

A SENSOR UNIT AND RESONATOR CIRCUIT THEREOF

5

TECHNOLOGICAL FIELD

The present disclosure is in the field of microwave resonators and specifically relates to resonator for microwave control of spin ensembles.

10 BACKGROUND

Detecting RF electromagnetic radiation is essential for modern-day communication. The conventional technique uses the interaction between radiation and electrons in conductive or semiconductive materials, based on classical electromagnetism, enabling detection of strong signals. Alternatively, quantum
15 interactions between photons and specific material properties can detect signal photon radiation and their properties.

Color centers are crystalline defects that introduce additional light absorption or emission. A common type of color center used in various quantum metrology applications utilizes a Nitrogen Vacancy (NV) defect in diamond crystals. The NV center is a
20 nanoscale defect that can be initialized via optical pumping, readout by detection of fluorescent emission and undergo coherent manipulation using microwave (MW) fields.

The specific properties of color center in crystals, and specifically NV centers in diamond, make these centers suitable candidates for detection of electromagnetic radiation and magnetic fields in general. Further, coherent manipulation of color center
25 state enables enhanced detection properties.

Split ring resonators (SRR) are artificial electromagnetic structures used in radio frequency and microwave engineering to create resonant circuits. The structure of SRR circuits include one or more metallic rings that are split into two halves with a small gap between them, creating a capacitance and inductance (LC) circuit. The two halves of the
30 ring are also separated by a small gap, creating an inductance.

Split ring resonators have certain properties that make them useful in various applications. For example, SRRs can be used to create metamaterials that have negative refractive index, form lenses that can focus non-optical electromagnetic radiation. Split ring resonators are also used in microwave engineering to form band-stop and/or band-pass filters, which are used to block or allow certain frequencies of electromagnetic radiation. Further, SRRs are used in antenna design to improve the performance of antennas, e.g., by increasing the bandwidth or reducing the size of the antenna.

Split-ring resonators operate as LC circuits having a specific resonance frequency, determined by its size and shape of the ring. This enables the SRRs to interact with an incident electromagnetic wave by creating a phase shift in the wave's electric field, e.g., generating the appearance of a negative permittivity and permeability, effectively changing the properties of EM waves in the metamaterial etc. The split-ring shape allows for inductive and capacitive coupling to create the resonant behavior, making it a useful component in the design of metamaterials for various applications, such as negative index metamaterials, microwave filters, and sensing.

WO 2022/079,713 describe a sensor system comprising: a plurality of sensor units arranged in a predetermined arrangement to be exposed to an electromagnetic signal to be measured, a drive unit configured for providing one or more electromagnetic drive pulses to said sensing units to thereby affect one or more selected quantum properties associated with said plurality of sensor units, and an optical detector unit configured for detecting variation in one or more optical properties of the sensor units in response to input collected electromagnetic radiation; wherein said drive unit is configured to apply the electromagnetic drive pulses having a predetermined phase function on said plurality of sensor units.

T. Wolf, P. Neumann, K. Nakamura, H. Sumiya, T. Ohshima, J. Isoya, and J. Wrachtrup, Physical Review X 5, 041001 (2015) describe that Nitrogen-vacancy (NV) defect centers in diamond are promising solid-state magnetometers. Single centers allow for high-spatial-resolution field imaging but are limited in their magnetic field sensitivity. Using defect-center ensembles, sensitivity can be scaled with $\sqrt{N}$ when N is the number of defects. In the present work, we use an ensemble of $N \sim 10^{11}$ defect centers within an effective sensor volume of $8.5 \times 10^{-4} \text{ mm}^3$ for sensing at room temperature. By carefully eliminating noise sources and using high-quality diamonds with large NV concentrations,

we demonstrate, for such sensors, a sensitivity scaling as $1/\sqrt{t}$, where t is the total measurement time. The associated photon-shot-noise-limited magnetic-field sensitivity for ac signals of $f=20$ kHz is $0.9 \text{ pT}/\sqrt{\text{Hz}}$. For a total measurement time of 100 s, we reach a standard deviation of about 100 fT. Further improvements using decoupling
5 sequences and material optimization could lead to $\text{fT}/\sqrt{\text{Hz}}$ sensitivity.

K. Bayat, J. Choy, M. Farrokh Baroughi, S. Meesala, and M. Loncar, Nano letters 14, 1208 (2014) report on the development and utilization of a double split-ring microwave resonator for uniform and efficient coupling of microwave magnetic field into nitrogen vacancy (NV) centers in a diamond over a mm^2 area. Uniformity and magnitude
10 of delivered microwave field were measured using the Rabi nutation experiment on arrays of diamond nanowires with ensemble NV centers. An average Rabi nutation frequency of 15.65 MHz was measured over an area of $0.95 \times 1.2 \text{ mm}$, for an input microwave power of 0.5 W. By mapping the Rabi nutation frequency to the magnetic field, the average value of the magnetic field over the aforementioned area and input microwave
15 power was 5.59 G with a standard division of 0.24 G.

