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Circularly polarized antenna for coherent manipulation of NV-centers in diamond

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Abstract. Dielectric resonator antenna with circular polarization of microwave magnetic field for efficient, coherent and uniform spin manipulation at nitrogen-vacancy centers in diamond is discussed. The results of numerical simulations of the microwave magnetic field generated by the antenna are reported and analyzed. The uniform magnetic field with circular polarization is obtained inside the antenna. Using the simulated amplitude of the magnetic field inside the antenna the Rabi frequency is estimated. The Rabi frequency of 41 MHz with inhomogeneity less then 1 % for the diamond volume of 3 mm^3 is demonstrated under 10 W of input microwave power.

Introduction

Nitrogen-vacancy (NV) center is one of numerous point defects in a diamond with unique properties, which could find a wide range of application in quantum information [1], sensing of magnetic fields [2] and temperature [3] etc. Electron spins in NV-centers, localized at atomic scales, can be manipulated at room temperature by applying a microwave (MW) magnetic field at the frequency of 2.87 GHz. For sensing applications it is highly important to coherently manipulate the spins of NV-centers in relatively high volume of a diamond. Thus the MW antenna producing large and uniform MW magnetic field in a large volume is in a high demand. Moreover, the circular polarization of the magnetic field is useful for addressing different orientations of NV-centers. Several designs of MW antennae and devices with linear and circular polarizations of MW magnetic field have been proposed recently [4–6]. However, they provide high intensity and uniform MW magnetic field over a large area and can be used to coherently manipulate the ensemble of NV-centers only in a plane.

In this paper we propose the design of circularly polarized MW antenna producing uniform MW magnetic field that will be able to coherently manipulate the ensemble of NV-centers in diamond in a volume at the room temperature. We study the antenna performance numerically using CST Suite Studio 2017 and demonstrate that high intensity microwave field can indeed be generated by the antenna. The obtained results of magnetic field simulations are used to estimate mean value and inhomogeneity of the Rabi frequency. We found that the Rabi frequency of 41 MHz with inhomogeneity of less than 1 % for the diamond volume of 3 mm^3 can be achieved under 10 W of input microwave power.

Dielectric Resonant Antenna Design

The dielectric resonator antennae (DRA) are well studied and became a promising candidate for replacing traditional metallic radiating elements at microwave frequencies [7]. This is mainly attributed to the fact that DRAs do not suffer from conduction losses and are characterized by high radiation efficiency. In this study, we consider the DRA which consists of a dielectric hollow cylindrical resonator with two metallic loops, placed in orthogonal planes as demonstrated in Fig. 1 (a). With this type of excitation we are able to excite the $HEM_{11\delta}$ mode of the dielectric resonator [7, 8]. Providing the phase difference between the loops of 90° it is possible to obtain the circular polarization of the MW magnetic field inside the DRA [8, 9]. Here we consider the microwave ceramic with permittivity of $\varepsilon = 520$ and loss tangent of $\tan(\delta) = 0.002$ measured at 3 GHz [10]. To estimate the resonance frequency of $HEM_{11\delta}$ mode [8] of the dielectric resonator as a function of its geometrical parameters we use the equation [8]:

$$f_{HEM_{11\delta}} = 2.735\frac{c\varepsilon^{-0.436}}{2\pi R}\left[0.543 + 0.589\frac{R}{T} - 0.05\left(\frac{R}{T}\right)^2\right], \tag{1}$$

where c is the speed of light, R is the resonator's outter radius, T is the resonator's height, ε is the permittivity of the dielectric material. Figure1 (b) demonstrates the calculated resonance frequency of $HEM_{11\delta}$ mode as a function of resonator's geometrical parameters for the fixed value of the permittivity. The $HEM_{11\delta}$ mode at the frequency of 2.87 GHz exists for the resonator of the height of T = 5 mm and the radius of R = 3 mm.

Results of Numerical Simulation

The numerical simulation of the DRA performances was done in CST Suite Studio 2017. Note, that now we consider the hollow dielectric resonator with the bore radius of 1.6 mm. The hole in the DRA is needed to place a diamond in the maximum of the magnetic field. It is important to mention that the presence of the bore affects the $HEM_{11\delta}$ mode frequency. Thus, a numerical optimization of the resonator's geometrical parameters to adjust the operational frequency to 2.87 GHz has been done. After this optimization the required dielectric resonator's height of T = 5.05 mm and outter radius of R = 2.76 mm have been found. To achieve a good matching of the DRA the position of feeding loops was also optimized. The feeding loops are identical in size, having the radius of 1.5 mm and wire size of 0.25 mm. The ports with 50 Ohm impedances

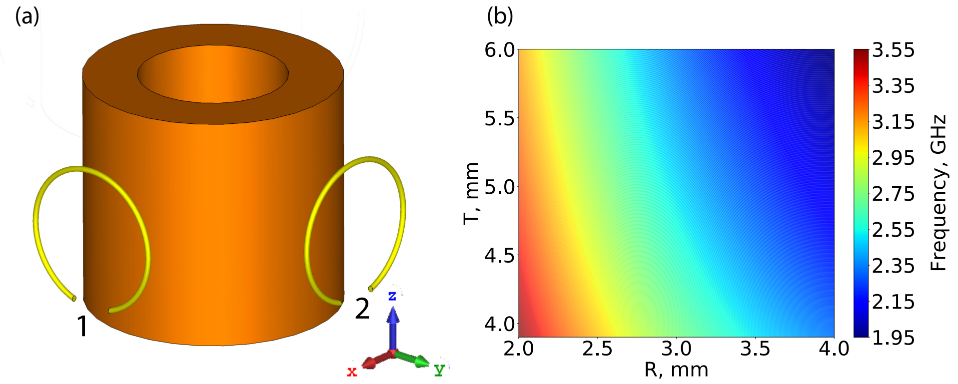

Figure 1. (a) Design of the DRA producing circular polarization of microwave magnetic field; (b) $HEM_{11\delta}$ mode frequency as a function of the resonator's height and radius for the permittivity of $\varepsilon = 520$.

