An Artificial Dielectric Material of Huge Permittivity with Novel Anisotropy and its Application to a Microwave BPF

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***Abstract* — Artificial dielectrics of very high equivalent permittivity is designed and fabricated by use of patterned PCB printed circuit board. Rectangular metal patterns are etched out to attain as big capacitance with each other as possible but as small current as possible, which is important to have as large permittivity and as small loss as possible, respectively. Artificial dielectric disk resonators are created to excite $TE_{01\delta}$ mode selectively, aligning the rectangular metal patterns along the direction of the mode electric field lines. Thus, a miniaturized BPF with superior spurious characteristics is fabricated using three disk resonators.**

I. INTRODUCTION

Study of artificial dielectrics has a long history of more than 50 years [1]. Though its application to a lens antenna [2] was not realized in practice at last, the present authors proposed a new application to a microwave resonator, taking advantage of its possibly quite large permittivity [3]. It will contribute to obtain a resonator of reduced size, and as a result, a miniaturized BPF. The principles of realizing as high permittivity as possible should be found first and will be reported in this article.

Secondly, the effective loss tangent has to be as small as possible in order to enjoy the high permittivity of the material. In the artificial dielectric made of metal patterns, the origin of the dissipation is the conduction current on the surface of each metal element. Thus, we have to devise an element of small current density.

In the third, the artificial dielectric made of metal strips is anisotropic in principle, because the polarizability of each rectangular strip of the dimension a*b*c is different according to the direction of the electric field. The aspect ratio is made large to effectuate the anisotropy. It discriminates the resonant modes depending on the coincidence of the anisotropy axis and the electric field direction. Moreover, the anisotropy can be controlled beyond the possibility of crystallography. In fact, our material has a circular cylindrical anisotropy as is stated later.

A disk resonator made of the artificial dielectric explained above would resonate with a quite low frequency and have a superb spurious property. Therefore we will create a 3-stage BPF to show the unique prospect of our new material.

II. EFFECTIVE DIELECTRIC CONSTANT AND LOSS

The basic structure of the artificial dielectric is shown in Fig.1, in which the aligned metal strips polarize with the applied electric field and shows an effective dielectric constant macroscopically if the dimensions of each strip is small enough compared with the signal wavelength. Based on the numerical calculations by use of a commercial EM software HFSS®, we found the effective permittivity becomes larger when

(1) strip length is larger,
(2) gaps between strips are smaller,
(3) the density of strips in a unit volume is higher,
(4) each strip takes face-centered orthorhombic lattice structure ,

and confirmed them partly by experiments[3][4].

In addition to these criterions, the host material in which metal strips are embedded is important. Surprisingly, the effective relative permittivity is given by the product of the effective permittivity of aligned metal strips and that of host material [5]. Thus, if we adopt a host material with 100 of relative permittivity, for example, it is not difficult to realize 10000 of effective relative permittivity for an artificial dielectric.

It is desired that a high permittivity is accompanied with a low dielectric loss. Thus, we have tried to find a scheme to reconcile both. Analyzing the loss mechanism of our material, we found the loss originates from the imaginary part of permeability, that is, circulating conduction current loss on the metal element. Hence, we should reduce the width of the metal strips, while we should keep the width of the adjacent strips confronting each other to give the mutual capacitance. The compromise of these two effects is the dumbbell shape of the metal element as shown in Fig.2. The calculated real and imaginary part of the relative permeability are shown versus frequency in Fig.3. It is noted that the dumbbell gives a smaller imaginary part, and hence smaller loss.

III. $TE_{01\delta}$ MODE RESONATOR

The electric lines of force of $TE_{01\delta}$ mode in a circular disk dielectric resonator is depicted in Fig.4 together with the magnetic field. If we fabricate an artificial dielectric resonator that has the metal strips along the direction of the concentric electric field line in Fig.4, we will have a quite good mode selectivity for $TE_{01\delta}$ mode. Based on this concept, we fabricated an artificial dielectric disk resonator depicted in Fig.5, piling up the etched PCBs one another with 90 degrees rotation. This alternated alignment is important to attain a large effective permittivity with a quasi-face-centered lattice structure mentioned before.