R. Marqu es, F. Mesa, J. Martel, and F. Medina, IEEE Transactions on antennas and propagation 51, 2572 (2003) develop a quasi-analytical and self-consistent model to compute the polarizabilities of split ring resonators (SRRs). An experimental setup is also proposed for measuring the magnetic polarizability of these structures. Experimental data
20 are provided and compared with theoretical results computed following the proposed model. By using a local field approach, the model is applied to the obtaining of the dispersion characteristics of discrete negative magnetic permeability and left-handed metamaterials. Two types of SRRs, namely, the so-called edge coupled- and broadside coupled- SRRs, have been considered. A comparative analysis of these two structures has
25 been carried out in connection with their suitability for the design of metamaterials.

GENERAL DESCRIPTION

As color centers are being commonly used in detection of magnetic fields, employing a large ensembles of color centers, or NV centers in particular, may lead to a
30 boost in detection sensitivity. However, exploiting the scaling of large color centers ensembles requires overcoming several hurdles including e.g., providing a suitable MW

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driving field that can cover inhomogeneous broadening of the ensemble and maintaining field homogeneity.

The present disclosure provides a sensor unit and corresponding resonator circuit configured to utilize an ensemble of color centers and apply generally uniform microwave driving to the ensemble of color centers. The resonator circuit comprises a first and a second split rings having respective first and second diameters. The first and second split rings are positioned in respective first and second parallel planes, allowing placement of one or more crystal structures carrying an ensemble of color centers in an intermediate plane between said first and second parallel planes. The first and second split rings generate an effective cylindrical volume and provide a generally uniform magnetic field within at least a portion of the volume, allowing uniform coherent manipulation of the ensemble of color center.

According to a broad aspect, the present disclosure provides a sensor unit comprising at least one crystal structure comprising an ensemble of color centers, and a resonator arrangement for applying selected magnetic field on said ensemble of color centers; said resonator comprises a first split ring having a first diameter and a second split ring having a second diameter; wherein said first split ring and said second split ring are positioned within first and second parallel planes, and wherein said at least one crystal structure is located in an intermediate plane between said first and second parallel planes.

According to some embodiments, the first and second split rings may define a virtual cylindrical space between them, and said at least one crystal structure is located within volume of said virtual cylindrical space.

According to some embodiments, the at least one crystal may be a diamond crystal, and said ensemble of color centers comprise a plurality of Nitrogen Vacancy centers within said diamond crystal.

According to some embodiments, a gap within said first split ring and a gap within said second split ring are placed at opposing orientations.

According to some embodiments, a gap within said first split ring and a gap within said second split ring are placed at 180 degrees respective orientation.

According to some embodiments, a distance between said first and second parallel planes may be in a range between 0.1mm and 20mm. The distance between said first and second parallel planes may be for example 0.5 ± 0.05 mm, or 0.6 ± 0.05 mm, or 0.7 ± 0.05 mm, or 0.8 ± 0.05 mm or 0.9 ± 0.05 mm or 1 ± 0.05 mm, or 1.1 ± 0.05 mm, or

1.2±0.05mm, or 1.3±0.05mm, or 1.4±0.05mm, or 1.5±0.05mm, or 1.6±0.05mm. in some embodiments, the distance between said first and second parallel planes may be 0.4±0.05mm, or 0.3±0.05mm, or 0.2±0.05mm, or 0.1±0.05mm.

According to some embodiments, the first and second diameters of said first and second split rings are similar. The first and second diameters of said first and second split rings may be in a range between 0.5mm and 20mm. For example the first and second diameters may be 0.5mm, or 1mm or 2mm, or 3mm, or 4mm, or 5mm, or 6mm, or 7mm, or 8mm, or 9mm, or 10mm. The first and second diameters may be selected in accordance with physical parameters of the first and second split rings to obtain a desired resonance frequency.

According to some embodiments, the sensor unit may be formed on a printed circuit board (PCB).

According to some embodiments, the first and second split rings may form a resonator having resonance frequency within a range between 0.5GHz and 50GHz. In some embodiments, the resonance frequency may be selected to be between 0.5GHz and 12GHz. Generally, the resonance frequency may be determined in accordance with frequency of color centers used in the sensor.

According to some embodiments, the sensor unit may further comprise a first lead associated with said first split ring and a second lead associated with said second split ring, said first and second leads provide excitation signal to respective one of said first and second split rings.

According to some embodiments, the sensor unit may further comprise at least one microwave signal generator connected using one or more switched to said first and second leads for driving said first and second split rings with one or more selected signals.

According to some embodiments, the sensor unit may further comprise at least one laser unit and optical arrangement adapted to provide selective optical excitation of said at least one crystal.

According to some embodiments, the sensor unit may further comprise a magnetic field generator adapted to provide static magnetic field onto said at least one crystal. In some embodiments the magnetic field generator may be adapted to selectively vary magnitude of said static magnetic field.

According to some embodiments, the sensor unit may further comprise an optical collection arrangement and at least one detectors, said optical collection arrangement is

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positioned for collecting optical emission from said ensemble of color centers in said at least one crystal and direct said optical emission to be detected by said at least one detector.

According to some additional broad aspects, the present disclosure provides a
5 sensor array system comprising an array of sensor units comprising at least one sensor unit configured as described herein.

According to some additional broad aspects, the present disclosure provides a sensor array system comprising an array of sensor units each sensor unit being configured as described herein.

