IF-TH-3

New Design of High-Q Sapphire Resonator with Distributed Bragg Reflector

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Abstract - **In this paper, new sapphire resonator designs based on Bragg reflectors are presented. This study is based on the Method of Lines and is shown to be in good agreement with experiment. The resonant frequencies, field distribution and quality factors can be calculated by this method. An initial design using a $TE_{01\gamma}$ mode in a sapphire ring resonator is presented. A Q-factor of 100,000 was measured. We show that with further optimization a Q-factor about 200,000 is possible.**

I Introduction

Dielectric resonators are utilized in a variety of applications including filter and oscillator. These structures are compact, reasonably priced and have a good temperature stability. In this study, because of the low losses, sapphire crystal is utilized to build a cylindrical resonator incorporating Bragg reflectors.

To obtain a high Q-factor at room temperature, the field needs to be confine in a dielectric resonator in order to decrease metallic losses. One of the solutions is to use a Whispering gallery mode. For WGE modes room temperature (290K) sapphire resonators allow Q-factors of order 170,000 [1]. Because WG modes are high order, resonators have large dimensions and consequently a high density of spurious modes. Unlike, fundamental mode $TE_{01\gamma}$, which has good isolation and low spurious mode density, the disadvantage is that metallic losses of cavity are significant. Q-factors at room temperature are less than 70,000 depending on the size of the enclosed cavity [2].

Other work has introduced Bragg reflectors as a method to improve the Q-factor of empty cavity [3]. They consists of several thin plates of sapphire designed to confine most of field of the resonant mode in free space and decrease metallic losses. Q-factor of about 650,000 has been achieved, however this structure is very sensitive to alignment of plates and there is a large spurious mode density.

In this paper, we utilize the Bragg reflector concept to reduce metallic losses in a $TE_{01\gamma}$ ring resonator. First we apply the concept just along the cylinder axis with calculations verified by experiment. Then, using Method of Lines [4] we introduce a new design that considers Bragg reflector in the radial as well unloaded Q-factor. Results will be compare by Finite Element Method [5].

II Presentation of Method of lines

The Method of Lines is a vectorial technique and it's a finite difference approach. A differential system is obtained for each layer of the structure. Electromagnetic fields are derived from two scalar potentials (Ψe and Ψh) that are solutions of Helmholtz (1) and Sturm-Liouville differential (2) equations in cylindrical coordinates and without azimuthal variation.

$$\frac{\partial^2 \Pi\varphi}{\partial z^2}+\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(r\Pi\varphi)\right)+k_0^2\varepsilon r\,\Pi\varphi=0 \qquad (1)$$

$$\frac{\partial^2 \Pi r}{\partial z^2}+\varepsilon r\frac{\partial}{\partial r}\left(\frac{1}{\varepsilon r}\left(\frac{1}{r}\frac{\partial}{\partial r}(r\Pi r)\right)\right)+k_0^2\varepsilon r\,\Pi r=0 \qquad (2)$$

For solution of the equations and for the determination of the field components, the potentials are discretized in one direction, along the radial direction. The mesh is non-equidistant: it is fine in the region where the field exhibits high concentration or rapid variations. Symmetries are also taken into account to reduce the analysis domain and consequently time for analysis. The lateral boundary conditions of the potentials can be satisfied with 2 different line systems (figure 1) representing respectively each potential. Matching the tangential field components at the interface between 2 adjacent layers, we can achieve the resonant frequencies and the distribution of electromagnetic fields and an unloaded Q-factor.

Computational programs were developed for MATLAB software. Method of Lines was be used to optimize structure's dimensions in order to get the best Q-factor for a frequency of 9GHz.

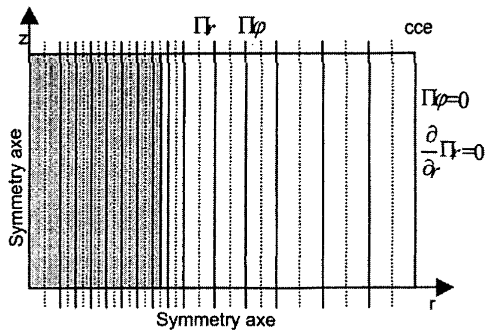

Fig. 1. Non-equidistant discretization of a layer.

II Resonator with l Bragg reflectors along the z-axis.

In the single framework of one dimension, a Bragg reflector is λ/4 thick or λ/2 if it's adjacent to metallic wall. For a three dimensional resonator, these values are not exactly correct. In fact, the more general condition of an anti-resonance is required [2]. Furthermore, Bragg reflection only exists if the electric field has transverse character at the dielectric interface.

First we studied the requirement of Bragg reflector along the z-axis (axial) of the structure as shown in Fig. 2 .

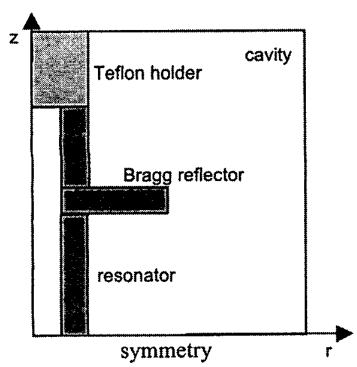

Fig. 2. Sapphire resonator with Bragg reflector along z-axis.

The resonator and Bragg reflectors are made from sapphire, and the holders are made from Teflon. Teflon has low losses at room temperature. (Table 1) The topology of a ring resonator was used because the Q-factor may be larger and spurious modes may be eliminated.

material	$\varepsilon_\perp$	$\varepsilon_{//}$	tan $_\perp$	tan $_{//}$
sapphire	9.38987	11.57579	8.000E-06	5.000E-06
teflon	2.06	2.06	1.60E-04	1.60E-04
copper	Rs=31,4 mΩ			

Table 1. Material properties of sapphire, Teflon and copper at 290K

Figure 3 shows the $|E|^2$ field in resonator and anti-resonance in Bragg reflector. Energy is more confined inside the dielectric and metallic losses are reduced.