The measurement of the resonant frequency and unloaded Q of $TE_{01\delta}$ mode was carried out in a metal shield shown in Fig.6 (a). Another 3 exciting probe configurations including a linear probe shape and sidewall excitation were also tried to select $HE_{11\delta}$, $EH_{11\delta}$ and $TM_{01\delta}$ modes as shown in Fig.6 (b), (c) and (d). The results in Fig.7 evidently inform us that there is no higher mode excitation up to the cutoff frequency 6.0GHz of the shield case except the lowest $TE_{01\delta}$ mode at 0.68GHz, the perfect spurious suppression.

Assuming that the effect of polarization of each metal strip is averaged in a macroscopic point of view, we have calculated the effective dielectric constant of the artificial resonator from the measured frequency based on the simple magnetic wall boundary condition in Fig.8. The governing equations for the $TE_{01\delta}$ mode are:

$$\begin{cases} x_z \tan(x_z \xi) = x_\alpha , \\ J_0(x_\rho) = 0 , \\ x_\rho^{\ 2} + x_z^{\ 2} = \varepsilon_r x_0^{\ 2} , \\ x_\rho^{\ 2} - x_\alpha^{\ 2} = x_0^{\ 2} , \end{cases}$$

where $x_z = k_z a$, $x_\rho = k_t a$, $x_\alpha = \alpha a$, $x_0 = (2\pi/\lambda_0)a$, $\lambda_0 = c/f$, $\xi = L/2a$. The obtained relative permittivity is as high as 3600 for the resonator shown in Fig.5. If we use a host material of the relative pemittivity 10, the effective permittivity of more than 10000 would be possible for the resonator.

The measured Q value was not high for the resonator shown in Fig.5 having only 80, probably because of poor contact and alignment of PCB sheets in adddition to the dielectric loss of the sheet. The improvement of Q value is carried out using dumbbell -shaped metal elements as explained in the previous section. The etched metal strips on 10 pieces of FCB sheet shown in Fig.2 (b) were layered to make a disk resonator, giving 160 of Q value with less effective relative permittivity 2540. Therefore, further improvement will be continued along the line with this principle.

IV. 3-STAGE BPF

We have created a 3-stage bandpass filter using our resonators to demonstrate the practical importance of the artificial dielectrics. The overall structure and dimensions are shown in Fig.9. Due to the poor fabrication technique of the shield case as well as the resonator itself, the insertion loss in Fig.10 (a) is extraordinarily high. But it still shows the bandpass characteristics and above all, the spurious characteristics in (b) are exceptionally good. Figure11 shows the transmission characteristics of a 3-stage BPF just exchanged by conventional dielectric resonators, for comparison. Its poor spurious characteristics would show the excellence of our resonators.

In addition, it should be noted that the center frequency of the BPF in Fig.10 is quite low compared with that in Fig.11. It is the miniaturization effect due to the huge dielectric constant of the artificial dielectric material. It should be exploited further together with other remarkable characteristics.

V. CONCLUSION

We have proposed an artificial dielectric resonator with a huge premittivity and novel anisotropy. These properties are well-suited for miniaturization and good spurious characteristic of a BPF. More realistic demonstration of this proposal is under way based on LTCC techniques. The more reliable property and the possibility of this material will be shown later including temperature characteristics.

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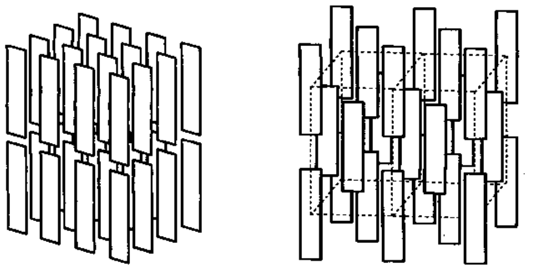
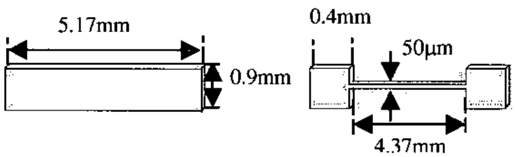


