

Q-Factor of Microstrip WGM Resonators Based on YBaCuO and Normal Metal Films

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Abstract— The paper analyzes the dissipative properties of microstrip (planar) whispering gallery mode (WGM) resonators by comparing the Q-factors of resonators based on both HTS and normal metal films. The analysis was performed in the frequency range from 1.5 GHz to 40 GHz. By using numerical simulation of partial Q-factors it is shown that the value of the total (eigen) Q-factor at a temperature of 77 K for the microstrip WGM $\text{YBa}_2\text{Cu}_3\text{O}_{7.8}$ - based resonator exceeds the Q-factor value obtained for the similar copper-based resonator in the entire frequency range under study. This superiority is about 2 orders of magnitude at 1.5 GHz and about 5 times at 40 GHz.

Keywords—High-temperature superconductor, normal metal, thin film, dielectric substrate, frequency spectrum, radiation losses, eigen Q-factor.

I. INTRODUCTION. MOTIVATION

Whispering gallery mode (WGM) dielectric resonators are actively used in a very wide frequency spectrum of electromagnetic waves, namely, from microwaves (see e.g. [1]–[2]) to optical waves (see e.g. [3]–[4]). WGM resonators have remarkable electrodynamic properties, such as the highest Q-factor, acceptable dimensions in the millimeter wave range, and ease of control of the coupling between the transmission line and the resonator [1]. Therefore they are used as highly sensitive sensors for material characterization [5]–[6] and in low phase-noise oscillators [7]–[8]. However, they also have disadvantages: their frequency spectrum is very complex, and mode interaction occurs very often; in some cases, the twofold degeneracy of the whispering gallery wave is removed, which complicates the practical use of the resonators. The fundamental disadvantage of these resonators is their incompatibility with planar technology. To overcome this emphasized shortcoming, a planar modification of the WGM resonator was proposed [9]. Whispering gallery modes were excited in a new type of microstrip circular resonator under a conducting disc placed directly on or above a continuous dielectric layer. The well-known WGM excitation condition was generalized to the case of a curved virtual interface formed between two regions with different effective permittivities in a single

dielectric medium. Q-factor of such a resonator is determined by conductor losses.

To further increase Q-factor of this type of resonator, HTS films, which allow reducing microwave losses [10]–[11] can be used. However, in [9]–[11] there was no consistent analysis of the quality factor of the proposed resonators.

In this paper, the results of the consistent analysis of the microstrip WGM resonators based on films of normal metals and HTS depending on the frequency of the microwave field are reported.

II. SIMULATION APPROACHES

The investigated microstrip resonator is a conductive disk (1) with a thickness of h_c on a dielectric layer (2) with a thickness of h_d (Fig. 1). The conductor is a superconductor or a normal metal. Simulation studies of the structure were performed using the resonator model created in the Radiofrequency module of the Comsol Multiphysics program. The model allows us to obtain eigen values of both frequency and Q factor of the resonator. The research was performed in a wide range of frequencies (from 1.57 to 42 GHz). Changing the frequency was achieved by changing the radius R_{res} of the conductive film, which corresponds to the

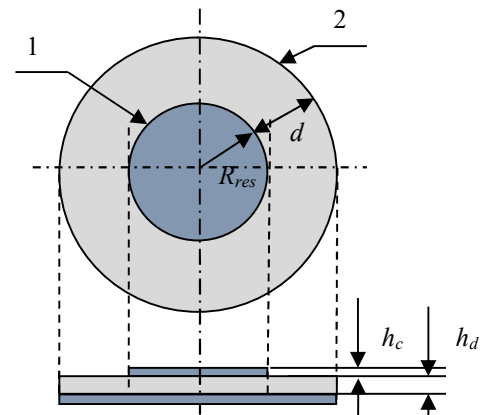


Fig. 1. Schematic representation of a microstrip WGM resonator

radius of the resonator, from 5 to 30 mm (Fig. 1). The distance d between the edges of the conductive disk and the dielectric substrate was chosen in such a way that the edge of the dielectric did not affect the intrinsic characteristics of the structure. Preliminary calculations showed that it is enough to use $d = 3$ mm. A single crystal layer of MgO or Al_2O_3 with a thickness of $h_d = 0.5$ mm was used as a dielectric substrate. In numerical studies, the thickness h_c of the conductive disk was chosen equal to 0.034 mm. The dielectric layer on the opposite side was also covered with a conductive film.

To simulate the free space around the resonator, the boundary condition Scattering conditions (1) are used in combination with Perfectly matched layers (2) (Fig.2). This combination is used in the Radiofrequency module to model the boundary of the region through which an electromagnetic wave passes without reflection. The inner edge of the matching layer is placed more than 20 mm from the edge of the resonator structure (3) to minimize the influence of the border on the characteristics of the resonator.

