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APPLIED RADIO PHYSIC

ESR-Cell Based on Disk Dielectric Resonator with Tunable Marker

A. Girich[1, 2], T. Kalmykova[1], and S. Tarapov[1]

[1]A. Usikov Institute of Radio Physics and Electronics,
National Academy of Sciences of Ukraine
12, Academician Proskura St., Kharkiv 61085, Ukraine
[2]Kharkov National University of Radio Engineering and Electronics,
14, Lenin Ave, Kharkiv, 61166, Ukraine

ABSTRACT: The technique of detecting the Electron Spin Resonance (ESR) response separately from the magnetic specimen under study and for the ESR-marker placed into the resonator without destroying its geometrical parameters is offered. The disk dielectric resonator (DDR) is proposed as an adequate resonator cell. The reliability of technique is demonstrated both theoretically and experimentally.

INTRODUCTION

The Electron Spin Resonance (ESR) technique is one of the most informative methods to study extra high frequency features of magnets. Increasing of sensitivity of the method is a regular problem, which demands special electrodynamical researches. The known way to improve the sensitivity of ESR technique is increasing the frequency of experiment. It, in turn, demands the modification of resonator experimental cell containing the specimen under study.

The learning the extra high frequency bands up to 100-150 GHz and more [1,2] started as far back as 30 years ago. The thorough research of two-mirror open resonator structures [3,4] provides a success in this area. Main advantages of such resonators are: the high quality factor $\left((5-7)\cdot 10^3\right)$; the rarefied electrodynamic spectrum (in comparison with volumetric resonators); the possibility of adjustment of coupling the specimen with the resonance field.

However, the impossibility to achieve the quality factor more than 10^4 remains one of most sufficient obstacles for the further development of ESR radiospectroscopy. Quite effective way of the solving the problem seems the application of the Disk Dielectric Resonator (DDR) as the ESR cell [5,6].

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However bringing the specimen into such high quality resonator leads, as a rule, to large perturbation of the resonant field, and as a sequence gives the distortion of the ESR-peak under research. Therefore, to provide the correctness of the experiment one needs to introduce into the resonator a reference specimen (the ESR-marker), i.e., the specimen possessing well-known magnitudes of the resonant frequency and a resonant magnetic field for the calibration. Besides, it is extremely desirable to have possibility to remove such reference specimen before introducing the investigated specimen into resonator in order to diminish the resonator field distortion.

The partial solution of the problem has been suggested in [6]. It was proposed to apply the DDR with the "eigen marker" (namely, the ruby DDR where paramagnetic ions Cr^{+3} play the role of eigen marker) as the ESR cell. Such resonator possesses a number of merits. As the ruby is a well-known material, so the ESR-spectrum of the ruby DDR demonstrates a reference ESR-peaks allowing definition a resonant magnetic field with pinpoint accuracy. Besides, whispering gallery modes (WGM) are excited effectively in such DDR. They provide the quality factor of oscillations in order larger than quality factor of two-mirror open resonator. However, main disadvantage of the ruby DDR is the impossibility to remove the ESR-marker during the ESR-experiment.

The solution of the problem is suggested in the given paper. Namely, the sapphire DDR with paramagnet insert (ESR-marker) has been applied to realize the registration of the ESR-response separately - from the investigated specimen and from the ESR-marker. To provide the correct usage of this technique both experimental and theoretical learning of electrodynamical characteristics of sapphire DDR with insert (ruby, sapphire) and without them have been executed.

COMPUTATIONAL SIMULATION

The main idea of research is the following. It is known [7] that to provide the ESR conditions in the specimen under study it is necessary, that magnetic component of an electromagnetic field $\vec{h}$ should be aligned normally to the vector of permanent magnetic field $\vec{H}_0$ (Fig. 1). Easy to see that the excitation of DDR by the waveguides oriented as it shown in Fig. 1(a) provides the satisfaction of ESR-conditions for any point of DDR in the vicinity of WG mode. However, the excitation way, shown in Fig. 1(b) provides the ESR-conditions ($\vec{h} \perp \vec{H}_0$) only in the crossing region of WG mode and axes of waveguides. Thus it is possible to introduce either the specimen or the ESR-marker into this region while rotating DDR around its symmetry axis. So, it is possible to detect the ESR-response either from the ESR-marker or from the specimen independently.

