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Microstrip-line resonator with broadband, circularly polarized, uniform microwave field for nitrogen vacancy center ensembles in diamond

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ABSTRACT
We proposed an annular microstrip-line resonator (AMLR) to provide a broadband, circularly polarized and uniform microwave field for state manipulation of negatively charged nitrogen-vacancy (NV\textsuperscript{−}) center ensembles in order to achieve wide magnetic field detection range and large area microwave synchronous manipulation in miniaturized magnetic sensing devices. The bandwidth of the designed AMLR was 410 MHz when the input return losses was -10dB. With the designed bandwidth, a magnetic field detection range of 292 G was achieved based on the NV\textsuperscript{−} center ensembles. The relationship between the direction of the magnetic field and the phase of the source signal indicated that the generated microwave field of AMLR was circularly polarized. Furthermore, the magnetic field magnitude homogeneity is higher than the parallel-microstrip-lines resonator (PMLR) and the intersected-microstrip-lines resonator (IMLR), and the magnetic field magnitude of AMLR had a difference of 0.012 G in the center of a 1×1 mm\textsuperscript{2} area. The AMLR has a great potential in magnetic field detection, temperature and pressure detection, which is useful for quantum applications with NV\textsuperscript{−} center ensembles in diamond.

I. INTRODUCTION

The negatively charged nitrogen-vacancy (NV\textsuperscript{−}) center in diamond consisting of a substitutional nitrogen atom together with an adjacent vacancy\textsuperscript{−} are widely used in quantum information and sensing.\textsuperscript{4,5} The NV\textsuperscript{−} center ensemble is promising for magnetic measuring and temperature measuring devices\textsuperscript{6,7} according to its extraordinary properties, such as long spin coherence time,\textsuperscript{8} visible initialization and read-out\textsuperscript{9} and microwave (MW) manipulation.\textsuperscript{10,11} State manipulation\textsuperscript{12} of the NV\textsuperscript{−} center ensembles through the MW field\textsuperscript{13,14} provides strong technical support for measurement of the magnetic field.\textsuperscript{15,16} However, the manipulation of the spin state relies on an applied bias magnetic field provided by Helmholtz coils in general, which is difficult to reduce the device volume. Aim at this problem, the spin transitions selectively by the circularly polarized MW field takes advantage of polarization selection rules, making the magnetic field measurement in zero magnetic field possible.\textsuperscript{17} Besides, broadband MW field can achieve a wide magnetic field detection range in magnetic resonance experiments.\textsuperscript{18} In addition, NV\textsuperscript{−} center ensemble enhances the measurement sensitivity but the synchronously manipulation with MW field is difficult, which requires high uniformity of the MW field.

The MW resonators divided into circularly polarized and non-circularly polarized have been reported. M. Mrozek et al. described a circularly polarized microstrip circuit that could provide MW field with arbitrary adjusted polarization but the MW field is inhomogeneous.\textsuperscript{19} And another circularly polarized planar MW resonator was proposed by Johannes Herrmann et al.,\textsuperscript{20} but the bandwidth of the resonator was only 60 MHz when the input return loss (S\textsubscript{11}) was -10 dB. Besides, a non-circularly polarized resonator with high...
homogeneity was proposed by Ning Zhang et al.\textsuperscript{14} And the resonator with an ultra-broadband (15.8 GHz) coplanar waveguide for optically detected magnetic resonance (ODMR) ensured that electron spins could be manipulated under external magnetic field up to 5000 G.\textsuperscript{13} Both the loop-gap resonator used by D. Suter et al\textsuperscript{21} and the two-port MW resonator used by David D. Awschalom et al\textsuperscript{5} can provide non-circularly polarized MW field with high homogeneity. The above resonators cannot meet the application of miniaturization sensors for magnetic measurement with a wide magnetic field detection range and large area MW synchronous manipulation at the same time. Therefore, the resonator that can provide MW field with broadband, circular polarization and uniform characteristics is highly desired.