In fact, such a resonator is a quasi-optical structure, because at least along one of the coordinate axes (in this case, in the azimuthal direction) we have a geometric size of the resonator equal to several wavelengths. Whispering gallery modes can be excited in the dielectric under the conductor disk or film [9]. Therefore, such a resonator is called a microstrip quasi-optical resonator (MQR) or a microstrip WGM resonator.

Fig. 3 shows the field distribution of the $\text{HE}_{12,1,1}$ = $\text{HE}_{12,1,1}$ whispering gallery mode in the microstrip resonator.

The azimuthal $n = 12$ and radial $m = 1$ indices reflect the number of wavelengths along the perimeter of the conducting disk and the number of field variations in the radial direction, respectively [1]. In the axial direction, the field is uniform (Fig. 3(c)), so the axial index $s = 0$.

III. Q-FACTOR OF MICRSTRIP WGM RESONATORS

The intrinsic (eigen) quality factor of the microstrip WGM resonator can be expressed by the following well-known relation [12]:

$$Q_0^{-1} = Q_d^{-1} + Q_c^{-1} + Q_{rad}^{-1}, \quad (1)$$

where $Q_d = k \tan\delta$ is the partial Q-factor associated with losses in the dielectric; k is the dielectric inclusion factor; $\tan\delta$ is the dielectric loss tangent; $Q_c^{-1} = A_s R_s$ is the partial Q-factor associated with losses in the conductor, A_s is the inclusion factor (factor of interaction with the microwave field) of the conductor;

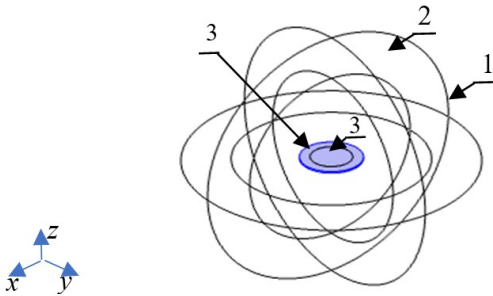


Fig. 2. Model of a microstrip resonator made in the Comsol Multiphysics program [13].

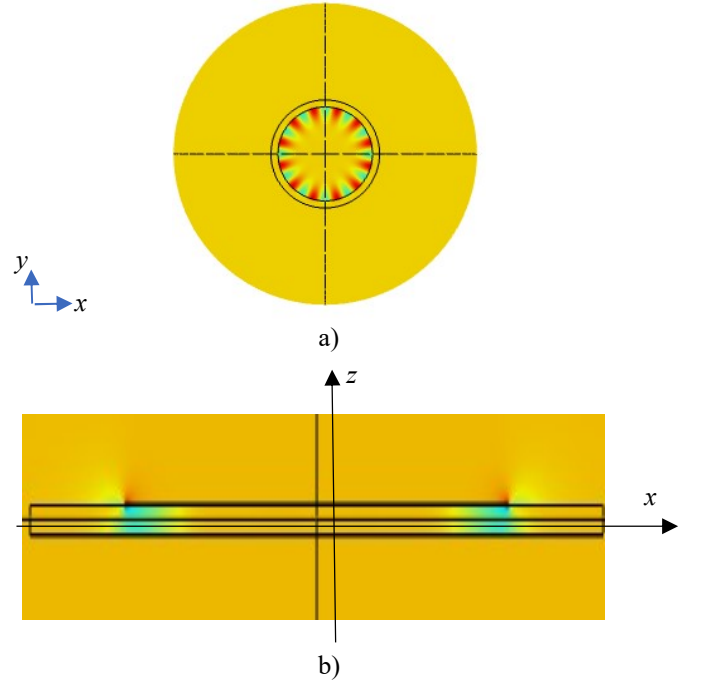


Fig. 3. Distribution of $\text{HE}_{12,1,1}$ mode field in a microstrip resonator with a radius $R_{res} = 20$ mm (a) and a cross-section of the resonator in the axial direction (b).

R_s is the surface resistance of the conductor; Q_{rad} is the radiation partial Q-factor of the resonator and Q_0 is the intrinsic quality factor. Using the Comsol Multiphysics model of microstrip WGM resonator (see Section II), one can obtain the Q_{rad} , as well as the coefficients k and A_s (Fig. 4, 5). To obtain the radiation Q-factor, the model uses an ideal dielectric $\tan\delta = 0$ and an ideal conductor $R_s = 0$. To obtain the dielectric inclusion coefficient, the model uses a dielectric substrate with an arbitrary value of $\tan\delta$, which is close to $\tan\delta$ of MgO single crystal, an ideal conductor ($R_s=0$), and the previously calculated value Q_{rad} . A dielectric with an arbitrary value of $\tan\delta$, a conductor with an arbitrary value of R_s , and a previously calculated value of Q_{rad} are