10 According to yet another broad aspect, the present disclosure provides a resonator circuit for applying electromagnetic excitation onto an ensemble of color centers comprising:

first and second split rings having respective first and second diameters; said first and second split rings are positioned within respective first and second parallel planes,
15 and at least one crystal structure carrying said ensemble of color centers located in an intermediate plane between said first and second parallel planes.

The resonator circuit of claim 20, wherein said first and second split rings are configured as an electrically conducting rings having a gap forming discontinuity in conductivity along circumference of the rings.

20 According to some embodiments, the ensemble of color centers is located within at least one diamond crystal, and said ensemble of color centers comprise a plurality of Nitrogen Vacancy centers within said diamond crystal.

According to some embodiments, a gap within said first split ring and a gap within said second split ring are placed at opposing orientations.

25 According to some embodiments, a gap within said first split ring and a gap within said second split ring are placed at 180 degrees respective orientation.

According to some embodiments, a distance between said first and second parallel planes is in a range between 0.1mm and 20mm. According to some embodiments, a distance between said first and second parallel planes is 0.5 ± 0.05 mm. The distance
30 between said first and second parallel planes may be for example 0.5 ± 0.05 mm, or 0.6 ± 0.05 mm, or 0.7 ± 0.05 mm, or 0.8 ± 0.05 mm or 0.9 ± 0.05 mm or 1 ± 0.05 mm, or 1.1 ± 0.05 mm, or 1.2 ± 0.05 mm, or 1.3 ± 0.05 mm, or 1.4 ± 0.05 mm, or 1.5 ± 0.05 mm, or

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1.6±0.05mm. in some embodiments, the distance between said first and second parallel planes may be 0.4±0.05mm, or 0.3±0.05mm, or 0.2±0.05mm, or 0.1±0.05mm.

According to some embodiments, the first and second diameters of said first and second split rings may be similar. According to some embodiments, the first and second
5 diameters of said first and second split rings may be in a range between 0.5mm and 20mm. For example, the first and second diameters may be 0.5mm, or 1mm or 2mm, or 3mm, or 4mm, or 5mm, or 6mm, or 7mm, or 8mm, or 9mm, or 10mm. The first and second diameters may be selected in accordance with physical parameters of the first and second split rings to obtain a desired resonance frequency.

10 According to some embodiments, the resonator circuit may be formed on a printed circuit board (PCB).

According to some embodiments, the first and second split rings form a resonator having resonance frequency within a range between 0.5GHz and 100GHz. In some embodiments, the resonance frequency may be selected to be between 0.5GHz and
15 50GHz. In some embodiments, the resonance frequency may be selected to be between 0.5GHz and 12GHz. Generally, the resonance frequency may be determined in accordance with frequency of color centers used in the sensor.

According to some embodiments, the resonator circuit may further comprise a first lead associated with said first split ring and a second lead associated with said second
20 split ring, said first and second leads provide excitation signal to respective one of said first and second split rings.

According to some embodiments, the resonator circuit may further comprise at least one microwave signal generator connected using one or more switched to said first and second leads for driving said first and second split rings with one or more selected
25 signals.

According to some embodiments, the resonator circuit may further comprise at least one laser unit and optical arrangement adapted to provide selective optical excitation of said at least one crystal.

According to some embodiments, the resonator circuit may further comprise a
30 magnetic field generator adapted to provide static magnetic field onto said at least one crystal. In some embodiments the magnetic field generator may be adapted to selectively vary magnitude of said static magnetic field.

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According to some embodiments, the resonator circuit may further comprise an optical collection arrangement and at least one detector, said optical collection arrangement is positioned for collecting optical emission from said ensemble of color centers in said at least one crystal and direct said optical emission to be detected by said
5 at least one detector.

According to yet some broad aspect, the present disclosure provides a sensor array system comprising an array of resonator circuits comprising at least one sensor unit configured as described herein.

According to yet some broad aspect, the present disclosure provides a sensor array
10 system comprising an array of resonator circuits each resonator circuits being configured as described herein.

According to yet further broad aspect, the present disclosure provides method for use in operation of electromagnetic sensor comprising an ensemble of color centers, the method comprising:

15 providing a first split ring at a first plane at one side of said ensemble of color centers, where axial center of said first split ring aligns with center of said ensemble of color centers;

providing a second split ring at a second plane at an opposite side of said ensemble of color centers, where axial center of said second split ring aligns with center of said
20 axial center of said first split ring;

providing selected excitation signal to said first and second split rings thereby applying corresponding selected magnetic field excitation to said ensemble of color centers, to thereby initiate said ensemble of color center at selected state for sensing electromagnetic signal impinging thereon.

25 According to some embodiments, the ensemble of color centers is an ensemble of Nitrogen Vacancy centers within a diamond. Various additional modification of the method as also described herein.

