



- (51) International Patent Classification:
G01N 24/08 (2006.01) G01R 33/62 (2006.01)
G01R 33/60 (2006.01)
- (21) International Application Number:
PCT/GB2014/052289
- (22) International Filing Date:
25 July 2014 (25.07.2014)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
1313601.5 30 July 2013 (30.07.2013) GB
- (71) Applicant: THE UNIVERSITY OF WARWICK
[GB/GB]; University House, Kirby Corner Road, Coventry
Warwickshire CV4 8UW (GB).
- (72) Inventors: MORLEY, Gavin William; 12 The Meadway,
Milton Keynes Buckinghamshire MK5 8AN (GB). NEW-
TON, Mark Edward; 131 Woodcote Avenue, Kenilworth
Warwickshire CV8 1BE (GB).

(74) Agent: FORSYTHE, Dominic; 14 South Square, Gray's
Inn, London, Greater London, WC1R 5JJ (GB).

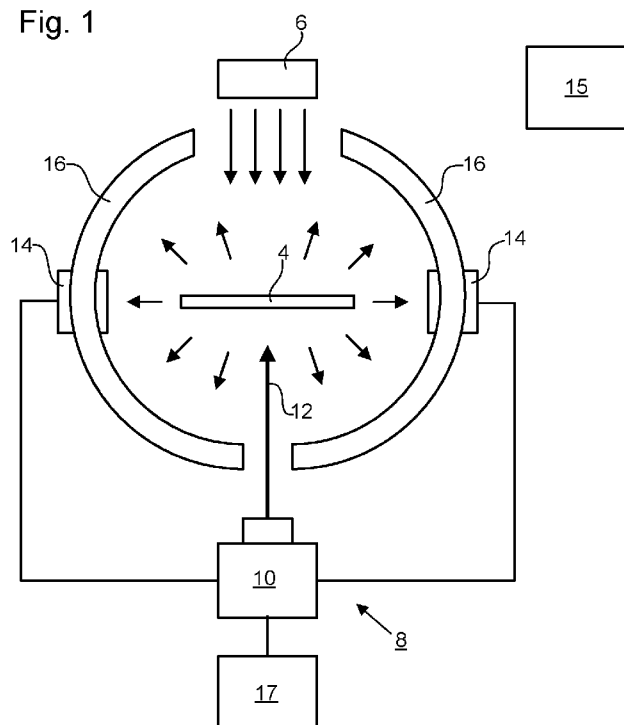
(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,
BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM,
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR,
KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME,
MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,
SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM,
TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM,
ZW.

(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ,
UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ,
TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,
EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,
MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM,
TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW,
KM, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: SENSITIVE DETECTOR

Fig. 1



(57) Abstract: Detectors and methods for detecting electro-
magnetic radiation and/or EPR/NMR are disclosed, which
exploit the electron-spin-dependent fluorescence of a colour
centre in a solid. In one example, a detector comprises a sub-
strate arranged to receive an input radiation to be detected
and comprising a colour centre of a type that exhibits elec-
tron-spin-dependent fluorescence, and a spin measurement
section for probing the spin state of the colour centre using
fluorescence, thereby detecting input radiation that is such as
to change the spin state of the colour centre.



Published:

— with international search report (Art. 21(3))

— before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))

SENSITIVE DETECTOR

The present invention relates to a detector for electromagnetic radiation and/or EPR/NMR (electron paramagnetic resonance/nuclear magnetic resonance), which exploits the electron-spin-dependent fluorescence of a colour centre in a solid. The detector may be used in a wide range of applications, including as part of a communication system or as part of an imaging, EPR or NMR system. The detectors can be selectively tuned to be sensitive to frequencies in the range of 1 Hz to 10 THz.

Many existing devices require detectors operating within this frequency range and would benefit from a detector having higher sensitivity. Higher sensitivity may allow detection of signals that would otherwise not have been detectable, detection of signals at lower cost, transmission of information at higher rates and/or transmission of data at lower powers. Reducing the power requirements for data transmission saves energy and, in portable devices, may usefully prolong battery life or allow a smaller battery to be used.

Examples of devices requiring such detectors include mobile phones, mobile phone base stations, radar (including weather radar), WiFi devices, cordless telephones, wireless headphones, video senders, walkie talkies, Bluetooth, telemetry, GPS, astronomy and imaging.

Detectors for performing single-molecule NMR experiments need to be highly sensitive to the magnetic field originating from individual atoms of the molecule under study. It has been proposed [23, 24] that the NMR of single molecules could be studied by using a single nitrogen vacancy (NV) centre in diamond as a scanning magnetometer. In the proposed methodology the scanning is performed at low magnetic field, which involves considerable spectral overlap between different NMR resonances. This is addressed by scanning the magnetometer around in real space so that it sequentially visits each nucleus. However, the scanning procedure is slow and nuclei in the middle of a large molecule are inaccessible to the magnetometer.

It is an object of the invention to at least partially address one or more of the challenges described above.

According to an aspect of the invention, there is provided a detector, comprising: a substrate arranged to receive an input radiation to be detected and comprising a colour centre of a type that exhibits electron-spin-dependent fluorescence; and a spin measurement section for probing the spin state of the colour centre using fluorescence, thereby detecting input radiation that is such as to change the spin state of the colour centre.

The present invention thus exploits the fact that certain colour centres in solids exhibit electron-spin-dependent fluorescence at relatively high frequencies (for example at optical frequencies), and that electromagnetic radiation with a lower frequency (for example lower than optical frequencies, for example microwave frequencies) can flip these spins via magnetic resonance, to provide a practical device that is capable of sensitively detecting the presence of the lower

frequency electromagnetic radiation. It is generally the case that higher frequency photons can be detected more sensitively than lower frequency photons, so converting the lower frequency input photons to higher frequency ones tends to increase the sensitivity with which they can be detected. In the case where the higher frequency photons are optical photons, for example, it is well known that there are a wide variety of devices capable of detecting optical photons with very high sensitivity. The frequency sensitivity of the detector can be tuned by applying an appropriate magnetic field to the colour centres. The magnetic field changes the separation between energy levels associated with different electron spin states, which results in a change in the frequency or frequencies of magnetic resonance.

The spin state of an NV^- centre in diamond for example can be changed by a single microwave photon, which can then be detected using an optical detector due to the spin-dependent fluorescence of the NV^- centre. It is relatively routine to measure single optical photons, whereas single microwave photons cannot currently be detected with room temperature equipment because the energy of a microwave photon is over 100,000 times less than that of a single optical photon. Single microwave photons can be detected with advanced equipment based on superconducting electronics, but this requires cooling to liquid helium temperature of 4K (or below) which is impractical for large-scale commercial applications. A detector according to an embodiment of the present invention, using for example an NV^- centre in diamond, can work efficiently at room temperature (and pressure).

In an embodiment, the detector is used in a communication device, such as a mobile phone or mobile phone base station. Frequencies currently used most commonly in this context are around 0.9 – 2 GHz. The use of the detector in the base-station could greatly reduce the amount of power that a mobile phone needs to transmit, due to its increased sensitivity, thus reducing the power consumption of the device. The extra detection sensitivity would also allow more data to be transmitted.

