Method for calibrating a quantum sensor, and quantum sensor

The present invention relates to a method for calibrating a quantum sensor, in particular a magnetic field sensor, which has a crystal with color centers, in particular a diamond crystal with NV centers. The invention also relates to a quantum sensor comprising: a crystal with color centers, in particular a diamond crystal with NV centers; an excitation light source for irradiating the crystal with excitation light; a microwave generator for coupling a microwave field into the crystal; a detector for detecting fluorescence light, which is emitted upon excitation of the color centers, and an evaluation device for determining at least one measured variable, in particular of a magnetic field, based on the detected fluorescence light, wherein the evaluation device comprises a demodulator, preferably in the form of a lock-in amplifier.

Quantum sensors play a central role in many technical fields of application and can be used to determine various physical measured variables. Crystals doped with color centers are typically used as sensor elements for quantum sensors. In particular, a diamond crystal doped with color centers, usually nitrogen vacancy centers (hereinafter referred to as “nitrogen vacancy,” NV centers), can be used as a sensor element. NV centers in diamond exhibit a characteristic electronic structure that changes in response to variations in certain measured variables, such as an external magnetic field, temperature, pressure, or electric field.

DE102022201185A1 describes a pressure sensor comprising at least one sensitive component in the form of a deflectable diamond membrane that has at least one subvolume doped with color centers, preferably NV centers.

The color centers are excited by irradiation with excitation light in the optical range and by irradiation with a microwave field of varying frequency in the microwave range, and the fluorescence light thereby induced in the color centers is detected and analyzed by a detector.

The sensitivity of such a quantum sensor depends on various parameters. It is not easy to determine the optimal operating parameters for the most sensitive operation of a quantum sensor, specifically a magnetic field sensor, through theoretical estimation or simulation, as certain assumptions and simplifications are necessary

for this purpose. Furthermore, the optimal operating parameters may vary among different devices of the same type of quantum sensor. Manual calibration of a quantum sensor is time-consuming and has only limited validity, both in terms of time and depending on the location where the quantum sensor is used.

The article “Sensitivity Optimization for NV-Diamond Magnetometry” by John F. Barry et al., Review of Modern Physics 92, no. 1, 2020, 015004, describes how quantum sensors in the form of magnetometers based on NV centers in diamond exhibit a sensitivity that is orders of magnitude far from the theoretical limits. The article describes various approaches for optimizing the sensitivity of magnetometers.

The article “Fiber-coupled Diamond Magnetometry with an Unshielded 30 pT /$\sqrt{Hz}$ Sensitivity,” by S. M. Graham et al., Physical Review Applied 19, no. 4, 044042, an NV-center magnetometer with a sensitivity on the order of approximately 30 pT/$\sqrt{Hz}$ over a frequency range of 10 to 500 Hz is described. This high sensitivity can be achieved, among other things, by optimizing the operating parameters of a microwave source and a lock-in amplifier.

CN115128518A describes a highly sensitive differential magnetic detection system based on NV centers, which utilizes frequency-agility microwave modulation technology. The sensing system includes a magnetic signal calibration module comprising a magnetic coil for applying a bias magnetic field. The detection system varies the strength of the magnetic field to obtain multiple data sets and processes the output data differentially to suppress thermal noise and improve sensitivity to the magnetic signal.

CN112068046B describes a magnetic field measurement device and a method for measuring magnetic fields based on NV color centers. In the method, a calibration signal with a known field strength and a known direction is supplied to the measurement device, and a fluorescence signal detected by a detection module is calibrated using the supplied calibration signal.

Object of the Invention

The invention is based on the object of providing a method for calibrating a quantum

sensor, in particular a magnetic field sensor, which enables the quantum sensor to operate with the highest possible sensitivity.

Subject Matter of the Invention

This object is achieved by a method of the type mentioned at the outset, in which the quantum sensor is operated in a calibration mode during calibration, comprising the following steps: a) automatically setting a plurality of values of at least one operating parameter that influences the sensitivity of the quantum sensor, b) automatically determining a measure of the sensitivity of the quantum sensor for the plurality of values of the at least one operating parameter, and c) automatically selecting a value of the at least one operating parameter that is optimal for the sensitivity of the quantum sensor. The selection of the (at least one) optimal value is based on the measure of the quantum sensor sensitivity determined in step b).

