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Method of full polarization control of microwave fields in a scalable transparent structure for spin manipulation

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ABSTRACT

The application of transparent conducting oxides in electronic devices like solar cells or displays is common. By transferring this technology to quantum sensing and computing in the form of microwave conductors, it is possible to benefit from the advantages of these materials. By using indium tin oxide (ITO), it is demonstrated that at an arbitrary position below the conductor, an arbitrary elliptical microwave polarization can be produced by two independent sources. This is independent of the geometry and size of the ITO, whereby a non-resonant microwave approach can be chosen. Using single nitrogen vacancy (NV) centers in diamond in combination with a cross-like ITO structure, each NV center can be addressed with an ideal (clockwise or anticlockwise) microwave polarization. By optimizing the coupling of the microwave field to the NV centers and minimizing the conductor size, the creation of smaller devices compared to common approaches is possible.

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I. INTRODUCTION

The application of microwave radiation to manipulate the spin of color centers is an established method. Silicon carbide (SiC)1–4 and diamond5–7 are the most prominent systems where such centers can be found. In recent years, especially the nitrogen vacancy (NV) center in diamond received a tremendous increase in research interest in all kinds of areas, e.g., magnetic8 and electric9 field sensing, machine learning,10 quantum information,11,12 quantum computing,13–16 and biological applications.17,18 For the various applications, there are different requirements for the microwave radiation. The important parameters are field strength, field direction, and polarization.

While most of the sensing techniques rely on linearly polarized fields due to the simplicity of their generation, some experiments utilize a circular polarization.19 The spin transitions of the NV center can only be driven by alternating magnetic field components that are perpendicular to the NV center quantization axis. The transitions from \(|m_s = 0\) to \(|m_s = \pm 1\) can thereby only be influenced by circularly polarized fields, where the handedness of the polarization defines which transition can be driven.20

Different applications can profit from the possibility of full control over the polarization of the microwave field, e.g., magnetometry, quantum information, or quantum computing. A prominent technique for magnetic field measurements is optically detected magnetic resonance (ODMR), which relies on the splitting of the states \(|m_s = \pm 1\) due to the Zeeman effect. For external fields near zero and linearly polarized microwave fields, both transitions between \(|m_s = 0\) and \(|m_s = \pm 1\) will be driven equally.

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Thus, it is not possible to determine the external magnetic field due to the overlap of the resonances. By using circularly polarized fields, only one of the resonances will be present depending on the handedness, enabling near zero-field magnetometry.\footnote{21} For some quantum information applications, the bias field needed could be reduced by using circularly polarized fields.\footnote{22,23} In quantum computing, it was shown that the NV center can be used as a universal quantum gate under zero external magnetic field if circularly polarized microwaves are used.\footnote{16}

There are several designs for microwave structures to deliver the needed polarizations with the correct direction and high field strength. Although there are many different approaches, each has limitations that can be disadvantageous in some applications. These designs are mostly resonator based, resulting in a strong frequency dependence of the field strength. Many of the resonators are based on printed circuit boards (PCBs) and are therefore only a few micrometers thick but have lateral dimensions in the centimeter range.\footnote{29} For these cases, the diamond would lay on top of the structure, which will shift the resonance frequency. A slightly smaller approach uses a tube-like structure, where the diamond is sitting inside the resonator. This makes the sample preparation more difficult, and the width and height of the tube are in the millimeter range.\footnote{30,31} In order to avoid the frequency dependence of the field strength, a double wire PCB structure was proposed.\footnote{21,32} This design is scalable since the distance between the wires can be freely changed. However, the circular polarization plane is created perpendicular to the PCB, meaning the strength and polarization degree is only constant for a small line between the two wires in a certain distance. The simplest design to create a circular polarization is to cross two wires perpendicular, which has a large bandwidth.\footnote{16,33} For such a structure, the field strength decreases with \(1/r\), where \(r\) is the distance from the wires.

In this work, we show that it is possible to create any microwave polarization for an arbitrary structure with two microwave sources. We combine the cross structure resonator\footnote{24} with the wire based approach\footnote{33} and a transparent conductor\footnote{34} to a scalable structure with high field strength and bandwidth, giving full control over the polarization state.