In an embodiment, the detector is used to detect the radiation absorbed or emitted in a magnetic resonance experiment. For nuclear magnetic resonance (NMR) the frequencies currently used most commonly are around 0.1 – 1 GHz. For electron paramagnetic resonance (EPR) the frequencies currently used most commonly are 1 – 100 GHz. The detector can be tuned to be sensitive to these frequencies by appropriate application of an external magnetic field.

In other embodiments, the detector is used in a radar (including weather radar), WiFi, cordless telephones, wireless headphones, video senders, walkie talkies, Bluetooth, telemetry, GPS, astronomy and imaging.

According to an alternative aspect of the invention, there is provided an apparatus for carrying out nuclear magnetic resonance, comprising: a magnet configured to generate a magnetic field of equal to or greater than 5T in a test region of the magnet; and a probe comprising a sample receiver for receiving a sample, the probe being insertable into the magnet so as to position the sample receiver in the test region, wherein the probe comprises: a substrate comprising a colour centre of a type that exhibits electron-spin-dependent fluorescence, the colour centre being positioned so as to be directly

adjacent in use to a sample in the sample receiver; a first coupling system for directing first electromagnetic radiation to the colour centre to control the electron spins of the colour centre using electron paramagnetic resonance and a second coupling system for directing second electromagnetic radiation to the sample in order to control the nuclear spins of the sample using nuclear magnetic resonance; and a third coupling system for directing third electromagnetic radiation to and from the colour centre in order to measure a change in the fluorescence of the colour centre resulting from a contribution to the magnetic field at the colour centre from one or more nuclei of the sample that are closest to the colour centre.

Thus, according to this embodiment colour centres are used as the basis for sensitive magnetometers in a high field NMR system. In an embodiment, the colour centres are used for single-molecule NMR. In an embodiment, a plurality of the colour centres are used to simultaneously probe different molecules in a sample of many molecules which may be identical. The different identical molecules will be oriented differently with respect to their respective detectors, so different parts of the molecule will be studied by each detector. This approach greatly increases the throughput of single-molecule NMR experiments.

The invention will be further described by way of example with reference to the accompanying drawings in which:

Figure 1 depicts an example configuration in which microwave input radiation is directed to a substrate containing colour centres and the resulting optical fluorescence measured;

Figure 2 depicts an alternative example configuration in which a substrate contains a plurality of the colour centres and a branched system of wires for directing input radiation to each of the colour centres;

Figure 3 depicts an example of a resonator for focusing input radiation onto a colour centre; and

Figure 4 depicts an example of a sample receiver comprising a plurality of colour centres and associated optical fibres for performing fluorescence measurements.

In the specific example shown in Figure 1, a detector is provided that has a substrate 4, a coupling device 6 and a spin measurement section 8. The substrate 4 comprises a plurality of colour centres that are each of a type that exhibits electron-spin-dependent fluorescence. In other embodiments, a substrate may be provided that has only one colour centre or a plurality of different substrates may be provided that each comprise one or a plurality of colour centres. The colour centres may all be of the same type or some or all of them may be of different types. The coupling device 6 is configured to direct an input radiation beam to be detected to the colour centres in the substrate 4. The coupling device 6 may comprise a waveguide, an antenna, a resonator, one or more reflectors, or any combination of these, for example. In other embodiments, a coupling device 6 is not provided, with the substrate 4 being instead directly exposed to the input radiation.

In an embodiment, the spin measurement section 8 is configured to output a measure of the phase and/or intensity and/or frequency of the input radiation, based on the fluorescence. In an embodiment, the spin measurement section 8 is configured to output a measure of the phase and/or intensity and/or frequency as a function of time. The output may be provided for example by measuring the rate at which spins are flipped in a given colour centre or in a plurality of colour centres, for example.

The frequency could be measured by a) having different colour centres which undergo EPR at different frequencies and/or b) by applying different magnetic fields to tune the EPR resonant frequency of the colour centres. The different magnetic fields could be applied sequentially to one or more colour centres and/or the tuning magnetic fields could be kept constant in time but chosen to be different for different colour centres. The amplitude of the signal could be detected by observing the nutation rate (Rabi oscillation frequency) of the colour centre spin(s). The intensity can be calculated from the amplitude. The phase of the signal could be detected by measuring the signal amplitude relative to the phase of a reference signal applied to the colour centres and using standard methods of phase-sensitive detection [David M Pozar, Microwave Engineering, John Wiley & Sons; 4th Edition (2011)].

In an embodiment, a magnetic field control system 15 is provided for controlling the magnetic field in the region of the colour centre or centres to control the absorption spectrum (i.e. the magnetic resonance frequencies) of the colour centre or centres. The magnetic field control system may be used to make the detector sensitive to one or more frequencies in the range of 1 Hz to 10THz, for example.

In an embodiment, the detector is used as part of a communication apparatus. In such an embodiment, the detector may further comprise a demodulator 17 for receiving the output from the spin measurement section and extracting therefrom information that was modulated onto the input radiation.

In this particular example, the substrate 4 is provided in the form of a wafer, which has a thickness in the direction parallel to the input direction of the radiation that is several orders of magnitude smaller than the dimensions of the substrate perpendicular to the direction of incidence. This geometry tends to increase the chance that one of the photons to be detected hits the detector without making it unduly difficult for optical photons to enter and leave the substrate (for the purposes of measuring the fluorescence – see below). However, other geometries of substrate may be used.

In the embodiments shown, the spin measurement section 8 comprises an input radiation source 10 for directing input radiation 12 for fluorescence onto the substrate 4 and detectors 14 for detecting the resultant fluorescence. In the particular geometry shown fluorescent photons emerge in all directions so conventional optics such as mirrors (shown schematically as elements 16) could be

used to collect as many as possible on the detectors 14. Standard techniques such as the use of a holographic notch and red pass filter could be used to suppress stray light [2].

In an embodiment, the input radiation 12 for fluorescence can be polarised to assist with suppression of stray light. For example, the colour centres could be excited with linearly polarised light and some of the detected fluorescence would then be orthogonally polarised with respect to the excitation, enabling efficient filtering with a polariser. For this polarisation-sensitive detection it is desirable for the colour centres to be aligned with each other. Lower excitation power has been found experimentally and theoretically to provide higher contrast and hence greater sensitivity to the photons to be detected (see pages 17-24 of PhD thesis reference [13]).

Aligning the colour centres with each other also ensures that they behave in the same manner with respect to the radiation to be detected. This will tend to increase measurement sensitivity. However, in other embodiments the plurality of colour centres may comprise colour centres having different orientations. The different orientations would be sensitive to different excitations (i.e. radiation at different wavelengths), which may increase the range of frequencies of input radiation that can be detected with high sensitivity. The variation in performance arises due to the different orientations of the colour centres relative to any external magnetic field. The size of the energy splitting between different spin states depends on the orientation of the external magnetic field relative to the orientation of the colour centre.

According to an embodiment, the detector is configured to operate at room temperature, which is convenient for many applications. However, reducing the temperature of the colour centres will tend to increase the sensitivity of the optically-detected magnetic resonance (ODMR) process [5], so would provide an even more sensitive detector. Some applications demand temperatures above room temperature, which would also be compatible with embodiments of the invention.

In an embodiment, the colour centre is a nitrogen vacancy (NV^-) colour centre in diamond.