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BRIEF DESCRIPTION OF THE DRAWINGS

In order to better understand the subject matter that is disclosed herein and to exemplify how it may be carried out in practice, embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in
5 which:

Fig. 1 schematically illustrates certain elements of a sensor and resonator according to some embodiments of the present disclosure;

Fig. 2 illustrates an additional example of sensor and resonator according to some embodiments of the present disclosure;

10 **Fig. 3** shows a three-dimensional illustration of a resonator structure according to some embodiments of the present disclosure;

Fig. 3 illustrates a multi sensor arrangement according to some embodiments of the present disclosure;

15 **Fig. 4** shows design for simulated and fabricated resonator circuit and crystal structure according to some embodiments of the present disclosure;

Fig. 5 shows z component of magnetic field generated by the resonator structure according to some embodiments of the present disclosure;

Fig. 6 shows simulated response of resonator circuit according to some embodiments of the present disclosure to drive of different frequencies ;

20 **Fig. 7** shows simulated data on response of resonance frequency to variation of construction parameters of a resonator circuit according to some embodiments of the present disclosure;

Fig. 8 shows experimental ring down measurement of a resonator according to some embodiments of the present disclosure having Radius $R=2.95\text{mm}$;

25 **Fig. 9** shows characteristics measured Rabi oscillations;

Fig. 10 shows measurement of magnetic field inside the resonator according to some embodiments of the present disclosure as a function of input power;

Fig. 11 shows measured reflection coefficient (S_{11}) for resonators according to some embodiments of the present disclosure having different ring radius; and

30 **Fig. 12** shows measured inhomogeneity in field excitation by a resonator circuit according to some embodiments of the present disclosure.

DETAILED DESCRIPTION OF EMBODIMENTS

The present disclosure provides a sensor unit, and a resonator circuit configured for applying selected magnetic field excitation to an ensemble of color centers within a crystal structure. **Fig. 1** shows a schematic illustration of a resonator circuit **60**, that may be used in a sensor unit **100** according to some embodiments of the present disclosure. The sensor unit **100** utilizes a crystal structure **50** having a plurality of color centers **55** embedded therein. The crystal structure **50** is positioned within a resonator circuit **60** formed by first **62** and second **64** split rings that are placed in respective first and second planes, generally above and below (or in two opposite sides) of the crystal structure **50**.

Generally, color centers crystals, such as a Nitrogen Vacancy centers in diamonds, are defects in the crystalline structure that introduce additional light absorption or emission. In various applications, color centers, and specifically NV diamond defects, may be used as high sensitivity detectors for electromagnetic radiation or in generally to varying magnetic fields. The color centers may be manipulated using optical illumination, and magnetic fields to provide enhanced sensing with selected detection properties. For example, WO 2022/079,713 describes detection of electromagnetic radiation using color centers such as NV centers being coherently manipulated by microwave pulses.

Proper manipulation of the quantum state of color centers enables selection of the sensing properties and may be used for detection of phase information in collected varying magnetic fields (e.g., electromagnetic radiation). However, applying selected magnetic of microwave manipulation on an ensemble of color centers poses a challenge in generating sufficiently uniform magnetic field. The resonator configuration of the present disclosure provides generally uniform magnetic field in a desired volume within the resonator circuit allowing uniform coherent manipulation to an ensemble of color centers, and operation of the ensemble of color centers as a sensor unit for electromagnetic signals.

To this end, the resonator **60** of the present disclosure is formed of a first split ring **62** placed in a first plane, and a second split ring **64** placed in a second plane, being generally above of below the first split ring **62**. Each of the first **62** and second **64** split rings is formed of a conducting material in a ring shape and having a gap in conductivity around the ring. The first **62** and second **64** split rings are generally aligned along a shared axial axis and being oriented with different, and preferably opposite gaps directions. This

configuration forms an effective cylindrical volume located between the split rings **62** and **64** and defined by circumference of the split rings and distance between them.

The first **62** and second **64** split rings are coupled to respective first **72** and second **74** electrical leads positioned at close vicinity to the rings and configured to couple electrical signals thereto. More specifically, the first **72** and second **74** leads are connectable to an electronic circuit for directing electrical excitation of selected frequency and amplitude toward the respective first **62** and second **64** split rings. The electrical excitation is coupled to the rings and generates corresponding excitation of the split rings, thereby generating current excitation flowing through the rings. This in turn generate magnetic field variation around the split rings. Excitation of the first and second split rings with electrical signal having frequency close to resonance frequency of the split rings and having suitable phase relation between excitation of the first **62** split ring and the second **64** split ring can generate a magnetic field that varies with time and is spatially uniform within a volume between the split rings.

The resonator circuit **60** is adapted to hold a crystal structure **50** at a selected location between the first **62** and second **64** split rings. Typically, dimensions of the resonator circuit **60** are determined in accordance with dimensions of the crystal structure **50** selected to operate therewith. Typically, diameter of the first **62** and second **64** split rings, may be determined to be larger than width or length of the crystal structure **50**, and distance between the split rings along the axial axis thereof is determined to be larger than height of the crystal structure **50**. The dimensions are generally selected to allow placement of the crystal structure **50** within a region having generally spatially uniform magnetic field, while avoiding field variations at edges thereof.

Further, the first **62** and second **64** split rings may be of selected similar dimensions, including ring diameter, gap length, material thickness and material selection. Alternatively, the material selection and split ring dimensions may be selected to provide a generally similar resonance frequency for the first **62** and second **64** split rings, to thereby enable generating combined magnetic field that is spatially uniform within the selected region between the rings.