In the method according to the invention, the quantum sensor is operated in a calibration mode in which optimal values of operating parameters are automatically determined at which the sensitivity of the quantum sensor is as high as possible or maximal. Following the calibration mode, the quantum sensor can be operated in a measurement mode using the optimized value(s) of the at least one operating parameter that were selected during calibration mode. The calibration of the quantum sensor in calibration mode can be fully automated, meaning that manual calibration of the quantum sensor is not required.

The operating parameters for which a plurality of values are set or specified can generally be varied continuously. From the possible values of the respective operating parameter, a plurality of values are set sequentially, all of which fall within a specified value or variation range of the operating parameter. The values can be set within the specified range using a predetermined step size, but this is not strictly necessary. For each of the values, a measurement time is specified during which the quantum sensor is operated with the set value of the operating parameter. The measurement time is chosen such that the sensitivity of the quantum sensor can be determined for the respective set value. The number of operating parameter values set is typically five or more, ten or more, or one hundred or more. However, the number of values set may also be lower if necessary.

In this method, the specified number of values can be set and the sensitivity level determined for only one operating parameter (one-dimensional scan), however, it is also possible to perform the variation in a multidimensional manner, i.e., for multiple operating parameters simultaneously. The sensitivity value is assigned to and stored for each set value or each combination of set values of the operating parameters. At the end of the calibration process, the value of the operating parameter, or the combination of values, at which the sensitivity of the quantum sensor is maximal or optimal is selected.

It goes without saying that, in addition to the operating parameters set during the method, there are also parameters that influence the sensitivity of the quantum sensor but cannot be set, or only inadequately set. These parameters include, for example, the properties of the (diamond) crystal, such as the concentration of color centers, relaxation times, orientation, strain, impurities, etc., the collection efficiency of the fluorescent light, the noise in the current, the bias magnetic field (homogeneity, noise), the homogeneity of the microwave field, the shape or caustic of the pump laser beam, and the pump laser wavelength. These parameters should be optimized in advance during the design of the quantum sensor with regard to sensitivity.

In one variant, in step a), a plurality of values of a first operating parameter and a plurality of values of a second operating parameter are set, and in step c), an optimal value of the first operating parameter and an optimal value of the second operating parameter are selected. In this variant, a two-dimensional variation of the values of the first and second operating parameters takes place, i.e., a two-dimensional scan of the operating parameters. This is particularly advantageous when the first operating parameter and the second operating parameter are interrelated, as is the case, for example, with the (laser) power of the excitation light source and the microwave power of the microwave generator of the quantum sensor, see the article by C. Zhang et al., “Diamond magnetometry and gradiometry toward subpicotesla DC field measurement,” Phys. Rev. Applied, vol. 15, no. 6, p. 064075, June 2021, e.g., Fig. 3(a). It goes without saying that in step a), a plurality of values for a third, fourth, … operating parameter can also be set, from which, in step c) a respective optimal value is selected.

In a further development of this variant, in step a) the set of values for the first operating parameter and the set of values for the second operating parameter are set according to a fractional factorial design. The variation of two or more operating parameters or factors can, in principle, be carried out using a full factorial design, in which all combinations of values for the first operating parameter and values for the second operating parameter are set iteratively or sequentially. However, this is already very time-consuming. An alternative to varying operating parameters using a full factorial design is to vary or set the operating parameters using a fractional factorial design, in which only a specific fraction of the factor combinations included in a full factorial design are varied. The operating parameters or factors are examined at two factor levels, resulting in the mathematical notation 2^{k-p}, where k represents the number of factors and p represents the fraction of factor combinations tested. Using a fractional factorial design for the joint variation of operating parameters can accelerate 2-dimensional and multidimensional scans of the operating parameters.

In an alternative version, steps a) through c) are performed for a first operating parameter, and steps a) through c) are subsequently performed for a second operating parameter, using the selected optimal value of the first operating parameter as a reference. It goes without saying that steps a) through c) can subsequently be performed for a third operating parameter, using the selected optimal value of the second operating parameter as a reference, and so on. In the variant described here, a one-dimensional scan of the first operating parameter is first performed, followed by, using the optimized value for the first operating parameter, a one-dimensional scan of the second operating parameter. In this way, the duration of the calibration process can be reduced compared to the duration required for a two- or multi-dimensional scan of the operating parameters.