NV^- colour centres in diamond exhibit electron-spin-dependent fluorescence allowing the measurement of ODMR [1]. Developing this technique has permitted single NV^- centres to be studied with high sensitivity [2-4]. In zero magnetic field the frequency needed to drive the magnetic resonance (also referred to as electron paramagnetic resonance, EPR) transition is 2.88 GHz. In a magnetic field, the required frequency is around 28 GHz per Tesla of applied magnetic field ± 2.9 GHz. By aligning a small external magnetic field such that it opposes the internal crystal field (which produces the zero-field splitting), frequencies below 2.88 GHz are required to drive EPR. Other ways to tune this frequency include the application of strain and electric fields. It is possible to tune the frequency to which the detector is sensitive to anywhere from 1 Hz to 10 THz, both for NV^- colour centres in diamond, and other colour centres.

Alternative colour centres to the NV^- in diamond include, but are not limited to:

- other vacancies and vacancy-related centres in diamond [14]
- the silicon-vacancy centres in diamond [15, 16]

- the NE8 centre in diamond [4]
- chromium-related centres in diamond [17, 18]
- colour centres in silicon carbide [19]
- colour centres in solids other than diamond including crystals such as quartz and amorphous solids such as amorphous SiO₂
- all of the centres and defects mentioned in the review article by Bridges et al [20] and the book by Field [21]
- any other centre in a solid, particularly those which have an ODMR signal.

Anywhere that NV⁻ centres are referred to in this document, one or more of these alternatives could be used instead. Furthermore, the use of multiple coupled centres may be more sensitive, so these could also be used instead of NV⁻ centres. Anywhere that diamond is referred to, one or more of these hosts (such as quartz) could be used instead. More than one of these centres could be combined in the same or different host materials to increase the sensitivity and/or permit detection of more than one frequency.

Noise photons which exist at the fluorescence frequency may limit the sensitivity of the detector. If there are many centres fluorescing and only one of these absorbs a photon to be detected, then the fluorescence of the other centres may prevent detection. For this reason, it could be advantageous to use a single centre. However, this approach leads to a greatly reduced dynamic range (the output signal is only one bit). Additionally, it can be challenging to direct the photons one wants to detect onto the tiny (atomic scale) colour centre.

Figure 2 is a schematic illustration of a detector which addresses the above issues by providing a substrate 4 having a plurality of colour centres and a coupling device that is configured to direct input radiation directly to all of the plurality of colour centres. The provision of a plurality of colour centres increases the dynamic range, and a coupling device 6 directs incoming radiation specifically to the plurality of colour centres. In the particular example disclosed, the coupling device 6 comprises an antenna 6C, a coaxial cable 6B and a branched system of wires 6A embedded on or within the substrate 4. In the embodiment shown, the input radiation will be captured by the antenna 6C, conveyed to the branched system of wires 6A by the coaxial cable 6B and directed to individual colour centres located at the tips of the branches of the branched system of wires 6A. The tip region 20 of one of the branches is shown in a magnified inset 20. In this embodiment, a single colour centre 22 is provided in the region of the tip with dedicated optics 24 for probing the spin-dependent fluorescence of the colour centre. The optics 24 may comprise optical excitation and detection devices and/or lenses to direct the exciting and/or emitted radiation to their respective targets. The optical excitation and detection could consist of one or more excitation sources (such as a green laser) which could be split up, for example, to excite all of the different single colour centres (or separate sources could be used for each of the colour centres or subsets of the colour centres). In an embodiment, the optical detection comprises one or more detectors for the emitted radiation (such as

avalanche photo-diodes) to which the signals from all of the different single colour centres could be routed.

In the embodiment shown in Figure 2, the coupling device 6 comprises a metal wire split into a system of branches 6A within the substrate 4. This could be achieved using standard lithography techniques, for example, such as optical or electron-beam lithography. In an embodiment, the wires may be formed so as to be about 10 microns wide and 100 nm thick, for example. In other embodiments, different structures (e.g. waveguides) may be formed within the substrate 4 for directing the input radiation onto the colour centres.

In an embodiment, a resonator 25 is provided, for example as a replacement of a portion of the wire in each of one or more of the tip regions of the branched structure shown in Figure 2. The resonator 25 may be of the type illustrated in Figure 3 for example, comprising two parallel, conducting lines 26 and 28 connected to a conducting loop 27. This design is a variant of the commonly used loop-gap resonator [6]. The radius of the loop, r , can be chosen to be relatively small (e.g. 10 microns) so as to concentrate the magnetic field associated with the input radiation as much as possible onto the atomic-scale colour centre. Using such small sized loops tends to increase the resonant frequency of the resonator above the resonant frequency of the colour centre (for example, in the region of about 3GHz for NV^- colour centres in diamond in low magnetic fields), but the frequency can be brought back down to any desired value by adding extra capacitance. This can be achieved by increasing the length L of the resonator, for example, or in other ways, such as by putting in a capacitor of chosen value connecting the two wires 26 and 28. The resonator 25 could be made with 1, 2 or a multitude of stacked planar structures. The two parallel lines 26 and 28 in Figure 3 could be in the same plane as the loop 27, or stacked on top of each other with a dielectric material in between. The resonators 25 can be above and/or below the colour centre. The resonators for different colour centres could be the same, to increase the coupling strength, or different so as to have different resonant frequencies (thereby increasing the bandwidth of operation of the detector 2).

Academic papers providing further details of the use of such micrometer-scale resonators in a general sense can be found in references [7-12].

The typically required dimensions of the resonator 25 (involving length scales of the order of 5-10 microns for example) allow convenient fabrication using optical lithography. These length scales are also convenient having regard to the diffraction limit of visible light for ODMR readout (it is hard to focus light down to much less than its wavelength), as well as for the skin depths of the radiation to be detected (e.g. microwaves) in metal (the metal should generally be thicker than the skin depth to avoid too much of the input radiation power passing right through the metal). However, in principle any length scale is appropriate.

In an embodiment, the detector is configured for use in an apparatus for performing electron paramagnetic resonance (EPR) imaging. In such a configuration, the detector is configured to detect the radiation absorbed or emitted due to EPR in the object being imaged.

EPR is also known as electron spin resonance (ESR) and electron magnetic resonance (EMR). Most electron spins have a g -factor of around 2, meaning that the frequency needed to drive EPR is around 28 GHz per Tesla of magnetic field applied. For the detector 2 to be sensitive to this frequency, it is required that the magnetic field experienced by the colour centres should be adjusted to meet the ODMR resonance condition. When the sample is in a large magnetic field of 1 T or more, this could be achieved simply by placing the colour centres slightly outside of the field-centre of the magnet used for the EPR.

More generally, it is necessary to be able to detect EPR spectra rather than being restricted to just one g -factor. This could be achieved by including a magnet coil around the colour centres so as to change their local magnetic field relative to that at the sample. This coil would tend to also change the magnetic field at the sample, but by a lesser amount. This error could be removed in the software as long as it was first measured for a standard sample (with a known g -factor and a small linewidth) as a function of the magnetic field applied to the NV^- centres. Another approach would be to have such a standard sample permanently present next to the sample and measure its EPR again when the magnetic field applied to the colour centres is changed.

For any EPR experiment it is possible for the detection to be performed *in transmission* (where the microwaves pass through the sample to the detector) or *in reflection* (where the microwaves are reflected from the sample to the detector with or without the aid of a circulator to reduce the microwaves coming directly to the detector from their source). Embodiments of the detector could be used with both configurations.