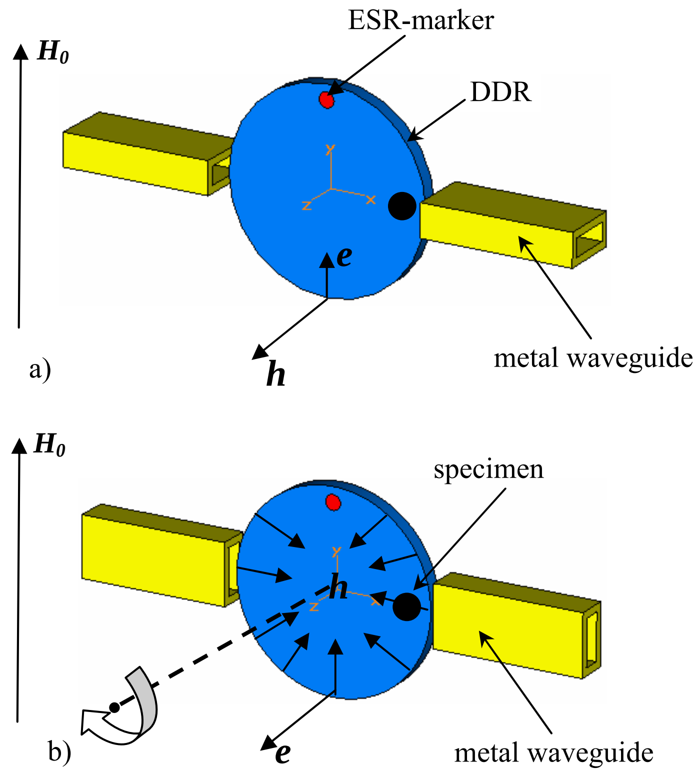

FIGURE 1. Excitation positions: a) the TE orientation DDR (ESR-nontunable case); b) the TM orientation DDR (ESR-tunable case).

In order to verify the efficiency of suggestions above the sapphire DDR (Fig. 1) with the insert, which parameters are given below, has been investigated by the numerical simulation. The object of simulating is the sapphire disk ($\varepsilon = 9.6$), with diameter 26.6 mm and with the ESR-marker-hole in diameter of 2 mm. The hole centre is located on the distance 24.6 mm from the DDR axis. The resonator is exciting by metal hollow waveguides with cross-section 7.2×3.4 mm^2 placed far enough from the disk.

Let us consider such DDR, more detailed. Let us call firstly the case (Fig. 1(a)) as TE orientation ($\vec{h} \perp \vec{H}_0$) and the case (Fig. 1(b)) as TM orientation ($\vec{e} \perp \vec{H}_0$) correspondingly. Now the TE orientation can be called as a "non-tunable ESR orientation" and the TM one as a "tunable ESR orientation". To estimate the influence of the specimen/marker perturbations on the DDR spectra, we calculated of a spectrum of such DDR, for various filling of the ESR-marker-hole, using the method of final differences in time domain (FDTD) with scheme a "Leap Frog".

The result of calculation of a DDR spectrum in frequency area of 25-40 GHz is presented in Fig. 2 for TM (a) and TE (c) -cases. Area marked by rectangle in Fig. 2(a), is presented in details in Fig. 2(b).