In another variant, steps a) through c) are performed iteratively, that is, repeated once or more times, for at least two operating parameters. In particular, if steps a) through c) are performed for a first operating parameter and steps a) through c) are subsequently performed for a second operating parameter while setting the selected optimized value of the first operating parameter, steps a) through c) can then be performed again for the first operating parameter while setting the selected optimized value of the second operating parameter, and so on, that is, the two operating parameters can be optimized iteratively in alternation.

In one variant, the operating parameter or one of the operating parameters is an excitation light operating parameter relating to excitation light irradiated into the crystal to excite the color centers. As described above, the crystal or the color centers of the crystal are excited by excitation light whose properties have a significant influence on the sensitivity of the quantum sensor.

In a development, the excitation light operating parameter refers to the power of the excitation light or a pulse parameter of the excitation light during pulsed operation of the quantum sensor. The sensitivity of the quantum sensor is typically strongly influenced by the (laser) power of the excitation light or by the (laser) pump current of the excitation laser source. Variations in laser power during calibration mode may require adjustment of the light source temperature control, that is, an upstream calibration method is performed for, e.g., a thermoelectric cooler (TEC) depending on the power of the excitation light, because both during calibration and measurement modes of the quantum sensor, care must be taken to ensure that the excitation light source reaches a low-noise operating point for exciting the color centers. This can be achieved, for example, by readjusting the temperature or the pump current of the excitation light source. As a control signal, for example, an AC-coupled signal from a photodiode (e.g., a monitor photodiode housed within the excitation light source) can be used, or the demodulated signal from the quantum sensor itself.

The light source parameter may also be a pulse parameter of the excitation light if the quantum sensor is operated in a pulsed mode, for example, the pulse duration or the pulse shape of a respective (laser) pulse, but also the temporal sequence of the various pulses.

In another variant, the operating parameter, or one of the operating parameters, is a microwave operating parameter of a microwave field coupled into the crystal. The properties of the microwave field coupled into the crystal or into the color centers of the crystal also have a significant influence on the sensitivity of the quantum sensor.

In a further development of this variant, the microwave operating parameter is selected from the group comprising: the power of the microwave field, the modulation

depth of the microwave field, and the pulse parameters of the microwave field during pulsed operation of the quantum sensor. The power of the microwave field is frequency-dependent due to the frequency response of the structure generating the microwave field, for example, in the form of a microwave antenna or a microwave coupler. To measure/calibrate the structure generating the microwave field, for example, a microwave antenna, a resonance curve for the microwave antenna can be recorded by varying the bias field (in the case of electromagnets) or by applying an external bias field in a test setup. This table can then be used to set the optimal power of the microwave field, so that a new calibration of the microwave field power is not required for every (e.g., temperature-dependent) shift in the (ODMR) spectrum.

The modulation depth MD of the microwave field can also be set as an operating parameter, which is defined by

$$MD = 100\% \ \frac{A_{max} - A_{min}}{A_{max} + A_{min}}$$

where A denotes the amplitude of the microwave field. As an alternative to the amplitude, the frequency or phase of the microwave field can be varied, in this case, A denotes the frequency or phase of the microwave field, respectively.

Alternatively or in addition, the modulation frequency of the microwave field can be set or varied. When determining the optimal value for the modulation frequency of the microwave field, special attention must be paid to the fact that, at certain frequencies, interference signals from the environment can impair the sensitivity of the quantum sensor in these frequency bands (e.g., 50 Hz/60 Hz and 16 Hz signals from the mains voltage or the rail transit power supply). It may therefore be advisable to limit the range of values within which the microwave frequency is set or varied by excluding these frequency bands and their multiples from the variation value range.

The microwave operating parameter may also be a pulse parameter of the microwave field if the quantum sensor is operated in a pulsed mode. For example, it may be a pulse duration or a pulse shape of the microwave pulses, or the temporal sequence of the microwave pulses.