In a continuous-wave EPR experiment one could continuously illuminate the colour centres with optical light and observe the changes in the fluorescence that occur as the sample absorbs some of the radiation (e.g. microwaves) that is impinging on it. The EPR signal would then appear as a reduced fluorescence because of a reduced intensity of radiation reaching the detector. If a tuned microwave resonator is used then the absorption of radiation by EPR in the sample may mean that the resonator is no longer tuned resulting in an increase in radiation reaching the detector. In either case, the experiment could be performed with chopped or pulsed optical illumination and lock-in or boxcar fluorescence detection.

To perform a pulsed EPR experiment one could use the *free-induction decay* (FID) as the signal by sending in one radiation (e.g. microwave) pulse to the sample and measuring the radiation emitted by the sample. To avoid the unwanted signal due to the strong driving pulse of radiation, one could send in the optical-frequency photons to the colour centres to refresh them during (and/or for a short time after) the driving pulse. For this application it is desirable for the colour centres to refresh fast, on a timescale of ns. As NV^- centres do not refresh as fast as this, one may prefer other centres such as the silicon-vacancy centres [15, 16] or the vacancy-related defects [14]. To further avoid the unwanted signal due to the strong driving pulses one could use a spin echo sequence whereby two pulses separated by a time t produce an echo which is emitted from the sample after a time of

approximately t following the second pulse. The colour centres have time to refresh in this time period of t .

Any EPR experiment, including those in reference [22] could be performed with a detector according to an embodiment of the invention replacing the detection techniques used previously.

5 NMR experiments are performed more frequently than EPR because unpaired nuclear spins are more common than unpaired electron spins. Magnetic resonance imaging (MRI) is a popular example of NMR. Embodiments of the detector can be used for detecting NMR in a similar way to the EPR case described above. For a given magnetic field, the resonant frequency for NMR tends to be around 1000 times lower than for EPR. The magnetic field applied to the sample in an NMR
10 experiment is generally kept constant, in contrast to many EPR experiments.

The sensitivity of prior art detectors for the lower-frequency radiation (100-1000 MHz) used in NMR experiments is generally even worse than for current microwave detectors (used for EPR for example). This is due to the lower energy of MHz photons than GHz photons:

$$15 \qquad \qquad \qquad \text{Photon energy} = h \nu \qquad \qquad \qquad (1)$$

where h is Planck's constant (6.626×10^{-34} Js) and ν is the frequency of the radiation. The gain in sensitivity over existing detectors may therefore be even larger at these lower frequencies. Detecting these lower frequencies with NV⁻ centres for example, would use a (preferably aligned) magnetic field
20 of around 50 mT to access the anti-crossing between the $m_s = 0$ and $m_s = -1$ states of the electron spin triplet ground state (see Figure 3A in reference [3]).

These MHz frequencies are currently used extensively for radio and they benefit from long distance transmission because the long wavelengths are not heavily disturbed by hills and buildings or absorbed too strongly by water vapour in the air. However, the enhanced sensitivity possible using a
25 detector according to an embodiment of the invention could make them suitable for new applications such as mobile phones and indeed any of the other applications mentioned in this application. In an embodiment, a mobile phone and/or base station comprises a detector according to an embodiment of the invention that is tuned to detect input radiation of less than 700 MHz, preferably less than 500 MHz.

30 In the embodiments described above, the detector is configured to detect radiation having a frequency corresponding to the EPR frequencies of the colour centres involved. As discussed, these frequencies are dependent on the applied magnetic field. This allows the frequency sensitivity to be tuned so as to be appropriate to particular applications. However, the sensitivity to magnetic field can also be exploited directly by using the colour centres as sensitive magnetometers.

35 According to an embodiment, this effect is exploited to provide a detector (acting as a magnetometer) for use in single-molecule NMR following references [23] and [24]. In contrast to the application to NMR discussed above, where the detector was configured to detect radiation associated

with nuclear magnetic resonances, in the present embodiment a colour centre is used directly to detect a change in magnetic field at the colour centre caused by the magnetism (spin) of one or more nuclei that are brought into close proximity with the colour centres. The change in magnetic field is detected by monitoring a change in the EPR characteristics of the colour centre (e.g. by monitoring the
5 variation in fluorescence as a function of the frequency of applied microwave radiation.

In an embodiment, in order to speed up sampling of the different NMR resonances, the sample is subjected to a high magnetic field (e.g. > 5T, preferably >10T, 15T, 20T or 25T). The higher the applied magnetic field the greater the separation between different NMR resonances (the less these resonances will overlap spectrally), which allows for example the detector to distinguish
10 between resonances of different nuclei or nuclei in different environments.

In an embodiment, a sample 32 to be tested is mounted on a probe and inserted into the bore of a high field magnet. In an embodiment, the sample 32 is mounted or received in a sample receiver 30 that is configured to allow use of colour centres as magnetometers. The sample 32 may for example be adsorbed, as a dry solid, or may be in solution (but not rotating too quickly compared to
15 the experimental timescale). An example of such a configuration is shown in Figure 4.

In an embodiment, the sample receiver 30 comprises a substrate 34 comprising a plurality of colour centres 22 (see lower magnified inset 35, which is a magnified view of a portion of the sample receiver 30 at the interface between the sample 32 and the receiver 30). Each of the colour centres 22 is provided in close proximity to a different portion of the sample 32. In this way, the colour centres
20 22 will be influenced by molecules that have various different orientations relative to the colour centres, which allows the colour centres collectively to sample different nuclei and/or combinations of nuclei of the molecule under study at the same time. A coupling system 38 may be provided for directing electromagnetic radiation to the colour centres 22 and to the sample 32 in order respectively to control the electron spins of the colour centres using electron paramagnetic resonance and the
25 nuclear spins of the sample using nuclear magnetic resonance. The coupling system 38 may be referred to as a combination of a “first coupling system” (for directing electromagnetic radiation to control the spins of the colour centres) and a “second coupling system” (for directing electromagnetic radiation to control the nuclear spins), which may be integrated into a single coupling system (as shown) or may be separate coupling systems. In this particular embodiment, a plurality of optical
30 fibres 36 are provided in the sample receiver 30 for the purposes of individually probing the fluorescence of each of the different colour centres 22. The optical fibres 36 may be considered as part of a third coupling system. The upper magnified inset 37 depicts a magnified top view of a portion of the substrate receiver 30 and shows how the colour centres 22 can be provided in a two-dimensional array with dedicated loop-gap resonators 40 associated with each of the different colour
35 centres 22. It is understood that each of the colour centres 22 in the two-dimensional array shown in the inset 37 will have its own optical fibre 36 positioned beneath for probing the spin state of the colour centre 22 using fluorescence.

The approach of this embodiment allows single-molecule NMR experiments to be performed sensitively and efficiently (quickly).

The desirable static magnetic field for NMR is as high as possible to get more spectral resolution, but is currently limited to between 20 and 30 T by the cost of making high-field superconducting magnets. At these magnetic fields of 5 to 30 T, the frequency needed to excite the electron spins becomes high: 140 to 850 GHz. This frequency region is technologically inconvenient, but accessible with modern equipment. It is very convenient for making small loop-gap resonators with $r \sim 50 \mu\text{m}$ scale, as no extra capacitance is needed, allowing $L \sim 0$.

