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3D uniform manipulation of NV centers in diamond using dielectric resonator antenna

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Ensembles of nitrogen-vacancy (NV) color centers in diamond have been the focus of significant interest over the last decade. In particular, many metrological applications have been found, including ultra-precise magnetometers [1–4], biocompatible thermometry [5, 6], electron and nuclear magneto resonance imaging [7–9], electric field sensors [10, 11], and strain sensors [12]. Many of these applications rely on large ensembles of NV centers in a single diamond plate, which make the detector sensitive. For example, with diamond bulk crystals, sensitivity at subpicotesla level in alternating current (AC) regime already have been demonstrated [3].

One of the possible way to improve current NV magnetometers sensitivity is to increase diamond sample size with simultaneous improvement of the microwave (MW) magnetic field uniformity. Different designs of MW antennae and devices have been recently proposed [13–16]. Among them there are several antennae implemented using printed circuit board (PCB) technology. They provide uniform magnetic field in plane giving an opportunity to drive NV centers of planar diamond substrates. However, the magnetic field decays rapidly in perpendicular direction from the surface of the PCB. In this manner the uniform manipulation of NV centers over a volume becomes impossible.

In this paper, a dielectric resonator antenna (DRA) design providing a 3D-uniform MW field in sufficient volume to efficiently excite NV centers in commercially available samples is proposed and studied experimentally. The DRA utilizes a high-permittivity, low-loss dielectric resonator excited by a small coupling loop, as shown in Fig. 1. The current circulating in the loop excites the transverse electric $TE_{01\delta}$ mode of a hollow, cylindrical dielectric resonator. This mode naturally provides a uniform field inside the resonator, while the large quality factor of the resonator enhances MW magnetic field inside the DRA. The entire bore of the dielectric resonator is used to position diamond sample inside.

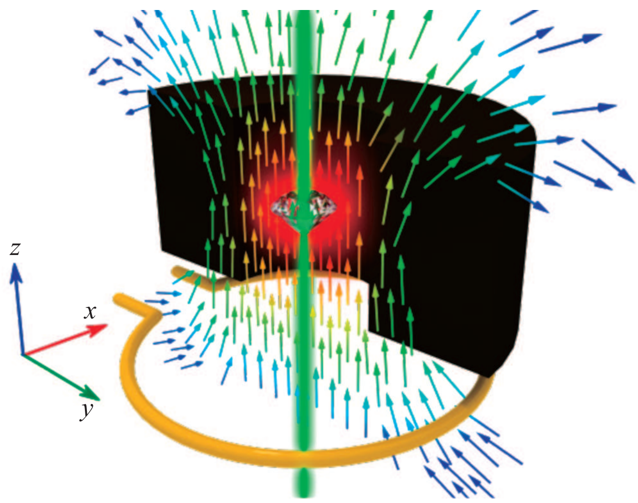

Fig. 1. (Color online) Artist's view of the DRA with a diamond placed in the entire bore

The frequency of the $TE_{01\delta}$ mode is defined by the geometrical size of the dielectric resonator and its permittivity [17–19]. Geometrical parameters of the DRA were numerically optimized with the frequency solver of CST Microwave Studio for a hollow cylindrical dielectric resonator made of $BaLn_2Ti_4O_{12}$, which is characterized at 3 GHz by permittivity $\varepsilon = 80$ and loss tangent $\tan(\delta) = 0.0003$ [18]. For the operational frequency of 2.84 GHz, slightly detuned from zero field splitting of optically detected magnetic resonance (ODMR) of an NV center, the following dimensions of the dielectric res-

[1)] e-mail: p.kapitanova@metalab.ifmo.ru onator were found: an outer diameter 12.5 mm, height 6 mm and bore diameter of 3.2 mm. To provide impedance matching of the resonator and maximum MW magnetic field amplitude inside of the entire bore, the distance between dielectric resonator and excitation loop was varied and the optimal value of 4 mm was found. With respect to the results of numerical simulations the reflection coefficient is better than 0.5 within 30 MHz bandwidth having the minimum at 2.84 GHz. The magnitude of the magnetic field in the middle of the entire bore reaches 132 A/m at 2.84 GHz for input power of 0.5 W.

The practically important value that defines an NV-based sensor's performance is Rabi frequency uniformity. To test the uniformity of the Rabi frequency created by the DRA for selected orientation of an NV center, a bulk diamond sample with a relatively high concentration of NV centers was placed in the middle of the DRA bore and experimentally studied using a home-built scanning microscope [19]. The measured distribution of the Rabi frequency in the radial direction reaches $\Omega = 2\pi \cdot 10\,\mathrm{MHz}$ at 5.2 W feeding power and agree well to the results predicted by the numerical simulations. One should note that the key advantage of this design is the long depth of the MW magnetic field along the DRA axis, which was also confirmed experimentally.