In a further variant, the operating parameter or one of the operating parameters is a demodulator operating parameter, in particular an amplifier operating parameter of a lock-in amplifier, an evaluation device of the quantum sensor. For the evaluation, the fluorescence signal detected by a detector is demodulated using a demodulator, for example, a lock-in amplifier. In calibration mode, this variant determines the sensitivity of the quantum sensor based on the demodulated signal, such that the lock-in amplifier's operating parameters influence the sensitivity or the measure of sensitivity. The amplifier operating parameter(s) may, for example, be the low-pass bandwidth of the lock-in amplifier, the low-pass order or the spectral filter response of the lock-in amplifier, or the chunk width, provided that the lock-in amplifier is implemented in software.

In another variant, the operating parameter or one of the operating parameters is a discrete, specifically, a binary, operating parameter of the quantum sensor. A discrete, e.g., binary, operating parameter of the quantum sensor can, in principle, only assume a limited number of values. The discrete operating parameter therefore cannot be varied continuously, as is the case, for example, with the power of the excitation light or the power of the microwave field. The discrete operating parameter may, for example, be the form of modulation of the microwave field, i.e., whether the amplitude or the frequency of the microwave field is modulated. Depending on the design of the quantum sensor, it may be the orientation of the offset magnetic field. Another discrete or binary operating parameter is the type of resonance drive of the quantum sensor, i.e., whether it is a single-resonance drive or a double-resonance drive. In the case of a single-resonance drive the microwave field excites, in particular, only the transition between the spin-0 level and a spin-±1 level of an NV center, whereas double-resonance drive excites the transitions to both spin-± levels. Whether hyperfine structure (HFS) driving (which occurs at 2.16 MHz for NV centers) is enabled or disabled also represents a discrete or binary operating parameter. HFS drive is an operating mode in which, in addition to a central microwave frequency, one frequency above and one below the central frequency are applied, with their frequency differences corresponding to the central frequency of the hyperfine splitting.

In another variant, the first operating parameter is an excitation light operating parameter, specifically, the power of the excitation light, and the second operating

parameter is a microwave operating parameter, specifically, the power of the microwave field, or vice versa. The power of the excitation light and the power of the microwave field are operating parameters that have a significant influence on the sensitivity of the quantum sensor. As described above, these two operating parameters can be varied within a predetermined range of values by means of a two-dimensional scan or by two successive one-dimensional scans, wherein in the latter case, the optimal value of the operating parameter from the first one-dimensional scan is set for performing the second one-dimensional scan. This process can be repeated iteratively.

It is typically advantageous to optimize the operating parameters in the order of their impact on the sensitivity of the quantum sensor, i.e., the operating parameters that have the greatest influence on the sensitivity of the quantum sensor should be optimized first. During the calibration mode, the power of the excitation light and the power of the microwave source can initially be optimized as the first and second operating parameters, and subsequently, using the optimal values of these two operating parameters, other operating parameters can be optimized, such as the modulation depth and the modulation frequency of the microwave field. In the case where the quantum sensor is operated in a pulsed mode, the pulse parameters, such as the pulse duration, the pulse shape, and the sequence of the excitation light pulses or the laser pulses and the microwave pulses, can also be optimized. The discrete operating parameters described above and the amplifier operating parameters can also be optimized in one or more subsequent optimization steps.

In another variant, after the calibration operation, the measure of the quantum sensor sensitivity is determined again at the selected optimal value of the at least one operating parameter and compared with the measure of the quantum sensor sensitivity determined during the calibration mode, wherein based on this comparison, a decision is made, preferably on performing another calibration operation, and/or changes in the structural condition, in particular degradation, of the quantum sensor. After the calibration mode is successfully completed, measurement mode begins. At predetermined time intervals during measurement mode, the sensitivity of the quantum sensor at the selected optimal value(s) can be determined again. Based on the comparison, a decision can be made as to whether to perform another calibration mode. The new calibration mode or recalibration can be

performed if the sensitivity value of the quantum sensor, as determined during the recalibration, deteriorates by a specified amount compared to the sensitivity value determined during the calibration mode. During the new calibration mode, the value ranges for varying the operating parameters can typically be set significantly smaller than in the calibration mode, and optimization can be performed to find a local optimum. It should also be noted that certain components of the quantum sensor exhibit long-term fluctuations, which may also necessitate recalibration.