In an embodiment, the optical fibres 36 have a diameter of $100 \mu\text{m}$. Allowing one per colour centre, this would leave room for over 1000 single-molecule colour centre NMR spectrometers to be squeezed into a standard 4 mm diameter chip. Such a chip would fit into existing NMR spectrometers, simply by replacing the NMR probe (the magnets and consoles cost more than the probes). All of the colour centre spectrometers in the array would experience the same static magnetic field and RF field (a lower frequency for exciting the nuclear spins) because their homogeneity across several mm is standard practice in commercial NMR. The superconducting magnet would not need to be as homogeneous as existing NMR magnets as the sample in each experiment would be on the molecular scale over which the magnetic field would look very homogeneous in comparison with the mm-scale samples currently used. In one experiment, a sample would cover the 4 mm scale chip and NMR information about 1000 molecular orientations would come out simultaneously. Each of the colour centre spectrometers would see only the part of the molecule closest to it: the colour centre would only see 1-5 nuclei that are the closest to it, but these are coupled to others in the molecule which could be probed by sending in NMR pulses to find the resonances. Analysing this information with dedicated software would allow the puzzle pieces to be put together revealing the full shape of the molecule.

As indicated above, the detectors may be tuned to be sensitive to frequencies in the broad range of 1Hz to 10THz (although in other embodiments the invention may find use outside this range). However, in practice, the majority of applications will fall in the range 1MHz to 2 THz and, within this, the most preferred frequency range is 100MHz to 10GHz.

References

- [1] E. van Oort, N. B. Manson & M. Glasbeek, *Optically detected spin coherence of the diamond N-V centre in its triplet ground state*, Journal of Physics C-Solid State Physics **21**, 4385 (1988).
- [2] A. Gruber, A. Drabenstedt, C. Tietz, L. Fleury, J. Wrachtrup & C. von Borczyskowski, *Scanning confocal optical microscopy and magnetic resonance on single defect centers*, Science **276**, 1212 (1997).

- [3] P. Neumann, J. Beck, M. Steiner, F. Rempp, H. Fedder, P. R. Hemmer, J. Wrachtrup & F. Jelezko, *Single-Shot Readout of a Single Nuclear Spin*, *Science* **329**, 542 (2010).
- [4] J. Wrachtrup & F. Jelezko, *Processing quantum information in diamond*, *Journal of Physics-Condensed Matter* **18**, S807 (2006).
- 5 [5] F. Jelezko, I. Popa, A. Gruber, C. Tietz, J. Wrachtrup, A. Nizovtsev & S. Kilin, *Single spin states in a defect center resolved by optical spectroscopy*, *Applied Physics Letters* **81**, 2160 (2002).
- [6] W. Froncisz & J. S. Hyde, *The loop-gap resonator - a new microwave lumped circuit electron-spin-resonance sample structure*, *Journal of Magnetic Resonance* **47**, 515 (1982).
- [7] G. Boero, M. Bouterfas, C. Massin, F. Vincent, P. A. Besse, R. S. Popovic & A. Schweiger,
- 10 *Electron-spin resonance probe based on a 100 μ m planar microcoil*, *Review of Scientific Instruments* **74**, 4794 (2003).
- [8] Y. Twig, E. Dikarov, W. D. Hutchison & A. Blank, *Note: High sensitivity pulsed electron spin resonance spectroscopy with induction detection*, *Review of Scientific Instruments* **82**, 076105 (2011).
- 15 [9] R. Narkowicz, D. Suter & R. Stonies, *Planar microresonators for EPR experiments*, *Journal of Magnetic Resonance* **175**, 275 (2005).
- [10] A. C. Torrezan, T. P. Mayer Alegre & G. Medeiros-Ribeiro, *Microstrip resonators for electron paramagnetic resonance experiments*, *Review of Scientific Instruments* **80**, 075111 (2009).
- [11] P. H. Bolivar, M. Nagel, F. Richter, M. Brucherseifer, H. Kurz, A. Bosserhoff & R. Buttner,
- 20 *Label-free THz sensing of genetic sequences: towards 'THz biochips'*, *Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences* **362**, 323 (2004).
- [12] H. M. Quddusi, C. M. Ramsey, J. C. Gonzalez-Pons, J. J. Henderson, E. del Barco, G. de Loubens & A. D. Kent, *On-chip integration of high-frequency electron paramagnetic resonance spectroscopy and Hall-effect magnetometry*, *Review of Scientific Instruments* **79**, 074703 (2008).
- 25 [13] R. S. Schonfeld, in *Institut für Experimentalphysik* (Freie Universität Berlin, 2011), p. 143.
- [14] G. Davies, S. C. Lawson, A. T. Collins, A. Mainwood & S. J. Sharp, *Vacancy-related centers in diamond*, *Physical Review B* **46**, 13157 (1992).
- [15] U. F. S. D'Haenens-Johansson, A. M. Edmonds, B. L. Green, M. E. Newton, G. Davies, P. M.
- 30 Martineau, R. U. A. Khan & D. J. Twitchen, *Optical properties of the neutral silicon split-vacancy center in diamond*, *Physical Review B* **84**, 245208 (2011).
- [16] C. L. Wang, C. Kurtsiefer, H. Weinfurter & B. Burchard, *Single photon emission from SiV centres in diamond produced by ion implantation*, *J. Phys. B-At. Mol. Opt. Phys.* **39**, 37 (2006).
- [17] I. Aharonovich, S. Castelletto, B. C. Johnson, J. C. McCallum, D. A. Simpson, A. D.
- 35 Greentree & S. Prawer, *Chromium single-photon emitters in diamond fabricated by ion implantation*, *Physical Review B* **81**, 121201(R) (2010).

- [18] I. Aharonovich, S. Castelletto, D. A. Simpson, A. D. Greentree & S. Prawer, *Photophysics of chromium-related diamond single-photon emitters*, Physical Review A **81**, 043813 (2010).
- [19] W. F. Koehl, B. B. Buckley, F. J. Heremans, G. Calusine & D. D. Awschalom, *Room temperature coherent control of defect spin qubits in silicon carbide*, Nature **479**, 84 (2011).
- 5 [20] F. Bridges, G. Davies, J. Robertson & A. M. Stoneham, *The spectroscopy of crystal defects - a compendium of defect nomenclature*, Journal of Physics-Condensed Matter **2**, 2875 (1990).
- [21] J. E. Field, *The Properties of Diamond* (Academic Press: London and New York, 1979).
- [22] A. Schweiger & G. Jeschke, *Principles of Pulse Electron Paramagnetic Resonance* (Oxford University Press, Oxford, 2001).
- 10 [23] T. Staudacher, F. Shi, S. Pezzagna, J. Meijer, J. Du, C. A. Meriles, F. Reinhard & J. Wrachtrup, *Nuclear Magnetic Resonance Spectroscopy on a (5-Nanometer)³ Sample Volume*, Science **339**, 561 (2013).
- [24] H. J. Mamin, M. Kim, M. H. Sherwood, C. T. Rettner, K. Ohno, D. D. Awschalom & D. Rugar, *Nanoscale Nuclear Magnetic Resonance with a Nitrogen-Vacancy Spin Sensor*, Science **339**,
15 557 (2013).