Table 2 presents experimental and theoretical results with the Finite Element Method (FEM). The addition of the Bragg reflector increases the Q-factor by about 30%. The Q-factor is mainly limited by sapphire losses.

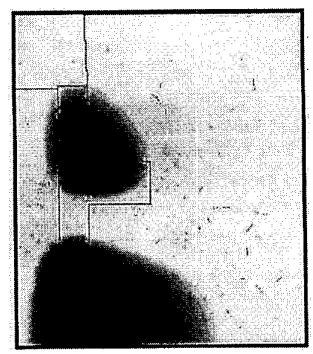

Fig .3. Electric field density of the $TE_{01\gamma}$ mode.

	Freq (GHz)	Q-factor (10^3)
FEM	8.7827	105
measured	8.7926	100

Table 2. Simulated and measured results.

III New resonator design with axial and radial Bragg reflectors.

In order to improve the unloaded Q-factor, we added a additional radial Bragg reflector. We start to calculate optimal dimensions of structure seen in Fig. 4 to improve the Q-factor. When resonance of TE mode's resonator and anti-resonance of reflector is at the same frequency, field of $TE_{01\gamma}$ is pushed away from the reflector (Fig 5). Q-factor in no more limited by dielectric losses of sapphire as most of the field is in empty space. For this structure, we can get dielectric Q-factor about 470000. Q-factor is limited by metallic losses.

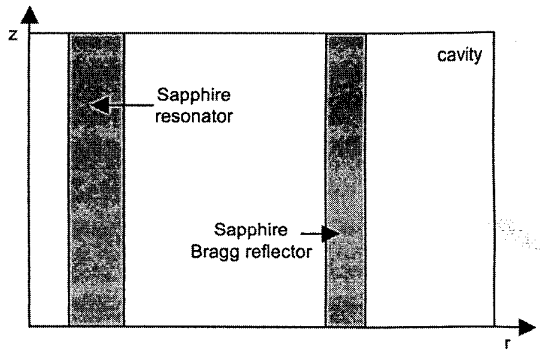

Fig .4. Sapphire resonator with sideways Bragg reflector

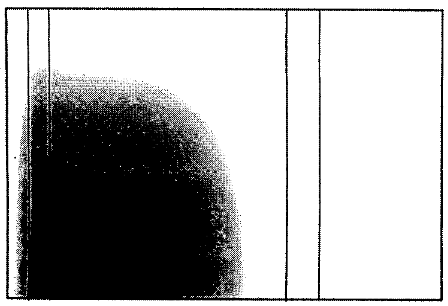

Fig .5. Electric field density of the $TE_{01\gamma}$ mode.

Then an association of axial and radial Bragg reflectors with ring resonator is realized as shown Fig 6. Because of a lot of degree of freedom, this structure could be difficult to optimize to work at 9 GHz. But with Method of lines, a program can be realized to adjust the thick of resonator (LR) and to keep frequency equal at the designed value.

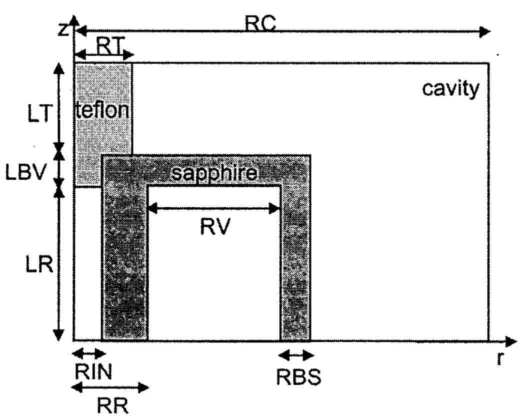

Fig .6. Sapphire resonator with vertical and sideways Bragg reflector.

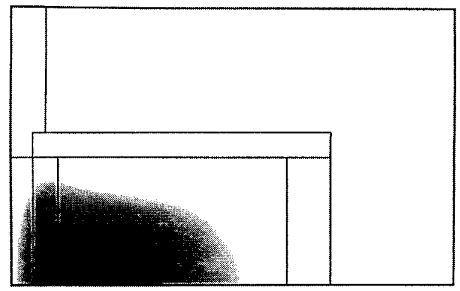

Fig .7. Electric field density of the $TE_{01\gamma}$ mode.

Scale diagram is shown in Fig 7 along with the electric density field plot. It's evident with this plot that much of electric field is confined in the vaccum inside sapphire structure and we can see anti-resonance in axial and radial Bragg reflectors. We obtain a Q-factor about 195000 for the dimensions given in Table 3.

RIN	RR	RV	RBS	RC	RT	LR	LBV	LT
2	3.9	17.2	3.2	33.6	3	14.51	2.7	13.5

Table 3. Dimensions for the optimal structure in mm.

We present in the Table 4 results of Method of Lines (MOL) and by Finite Element Method (FEM).

	Freq (GHz)	Q0 (10^3)	QDIEL (10^3)	Q copper (10^3)
MOL	9.000	194	243	966
FEM	9.001	195	245	973

Table 4. Results for optimal structure.

V. CONCLUSION

New design of dielectric resonator has been presented. Bragg reflector has used to confine energy in the vaccum between resonator and Bragg reflector in the order to decrease metallic losses and to increase dielectric Q-factor. A unloaded Q-factor of 195000 can be obtained with this structure. The Method of Lines permits to optimize dimensions for a frequency of 9Ghz with less computational effort.

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