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Whispering gallery modes in hollow spherical dielectric resonators

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Abstract

Whispering gallery modes have been used for precise measurements of dielectric losses in hollow spherical samples of single crystal quartz versus single crystal YAG at frequency range from 10 to 40 GHz. It has been shown that for single crystal YAG the product of frequency times Q-factor due to dielectric losses is almost constants, while for single crystal quartz dielectric loss tangent increases much slower than linearly.

Keywords: Dielectric properties; Spherical dielectric resonators

Continuous search for new high Q microwave materials and components is one of the main aims of materials science and technology. Only recently the authors have constructed a simple single-shell spherical dielectric Bragg resonator,[1] shown in Fig. 1, that exhibits Q-factor higher then 100,000 at frequency about 26 GHz.

At millimeter wave frequencies such structures may substitute traditional pill-box dielectric resonators. In this paper, we present theory and applications of TE_{nm1} whispering gallery modes in open and shielded hollow spherical dielectric resonators. We have employed these modes for characterization of dielectric properties of hemispherical dielectric shells made of low loss dielectrics that can be further used for construction of Bragg reflection spherical dielectric resonators. In general, Q-factor of a specific mode of the resonant structure shown in Fig. 1 depends either on conductor and dielectric losses for close structure or radiation and dielectric losses for open structure. Let us first consider the structure fully enclosed by a metal shield. In such a case, radiation losses can be neglected and its Q-factors for a specific mode can be expressed in terms of material properties (tan δ and the surface resistance Rs), electric energy filling factor and geometric factor.[2] For the structure shown in Fig. 1, geometric factor and electric energy filling factor can be rigorously evaluated, as it has been described in,[1] for both TE_{n0p} and TM_{n0p} mode families. With increasing mode index "n", geometric factor values increase and losses in metal enclosure

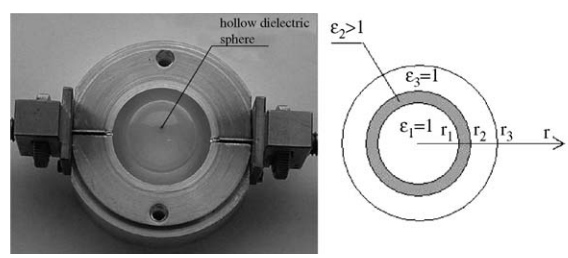

Fig. 1. Hollow spherical dielectric resonator.

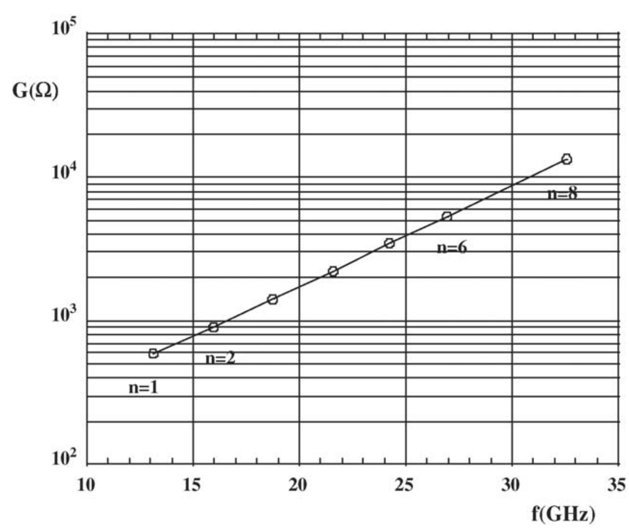

Fig. 2. Geometric factor vs. frequency for subsequent TE_{n01} modes in spherical resonator made of single crystal quartz. $r_1 = 7.74$ mm, $r_2 = 9.03$ mm, $r_3 = 12.02$ mm, $\varepsilon_\perp = 4.44$.