CLAIMS

1. A detector, comprising:
 - 5 a substrate arranged to receive an input radiation to be detected and comprising a colour centre of a type that exhibits electron-spin-dependent fluorescence; and
 - a spin measurement section for probing the spin state of the colour centre using fluorescence, thereby detecting input radiation that is such as to change the spin state of the colour centre.
- 10 2. A detector according to claim 1, wherein the spin measurement section is configured to output a measure of the phase, amplitude, intensity and/or frequency of the input radiation based on the fluorescence.
3. A detector according to any of the preceding claims, wherein the detector comprises a
15 plurality of the colour centres in the same or different substrates.
4. A detector according to any of the preceding claims, further comprising a coupling device for directing the input radiation to the colour centre.
- 20 5. A detector according to claim 4, wherein the coupling device comprises one or more of the following: a waveguide, an antenna, a resonator.
6. A detector according to claim 4 or 5, wherein the coupling device is configured to direct the
input radiation along a plurality of different paths, each leading to a different colour centre or group of
25 colour centres.
7. A detector according to any claim 6, wherein the coupling device comprises an antenna connected to a wire or waveguide that branches into a plurality of sub-branches, the plurality of sub-branches defining the plurality of different paths.
30
8. A detector according to any of the preceding claims, wherein the coupling device comprises a loop-gap microwave resonator.
9. A detector according to any of the preceding claims, wherein the detector comprises a
35 plurality of colour centres and the coupling device comprises a plurality of microwave resonators, each configured to couple the input radiation to a different one or group of colour centres, wherein

two or more of the microwave resonators are configured to have different resonant frequencies in order to increase the bandwidth of the detector.

10. A detector according to any of the preceding claims, further comprising a magnetic field control system for controlling the magnetic field in the region of the colour centre or centres to control the frequency or frequencies of input radiation to which the colour centre or centres are sensitive.

11. A detector according to any of the preceding claims, further comprising a demodulator for receiving the output from the spin measurement section and extracting therefrom information that was modulated onto the input radiation.

12. A detector according to any of the preceding claims, wherein the spin measurement section comprises an optical excitation device configured to generate fluorescence of the colour centre or centres and a detection device for detecting the fluorescence.

13. A communication apparatus, comprising:
a receiver configured to receive an electromagnetic signal having input information to be received modulated thereon, wherein:
the receiver comprises a detector according to any of the preceding claims.

14. A communication apparatus according to claim 13, further comprising a transmitter configured to transmit an electromagnetic signal modulated with output information to be transmitted.

15. A communication apparatus according to claim 13 or 14, wherein the detector is tuned to detect input radiation at a frequency of less than 700 MHz.

16. An apparatus for performing nuclear magnetic resonance, comprising a detector according to any of claims 1-12 configured to detect the radiation absorbed or emitted due to nuclear magnetic resonance in the object being studied.

17. An apparatus for performing electron paramagnetic resonance, comprising a detector according to any of claims 1-12 configured to detect the radiation absorbed or emitted due to electron paramagnetic resonance in the object being studied.

18. An apparatus for carrying out nuclear magnetic resonance, comprising:
a magnet configured to generate a magnetic field of equal to or greater than 5T in a test region of the magnet; and

a probe comprising a sample receiver for receiving a sample, the probe being insertable into the magnet so as to position the sample receiver in the test region, wherein the probe comprises:

a substrate comprising a colour centre of a type that exhibits electron-spin-dependent fluorescence, the colour centre being positioned so as to be directly adjacent in use to a sample in the sample receiver;

a first coupling system for directing first electromagnetic radiation to the colour centre to control the electron spins of the colour centre using electron paramagnetic resonance;

a second coupling system for directing second electromagnetic radiation to the sample in order to control the nuclear spins of the sample using nuclear magnetic resonance; and

a third coupling system for directing third electromagnetic radiation to and from the colour centre in order to measure a change in the fluorescence of the colour centre resulting from a contribution to the magnetic field at the colour centre from one or more nuclei of the sample that are closest to the colour centre.

19. An apparatus according to claim 18, wherein:
the probe comprises a plurality of the colour centres.

20. An apparatus according to claim 19, wherein:
the third coupling system comprises a plurality of optical fibres, each of the plurality of optical fibres being configured to direct the third electromagnetic radiation to and from a different one of the plurality of colour centres.

21. A method of performing nuclear magnetic resonance on a sample, comprising:
subjecting the sample to a magnetic field of equal to or greater than 5T;
directing first electromagnetic radiation onto the sample to manipulate the nuclear spin state of the sample using nuclear magnetic resonance;

directing second electromagnetic radiation onto the sample to manipulate the electron spin state of a colour centre located directly adjacent to the sample, the colour centre being of a type that exhibits electron-spin-dependent fluorescence;

directing third electromagnetic radiation to and from the colour centre in order to measure a change in the fluorescence of the colour centre resulting from a contribution to the magnetic field at the colour centre from one or more nuclei of the sample that are closest to the colour centre.

22. A method according to claim 21, wherein:

a plurality of the colour centres are provided directly adjacent to the sample, with the first and second electromagnetic radiation being directed onto all of the colour centres; and

the method comprises directing the third electromagnetic radiation independently to each of the colour centres in order independently to measure a contribution to the fluorescence of that colour centre due to a contribution to the magnetic field from one or more nuclei of the sample that are closest to that colour centre.

5

23. A detector, apparatus or method according to any of the preceding claims, wherein one or more of the colour centres comprises one of the following: a vacancy centre in diamond, a vacancy-related centre in diamond, a silicon-vacancy centre in diamond, an NE8 centre in diamond, a chromium-related centre in diamond, a colour centre in silicon carbide, a colour centre in a solid other than diamond.

10

24. A detector, apparatus or method according to claim 23, wherein the colour centre is a nitrogen vacancy colour centre in diamond.

15

25. A detector, apparatus or method according to any of the preceding claims, wherein the colour centre is a silicon-vacancy centre in diamond.

26. A detector or apparatus arranged and configured to operate substantially as hereinbefore described with reference to and/or as illustrated in the accompanying figures.

20

27. A method substantially as hereinbefore described with reference to and/or as illustrated in the accompanying figures.