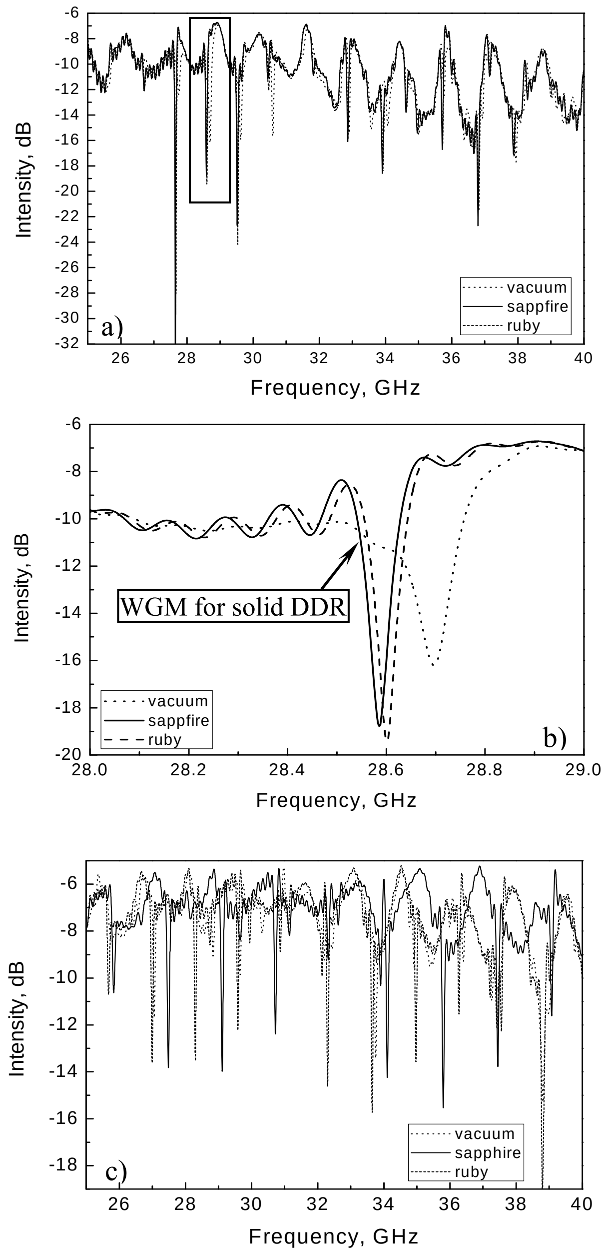

FIGURE 2. Simulation of the frequency spectrum for sapphire DDR with inserts in ESR-marker-hole; a) TM orientation; b) TM orientation (increased); c) TE orientation.

One can see from Fig. 2 that inserts in sapphire DDR affects essentially on the position of the WG-mode for both orientations. Namely, the typical shift of the WG-mode position for TM-case (which, is the most interesting for ESR) is $f = 15$ MHz for sapphire and ruby inserts (Fig. 2(b)) and $f = 110$ MHz for empty hole (the air filling). In order to estimate the influence of the ruby and sapphire inserts and the unfilled hole on the complex losses in the DDR, the quality factors were estimated for main most explicit modes for TE and TM orientations. Most high quality modes are excited in the DDR with a sapphire insert (Q 1900 for TM case and of about Q 650 - for TE case). It is not unexpected fact that the quality factor for non-filled DDR is lowest (approximately of about 300 both for TM and for TE cases).

The visualizations of the spatial distribution for the electric component of electromagnetic field for both TE and TM cases, presented in Fig. 3 allow to watch the formation of typical WG-modes in DDR. Fig. 3(a) describes the TM case ($f = 28.60$ GHz), and Fig. 3(b) - the TE case ($f = 32.30$ GHz).

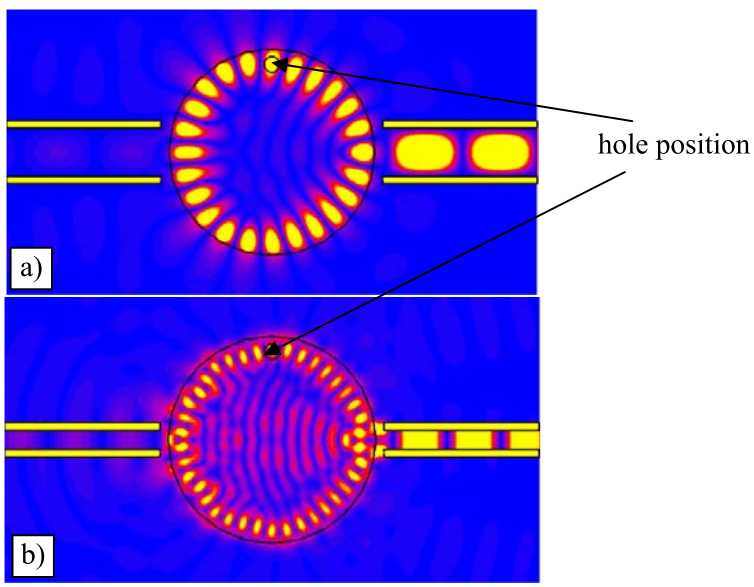

FIGURE 3. Spatial distributions of the electric component of EHF field for TE and TM orientations; a) TM orientation ($f = 28.60$ GHz); b) TE orientation ($f = 32.30$ GHz).