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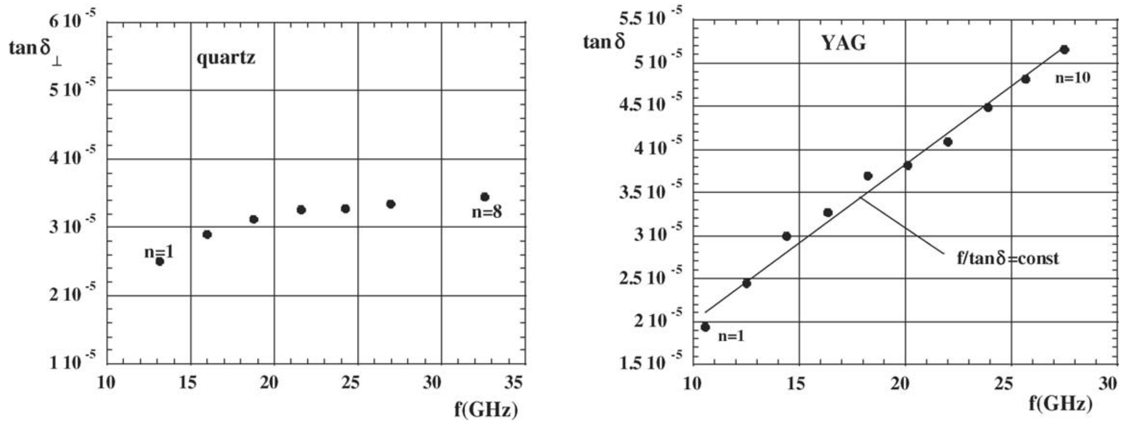

Fig. 3. Dielectric loss tangent of spherical samples made of single crystal quartz: $r_1 = 7.74$ mm, $r_2 = 9.03$ mm, $\varepsilon_\perp = 4.44$, and single crystal YAG: $r_1 = 8.1$ mm, $r_2 = 9.02$ mm, $\varepsilon = 10.6$, vs. frequency.

decrease as shown in Fig. 2. So their utilization allows accurate measurement of dielectric losses and thermal coefficient of resonant frequency of hemispherical dielectric shells. Results in Fig. 2 are shown for the modes with mode indices "n" up to 8 but for higher order modes geometric factor values further increase. One can notice that for $n = 8$, geometric value is equal to 1.3×10^4 Ω while surface resistance of silver at 33 GHz is equal to 54.5 mΩ resulting in a Q-factor value due to conductor losses equal to 220,000. Dielectric losses of quartz at this frequency are about 3.5×10^{-5}; therefore, the dielectric losses are about seven times larger than those of the conductor. As one can extrapolate form Fig. 2, for higher order modes conductor losses can be entirely neglected and dielectric loss tangent uncertainty becomes essentially the same as the unloaded Q-factor measurement uncertainty.

Results of measurements of dielectric loss tangent versus frequency for hollow spheres made of single crystal quartz and single crystal YAG are shown in Fig. 3. One can observe that for single crystal YAG, the assumption that the product of frequency times Q-factor is constant is well satisfied, while for single crystal quartz, dielectric loss tangent increases much slower than linearly. In fact, single crystal quartz and some low loss plastics like polyethylene or teflon are one of few exceptions from the rule that is valid for most ceramic materials and many single crystals. Low losses in single crystal quartz have been already measured by many researchers including,[3,4] but theoretical explanation of such a behavior would require rigorous studies of losses in complicate single crystal quartz structure.

For higher permittivity materials such as YAG or sapphire whispering gallery modes can be used to measure dielectric properties of hollow spheres in open space because radiation losses drastically decrease with increasing mode index "n". This can be seen in Fig. 4 where results of Q-factor measurements of semi-open hollow YAG sphere are shown. In this figure results of theoretical Q-factor evaluations due to radiation are also presented. It is seen that at frequency 29 GHz (mode index $n = 11$) Q-factor due to radiation losses is more that one order of magnitude larger than Q-factor due to dielectric losses. Therefore at millimeter wave frequencies whispering gallery modes with large indices can be effectively used for measurements of dielectric properties of hollow dielectric spheres.

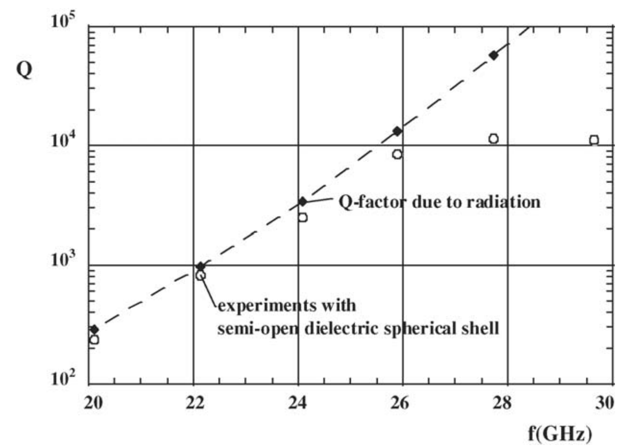

Fig. 4. Q-factor of open hollow spherical resonator made of single crystal YAG vs. frequency. Size of dielectric is the same as in Fig. 3.

Results of our experiments have shown that whispering gallery modes excited in hollow spherical samples can be used for very accurate measurements of dielectric losses versus frequency.

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