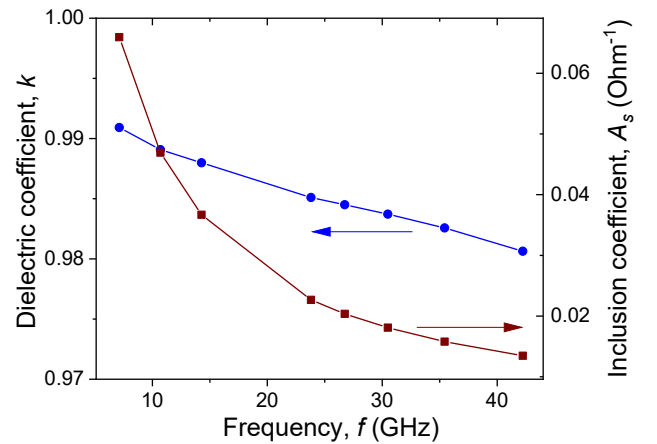


Fig. 4. The dielectric inclusion factor k and the conductor inclusion factor A_s of the microstrip WGM resonator as a function of the resonant frequency f .

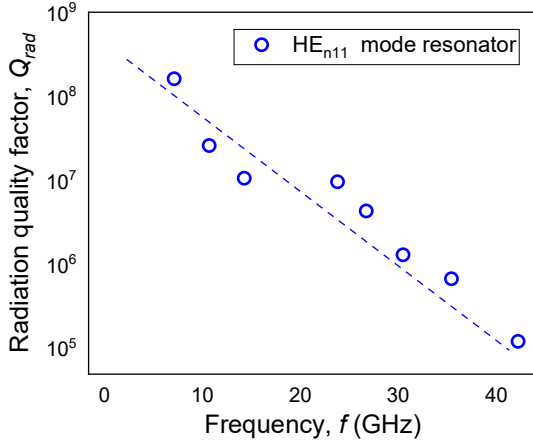


Fig. 5. The radiation factor Q_{rad} of the microstrip WGM resonator as a function of the resonant frequency f .

used to obtain the conductor inclusion factor A_s . One can see from Fig. 4 that the dielectric inclusion coefficient k practically linearly depends on the frequency, its value is close to 1, and its values change insignificantly (several %) over the entire frequency range. The conductor inclusion factor A_s changes much more strongly, by a factor of about 4 over the entire frequency range, which indicates a significant increase with frequency growth. Fig. 5 shows that the radiation Q-factor of the microstrip WGM resonator also changes almost linearly and has high Q-values: $Q > 10^5$ even at a frequency of 40 GHz, which is the result of the concentration of the EM field mainly under the conducting disk ($k \approx 1$). The high Q-factor of the resonator with the HE_{n11} mode indicates that such a resonator is promising in the microwave frequency range up to 40 GHz [14].

Comparison of the Q-factors of HTS- and normal metal- based microstrip resonators operating at different temperatures on the WGM and the fundamental modes as a function of frequency will be performed in a separate work.

Using the dependences $k(f)$, $A_s(f)$ and $Q_{rad}(f)$ shown in Fig. 4 and 5, as well as the dependences of the surface resistance $R_s(f)$ (Fig. 6) and the dielectric loss tangent $\tan\delta(f)$ (Fig. 7) it is possible to obtain the dependences of the partial Q-factors (Q_d , Q_c , Q_{rad}) on the resonant frequency, which is important for assessing the prospects of a microstrip WGM resonator (with the HE_{n11} mode) for their applications at high frequencies. The dependencies $R_s(f)$ for HTS $YBa_2Cu_3O_{7-\delta}$ were obtained based on $R_s(f) \sim f^2$ and data from [15], for copper those were obtained based on $R_s(f) \sim f^{1/2}$ and the tabulated conductivity values. The dependencies $\tan\delta(f)$ for dielectric substrate were obtained based on $R_s(f) \sim f$ and data from [16].

Dependencies of the partial Q-factors of the microstrip WGM resonator on the resonant frequency are shown in Fig. 8.

The calculations were performed for a resonator in which both HTS as a conductor and sapphire as a dielectric substrate operate at $T=77K$.

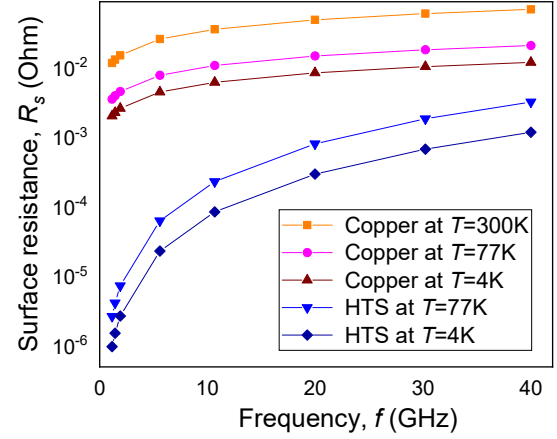


Fig. 6. Surface resistance R_s microstrip WGM resonator versus resonant frequency f .