To prove the possibility of ESR process detecting the simulation of the ESR-peak contour for typical reference specimen DPPH (diphenyl-picrylhydrazyl) placed on the DDR surface for TM case has been performed and presented in Fig. 1(b) for WG-mode at $f = 25.60$ GHz. One can see that the ESR-peak obtained has a typical Lorenz-type shape. The resonant magnetic field equals $H_{res} = 9.140$ kOe, the ESR linewidth [7] .

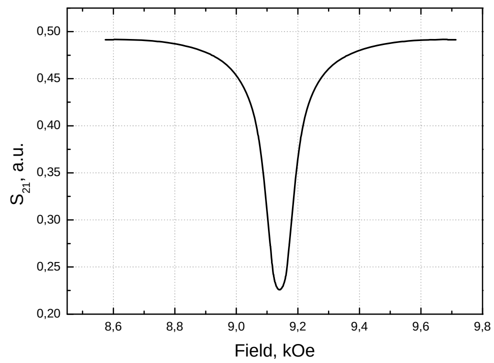

FIGURE 4. Simulation of ESR peak contour of diphenyl-picrylhydrazyl (DPPH) detected by sapphire DDR in ESR-tunable case (TM orientation).

The known formulas [7] describing a Lorenz type dependence permeability ($\dot{\mu}$) and magnetic susceptibility ($\dot{\chi}$) on the static magnetic field were applied for simulating process:

$$\dot{\mu}(H) = 1 + 4\pi\dot{\chi}\,;\ \dot{\chi}(H) = \chi' + i\chi'',$$

$$\chi'(H) \cong \frac{1}{2}\chi_0 \cdot \gamma \cdot H_0 \cdot T_2 \frac{\gamma(H - H_0)T_2}{1 + (H - H_0)^2 T_2^2 \gamma^2},$$

$$\chi''(H) \cong \frac{1}{2}\chi_0 \cdot \gamma \cdot H_0 \cdot T_2 \frac{1}{1 + (H - H_0)^2 T_2^2 \gamma^2},$$

where $\dot{\chi}$ is the magnetic susceptibility; $\dot{\mu}$ is the magnetic permeability; χ_0 is the static magnetic susceptibility; H_0 is the resonant magnetic field; T_2 is the spin-spin relaxation time; γ is the gyromagnetic ratio.

EXPERIMENT

On the basis of computational estimations the sapphire DDR (Fig. 5) with ruby and sapphire inserts has been manufactured. The DDR diameter is 26.6 mm; the thickness of 2 mm; the hole diameter is 2 mm.

The electrodynamical DDR spectra were studied in the frequency band 22-40 GHz (Fig. 6). Research was executed for three configurations, which have been analyzed theoretically:

1) DRY with the unfilled hole, 2) DRY with the sapphire insert, 3) DRY with the ruby insert.

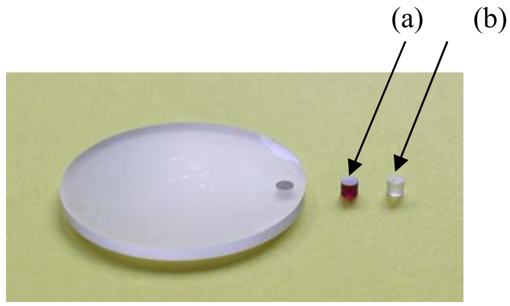

FIGURE 5. The sapphire disk resonator with a hole and inserts: (a)-ruby; (b) - sapphire.

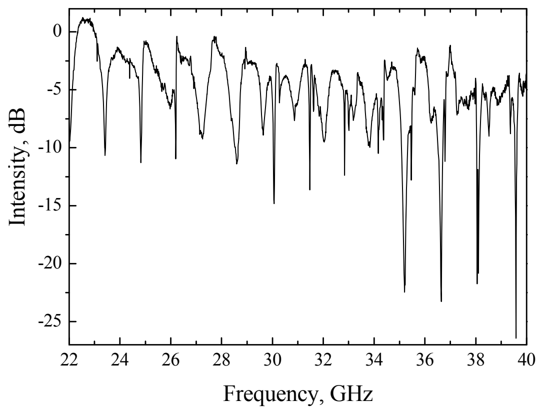

FIGURE 6. Spectrum of DDR mode with the unfilled hole (experiment).