By comparing sensitivities or analyzing data on how much the optimal operating point of the quantum sensor varies over time, it may also be possible to draw conclusions about the condition of the quantum sensor components, such as degradation of the laser or the laser system. For example, the drift of the optimal operating point or operating state of the laser system of the excitation light source can be monitored, e.g., in the form of the optimal laser pump current. In this way, for example, early detection or diagnosis regarding the service life of the quantum sensor can be achieved, and a predictive maintenance function can be implemented for any necessary replacement of the quantum sensor laser system as well as, if applicable, for other components of the quantum sensor. Furthermore, in the event of a drift in the optimal laser pump current, a readjustment can be performed if necessary, provided that the excitation light passes through the quantum sensor in free-beam propagation.

In another variant, the measure of the quantum sensor sensitivity is determined via the ODMR (optically detectable magnetic resonance) spectrum based on the parameters of fluorescence contrast (resonance depth) and the linewidth of the resonance. The magnetic resonance is detected over the variation in fluorescence light intensity as the incident microwave frequency is varied. The fluorescence intensity can be detected by demodulating the lock-in amplifier signal.

The following section describes how to determine the sensitivity of the quantum sensor using a magnetic field sensor as an example. It goes without saying that the sensitivity of a quantum sensor designed to measure a different measured variable can be determined in a similar manner.

The sensitivity η_B of a magnetic field sensor (in $T\sqrt{Hz}$) can be described by the

following formula:

$$\eta_B = \frac{\sigma\sqrt{t}}{dS/dB}$$

where σ is the standard deviation of the noise level of the measured signal S, *t is* the measurement time in seconds, and dS/dB describes a proportionality factor, i.e., the change in the signal S as a function of the magnetic field B.

In the ODMR spectrum of the detected fluorescence light from a magnetometer having a diamond crystal with NV centers, the shot-noise-limited sensitivity η_B is given by:

$$\eta_B = P \cdot \frac{FWHM}{\gamma_{NV} c_{det} \cdot \sqrt{R}}$$

where P denotes a numerical proportionality factor that depends on the mathematical description of the resonance curve (for a Lorentz curve, P = 4/(3*$\sqrt{3}$ = 0.77), FWHM denotes the spectral linewidth (FWHM) of the resonance curve, C_{det} denotes the signal contrast, R denotes the detected fluorescence photon rate, and γ_{NV} denotes the gyromagnetic ratio of the NV centers ($\gamma_{NV} \approx 28 GHz/T$).

The linewidth FWMH, the contrast c_{det}, and the baseline can be determined in a well-known manner by fitting (Lorentz) resonances in the ODMR spectrum. They also depend on the optical saturation parameter s and the Rabi frequency Ω_R. The detected photon rate R can be inferred from the baseline.

Alternatively or additionally, the sensitivity η_B of the magnetic field sensor can be determined using a signal demodulated from the spectral intensity profile of the fluorescence light by means of a demodulator, such as a lock-in amplifier. In this case, the sensitivity can be determined according to the following formula:

$$\eta_B = \frac{V_{NSD}}{\gamma_{NV}\alpha}$$

where V_{NSD} denotes the noise spectral density and α denotes the slope of the

demodulated signal V_{LIA} of the lock-in amplifier at a zero crossing (zero crossing slope, ZCS), and γ_{NV} is the gyromagnetic ratio of the NV centers. The noise spectral density V_{NSD} is the standard deviation of the demodulated signal divided by the square root of the noise-equivalent-power bandwidth of the low-pass filter in the lock-in amplifier, see also the article "https://www.zhinst.com/europe/en/blogs/noise-spectral-density-measured-lock-amplifiers." The zero-crossing slope α of the demodulated signal is typically determined by a linear fit. To measure the magnetic field, the microwave can be tuned to a resonance frequency or to a zero-crossing point in the demodulated spectrum, and the resulting signal can be measured.