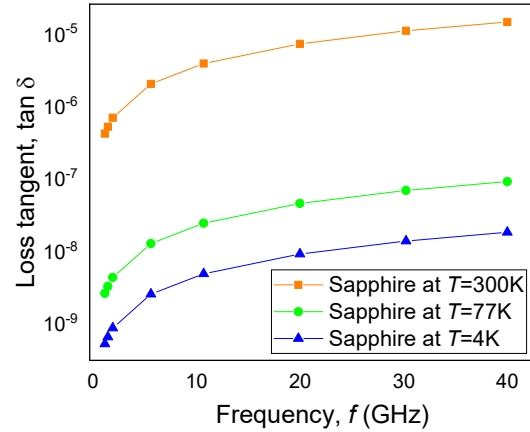


Fig. 7. Loss tangent $\tan\delta$ of the dielectric substrate as a function of resonant frequency f .

One can see from Fig. 8 that Q_d and Q_{rad} are much higher than Q_c , and $Q_0 \approx Q_c$, which indicates that the main losses are concentrated in the HTS film over the entire frequency range.

Comparison of Q-factor of HTS microstrip WGM resonator versus resonant frequency using different conductive materials at different temperatures (Fig.9) shows that Q-factors of HTS resonator are higher than Q-factors of the copper resonator at both temperatures: $T=77K$ and $T=4K$.

The use of HTS at $T=4K$ allows for increasing Q-factor of the resonator by about 2 times compared to the use of HTS at $T=77K$. Q-factor values reach $Q_0=350000$ ($f=1.5GHz$) and $Q_0=50000$ ($f=40GHz$).

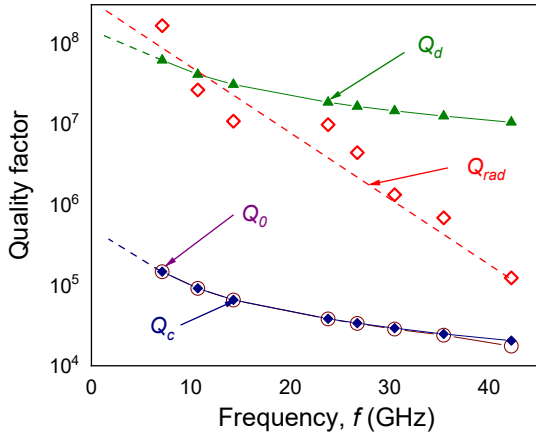


Fig. 8. Partial Q-factors of HTS microstrip WGM resonator versus resonant frequency f .

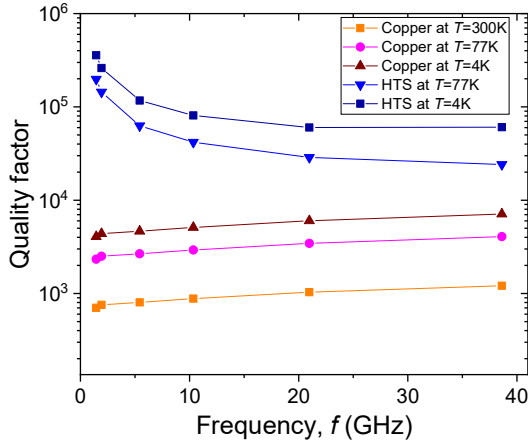


Fig. 9. HTS microstrip WGM resonator Q-factor versus resonant frequency using different conductive materials (HTS and copper) obtained for different temperatures.

IV. CONCLUSION

The paper analyzes the dissipative properties of microstrip (planar) resonators with whispering gallery modes (WGMs). These resonators use a virtual boundary between regions of a dielectric substrate with different values of effective permittivity. This boundary is formed under the circular disk of the conductor (high- T_c superconductor or normal metal) on the surface of the substrate. The analysis was performed by comparison of the Q-factors of resonators designed on the basis of HTS films and normal metals in the frequency range from 1.5 GHz to 40 GHz.

By using numerical simulation of partial Q-factors, it is shown that at a temperature of 77 K the values of the total (eigen) Q-factors of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ -based microstrip WGM resonator exceed those obtained for the similar copper-based resonator in the entire frequency range under study.

The change in superiority with increasing frequency is quantified. This superiority is 2 orders of magnitude at 1.5 GHz and approximately 5 times at 40 GHz.

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