High-Q Cylindrical Alumina Resonator Based on Bragg Confined Mode of Azimuthal Mode Number Greater Than Zero

J.-M. Le Floch[1,2], M.E.Tobar[1], D. Mouneyrac[1,2], D. Cros[2], J. Krupka[3]

[1] School of Physics, University of Western Australia, 35 Stirling Hwy, Crawley, WA, 6009

[2] XLIM - UMR CNRS n°6172 - Faculté des Sciences et Techniques - 123, avenue A. Thomas, 87060 Limoges Cedex, France

[3] Institute of Microelectronics and Optoelectronics, University of Technology, Koszykowa 75, Warsaw, Poland

***Abstract*— The author's report on the observation of a new type of Bragg confined mode in a dielectric loaded cavity. The structure is built from a hollow single layer dielectric cylinder loaded in a silver platted copper cavity. A resonance was observed at 13.4 GHz with an unloaded Q-factor of order 2×10^5, which is more than a factor of 6 above the dielectric loss limit. Previously such modes have only been realized from pure Transverse Electric modes with no azimuthal variations and only the E component. From simulations using a rigorous numeric technique it is shown that the mode has non-zero azimuthal variations and with dominant E_r and E electric field components and H_Z magnetic field component.**

I. Introduction

Low noise oscillators require high-Q resonators for low phase noise and high stability. The Q-factor of a standard dielectric resonator is usually limited by the dielectric loss-tangent of the material. One way of beating the loss-tangent limit is by building a layered structure that confines the mode mainly in the central air region through Bragg reflection. In the past this has solely been achieved with $TE_{m,n,p}$ modes of azimuthal mode number m = 0 in cylindrical resonators[1-6] (n is the radial mode number and p the axial). This is because the mode has only an E electric field that remains tangential to both the radial and axial surfaces, which is a requirement of Bragg reflection. In this work we show the discovery of new modes of m > 0, which also maintain Bragg confinement in hollow cylindrical structures. The modes are hybrid (all field components), However, the dominant fields for these modes are E_r , E and H_z and Bragg reflection is allowed as the radial component of the Electric field exists near the central region of the resonator and supplies a tangential boundary condition to the axial Bragg reflectors. In contrast the azimuthal electric field exists mainly at all boundaries of the Bragg reflectors and Bragg confinement of the mode is also achieved in the radial direction.

A hollow alumina cylinder of height 49.94 mm and diameter 65.6 mm was manufactured and supported by Teflon spaces in a cylindrical metallic cavity (see figure 1). The m = 1 mode was measured to have a frequency of 13.4 GHz with a Q-factor of order $2x10^{-5}$, which is more than 6 times the dielectric loss limit, in a single layer structure. In contrast single layered cylindrical structures using the lowest order fundamental m = 0 modes have only achieve about a factor of 2[6-8]. The field structure and properties were verified using Method of Lines. This result is greater than a high-Q sapphire Whispering Gallery mode resonator at room temperature, but achieved using a cheaper material, with the potential of constructing equivalent state-of-the-art low noise oscillators.

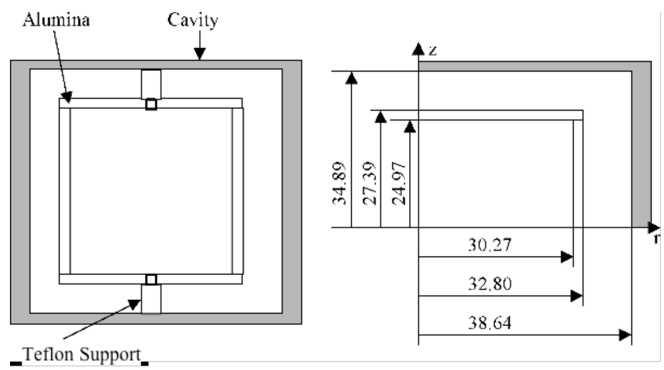

Figure 1. Left: Schematic of the cavity showing the hollow cylindrical Alumina structure supported by Teflon posts loaded inside a silver plated copper cavity. Right: Top right quadrant of the structure, showing dimensions

II. Characterization of the Alumina

To characterize the dielectric properties of the alumina we use the whispering gallery mode method[9-11]. Modes are simulated using Method of Lines (MoL) software[12] to predict the frequency, geometric factor and filling factor of the fundamental WGH mode family. Simulations are compared with measurements in order to estimate the loss tangent and the permittivity of the alumina sample. Results are given in table 1 and figure 2.