In a further development of this variant, the spectral noise density of the demodulated signal and/or the zero-crossing slope of the demodulated signal are determined as a measure of the quantum sensor sensitivity. As can be seen from the formula for the sensitivity η_B of the demodulated signal, the sensitivity depends on the spectral noise density V_{NSD} and on the zero-crossing slope. Depending on the operating parameter being varied, only one of these two variables can be determined for a fast measurement or calibration.

In a further development, the sensitivity of the quantum sensor is measured by determining the contrast and/or the width of at least one resonance in the spectral intensity profile of the fluorescent light and/or the height of the baseline of the spectral intensity profile of the fluorescent light. These are examples of how the measure of sensitivity can be determined based on the spectral intensity profile of the fluorescent light.

A second aspect of the invention relates to a quantum sensor, in particular a magnetic field sensor, of the type mentioned above, which comprises a calibration device configured to carry out the method described above.

The calibration device can take the form of appropriate hardware and/or software and enables the automated, possibly repeated, execution of the calibration mode. The quantum sensor with the automated self-calibration described here simplifies production. The calibration mode for the quantum sensor can be triggered

automatically or manually by an operator, that is, calibration can be performed at the push of a button without specialized knowledge, since the entire calibration process runs automatically. Additionally, wider ranges of operating parameters can be selected, if necessary, than with manual calibration. Continuous monitoring and recalibration as needed ensure that the quantum sensor is always operated in optimal condition, since no manual “readjustment” is required.

The quantum sensor may be a magnetic field sensor designed to determine a magnetic field within a measurement volume in which the crystal with the color centers is arranged. However, it is also possible for the magnetic field sensor to be configured as a gradiometer, in which the magnetic field is measured in two or more different measurement volumes by evaluating fluorescent light from the two or more measurement volumes to determine a magnetic field gradient. A gradiometer typically uses two or more independent measurement heads, which generally comprise the components described above. In a gradiometer, it is advantageous if the method described above is performed independently for each of the two or more measurement heads, i.e., if the calibration process described above is performed independently for both measurement heads. Some calibration steps, such as the calibration of the modulation frequency of one or more microwave fields, may be performed simultaneously for all sensing heads, if applicable.

In the event that vector magnetometry is to be performed using the magnetic field sensor, it is typically necessary to perform the calibration process for all four orientations of the NV centers, in some cases simultaneously. To determine the optimal (laser) power in this case, all four orientations must be considered simultaneously, while the microwave operating parameters for each orientation of the NV centers may, if necessary, be set partially individually.

Further advantages of the invention are apparent from the description and the drawing. Likewise, the features mentioned above and those listed below may be used individually or in any combination. The embodiments shown and described are not intended to be an exhaustive list, but rather serve as examples to illustrate the invention.

In particular:

Fig. 1 shows a schematic representation of a quantum sensor in the form of a magnetic field sensor,

Fig. 2 shows the dependence of the intensity of fluorescent light generated by NV centers of a diamond crystal on the frequency of a microwave field, and

Fig. 3 shows a signal demodulated using a lock-in amplifier as a function of the frequency of the microwave field.

In the following description of the drawings, identical reference numerals are used for components that are the same or perform the same function.

Fig. 1 shows a magnetic field sensor 1 (magnetometer) comprising a crystal 2, which is a diamond crystal doped with color centers 2a in the form of NV centers, indicated by dots in Fig. 1. The magnetic field sensor 1 has a microwave generator 5 for coupling a microwave field 5a into the crystal 2. For this purpose, the microwave generator 5 comprises a signal generator 3 that generates an alternating electric field with a power P_M, which is fed to a microwave coupler 4.

To determine the strength of a magnetic field B, the crystal 2 is irradiated with excitation light 6 from an excitation light source 7, in addition to the coupling of the microwave field 5a, which generates the excitation light 6 with a power P_A. The excitation light 6 has wavelengths in the range between 500 nm and 600 nm. When the color centers 2a are irradiated, they emit fluorescent light 8, which is detected by a detector 9 in the form of a photodiode. An evaluation device 10, comprising a lock-in amplifier 11, is used to determine the strength of the magnetic field B in the crystal 2. The magnetic field B is determined in a manner known per se; see, for example, the article cited at the beginning, “Sensitivity Optimization for NV-Diamond Magnetometry,” by John F. Barry et al., which is incorporated by reference in its entirety into the content of this application.