It was already shown that indium tin oxide (ITO) can be used as a transparent microwave conductor, featuring unique possibilities for applications.\footnote{35} Therefore, we used a cross-like structure consisting of ITO to create arbitrarily polarized microwave fields. The thin film had a thickness of 300 nm and was terminated with 50\&ohm; resistors on two neighboring arms of the cross. The other two arms were used as inputs for two independent identical microwave sources. In Fig. 1(a), a schematic of the diamond sample with the ITO structure used in this work is shown.

Optimization of the microwave coupling to the NV centers can be achieved by preferentially aligning these point defects along with the 111 crystal direction. In recent years, perfect preferential alignment was achieved by exploiting the nitrogen delta doping technique during a plasma-enhanced chemical vapor deposition diamond growth process.\footnote{35–39}

For a (111) oriented diamond with [111] oriented NV centers, only the component of an oscillating magnetic field that is parallel to the surface (x-y plane) can change the spin state of the NV.\footnote{35–39}
centers. Directly below the ITO structure, the z component of the magnetic field is small compared to the x and y components.\(^{(34)}\)

Therefore, this is the optimal configuration for manipulating the spin state of NV centers and we only need to consider the x and y components of the magnetic field.

In two dimensions, the magnetic field \(\mathbf{B}(t, \mathbf{r})\) at the position \(\mathbf{r} = (x, y)\) produced by two independent and identical sources, labeled 1 and 2, can be described by the following equation:

\[
\mathbf{B}(t, \mathbf{r}) = \begin{pmatrix} B_x(t, \mathbf{r}) \\ B_y(t, \mathbf{r}) \end{pmatrix}
\]

\[
= \begin{pmatrix} \sqrt{A}B_{x,1}(t) \cos(\omega t + \phi_{x,1} + \varphi) + B_{x,2}(t) \cos(\omega t + \phi_{x,2} + \varphi) \\ \sqrt{A}B_{y,1}(t) \cos(\omega t + \phi_{y,1} + \varphi) + B_{y,2}(t) \cos(\omega t + \phi_{y,2} + \varphi) \end{pmatrix},
\]

where \(B_{x,y,1,2}\) represents the amplitude and \(\phi_{x,y,1,2}\) the phase of the x and y components for each source at the position \(\mathbf{r}\). \(\omega\) is the angular frequency, \(\varphi\) is an extra phase applied only to source 1, and \(a\) is the ratio between the output power of sources 1 and 2. Equation (2) can also be written as a matrix transformation applied to a vector (see supplementary material).

\[
\mathbf{B}(t, \mathbf{r}) = \hat{b}(\mathbf{r}) \mathbf{B}(t) = \hat{b}(\mathbf{r}) \begin{pmatrix} \cos(\omega t) \\ \sin(\omega t) \end{pmatrix}. \tag{3}
\]

Under time evolution, the vector \(\mathbf{B}(t)\) in Eq. (3) describes a circle, which is equal to a circular polarization. To maintain the circular shape, the transformation matrix \(\hat{b}(\mathbf{r})\) can represent a scaling, a rotation, or a reflection. The scaling can be included in the rotation and reflection, so it is sufficient to consider only these cases. For a rotation, \(b_{11} = b_{22} = \cos(\psi)\) and \(b_{12} = -b_{21} = \sin(\psi)\) must hold. While for the reflection case, \(b_{11} = -b_{22} = \sin(\psi)\) and \(b_{12} = b_{21} = \cos(\psi)\) must be satisfied. If \(\hat{b}(\mathbf{r})\) is a rotation, the circular polarization will be anticlockwise (mathematically positive) and for a reflection it will be clockwise. It can be shown that we can analytically find \(\psi\) and \(a\) for each transformation and every position in space such that the transformation is either a rotation or a reflection and the resulting magnetic field is circularly polarized (see supplementary material). This is independent from the geometry of the conductor or the positioning of the two sources, unless the fields \(\mathbf{B}_1\) and \(\mathbf{B}_2\) produced by each source are linearly dependent. Furthermore, we can argue that, when a single source creates a linear polarization and two sources can always produce a circular polarization, it is also possible to create any polarization in between these two cases.\(^{(34)}\) This is not confined to (111) oriented samples since it can be shown that a perfect circular polarization can also be obtained for all NV directions, e.g., in a (100) oriented sample (see supplementary material). To quantify the circularity of the polarization, the ellipticity \(\epsilon\) is a good measure,

\[
\epsilon = 1 - \frac{d}{c} \tag{4}
\]

In this definition, \(c\) is the semi-major axis and \(d\) is the semi-minor axis of the ellipse described by the time evolution of the two-dimensional magnetic field. For a circular polarization, \(\epsilon\) is zero and a linearly polarized magnetic field will result in \(\epsilon = 1\). The orientation of the ellipse is not important since the spin transitions of the NV center are only sensitive to the circular portions of the elliptical polarization, which are invariant under rotation.

