center of the cavity.

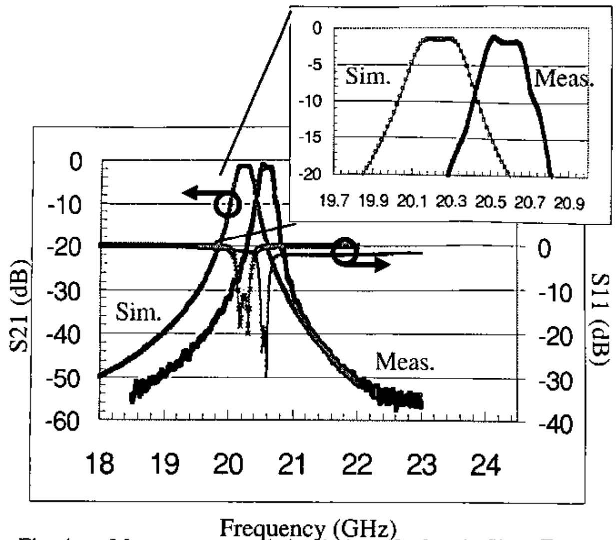

Fig. 4 - Measurement and simulation of a 2-pole filter. The Measured filter has 1.1% BW with 1.15 dB of insertion loss. The simulation is 1.3 % BW with 1.3 dB min. insertion loss.

V. Fabrication Technique

To demonstate this concept, the fabrication of the small scale ceramic features needed for this material required novel processing techniques. An extrusion process is used in which the Titania and a thermoplastic binder are forced through a die to create thin 1mm rods. The binder is then removed through a burn-out stage and then sintered to form a dense all titania rod. The resonators are sintered at 1400° C for 4 hours in order to sinter them to only partial density (90% dense as tested by an Archimedes density method). This schedule avoids loss created by oxygen deficiency and therefore allows relatively low loss high-K ceramic materials. The rods shrink in the burnout and sintering stage by 12%, resulting in 0.88 mm rods. The final diameter of the rods has been measured with fine scale calipers to be accurate to within +/- 1% (+/- 0.009mm) between rods. These rods are then inserted into a premachined Duroid host with periodic holes spaced 3.5 mm apart. Finally, the substrate is bonded between parallel metal plates which have coupling holes for the coaxial ports.

VI. Results and Measurements

For demonstration purposes, a two-pole filter was designed to have a bandwidth of 1.25 %. This bandwidth is created with two defects separated only one period away from each other in a periodic lattice of circular rods with a diameter to period of ratio of ~ 0.25. The measured and simulated results are shown in figure 4. The simulation showed a slightly increased bandwidth of 1.3% and a minimum insertion loss of 1.45 dB. The measured results gave a 3 dB bandwidth of 1.11% with an insertion loss of 1.15dB. Through an equivalent circuit representation of the filter, this performance was determined to represent an unloaded Q of 1080 in each of the resonators. The center frequency of the simulated filter is 20.25 GHz while the measured center frequency is 20.66 GHz, representing an approximate 2 % shift. This resonant shift is consistent throughout resonator and filter designs utilizing this material and is hypothesized to be due to an air gap between the rods and the parallel plate or variation in the dielectric constant.

A 4 pole filter was also designed and measured utilizing the same technique. It was measured to have an insertion loss of 1.69 dB and a bandwidth of 0.95 %. The measured result is once again narrower than the simulated design which had a bandwidth of 1.3 % with an insertion loss of 2.45 dB. These results show that the Q of the fabricated resonator is in fact greater than the Q of the simulated resonator. This favorable discrepancy may be due to the relatively unknown variation in the loss of the fabricated dielectric rods.

VII. Conclusions

A narrowband filter was created out of a periodic composite of high dielectric ceramic (Titania) and a low dielectric commercially available polymer based material (Roger's Duroid 5880). The relatively miniature Titania inclusions were fabricated using an extrusion process to form high quality, precision rods. The fabricated 1 % 2 and 4-pole filters have a good correlation with simulation and a low insertion loss (1.15 and 1.69 dB respectively) due to the relatively high unloaded Q of the resonator (greater than 1,000).

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