To calculate the loss tangent as a function of frequency, the results in table I are combined with equation (1) and plotted in figure 2 (note the filling factor in Teflon is very small and can be ignored).

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$$\tan\delta = \frac{Q_{meas}^{-1} - R_S/G}{Pe} \qquad (1)$$

Hear *Rs* is the cavity surface resistance, which was determined to be $R_S = 0.0085\sqrt{f[GHz]}$ from the Q-factor of the $TE_{0,1,1}$ mode in the empty cavity. The calculation in (1) is only accurate when $Q^{-1} > Rs/G$, which is the case in figure 2 when $f < 10$ GHz. Above 10 GHz the usual frequency dependence of the loss tangent is measured, and determined to be $2.4\text{x}10^{-6} f$.

TABLE I. CHARACTERISTICS OF THE $WGH_{M,0,0}$ MODE FAMILY (M IS THE AZIMUTHAL MODE NUMBER), INCLUDING MEASURED AND CALCULATED FREQUENCY [GHZ], MEASURED Q-FACTOR, AND CALCULATED ELECTRIC ENERGY FILLING FACTOR *PE*, AND G-FACTOR, *G*. THE PERMITTIVITY IS ESTIMATED TO BE 9.73 TO ALLOW AGREEMENT WITH THE CALCULATED AND MEASURED FREQUENCIES, THE MATERIAL LOSS TANGENT IS CALCULATED USING EQUATION (1) AND SHOWN IN FIGURE 2

m	f meas	Q meas	f MoL	Pe MoL	G
9	7.881	4.33×10^4	7.877	0.880	1.31×10^3
10	8.384	4.81×10^4	8.376	0.889	1.76×10^3
11	8.877	5.02×10^4	8.873	0.898	2.38×10^3
12	9.379	4.94×10^4	9.368	0.906	3.23×10^3
13	9.860	4.32×10^4	9.861	0.913	4.40×10^3
14	10.357	3.60×10^4	10.352	0.919	6.00×10^3
15	10.839	3.60×10^4	10.840	0.925	8.20×10^3
16	11.328	3.40×10^4	11.325	0.931	1.12×10^4
17	11.801	3.00×10^4	11.808	0.936	1.54×10^4
18	12.320	2.80×10^4	12.289	0.940	2.12×10^4
19	---	---	12.767	0.945	2.91×10^4
20	13.248	3.00×10^4	13.244	0.949	4.01×10^4
21	13.715	2.70×10^4	13.718	0.952	5.52×10^4

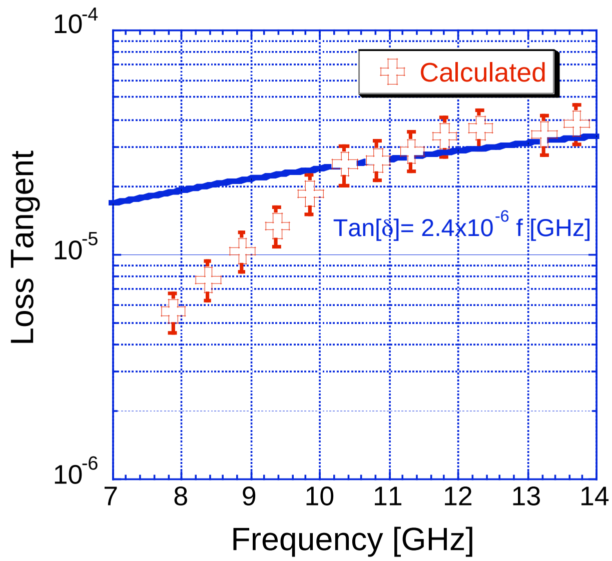

Figure 2. Calculated and fitted loss tangent from the results presented in table 1, and the calculation from (1). The calculation is only accurate above 10 GHz when $Q^{-1} > Rs/G$. Typically in this regime unloade Q-factor measurements are of order 20% accurate, which is reflected in the error bars.

III. HIGHER ORDER BRAGG MODES

Several confined higher order Bragg modes were measured in the structure with Q-factors of order 10^5 or larger. Modes were identified after the successful permittivity and loss-tangent characterization and results are shown in figure 3 and 4. In previous work only Bragg confined modes of $m = 0$ have been characterized, and here we unequivocally identify Bragg confined modes of azimuthal mode number $m > 0$.