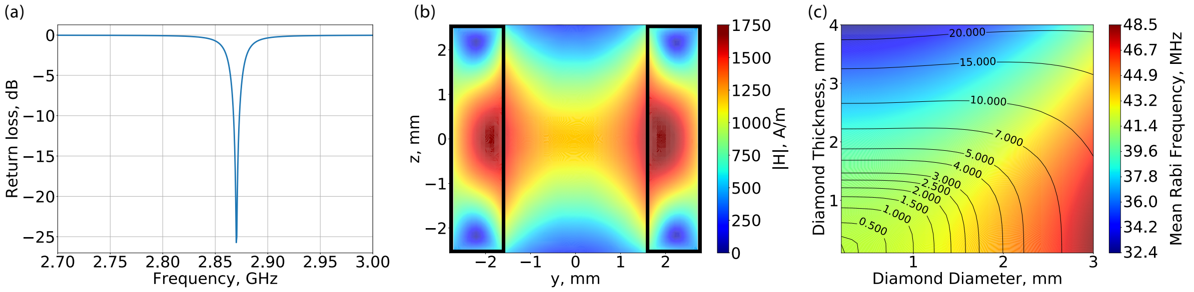

Figure 2. (a) Simulated return loss of the DRA; (b) Simulated distribution of the microwave magnetic field in $y - z$ plane for 10 W of input power; (c) Mean Rabi frequency as a function of the diamond volume (diameter and thickness) calculated by the Eq. (3) for 10 W of input power. The color represents the value of the mean Rabi frequency (MHz). Isolines represent the inhomogeneity (%) of the mean value of the Rabi frequency calculated by the the Eq. (3).

are placed in the 1 mm gap of the loops. The location of the loops at the center of the long axis of the resonator at a distance of 1.1 mm from its surface provides the return loss better than -25 dB at the frequency of 2.87 GHz (see Fig. 2 (a)).

The numerical simulation of the magnetic field of the DRA has been performed for the case when the feeding loops are excited with the 90° phase difference. The input power at each feeding loop was set at 5 W. The simulated magnetic field distribution inside the DRA is shown in Fig. 2(b). One can observe that the magnetic field is mostly concentrated in the dielectric walls of the DRA. The amplitude of the magnetic field reaches 1750 A/m. However, one can find the area in the middle of the bore where the magnetic field is uniform and its amplitude is about 1000 A/m.

To understand the efficiency of the coupling of the microwave magnetic field to the spins of NV-centers one needs to estimate the Rabi oscillation frequency. Normally, this value reaches tens of MHz at the relatively low power level of 5 W [4–6]. In the case of circular polarization of MW magnetic field the Rabi frequency can be calculated as [11]:

$$\Omega = \frac{\mu B}{h}, \tag{2}$$

where B is the amplitude of the magnetic field, h is the Planck constant, μ is the dipole moment. Here we consider the Rabi frequency not in a single point or a plane, but in volume. Thus we propose to calculate the mean Rabi frequency over the volume of a diamond which is placed in the middle of the entire bore of the DRA, where the homogeneous circularly polarized magnetic field is obtained. In this case we use the following equation, where the Rabi frequency is integrated over the diamond volume:

$$\langle \Omega \rangle = \frac{\int_V \Omega dV}{\int_V dV}, \tag{3}$$

where V is the volume of a diamond. To estimate the inhomogeneity of the mean Rabi frequency the standard deviation of its value is calculated as:

$$\sigma = \sqrt{\left(\frac{\int_V \Omega dV}{\int_V dV}\right)^2 - \left(\frac{\int_V \Omega^2 dV}{\int_V dV}\right)}. \tag{4}$$

For simplicity, we suppose that the diamond has a cylindrical shape and characterized by the diameter and thickness. Substituting the amplitude of the magnetic field numerically obtained inside the entire bore of the DRA to the Eq. (2), (3) and (4) and varying the diamond volume (diamond radius changes from 0.01 to 3 mm, diamond thickness changes from 0.01 to 4 mm) we obtain the mean value of the Rabi frequency and its inhomogeneity as demonstrated in Fig. 2 (c). The maximum Rabi frequency of 48.5 MHz with inhomogeneity less than 10% can be achieved for the diamond volume of 28 mm^2 x 1.5 mm. By reducing the diamond volume down to 3 mm^2 x 1 mm the Rabi frequency of 41 MHz with inhomogeneity less than 1% can be obtained.

Conclusion

The design of DRA with circular polarization of microwave magnetic field has been proposed. The antenna return loss and magnetic field distribution have been studied numerically. The obtained results of magnetic field have been used to estimate the mean value and inhomogeneity of the Rabi frequency. Over a diamond volume of 3 mm^3 the predicted value of Rabi frequency of 41 MHz with inhomogeneity of less than 1% can be achieved for 10 W of input power. The DRA prototype is under fabrication. We believe that after the optical examination it can be used for efficient, coherent and uniform spin manipulation of NV-centers in diamond.

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