In this study, we designed a four-port annular microstrip-lines resonator (AMLR) that can provide MW field with broadband, circular polarization and uniform characteristics simultaneously. The AMLR was designed and optimized with a -10 dB bandwidth of 410 MHz and a -15 dB bandwidth of 200 MHz. Variation of the MW magnetic field direction with changes in the phase of the source signal indicated that the AMLR provided circularly polarized MW field. Compared with the parallel-microstrip-lines resonator (PMLR) and the intersected-microstrip-lines resonator (IMLR), the magnetic field magnitude homogeneity of the AMLR is the highest, (PMLR) and the intersected-microstrip-lines resonator (IMLR), the MW field. Compared with the parallel-microstrip-lines resonator (AMLR) that can provide MW field with broadband, circular polarization and uniform characteristics is highly desired.

II. MANIPULATION THEORY AND MODEL OF RESONATOR

The AMLR was designed with a high frequency structure simulator (HFSS) software based on the existing technology. \( S_{11} \) represents the reflection from the impedance mismatch at the cable connection. \( S_{11} \) is the ratio of the reflected wave power to the incident wave power at the transmission line port, which is expressed in logarithmic form as

\[
S_{11} = -10\log\left(\frac{f_1}{f_2}\right),
\]

where \( f_1 \) and \( f_2 \) are the reflected wave power and the incident wave power, respectively. The resonator was designed following the principle of minimizing \( S_{11} \) at the resonant frequency in order to obtain high coupling efficiency between the microstrip antenna and the MW source.

The Hamiltonian of the NV\textsuperscript{−} center electron spin ground state can be written as

\[
\mathcal{H}_s = D_s s_z^2 + \gamma_e B_0 \cdot S,
\]

where \( \gamma_e = 2.8 \text{ MHz/G} \) is the electron spin magnetic ratio, the longitudinal zero field splitting parameter \( D = 2.87 \text{ GHz} \). The ground state of the NV\textsuperscript{−} center is an \( S = 1 \) spin triplet (\( ^3A_2 \)) with the \( m_s = \pm 1 \) sublevels lying \( D = 2.87 \text{ GHz} \) above the \( m_s = 0 \) sublevel under zero magnetic field,\textsuperscript{21} and an external magnetic field \( B_0 \) aligned parallel to the quantization axis splits the degenerate \( m_s = \pm 1 \) levels by \( 2\gamma_e B_0 \), as shown in Fig. 1(a). The range of magnetic measuring \( R \) can be written as

\[
R = 2\text{BW}/\gamma_e,
\]

where \( \text{BW} \) is defined as impedance bandwidth of resonator (hereafter referred to as the bandwidth for short). The bandwidth can be specified in terms of \( S_{11} \) over a frequency range. The well-matched bandwidth must totally cover the required operating frequency range for some specified level, such as a \( S_{11} \) of less than -10 dB or -15 dB. The measurement range of the magnetic field will increase with the bandwidth of the resonator. In addition, it cannot change the magnetic field resolution of the sample because the MW provided by the resonator will not affect the properties of the sample itself.

Polarization theory is usually explained based on changes in the amplitude and direction of magnetic field strength (or electric field strength):

\[
B_x(t) = B_{0x}\cos(\omega t),
\]

\[
B_y(t) = B_{0y}\cos(\omega t + \Delta\phi),
\]

\[
\Delta\phi = \varphi_y - \varphi_x,
\]