II. EXPERIMENTAL DETAILS AND MATERIALS

A. Simulations

Simulations of the magnetic field produced by the microwave excitation of the ITO structure were done with the RF-module of Comsol Multiphysics. The electrical properties of the ITO were taken from Ref. 34 to simulate a 3D 500 \(\times\) 500 \(\times\) 200 \(\mu_m^3\) model of the structure. The diamond surface was situated in the middle of the volume with a thickness of 100 \(\mu_m\) with the 300 nm thick ITO structure and 100 \(\mu_m\) air. The simulation space was enclosed in a perfectly matched layer (PML) to avoid reflections on the simulation boundaries.

B. Sample preparation

The sample used in this study is a preferentially aligned NV center containing (111) oriented, 220 nm thick, \(^{12}\)C isotopically enriched diamond layer, which is produced during chemical vapor deposition (CVD) synthesis. The preferential alignment was confirmed by ODMR measurements, where more than 99% of the NV centers point perpendicular to the diamond’s surface. In order to create this 220 \(\mu_m\) thin layer, whose presence was confirmed by secondary ion mass spectrometry (SIMS) measurements, the diamond substrate [(111) oriented, IIa type single crystal diamond from the supplier Applied Diamond Inc.] was exposed to a hydrogen plasma for 5 min for the creation of a hydrogen-terminated surface, which depicts the starting point for homoepitaxial growth (microwave power 1.92 kW, microwave frequency 2.46 GHz, pressure 52.5 mbar, temperature \(\approx 950 \degree\)C). During this time, the reaction chamber was flushed with a constant flow of hydrogen (400 sccm). Afterward, isotopically purified methane (99.99%; \(^{12}\)C) was added at a flow rate of 0.4 sccm. This source gas contained nitrogen in the order of 70 ppm. During the growth time of 1 h, preferentially aligned NV centers were created throughout the whole diamond layer.

The diamond was masked with a positive electron beam lithography resist [poly(methylmethacrylate) (PMMA), Allresist GmbH AR-P 671.05, thickness \(\approx 1 \mu_m\)] and an \(\approx 10 \mu_m\) thick conductive resist on top (Allresist GmbH Electra 92). Before the conducting resist was applied, the sample was annealed at 180 \degree\)C for 20 min. The electron dose for the electron lithography was 500 \(\mu_C (cm)^{-2}\). The ITO thin film was grown by pulsed laser deposition with a 248 nm KrF excimer laser (Coherent LPX PRO 305 F). On the target surface, the laser fluence was \(\approx 2 \text{J/cm}^2\). The target was composed of \(\text{In}_2\text{O}_3\) and 1 wt. % \(\text{SnO}_2\). A more detailed description of the target can be found in Ref. 34. A 300 nm film was produced with 10,000 total pulses with a repetition rate of 10 Hz. The lift off was done in a 1 h acetone bath with a micro manipulator, to minimize stress on the ITO. The four arms of the ITO were contacted with a silver epoxy paste (Epoxy Technologies EPO-Tek H20E), which dried for 2 weeks at room temperature. The hardened silver epoxy is not soluble by immersion oil.
C. Experimental setup

All measurements were performed with a home-build confocal setup. The excitation was managed by a 532 nm laser (LaserQuantum gem532), and the fluorescence was detected by two identical avalanche photodiodes (Excelditas SPCM-AQRH) through a 60 × 1.35 NA oil immersion objective. The used immersion oil was from Fluka (FL10976). The microwave source was a dual channel transceiver (70 MHz–6 GHz, Ettus USRP B210) with a broadband amplifier for each channel (Mini-Circuits ZHL-16W-43-S+). Each channel could be separately pulsed through a solid state switch (Mini-Circuits ZASWA-2-50DR+). The length from the transceiver to the self-designed printed circuit board with the sample was the same for each output.