In some exemplary embodiments, the first **62** and second **64** split rings may have respective first and second diameters similar dimensions. The first and second split rings may have diameters of said first and second split rings are in a range between 0.5mm and 20mm, and distance between the first and second split rings along the axial axis may be

in the range between 0.1mm and 50mm, or preferably between 0.1mm and 20mm. Additionally parameters that define resonance frequency of the first and second split rings include resistivity of the material, width of the conducting elements of the split rings, height of the split rings, gap distance, as well as excitation gap being a gap between the
5 split rings **62** or **64** and conducting leads **72** or **74** providing electrical excitation thereto. Generally, the resonator circuit **60** may be excited by electrical input directed via one lead, being lead **72** or **74**, or via both leads simultaneously.

An additional illustration of sensor unit **100** is shown in **Fig. 2**. Here, resonator circuit **60** is illustrated including a virtual cylindrical (or partly cone shaped) volume **40**
10 defined by the first **62** and second **64** split rings. Crystal structure **50** is positioned within the virtual volume **40**, typically centered on the axial axis of the first and second split rings, at mid distance between the split rings. The sensor unit **100** may also include one or more additional units for controlling and modifying excitation of the ensemble of color centers **55**. Such additional units may include one or more of: a static magnetic field
15 generator **80**, a light source unit **90**, and a light collection arrangement **95**.

The static magnetic field generator **80** may be a permanent magnet, electromagnet or other devices configured to provide a generally static magnetic field applied on the crystal structure **50** and the ensemble of color centers **55** embedded therein. Static magnetic field may be used to tune separation between spin states of the color centers.
20 A light source **90** may be used to provide optical illumination **92** for optically pumping the color centers. This may be used for providing selected excited state of the color centers as known in the art for operating color centers such as NV centers in diamond crystals for detection of magnetic field or electromagnetic radiation.

Light collection arrangement **95** is generally used for collecting optical emission
25 from the ensemble of color centers **55**. Typically, detection of radiation using one or an ensemble of color centers is performed by detection of optical radiation emitted by the color centers. To this end the light collection arrangement may include a light guide arrangement, e.g., formed by coupling waveguide portion **94** and transmission waveguide portion **96**, and optical detection unit **98**. In some embodiments of the present disclosure,
30 the coupling waveguide portion **94** may be configured with a trapezoid section and is positioned with narrow face directed at the crystal structure **50**. The coupling waveguide portion **94** is connected to, and may be an integral part of, transmission waveguide section **96**, which is configured to guide light coupled into the coupling waveguide portion **94**

toward the detector **98**. Detector **98** is located at far end of the transmission waveguide **96** portion and configured to generate electrical signals in response to optical illumination impinging thereon. The detector **98** may include one or more photodiodes and may be connected to a detection circuitry for collection of electrical signals indicative of detection
5 thereby.

Generally, the sensor unit **100** may also include an electrical circuit for generating electrical excitations and transmitting the electrical excitation via first **72** and second **74** leads. The sensor unit **100** may also include, or be associated with, a controller including one or more circuits for controlling operation of the various elements of the sensor **100**
10 and for collecting and analyzing data on signals detected by the sensor unit **100**.

The sensor unit **100** according to various embodiments of the present disclosure may be used as a single sensor arrangement, or in a sensor system including an arrangement of a plurality of sensor units. **Fig. 3** illustrates a sensor system **400** including an array **300** of sensor units **1001**, **1002** to **100n**, and a controller **500**. The sensor units
15 **1001** to **100n** generally include respective sensing elements such as crystal units having a plurality of color centers embedded within, e.g., using diamond crystals having a plurality of NV centers in each diamond. The sensor units **1001** to **100n** include one or more sensor units associated with a resonator circuit as exemplified herein with respect to **Figs. 1 and 2** and may also be associated with respective optical detectors
20 (photodiodes), light source stimulations and/or static magnetic field generators. In some embodiments, all of the sensor units **1001** to **100n** are configured as sensor unit **100** exemplified herein with respect to **Figs. 1 and 2**.

The array of sensors **300** may have any selected arrangement and geometry. For example, the array of sensors **300** may be a one-dimensional or two-dimensional array.
25 The array **300** may be operated for detection of spatial variations in electromagnetic radiation, e.g., using phased array techniques, and may include a readout circuit for collecting detection data from the plurality of sensor units **1001** to **100n**.

An exemplary design of the resonator circuit **60** according to some embodiments of the present disclosure is shown in **Fig. 4**. The resonator circuit was fabricated on
30 ceramic-PTFE composite PCB bored including first and second split rings having chosen parameters of: Radius $R=2.9\text{mm}$, Width $w=1\text{mm}$, gap separation $g_s=0.4\text{mm}$, gap to lead $g_c=0.1\text{mm}$, and vertical distance between the split rings is 2.2mm . This specific and not-limiting exemplary configuration was tested by simulation and experimental study to

analyze parameters of magnetic field generated thereby. The resonator circuit parameters were selected to provide resonance frequency around resonance frequency of NV centers in diamond that is 2.87GHz.

The simulations were conducted using a commercial finite elements
5 electromagnetic analysis package (CST). The simulations were used to extract data on the S11 parameter relating to reflection coefficient, and the magnetic field at the center along the normal axis (z), as a function of the exciting frequency.