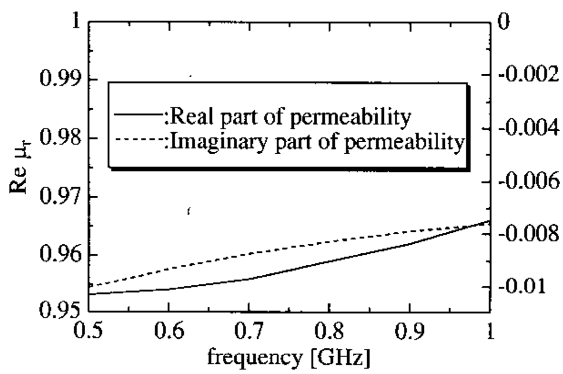
(a) simple orthorhombic (b) face-centered orthorhombic

Fig.1 Lattice alignment of metal element

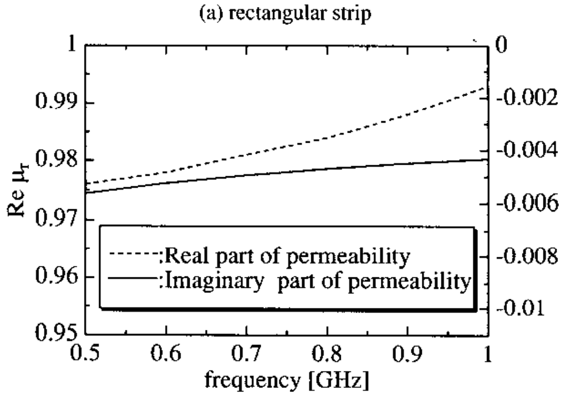


(a) rectangular strip (b) dumbbell strip

Fig.2 Metal strip element to reduce conduction loss(thickness:18 μm)



(a) rectangular strip



(b) dumbbell strip

Fig.3 Effect of dumbbell strip to reduce conduction loss

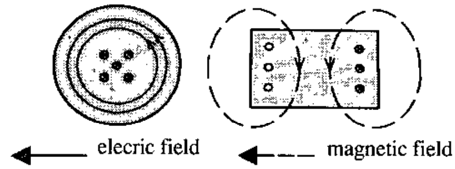


Fig.4 Electromagnetic field distribution of $TE_{01\delta}$ mode in a dielectric disk resonator

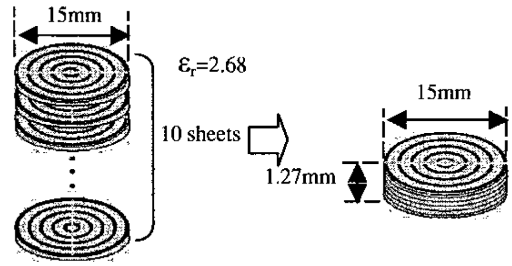
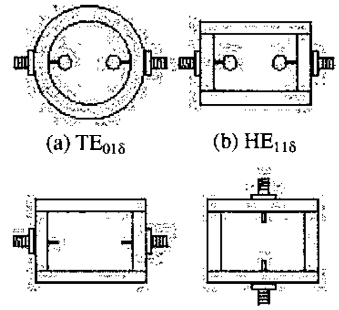


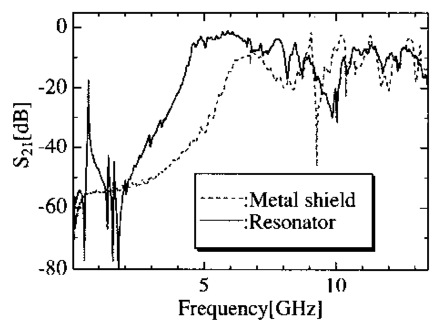
Fig.5 Fabrication of artificial dielectric disk resonator



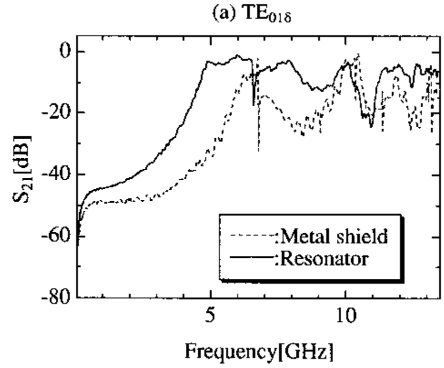
(a) $TE_{01\delta}$ (b) $HE_{11\delta}$

(c) $EH_{11\delta}$ (d) $TM_{01\delta}$

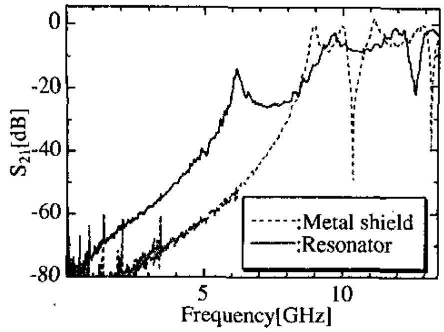
Fig.6 Metal shield to measure 4 lowest modes of a dielectric disk resonator