III. RESULTS

In Fig. 1(b), a laser scanning confocal microscope image of the used ITO cross is shown. The spectrally integrated fluorescence produced by the ITO is in the order of a single NV center, resulting in a higher background signal for NV centers below the cross structure. This can be clearly seen in the edges of the scan, where no ITO is sitting on top of the diamond. Rabi oscillations of single NV centers along a line below one of the cross arms were investigated in order to verify the magnetic field simulations. The line was ≈30 μm away from the cross center and is depicted by a dashed line in Fig. 1(a). By feeding only one input at a time with a microwave signal, it is possible to check the simulation of an input and a termination path at the same position. Far from the center of the cross, the phase mismatch of the x and y components of a single input is small and can therefore be neglected. The Rabi frequency $\omega_{\text{Rabi,1/x}}$ produced by either input 1 or input 2 at the position $r$ is then given by

$$\omega_{\text{Rabi,1/x}} = \gamma \cdot |B_{x,y,1/2,x}| = \gamma \cdot \sqrt{B_{x,1/2,y}^2 + B_{y,1/2,x}^2}. \quad (5)$$

The gyromagnetic ratio $\gamma$ is $\approx 2\pi \cdot 28 \text{ MHz/mT}$. At a static 42 mT field in the z direction, the Rabi frequencies for NV centers along the defined line were measured for each input. The measurement data are shown in Fig. 2.

The magnetic field produced by a single input was simulated with the Comsol RF module by a mode analysis. Magnetic fields can be superposed and therefore it is sufficient to simulate one input and rotate the simulation data by 90° for the second input. The difference between the inputs in terms of the strength of the Rabi oscillation is mainly explained by the position of the measurement line on the cross arm of input 2 since only a portion of the power fed into input 1 propagates into this arm. Also, the asymmetry of the plot for input 1 can be explained by the wave propagation from this input to the position of the measurement. The field lines for this case are not perfectly parallel to the measurement line in contrast to using input 2 (see supplementary material). Since the actual excitation power at the structure inputs is unknown, the simulation data must be linearly scaled to match the measurement data. With Eq. (5), we can use $\alpha \cdot \omega_{\text{Rabi,1/x}}$, where $\alpha$ is the fit parameter. For both inputs, the simulation fits well to the measured data with a standard deviation error of about 1%. This agrees with the predictions made in previous studies.

To understand the polarization distribution with respect to the cross, we simulated the structure while feeding both inputs simultaneously. Input 1 was given an additional phase shift $\psi = 90°$ with $a = 1$. In Figs. 3(a), 3(c), and 3(d), the ellipticity $\epsilon$, the semi-major axis $c$, and the semi-minor axis $d$ of the magnetic field polarization 110 nm below the cross are shown, respectively. The decrease of the magnetic field in the $z$ direction is small; therefore, we assume that the simulation is representative for the whole NV layer. The drop of the magnetic field strength between the surface of the diamond and a depth of 220 nm is less than 2%. The simulations were explored for excitation microwave frequencies in the range of 1.87 GHz–3.87 GHz. The magnetic field shape for the whole structure is similar over the complete frequency range; thus, we chose 2.87 GHz for all calculations. The field strength shows no resonances in this range, and the attenuation over the whole frequency range is less than 5.5 dB. To our knowledge, there is only one publication on the permittivity of ITO in this frequency range such that there is no information available for the dependencies of this quantity on the properties of the ITO film, like crystallinity or charge carrier density. Therefore, we assume that there will be a strong deviation in the field strength dependence between differently deposited ITO conductors. In Fig. 3(b), four polarization ellipses are shown, which correspond to the position of the circles of the same color in Figs. 3(a), 3(c), and 3(d).

For $a = 1$ and $\psi = 90°$, it can be seen that there are only three positions where a circular polarization will occur. All lie on the diagonal between the two inputs; one in the middle and one each before and after the edge of the cross facing away from the inputs. Outside the cross, the field strength in the $x$–$y$ plane is much weaker than below the ITO. The further away from the center under a cross arm, the more linear the polarization will be, while around the center of
the cross there is a large area with an ellipticity below 0.5 (the green ellipse has an ellipticity of 0.5). But the field strength is not homogeneous over the whole structure. There are especially strong fields on the three edges nearest to the inputs, which weaken to the center and the cross arms facing away from the inputs.