In the simulation, a crystal structure having thickness of about 0.5mm was simulated to be positioned within the resonator circuit. The crystal structure was excited
10 by laser excitation, exemplified by light source 90 in **Fig. 2**, directed through a selected one of the split rings. This configuration provides an effective excitation volume having a generally cylindrical shape with a height of 0.5 mm and a diameter between 0.1mm and 1.5mm.

Reference is made to **Figs. 5 to 7** showing parameters of the magnetic field
15 excitations generated by the resonator circuit of the present disclosure. **Fig. 5** shows z component of microwave excitation generated by the resonator circuit **60**; **Fig. 6** shows S11 response relating to reflection of electrical excitation transmitted to the resonator circuit; and **Fig. 7** shows the effect of variation in resonator circuit parameters and respective resonance frequency.

As shown in **Fig. 5**, the excitation field generated by the resonator circuit forms
20 an excitation field that is generally uniform within the cylindrical volume. The simulations include excitation transmitted through one or both of the split rings such that the average magnetic field within the cylindrical volume was determined to be 1.5Gauss/ $\sqrt{\text{Watt}}$ for single ring excitation, and 2Gauss/ $\sqrt{\text{Watt}}$ for excitation through both
25 rings. Further, Inhomogeneity of the excitation field (providing microwave drive) is defined herein as the standard deviation of the magnetic field, normalized by its mean value. Simulation of the resonator circuit described herein indicate an inhomogeneity of 0.43% for diameter of 0.5mm and excitation transmission through both the split ring (dual drive), or 0.71% for similar diameter and excitation transmission through one of the split
30 rings (single drive). These results show that although improved results are obtained with simultaneous excitation of both split rings, coupling between the first and second split rings in the resonator circuit provide efficient excitation with relatively high homogeneity. Field homogeneity in response to excitation through one of the split rings

may allow to simplify calibration of excitation power and phase for two channels. This is while such calibration may be needed to drive the first and second split rings to provide similar current directions and enhance the excitation field in the case of dual drive, i.e., simultaneous excitation of the first and second split rings.

5 **Fig. 6** shows reflection (**S₁₁**) curve for excitation as a function of excitation frequency and so-generated excitation field magnitude (**H_z**). As shown the resonator circuit provides different resonances. The resonance of lower frequency (**R₊**) is symmetric with both loops driven by current along the same direction. The higher frequency resonance (**R₋**) is anti-symmetric with current driving in opposite directions in
10 the two rings. As a result, the symmetric resonance **R₊** generates magnetic field along the normal axis as shown in **B_z** graph. This is while current directions in the **R₋** resonance cancel the z component of the magnetic field at location of the crystal structure.

Fig. 7 exemplifies results of simulation data on variation in the effect of several parameters on the position of the symmetric resonance **R₊**. The parameter varied include
15 radius of the split rings, width, distance between the split rings along the z axis (distance between planes) and width of the slit/gap of the split rings. As shown, variation of split rings radius leads to the most significant variation in resonance frequency of the resonator circuit. As shown in this not-limiting example, Radius variation leads to a sensitivity of the resonance to the radius of 1006MHz/mm, while the greater the radius,
20 the lower the resonance frequency. Additional design parameters that vary the resonance frequency include the distance between the first and second split rings that generate resonance frequency sensitivity of 67MHz/mm, variation of the width of the strip of the first and second split rings that varies the resonance frequency with sensitivity of -136MHz/mm, and the gap defined by the split in the split rings that varies the resonance
25 frequency with a sensitivity of 366MHz/mm. Thus, selection of resonator parameters and variation thereof may be used for tuning resonance frequency of the resonator. While the specific sensitivity to selected parameters may vary with specific resonator design, this exemplary data may suggest design parameters for optimization of the resonance frequency.

30 **Experiments**

 To conduct experimental study of the resonator circuit described herein. The circuit was fabricated on printed circuit board. In this example the circuit was fabricated on Rogers 6010.2LM PCB board selected for its high dielectric constant. The fabricated

circuit is designed as illustrated in **Fig. 4** above. Resonator circuit parameter were selected to be Radius $R=2.9\text{mm}$, Width $w=1\text{mm}$, gap separation $gs=0.4\text{mm}$, gap to lead $gc=0.1\text{mm}$ based on simulation data, providing resonance frequency of 2.87GHz .

The fabricated resonator circuit was used for several characterization
 5 measurements performed using a scanning confocal microscope on a relevant, high NV density diamond sample. Optical excitation was provided by a 532nm diode-pumped solid-state (DPSS) laser (Laser Quantum axiom 532) focused onto the diamond using a $10\times$, 0.25NA objective. The excitation laser was pulsed by focusing it through an acoustic-optical modulator (G&H R15260). NV fluorescence was collected through the
 10 same objective and separated from the excitation beam using a dichroic filter (Semrock Di02-R635- 25X36). The light was additionally filtered (using a Thorlabs high-pass FELH0650 and notch NF533-17) and focused onto a single-photon counting module (Excelitas Technologies SPCM-780-13-FC).

The resonator was driven by an amplified (Minicircuits ZHL-16W-43-S+) MW
 15 generator (Windfreak synthHD) and modulated by a switch (Mini-circuits ZASW-2-50DRA+). Microwave and optical pulses were controlled using a computer-based digital delay generator (Swabian Instruments Pulse-Streamer). Measurement protocols (pulse sequences, data acquisition, etc.) were controlled by custom software.