To determine the optimal operating parameters for the most sensitive operation of the magnetic field sensor 1, the magnetic field sensor 1 is operated in a calibration mode prior to the actual measurement operation, during which several steps of a

calibration method are carried out. To perform the calibration mode, the evaluation device 10 includes a calibration device 12, which is typically suitable software and/or hardware, or a computer program product, configured to carry out the steps of the calibration method.

The calibration method comprises the following steps:

a) automated adjusting a plurality of values of at least one operating parameter that influences the sensitivity η_B of the magnetic field sensor 1,

b) automated determining a measure of the sensitivity η_B of the quantum sensor for the plurality of values of the at least one operating parameter, and

c) automated selecting a value of the at least one operating parameter that is optimal for the sensitivity η_B of the quantum sensor. The selection of the (at least one) optimal value is based on the measure of sensitivity determined in step b).

During the calibration process, optimal values for operating parameters are automatically determined such that the sensitivity of the magnetic field sensor 1 is as high as possible or at its maximum. Following the calibration mode, the magnetic field sensor can be operated in a measurement mode using the optimized value(s) of the at least one operating parameter that were selected during the calibration mode. The calibration of magnetic field sensor 1 in the calibration mode can be performed fully automatically, i.e., manual calibration is not required.

The operating parameters for which a plurality of values are set can generally be varied essentially continuously. From the possible values of the respective operating parameter, a plurality of values are set sequentially, all of which fall within a predetermined range of the operating parameter. The values can be set within the predetermined range with a predetermined step size, but this is not strictly necessary.

In this method, a two- or multi-dimensional parameter scan can be performed, in which, in step a), a plurality of values of a first operating parameter and a plurality of values of a second operating parameter are set, and in which, in step c), an optimal value of the first operating parameter and an optimal value of the second operating parameter are selected. The sensitivity of the magnetic field sensor 1 is maximized at the optimal values of the two (or more) operating parameters. To speed up the

calibration process, the set of values for the first operating parameter and the set of values for the second operating parameter can be set according to a fractional factorial design in step a).

Alternatively, in the method, steps a) through c) can be performed for a first operating parameter, and steps a) through c) can subsequently be performed for a second operating parameter while setting the selected optimized value of the first operating parameter. In this case, a first dimension or a first operating parameter is first optimized, and the optimal parameter value of the first dimension is recorded. Starting from this optimized operating point, the parameter value of the second dimension or the second operating parameter is optimized.

The or one of the operating parameters may, for example, be an excitation light operating parameter of the excitation light 6 irradiated into the crystal 2 to excite the color centers 2a, such as the power P_A of the excitation light 6 or a pulse parameter of the excitation light 6 during pulsed operation of the magnetic field sensor 1. The operating parameter or one of the operating parameters may also be a microwave operating parameter P_M, MD, f_{MW}, ... of the microwave field 5a coupled into crystal 2, for example, the power P_M of the microwave field 5a, a modulation depth MD of the microwave field 5a, a modulation frequency f_{MW} of the microwave field 5a, or pulse parameters of the microwave field 5a during pulsed operation of the magnetic field sensor 1.

The operating parameter or one of the operating parameters may also be a demodulator operating parameter, more specifically, an amplifier operating parameter of the lock-in amplifier 11 of the evaluation unit 10 of the magnetic field sensor 1, for example, the low-pass bandwidth of the lock-in amplifier, the low-pass order or the spectral filter response of the lock-in amplifier, or the chunk width.

The operating parameter, or one of the operating parameters, may also be a discrete operating parameter of the magnetic field sensor 1, such as the form of modulation of the microwave field, for example, whether the amplitude or the frequency of the microwave field 5a is modulated. Depending on the design of the magnetic field sensor 1, it may also be the orientation of the offset magnetic field. Another discrete or binary operating parameter is the type of resonance drive or whether hyperfine

structure (HFS) driving is enabled or disabled.