where \( B_x \) and \( B_y \) are magnetic field components, \( B_{0x} \) and \( B_{0y} \) are their amplitudes, \( \varphi_x \) and \( \varphi_y \) are the phases of \( B_x \) and \( B_y \), respectively. The circular polarized MW field can be provided when the resonator receives two orthogonal MW source signals with a phase difference of 90 degrees and the same amplitude. A trace curve of circularly polarized MW is shown in the Fig. 1(b). Furthermore, the resonator...
A schematic of the AMLR is shown in Fig. 2(a). Figure 2(b) shows the area where a diamond sample was placed in Fig. 2(a). The AMLR was designed with four ports named ports 1-4 to provide circularly polarized MW field and impedance matching. Only Ports 2 and 3 are used for MW sources of phase difference to adjust polarization, and the other two ports are connected to 50 Ω terminators. L1 and W1 are the length and width of AMLR, respectively, and r and R are the radius of the inner and outer circle of the annulus, respectively. Furthermore, PMLR and IMLR, which are the two types of common resonators, were analyzed and compared to illustrate the characteristics of AMLR. The dimensions L1 and Ls1 were found to have a significant impact on the performance of the resonator in the process of optimizing the AMLR. And the primary parameters of PMLR and IMLR are optimized to ensure the same resonant frequency. The area of the two resonators where diamond samples are placed is shown in Figs. 2(c) and 2(d). The main geometric parameters of the three resonators are listed in Table I.

### III. RESULTS

The bandwidth and $S_{11}$ value in the resonators were analyzed by changing the dimensions of the resonators. The designed resonators were broadband, and the resonant frequency ($f_{MW}$) is set at 2.9 GHz, which could completely cover the longitudinal zero field literal parameter $D$. The $S_{11}$ of the three different resonators are shown in Fig. 3(a). The results indicate that $S_{11}$ was obtained within the 2-4 GHz range, and the $S_{11}$ values for the three resonators were all below -20 dB when the resonant frequency was approximately 2.9 GHz. The $S_{11}$ for the AMLR showed the deepest peak at -36 dB. Moreover, the AMLR with $f_{MW} = 2.9$ GHz exhibits bandwidth values of 410 MHz and 200 MHz when the value of $S_{11}$ were -10 dB and -15 dB, respectively. The bandwidth and $S_{11}$ values of the three resonators are plotted in Fig. 3(b). The left and right Y axes show the bandwidth and $S_{11}$ values of the resonators, respectively. The lowest $S_{11}$ value and widest bandwidth of the AMLR indicated that the AMLR showed the highest coupling efficiency between the microstrip antenna and the MW source, and about 292 G magnetic field detection range could be achieved in magnetic field measurement experiment.

### TABLE I. The optimized geometric dimensions of the resonators.

| Parameters | Value/mm | Parameters | Value/mm | Parameters | Value/mm |
|------------|----------|------------|----------|------------|----------|
| L1         | 52.0     | L2         | 74.00    | L3         | 107.00   |
| W1         | 27.0     | W2         | 27.00    | W3         | 27.00    |
| Ls1        | 0.35     | Ls2        | 1.27     | Ls3        | 0.35     |
| r          | 1.00     | a2         | 0.20     | a3         | 0.20     |
| R          | 1.50     | b2         | 2.40     | b3         | 2.40     |
|           |          | d2         | 1.00     | d3         | 1.00     |
The resonators were expected to provide circularly polarized field for manipulation of the NV– center ensemble with low $S_{11}$ values and wider bandwidth. For circularly polarized MW fields, the phase difference between the two MW source signals at port 2 and port 3 of the resonator must be maintained at 90 degrees. Figures 4(b)–(d) showed the variation of MW magnetic field direction at the selected point in the AMLR, PMLR, and IMLR, respectively, when the phase of two MW source signals ($\varphi$) synchronously changed from 0 to 360 degrees. The MW field rotated 27 degrees anticlockwise on the x-z plane with $\varphi$ changed from 0 to 80 degrees in the AMLR, as shown in Fig. 4(b). As $\varphi$ increased, the MW field continued to rotate counterclockwise. When $\varphi$ changed from 0 to 360 degrees, the MW field rotates 360 degrees counterclockwise. When $\varphi$ changed from 0 to 360 degrees, the MW field rotates 360 degrees counterclockwise. Figure 4(c) and 4(d) show the variation in the MW field direction with changes in the phase of the two source signals synchronously in the PMLR and IMLR, respectively. Compared to the AMLR and PMLR, the direction of magnetic field in the IMLR changes only 13.5 degrees when $\varphi$ changed from 40 to 160 degrees, and the magnetic field intensity is the weakest. The simulation results of the selected point indicate that each resonator could provide circularly polarized MW field. However, the amplitude of two orthogonal magnetic field components obtained from the selected point is not equal, which makes circularly polarized MW fields not perfectly. The detected changes in fluorescence between the two resonance peaks produced by the circularly polarized MW fields indicate the purity of circularly polarized MW. The experiments to verify the selective control effect of circularly polarized MW fields and increase its purity further are the next work plan.