The static magnetic field was applied with a permanent magnet whose distance
 20 and position relative to the NV center were controlled by three translation stages. The diamond position was controlled by 3 piezo-electric stages. The diamond sample used in these experiments was model DNV-B1 (Element Six), with an NV density of $\sim 300\text{ppb}$.

The resonator circuit was first characterized using a MW network analyzer, measuring the resonance and S parameters. **Figs. 8** shows experimental ring down
 25 measurement of a resonator having Radius $R=2.95\text{mm}$. **Fig. 9** shows characteristic Rabi oscillations of NV center in the resonator circuit. **Fig. 10** shows measurement of magnetic field inside the resonator as a function of input power. **Fig. 11** shows measured reflection coefficient (S_{11}) for resonators having different ring radius.

In the measurements, Q factor was extracted from the S_{11} curves (**Fig. 11**) and
 30 was found to range between 121 and 146 for resonators of different radii. Similarly, the resonator bandwidth was measured to range between 19 and 23 MHz.

The Rabi oscillations were measured in order to analyze the field homogeneity. A characteristic Rabi oscillation curve at a power of 9Watt is shown in **Fig. 9**. The magnetic

field generated by the resonator was measured at 8 different points at different distances from the axial center as shown in Fig. 10 for dual-port drive (solid) and single-port drive (dashed) and for different input power. These measurements show good agreement with the simulation for different design parameters indicating the ability to vary resonator parameters for selected resonance and field characteristics.

As indicated the Rabi frequency was determined at a plurality of points inside the resonator. The selected measurement points were arranged at equal distances from the center along a radial axis of the resonator. Measurement at each point was repeated for 4 points along the Z axis. Each point was measured both with dual drive excitation and with a single port. Finally, the standard deviation for each radius was determined with a weight term that takes into account the different distances between the points.

Fig. 12 shows simulated, and experimental field inhomogeneity of the magnetic field measured within the resonator circuit.

The experimental results shown in **Figs. 8 to 12**, show very good agreement with the simulations as a function of the different design parameters, including the resonance position, the effect of the ring radius, and the magnetic field amplitude. For example, the measured homogeneity agrees with simulations and is relatively high, being below 0.7% inhomogeneity at a diameter of 0.5mm for both single and dual drive excitations.

Thus, the present disclosure provides a sensor unit and a resonator circuit configured to provide a generally uniform magnetic field excitation. The resonator circuit is capable of applying uniform magnetic field excitation to an ensemble of color centers, such as NV centers, thus allowing for sensor with increased sensitivity and specificity.

It is to be noted that the various features described in the various embodiments can be combined according to all possible technical combinations.

It is to be understood that the invention is not limited in its application to the details set forth in the description contained herein or illustrated in the drawings. The invention is capable of other embodiments and of being practiced and carried out in various ways. Hence, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting. As such, those skilled in the art will appreciate that the conception upon which this disclosure is based can readily be utilized as a basis for designing other structures, methods, and systems for carrying out the several purposes of the presently disclosed subject matter.

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Those skilled in the art will readily appreciate that various modifications and changes can be applied to the embodiments of the invention as hereinbefore described without departing from its scope, defined in and by the appended claims.

CLAIMS:

1. A sensor unit comprising at least one crystal structure comprising an ensemble of color centers, and a resonator arrangement for applying selected magnetic field on said ensemble of color centers; said resonator arrangement comprises a first split ring having
5 a first diameter and a second split ring having a second diameter; wherein said first split ring and said second split ring are positioned within first and second parallel planes, and wherein said at least one crystal structure is located in an intermediate plane between said first and second parallel planes.
2. The sensor unit of claim 1, wherein said first and second split rings define a virtual
10 cylindrical space between them and said at least one crystal structure is located within volume of said virtual cylindrical space.
3. The sensor unit of claim 1 or 2, wherein said at least one crystal is a diamond crystal, and said ensemble of color centers comprise a plurality of Nitrogen Vacancy centers within said diamond crystal.
- 15 4. The sensor unit of any one of claims 1 to 3, wherein a gap within said first split ring and a gap within said second split ring are placed at opposing orientations.
5. The sensor unit of any one of claims 1 to 4, wherein a gap within said first split ring and a gap within said second split ring are placed at 180 degrees respective orientation.
- 20 6. The sensor unit of any one of claims 1 to 5, wherein a distance between said first and second parallel planes is in a range between 0.1mm and 20mm.
7. The sensor unit of any one of claims 1 to 6, wherein a distance between said first and second parallel planes is 0.5 ± 0.05 mm.
8. The sensor unit of any one of claims 1 to 7, wherein said first and second diameters
25 of said first and second split rings are similar.
9. The sensor unit of any one of claims 1 to 8, wherein said first and second diameters of said first and second split rings are in a range between 0.5mm and 20mm.
10. The sensor unit of any one of claims 1 to 9, formed on a printed circuit board (PCB).
- 30 11. The sensor unit of any one of claims 1 to 10, wherein said first and second split rings form the resonator arrangement having resonance frequency within a range between 0.5GHz and 50GHz.