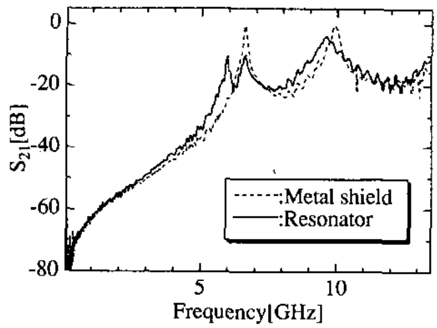
(a) $TE_{01\delta}$



(b) $HE_{11\delta}$



(c) $EH_{11\delta}$



(d) $TM_{01\delta}$

Fig.7 Transmission characteristics of 4 metal shields containing artificial dielectric disk resonator in Fig.5

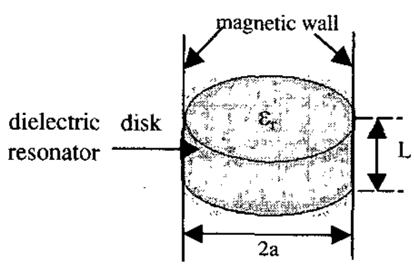


Fig.8 Approximate boundary condition to solve $TE_{01\delta}$ mode of dielectric disk resonator

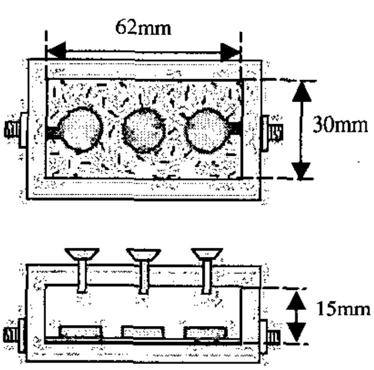
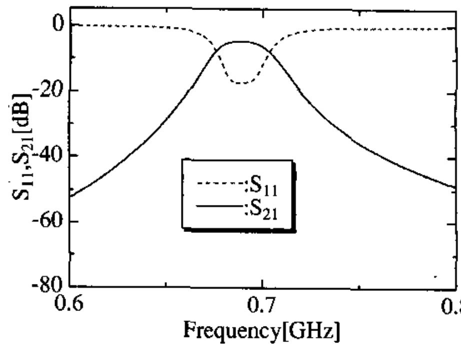
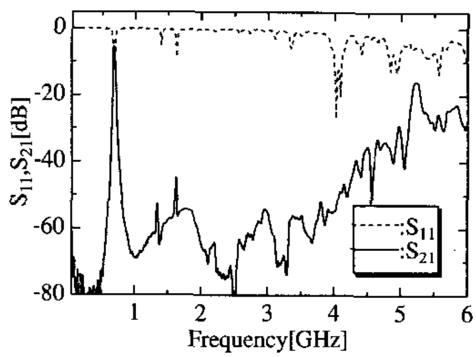


Fig.9 Structure of 3-stage BPF



(a) Narrow range property



(b) Spurious property

Fig.10 Transmission characteristics of 3-stage BPF made of artificial dielectric disk resonators in Fig.5

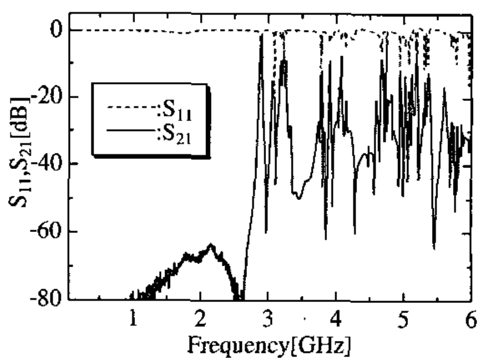


Fig.11 Transmission characteristics of 3-stage BPF made of conventional dielectric disk resonators ($2a=11.9mm, L=6.5mm, \varepsilon_r=93$)