The highest Q-factors are measured for the 11.34 ($Q = 2.25\ 10^5$) and 13.40 ($Q = 1.91\ 10^5$) GHz modes. Given that we measured the loss tangent of the alumina to be $Tan\delta_{Alumina}=2.4\times10^{-6}f$ [GHz] both modes are a factor of 6.1 above the dielectric loss limit. We may also compare the results to a sapphire whispering gallery WGH mode. Given that the loss tangent parallel to the c-axis is $Tan\delta_{Sapphire} = 4.2\times10^{-7}f^{1.09}$ [GHz][13] the 11.34 and 13.4 GHz modes have Q-factors of 1.3 and 1.4 times greater than sapphire WGH modes respectively.

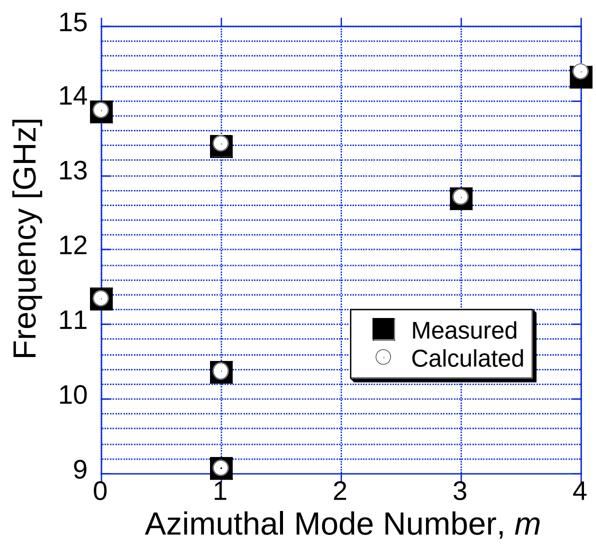

Figure 3. . Calculated and measured frequencies of some higher order confined Bragg modes.

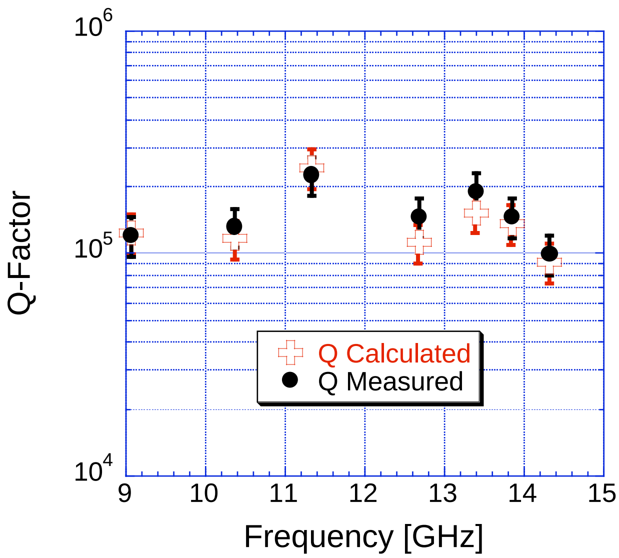

Figure 4. Figure 4. Measured and calculated unloaded Q-factors of the Bragg modes in figure 3. The measurement is made in by measuring the bandwidth in transmission in the low coupling regime, see figure 6, for example. Typically this types of measurement are about 20% accurate.

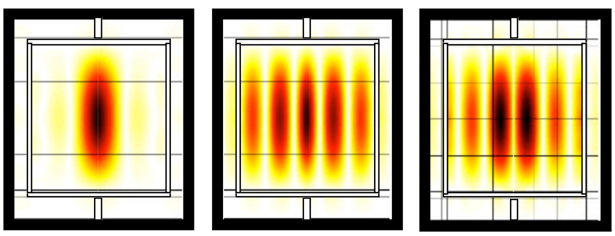

Figure 5. Density plot (modulus squared) of the dominant electric and magnetic field components for the 13.4 GHz mode of m = 1 as calculated using the Method of Lines [12] (see table I for filling factors). The hollow alumina cylinder is outlined (along with the Teflon supports), which confines the field in the internal free space region.

IV. Conclusion

We have shown for the first time the existence of a new type of Bragg mode with greater than zero azimuthal variations in a hollow ceramic Alumina structure. Higher order Bragg modes were measured with a Q-factor of 30 to 40% greater to that of sapphire WGH modes, and with a factor of 6.1 above the dielectric loss limit of the alumina dielectric.

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