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12. The sensor unit of any one of claims 1 to 11, further comprising a first lead associated with said first split ring and a second lead associated with said second split ring, said first and second leads provide excitation signal to respective one of said first and second split rings.
- 5 13. The sensor unit of claim 12, further comprising at least one microwave signal generator connected using one or more switches to said first and second leads for driving said first and second split rings with one or more selected signals.
14. The sensor unit of any one of claims 1 to 13, further comprising at least one laser unit and optical arrangement adapted to provide selective optical excitation of said at least
10 one crystal.
15. The sensor unit of any one of claims 1 to 14, further comprising a magnetic field generator adapted to provide static magnetic field onto said at least one crystal.
16. The sensor unit of claim 15, wherein said magnetic field generator is adapted to selectively vary magnitude of said static magnetic field.
- 15 17. The sensor unit of any one of claims 1 to 16, further comprising an optical collection arrangement and at least one detectors, said optical collection arrangement is positioned for collecting optical emission from said ensemble of color centers in said at least one crystal and direct said optical emission to be detected by said at least one detector.
- 20 18. A sensor array system comprising an array of sensor units comprising at least one sensor unit configured according to any one of claims 1 to 17.
19. A sensor array system comprising an array of sensor units each sensor unit being configured according to any one of claims 1 to 17.
20. A resonator circuit for applying electromagnetic excitation onto an ensemble of
25 color centers comprising:
- a. first and second split rings having respective first and second diameters; said first and second split rings are positioned within respective first and second parallel planes, and at least one crystal structure carrying said ensemble of color centers located in an
30 intermediate plane between said first and second parallel planes.
21. The resonator circuit of claim 20, wherein said first and second split rings are configured as an electrically conducting rings having a gap forming discontinuity in conductivity along circumference of the rings.

22. The resonator circuit of claim 20 or 21, wherein said ensemble of color centers is located within at least one diamond crystal, and said ensemble of color centers comprise a plurality of Nitrogen Vacancy centers within said diamond crystal.
23. The resonator circuit of any one of claims 20 to 22, wherein a gap within said first
5 split ring and a gap within said second split ring are placed at opposing orientations.
24. The resonator circuit of any one of claims 20 to 23, wherein a gap within said first split ring and a gap within said second split ring are placed at 180 degrees respective orientation.
25. The resonator circuit of any one of claims 20 to 24, wherein a distance between
10 said first and second parallel planes is in a range between 0.1mm and 20mm.
26. The resonator circuit of any one of claims 20 to 25, wherein a distance between said first and second parallel planes is 0.5 ± 0.05 mm.
27. The resonator circuit of any one of claims 20 to 26, wherein said first and second diameters of said first and second split rings are similar.
- 15 28. The resonator circuit of any one of claims 20 to 27, wherein said first and second diameters of said first and second split rings are in a range between 0.5mm and 20mm.
29. The resonator circuit of any one of claims 20 to 28, wherein said resonator circuit is formed on a printed circuit board (PCB).
30. The resonator circuit of any one of claims 20 to 29, wherein said first and second
20 split rings form a resonator having resonance frequency within a range between 1GHz and 100GHz.
31. The resonator circuit of any one of claims 20 to 30, further comprising a first lead associated with said first split ring and a second lead associated with said second split ring, said first and second leads provide excitation signal to respective one of said first
25 and second split rings.
32. The resonator circuit of claim 31, further comprising at least one microwave signal generator connected using one or more switched to said first and second leads for driving said first and second split rings with one or more selected signals.
33. The resonator circuit of any one of claims 20 to 32, further comprising at least one
30 laser unit and optical arrangement adapted to provide selective optical excitation of said at least one crystal.
34. The resonator circuit of any one of claims 20 to 33, further comprising a magnetic field generator adapted to provide static magnetic field onto said at least one crystal.

35. The resonator circuit of claim 34, wherein said magnetic field generator is adapted to selectively vary magnitude of said static magnetic field.
36. The resonator circuit of any one of claims 20 to 35, further comprising an optical collection arrangement and at least one detector, said optical collection arrangement is
5 positioned for collecting optical emission from said ensemble of color centers in said at least one crystal and direct said optical emission to be detected by said at least one detector.
37. A sensor array system comprising an array of resonator circuits comprising at least one sensor unit configured according to any one of claims 20 to 36.
- 10 38. A sensor array system comprising an array of resonator circuits each resonator circuits being configured according to any one of claims 20 to 36.
39. A method for use in operation of electromagnetic sensor comprising an ensemble of color centers, the method comprising:
- 15 a. providing a first split ring at a first plane at one side of said ensemble of color centers, where axial center of said first split ring aligns with center of said ensemble of color centers;
 - b. providing a second split ring at a second plane at an opposite side of said ensemble of color centers, where axial center of said second split ring aligns with center of said axial center of said first split ring;
 - 20 c. providing selected excitation signal to said first and second split rings thereby applying corresponding selected magnetic field excitation to said ensemble of color centers, to thereby initiate said ensemble of color center at selected state for sensing electromagnetic signal impinging thereon.
- 25 40. The method of claim 39, wherein said ensemble of color centers is an ensemble of Nitrogen Vacancy centers within a diamond.