To achieve circular polarization and simultaneously compensate for these inhomogeneities, we calculated $\psi$ and $a$ for Eq. (3) and scaled both inputs equally so that the magnetic field strength is identical to a reference field. In Figs. 4(a) and 4(b), $\psi$ and $a$ are shown for the case that the resulting $b(r)$ is a rotation, respectively. The field strength at the center point of the cross was chosen as a reference field ($\psi = 90^\circ$, $a = 1 = 0$ dB) to scale the inputs. In Figs. 4(c) and 4(d), the input power factors for input 1 and input 2 are shown, respectively.

The phases $\phi_{ij}$ produced by the two sources are only different near the edges of the cross. Therefore, for most positions $\mathbf{r}$, $a$ can be calculated with (see supplemental material)

$$a = \frac{B_{x,2,r}^2 + B_{y,2,r}^2}{B_{x,1,r}^2 + B_{y,1,r}^2}$$

(6)

This means it is sufficient to adjust the input power on both sources so that the Rabi frequency is the same for only using either source 1 or 2. Then, the phase $\psi$ must be matched to create a circular polarization. It is also possible to produce a linear polarization with both inputs and it can be shown that all possible polarizations between linear and circular can be created.
In Fig. 5(a), a simulation of the phase $\psi$ for linear polarization is shown. As an example, we investigated the position marked with a blue circle and calculated the ellipticity for different $\psi$ and input power ratios $a$ [Fig. 5(b)]. This position was chosen to highlight the capabilities of the design since the magnetic field lines are not perpendicular there and it is in a region of the structure where the field strength is one of the weakest (see supplementary material).

It can be seen that every 180° the polarization is linear ($\epsilon = 1$). This is independent of the power ratio. There are two points where a circular polarization is achieved, representing the clockwise and anticlockwise cases. We could construct an arbitrary number of paths between the linear polarized area and the circular polarized points, which will represent a continuous function of $\epsilon$. Such a path will cover the complete range of polarizations between linear and circular, which demonstrates full control over the polarization of the magnetic field. This holds for clockwise and anticlockwise polarizations.

To check our simulations, we swept $\psi$ in 5° steps from 0° to 360°. To further optimize the polarization, the ratio between the input powers was varied. This was done for the position marked with a blue circle in Figs. 3 and 5(a). The ODMR spectra for the linear polarization and the optimized clockwise and anticlockwise circular polarizations are shown in Figs. 5(c) and 5(d), respectively.

Linear polarization was achieved at $\psi = 235°$, where both resonances are equally excited. For the circular polarizations, perfect selectivity of the resonances depending on the handedness can be achieved.
The phase difference between the linear polarization and the clockwise is $72^\circ$ and the anticlockwise circular polarization is $70^\circ$. From the simulation in Fig. 5(b), we see that the two points for circular polarization are located at $285^\circ$ and $75^\circ$, which is in good agreement with the measurement. We can, therefore, deduce that the measured linear polarization corresponds to $\psi = 0^\circ$ in the simulations and that our laboratory frame is shifted by $-125^\circ$.

It is not possible to compare the power ratio between the sources since the paths between the sources and the ITO cross are not equal. This is caused by differences in the components like the amplifiers or variations of the silver paste and the soldering, which can also be the cause for the phase shift of the laboratory frame.

Also, small inhomogeneities and local impurities of the ITO structure can cause deviations from the simulations.

**IV. SUMMARY**

The cross structure presented here is only one of many possible microwave structures. But it proves the hypothesis that as long as a magnetic field is produced by two independent sources it is always possible to locally create an arbitrary polarization from linear to circular. From corrections shown in Fig. 4, it can be seen that with a power correction of $6 \, \text{dB}$ nearly the complete crossing area ($20 \times 20 \, \mu\text{m}^2$) can be covered to produce a circular polarization. Since the difference between clockwise and anticlockwise
corrections is small except at the edges of the crossing area, this is valid for both cases (see supplementary material).

With the approach demonstrated in this paper, it is possible to reduce the size of microwave structures since single centers can be observed through the conductor. It is not only of interest in magnetometry to minimize the device structure but also for quantum computing. By reducing the size of the microwave structures, it will be possible to increase the density of microwave lines on a sample and it could be a promising way to address qubits more efficiently.

**SUPPLEMENTARY MATERIAL**

See the supplementary material for details on the derivation of the parameters for linear, circular, and arbitrary polarization; the magnetic field line simulation of the structure; the circular polarization simulation for the reflection case; the derivation of Eq. (6); and the adjustments needed if a (100) oriented diamond would be used.

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The authors declare that there are no competing interests.

**DATA AVAILABILITY**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**REFERENCES**