25

Fig. 1

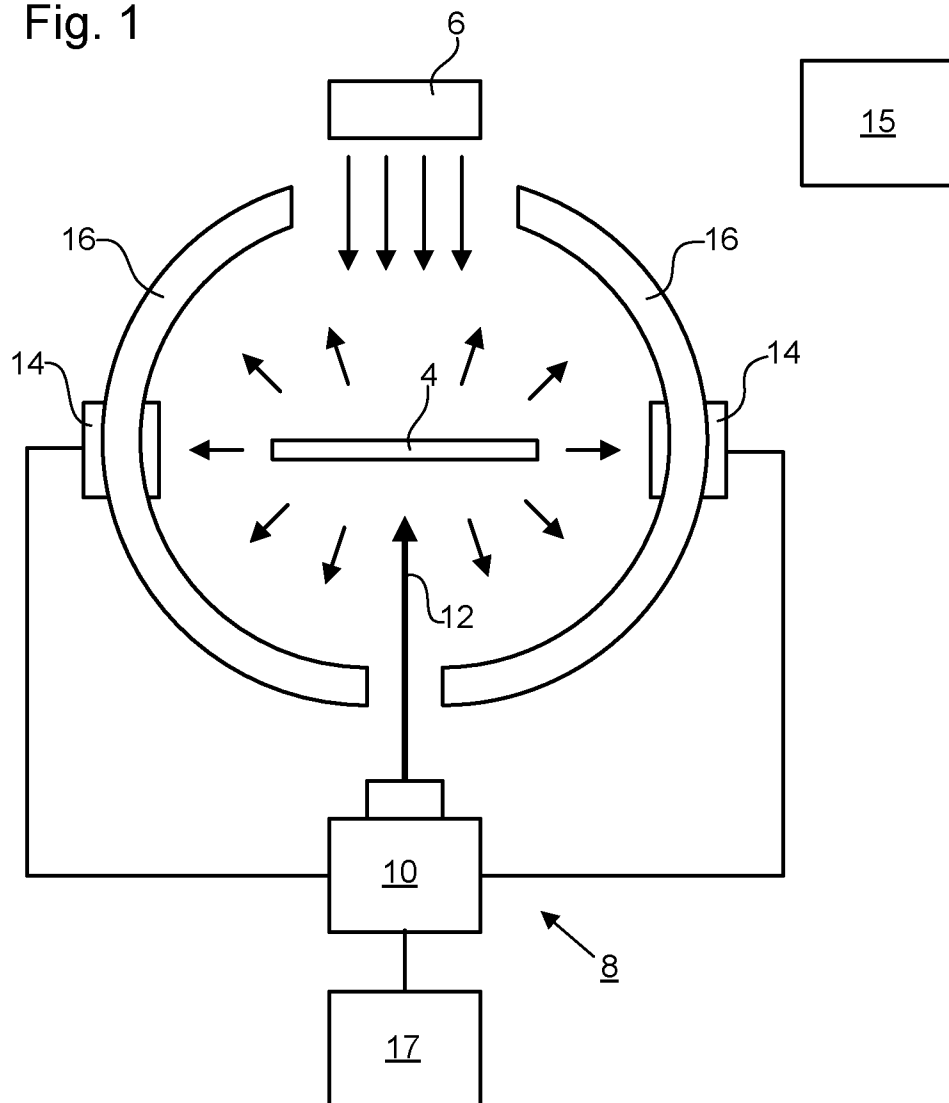


Fig. 2

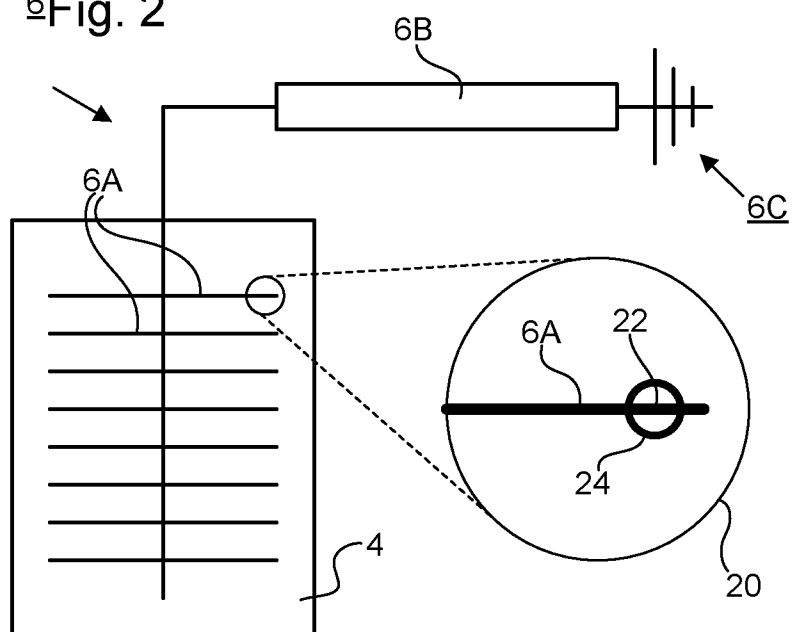


Fig. 3

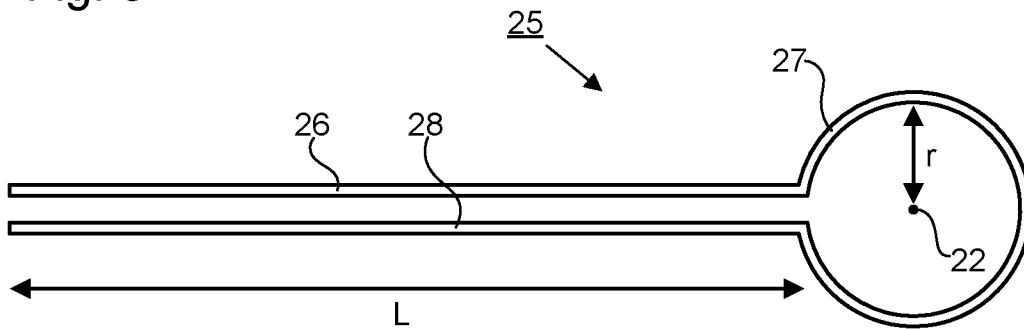
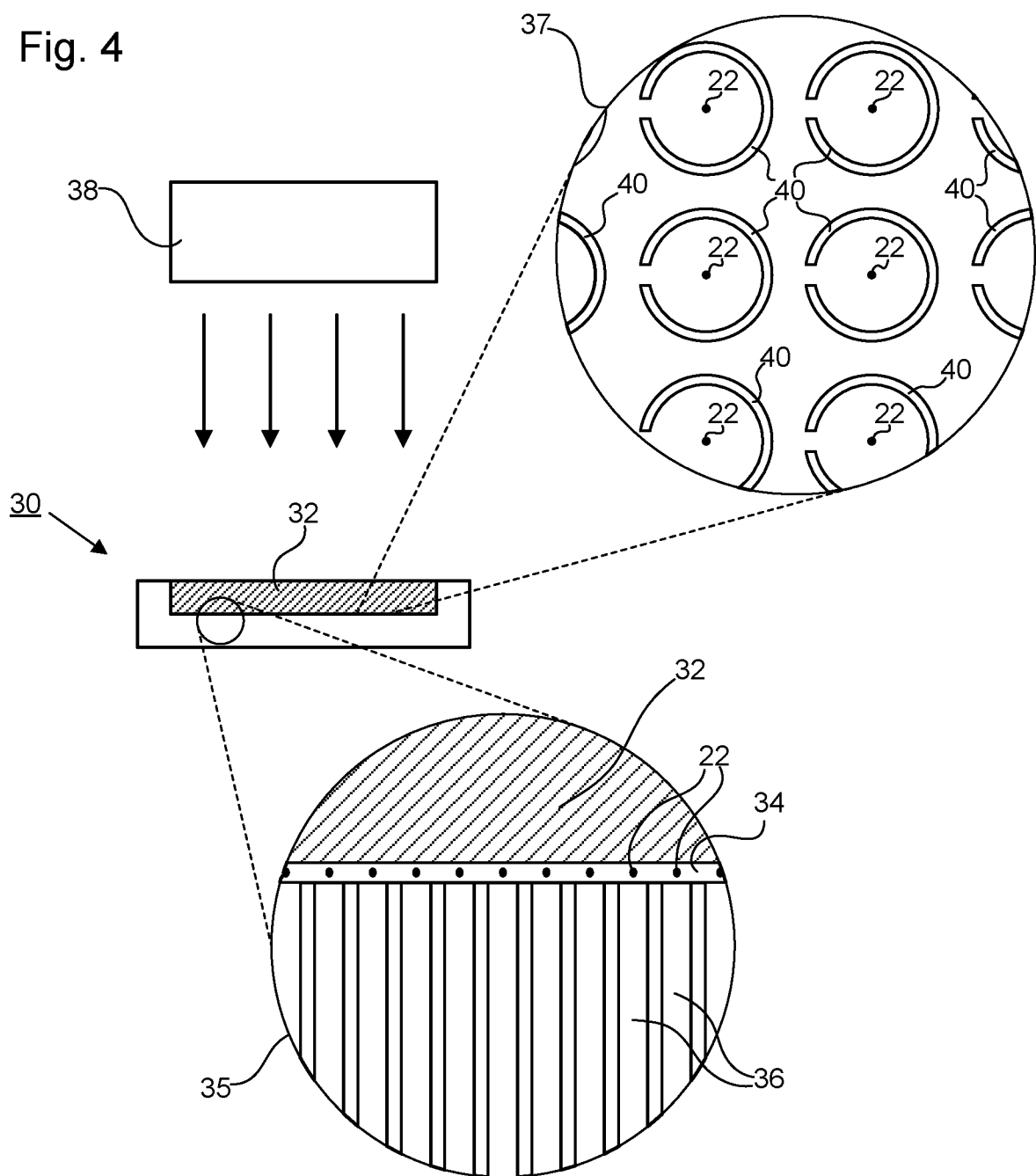