It is easy to see from a typical DDR spectrum (Fig. 6) that the spectrum is quite rarefied. Thus, six most high quality modes (see Table 1, Fig. 7) have been chosen for comparison with calculations. The experimental error does not exceed ±10 % and caused by the DRY- coupling conditions first of all.

It is not unexpected fact that the non-filled hole contributes the largest perturbations into the DRY spectra and the sapphire insert - the smallest ones. However, some important quantitative outcome could be extracted from Table 1 and Fig. 7. Namely, one can see that the hole in DDR reduces the quality factor of WG modes, which are suitable for ESR experiment, about 3 times, whereas the ruby insert - of about 3-10 %. This means that ruby ESR-marker introduces quite small perturbations into the spectrum of DDR.

Table 1.

F, GHz	DDR with unfilled hole		DDR with sapphire insert		DDR with ruby insert	
	Q_{uip}	T_{heory}	Q_{uip}	T_{heory}	Q_{uip}	T_{heory}
26.00	690	700	2010	3550	2100	2720
27.50	320	1760	2170	5730	1480	3440
29.90	520	380	1720	1240	1500	780
31.40	790	550	1420	970	1240	480
32.80	1020	650	1930	870	1600	710
34.20	470	510	1690	680	1820	660

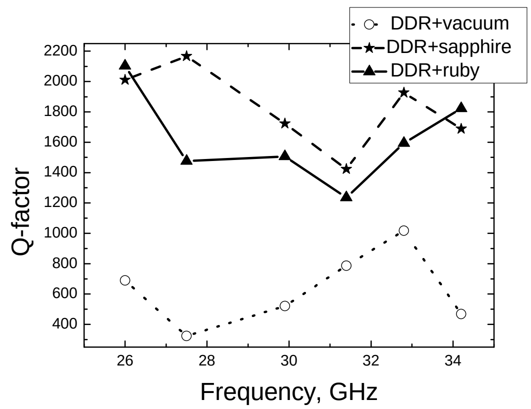

FIGURE 7. Quality factors of WG modes in DDR with various inserts (experiment).

To verify the theoretical estimations we detected experimentally the ESR-peak of reference specimen DPPH used as the ESR-marker in sapphire DDR.

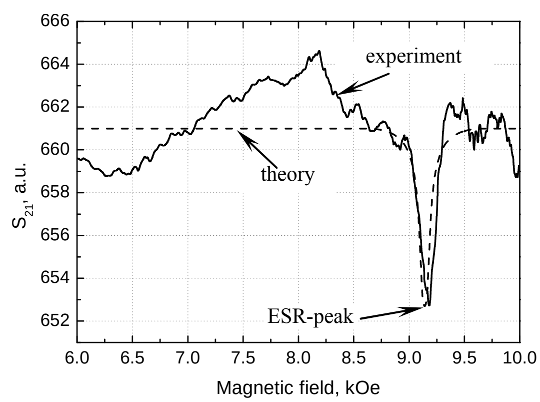

FIGURE 8. The sapphire DDR spectrum of the reference specimen (DPPH).

The experiment (Fig. 8, solid line) was executed for $f_{ESR} = 25.90$ GHz. Here the ESR-peak for DPPH is shown together with the theoretical one (simulated in see Fig. 1). The maximum of ESR-absorption nave been detected at magnetic field $H_{ESR} = 9.18$ kOe. The width of the peak detected is $\Delta H_{1/2} = 160$ Oe. The discrepancy between these experimental data and their theoretical estimations is quite small in the vicinity of the ESR-peak; lies within the imperfection of the theoretical model and confirms the reliability of the technique suggested.

CONCLUSIONS

Thus, the following conclusions should be made on the base of experimental data and theoretical numerical estimations executed:

1) The analysis of spectra and spatial resonance EHF-field distribution for tunable and nontunable ESR orientations has showed the presence of high quality WG modes suitable for ESR studies in DDR spectrum.

2) The influence of various inserts on DDR as on the ESR-cell has been studied and it was shown that the ruby insert contributes quite small perturbation in WG mode. This proves the applicability of the ruby ESR-marker for ESR experiment with DDR resonator.

3) The ESR-peak of DPPH using DDR with a tunable ESR-marker has been detected experimentally and simulated theoretically with high enough coincidence.

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