Due to of the NV– center ensemble within the detectable area needs to be controlled synchronously, broadband circularly polarized resonators should provide a uniform MW field. Figures 5(a)–(c) showed the MW magnetic field intensity distribution was simulated on a diamond surface within a 3×3 mm$^2$ area, in the AMLR, PMLR and IMLR, respectively. And the magnetic field intensity at the

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**FIG. 3.** (a) $S_{11}$ values for the three resonators. $S_{11}$ in the AMLR was -36 dB, which showed the lowest value compared to the PMLR and IMLR. The bandwidth of AMLR was 410 MHz when $S_{11}$ was defined at -10 dB. The -10 dB bandwidth peaks at 370 MHz and 270 MHz for the PMLR and IMLR, respectively. (b) Bandwidths and $S_{11}$ values in the three resonators.

**FIG. 4.** (a) The position of the selected point. The gray rectangle indicates the side of the resonator, the blue rectangle represents a diamond sample. The black dot shows the position of the selected point. A diamond sample is 3×3×0.3 mm$^3$, and the point is selected in a center position over the top surface of the diamond sample. (b)-(d) Variations in the magnetic field direction of AMLR, PMLR, and IMLR at the selected point with synchronously changes in the phase of two source signals. The $\varphi$ represents the phase of the two MW source signals, the dotted circles represent the rotation traces at the end of the magnetic field vector and the arrows (the color indicates the strength of the magnetic field) represent the different directions of MW field. Details are explained in the text.
dotted line was extracted, as shown in Fig. 5(d). Figure 5(a) shows the magnetic field intensity distribution in the AMLR. In the $1 \times 1$ mm$^2$ central area, the average magnetic field strength is 0.119 G and the strength of the magnetic field has a difference of 0.012 G. The magnetic field intensity in the PMLR and IMLR on the microstrip line is relatively stronger compared with the magnetic field strength in the area far from the microstrip line according to the simulation results, as shown in Fig. 5(b) and 5(c), respectively. Which lead to the homogeneity of the magnetic field strength were poor in the PMLR and IMLR. The difference of magnetic field intensity in the PMLR and the IMLR are 3 G and 1.1 G in the $1 \times 1$ mm$^2$ central area, respectively. Figure 5(d) shows the magnetic field strengths along the X and Y directions in the three different resonators in the 3 x 3 mm$^2$ magnetic field distribution area, and the MW magnetic field magnitude homogeneity in the AMLR is higher than the homogeneity in the PMLR and IMLR, which indicates large area MW synchronous manipulation can be achieved in AMLR based on the NV$^-$ center ensemble.

IV. CONCLUSION

In conclusion, we designed a broadband circularly polarized AMLR to achieve the state manipulation of NV$^-$ center electron spin ensembles. The AMLR exhibits the bandwidth of 410 MHz when $S_{11} = -10$ dB, which meant about 292 G magnetic field detection range in magnetic field measurement experiment. Variation in the field direction with synchronously changes in the phase of the two MW source signals indicated that AMLR can provide circularly polarized field for manipulating selectively the ground state energy level transitions. Besides, the magnetic field strengths in the AMLR showed a difference of 0.012 G in the $1 \times 1$ mm$^2$ central area, which meets the requirement of large area MW synchronous manipulation. The proposed resonator is significant for the advanced study of a NV$^-$ center ensemble in diamond for magnetometry, magnetic-field imaging and magnetic-resonance detection.

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