Fig. 4



INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2014/052289

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01N24/08 G01R33/60 G01R33/62
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01N G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011/062957 A1 (FU KAI-MEI CAMILLA [US] ET AL) 17 March 2011 (2011-03-17) paragraphs [0018], [0020], [0024] - [0051]; figures 1-5 ----- -/--	1-5, 10, 12, 23-25



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

1 October 2014

Date of mailing of the international search report

08/12/2014

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Lersch, Wilhelm

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2014/052289

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Rolf Simon Schönfeld: "Optical readout of single spins for quantum computing and magnetic sensing", Dissertation, Fachbereich Physik der Freien Universität Berlin, 1 May 2011 (2011-05-01), pages 1-143, XP055143403, Retrieved from the Internet: URL: http://www.diss.fu-berlin.de/diss/servlets/MCRFileNodeServlet/FUDISS_derivate_00000012199/Dissertation_Simon_Schoenfeld_PublicVersion-2.pdf;jsessionid=89A943688E59A31943E392CF5C20A935?hosts=[retrieved on 2014-09-30] cited in the application see chapters 2.4.2 and 4.2.3 -----	1-5,10, 12,17, 23-25
X	M. S. GRINOLDS ET AL: "Quantum control of proximal spins using nanoscale magnetic resonance imaging", NATURE PHYSICS, vol. 7, no. 9, 15 May 2011 (2011-05-15), pages 687-692, XP055105330, ISSN: 1745-2473, DOI: 10.1038/nphys1999 the whole document -----	1-5,10, 12,17, 23-25
X	JIANMING CAI ET AL: "Diamond-based single-molecule magnetic resonance spectroscopy", NEW JOURNAL OF PHYSICS, INSTITUTE OF PHYSICS PUBLISHING, BRISTOL, GB, vol. 15, 11 January 2013 (2013-01-11), pages 1-21, XP002712113, ISSN: 1367-2630, DOI: 10.1088/1367-2630/15/1/013020 the whole document -----	1-5,10, 12,17, 23-25
X	BERNHARD GROTZ ET AL: "Sensing external spins with nitrogen-vacancy diamond;Sensing external spins with nitrogen-vacancy diamond", NEW JOURNAL OF PHYSICS, INSTITUTE OF PHYSICS PUBLISHING, BRISTOL, GB, vol. 13, no. 5, 19 May 2011 (2011-05-19), page 55004, XP020190482, ISSN: 1367-2630, DOI: 10.1088/1367-2630/13/5/055004 the whole document ----- -/--	1-3,10, 12,17, 23-25

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2014/052289

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	G. DE LANGE ET AL: "Single-Spin Magnetometry with Multipulse Sensing Sequences", PHYSICAL REVIEW LETTERS, vol. 106, no. 8, 1 February 2011 (2011-02-01), XP055143512, ISSN: 0031-9007, DOI: 10.1103/PhysRevLett.106.080802 the whole document -----	1-5,12, 23-25
X	WO 2013/066446 A1 (UNIV COLUMBIA [US]; ENGLUND DIRK R [US]) 10 May 2013 (2013-05-10) page 5, line 16 - page 5, line 27 page 10, line 20 - page 15, line 33; figures 1,2,8 -----	1,3-5, 10,12, 17,23,24
A	WILLIAM F. KOEHL ET AL: "Room temperature coherent control of defect spin qubits in silicon carbide", NATURE, vol. 479, no. 7371, 2 November 2011 (2011-11-02), pages 84-87, XP055143514, ISSN: 0028-0836, DOI: 10.1038/nature10562 cited in the application the whole document -----	23-25

INTERNATIONAL SEARCH REPORT

International application No.
PCT/GB2014/052289

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-5, 10, 12, 17, 23-27

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-5, 10, 12, 17, 23-27

Detector for detecting, via electron-spin-dependent fluorescence of a colour centre, input radiation that is such as to change the spin state of the colour centre. This invention has no special technical features.

2. claims: 6, 7

The 2nd invention has the special technical feature that the input radiation is detected by means of a coupling device that is configured to direct the input radiation along a plurality of different paths, each leading to a different colour centre or group of colour centres. This invention solves the problem of increasing the dynamic range of the detector (see page 6, lines 15-25 of the description).

3. claim: 8

The 3rd invention has the special technical feature that a loop-gap microwave resonator is used for coupling the input radiation to the colour centre. This invention solves the problem of concentrating the magnetic field associated with the input radiation as much as possible onto the atomic-scale colour centre (see page 7, lines 10-15 of the description).

4. claim: 9

The 4th invention has the special technical feature that the detector comprises a plurality of colour centres to which the input radiation is coupled by means of a plurality of microwave resonators at least two of which are tuned to different resonance frequencies. This invention solves the problem of increasing the bandwidth of the detector (see page 7, lines 23-25 of the description).

5. claims: 11, 13-15

The 5th invention has the special technical feature that a detector according to the 1st invention is specifically used in a receiver of a communication apparatus for receiving information modulated onto an electromagnetic signal. This invention solves the problem of increasing the sensitivity (and thereby reducing the power requirements) of a communication apparatus (see, e.g., page 2, lines 19-23 of

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

the description).

6. claims: 16, 18-22

The 6th invention has the special technical feature that the detector according to the 1st invention is specifically used for performing nuclear magnetic resonance by measuring a change in the electron-spin-dependent fluorescence of the colour centre resulting from a contribution to the magnetic field at the colour centre from one or more nuclei of a sample positioned close to the colour centre.

This invention solves the problem of increasing the detection sensitivity of NMR measurements (see, e.g., page 9, lines 11-21 of the description).

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2014/052289

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2011062957	A1	17-03-2011	NONE

WO 2013066446	A1	10-05-2013	EP 2745360 A1 25-06-2014
		WO 2013066446 A1	10-05-2013