Sometimes it is more convenient to think of field quality in terms of variation of the field in a given volume. Thus, we have calculated the relative average Rabi frequency inhomogeneity from the measured data. The measured standard deviation of the average Rabi frequency over the volume of $7\,\mathrm{mm}^3$ (dimensions $1.7\times\varnothing 2.4\,\mathrm{mm}$) was found to be less than 1 %. Thus large volume ensembles of NV centers could be coherently manipulated without significant cost in the ODMR contrast or service time with the proposed DRA design.

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1. J. M. Taylor, P. Cappellaro, L. Childress, L. Jiang, D. Budker, P. R. Hemmer, A. Yacoby, R. Walsworth, and M. D. Lukin, Nat. Phys. **4**, 810 (2008).
2. M. Grinolds, S. Hong, P. Maletinsky, and L. Luan, Nat. Phys. **9**, 12 (2013).
3. T. Wolf, P. Neumann, K. Nakamura, H. Sumiya, T. Ohshima, J. Isoya, and J. Wrachtrup, Phys. Rev. X **5**, 041001 (2015).
4. H. Clevenson, M. E. Trusheim, T. Schroder, C. Teale, D. Braje, and D. Englund, Nat. Phys. **11**, 393 (2015).
5. I. V. Fedotov, N. A. Safronov, Y. G. Ermakova, M. E. Matlashov, D. A. Sidorov-Biryukov, A. B. Fedotov, V. V. Belousov, and A. M. Zheltikov, Sci. Rep. **5**, 15737 (2015).
6. I. V. Fedotov, L. V. Doronina-Amitonova, A. A. Voronin, A. O. Levchenko, S. A. Zibrov, D. A. Sidorov-Biryukov, A. B. Fedotov, V. L. Velichansky, and A. M. Zheltikov, Sci. Rep. **4**, 5362 (2014).
7. A. O. Sushkov, I. Lovchinsky, N. Chisholm, R. L. Walsworth, H. Park, and M. D. Lukin, Phys. Rev. Lett. **113**, 197601 (2014).
8. M. S. Grinolds, M. Warner, K. De Greve, Y. Dovzhenko, L. Thiel, R. L. Walsworth, S. Hong, P. Maletinsky, and A. Yacoby, Nat. Nanotechnol. **9**, 279 (2014).
9. I. Lovchinsky, A. O. Sushkov, E. Urbach, N. P. de Leon, S. Choi, K. De Greve, R. Evans, R. Gertner, E. Bersin, C. Müller, L. McGuinness, F. Jelezko, R. L. Walsworth, H. Park, and M. D. Lukin, Science **351**, 836 (2016).
10. F. Dolde, H. Fedder, M. W. Doherty, T. Nöbauer, F. Rempp, G. Balasubramanian, T. Wolf, F. Reinhard, L. C. L. Hollenberg, F. Jelezko, and J. Wrachtrup, Nat. Phys. **7**, 459 (2011).
11. E. H. Chen, H. A. Clevenson, K. A. Johnson, L. M. Pham, D. R. Englund, P. R. Hemmer, and D. A. Braje, Phys. Rev. A **95**, 053417 (2017).
12. S. Ali Momenzadeh, F. F. de Oliveira, P. Neumann, D. D. Bhaktavatsala Rao, A. Denisenko, M. Amjadi, Z. Chu, S. Yang, N. B. Manson, M. W. Doherty, and J. Wrachtrup, Phys. Rev. Appl. **6**, 024026 (2016).
13. K. Bayat, J. Choy, M. Farrokh Baroughi, S. Meesala, and M. Loncar, Nano Lett. **14**, 1208 (2014).
14. M. Mrózek, J. Mlynarczyk, D. S. Rudnicki, and W. Gawlik, Appl. Phys. Lett. **107**, 013505 (2015); https://doi.org/10.1063/1.4923252.
15. K. Sasaki, Y. Monnai, S. Saijo, R. Fujita, H. Watanabe, J. Ishi-Hayase, K. M. Itoh, and E. Abe, Rev. Sci. Instrum. **87**, 053904 (2016); https://doi.org/10.1063/1.4952418.
16. J. Herrmann, M. A. Appleton, K. Sasaki, Y. Monnai, T. Teraji, K. M. Itoh, and E. Abe, Appl. Phys. Lett. **109**, 1 (2016).
17. D. M. Pozar, *Microwave Engineering*, 3-rd ed., Wiley, Hoboken, NJ (2005).
18. A. S. Abdellatif, A. Taeb, N. Ranjkesh, E. Gigoyan, E. Nenasheva, S. Safavi-Naeini, S. Gigoyan, E. Nenasheva, and S. Safavi-Naeini, Int. J. Microw. Wirel. Technol. **8**, 33 (2016).
19. V. V. Vorobyov, V. V. Soshenko, S. V. Bolshedvorskii, J. Javadzade, N. Lebedev, A. N. Smolyaninov, V. N. Sorokin, and A. V. Akimov, Eur. Phys. J. D **70**, 269 (2016).