The magnetic field sensor 1 can be optimized, for example, in the manner described below:

First, the power P_A of the excitation light 6 is optimized as the first operating parameter, and an optimized value $P_{A,OPT}$ for the power P_A of the excitation light 6 is determined. Next, the power P_M of the microwave field 5a is optimized as the second operating parameter; that is, an optimal value $P_{M,OPT}$ for the power P_M of the microwave field 5a is determined. It is also possible to optimize the power P_A of the excitation light 6 and the power P_M of the microwave field 5a in reverse order. Furthermore, the power P_A of the excitation light 6 and the power P_M of the microwave field 5a can be optimized jointly in the form of a two-dimensional parameter scan, using a factorial design if necessary. Likewise, both parameters can be optimized iteratively in turn.

In a subsequent step, the operating parameter of the modulation depth MD of the microwave field 5a is first optimized, before the modulation frequency f_{MW} of the microwave field 5a is optimized in a further step. In the case of pulsed operation of the magnetic field sensor 1, the duration, shape, and sequence of the pulses of the excitation light 6 and the microwave field 5a can be optimized. Subsequently, those operating parameters that have a lesser influence on the sensitivity η_B of the magnetic field sensor 1 can be optimized, such as the discrete operating parameters and the amplifier parameters of the lock-in amplifier 11.

The following describes in detail the automated determination of the sensitivity η_B of the magnetic field sensor 1 in step b) of the calibration method described above.

Fig. 2 schematically shows the dependence of the intensity I of the fluorescent light 8 from the magnetic field sensor 1, detected by the detector 9, on the frequency f_{MW} of the irradiated microwave field 5a. As a result of magnetic resonance, the intensity I of the fluorescent light 8 exhibits a minimum M relative to a background value I_B. The magnetic field B at the location of the crystal 2 can be determined from the frequency f_{min} of the minimum M. The key parameters include the fluorescence contrast C_{det}, the full width at half maximum *FWHM* of the magnetic resonance, and the background value I_B. The photon-shot-noise-limited sensitivity η_B, or the smallest

theoretically measurable magnetic field B_{min}, is given by the formula

$$B_{min} = \frac{\eta_B}{\sqrt{\tau}}$$

where τ is the integration time. The photon-shot-noise-limited sensitivity η_B can be determined from the frequency-dependent intensity I of the fluorescence light 8 shown in Fig. 2 by fitting with a Lorentzian resonance curve.

Fig. 3 shows a demodulated signal V_{LIA} generated from the detected fluorescence light 8 using a demodulator in the form of a lock-in amplifier 11, plotted as a function of the frequency f_{MW}. As can be seen in Fig. 3, the demodulated signal V_{LIA} exhibits a dispersive shape and is linear around the respective resonance frequency f_{min}. From the demodulated signal V_{LIA}, the zero-crossing slope α of the linear region can be determined by a linear fit. The sensitivity η_B of the magnetic field sensor 1 can be determined from the demodulated signal V_{LIA} using the following formula:

$$\eta_B = \frac{V_{NSD}}{\gamma_{NV}\alpha},$$

where V_{NSD} denotes the spectral noise density and γ_{NV} denotes the gyromagnetic ratio of the NV centers. The noise spectral density V_{NSD} is the standard deviation of the demodulated signal V_{LIA} divided by the square root of the noise-equivalent-power bandwidth of the low-pass filter in the lock-in amplifier 11.

The measure of sensitivity η_B can be determined in the manner described in connection with Fig. 2 or in connection with Fig. 3. It is also possible to use the average of the two measured values determined in Fig. 2 and Fig. 3 as a measure of sensitivity η_B. To achieve the fastest possible calibration operation, particularly within certain parameter ranges, only the spectral noise density V_{NSD} of the demodulated signal V_{LIA} and/or the zero-crossing slope α of the demodulated signal V_{LIA} be used as a measure of the sensitivity η_B of the magnetic field sensor 1.

After the calibration mode is complete, the magnetic field sensor 1 operates in measurement mode using the optimal values $P_{A,OPT}$, $P_{M,OPT}$, ... After calibration, the sensitivity η_B of magnetic field sensor 1 can be remeasured at specific intervals using the selected optimal values $P_{A,OPT}$, $P_{M,OPT}$, ... of the at least one operating parameter P_A, P_M, ... and compared with the sensitivity value η_B determined during the calibration mode. If

it turns out that the sensitivity η_B of the magnetic field sensor 1 has deteriorated by a predetermined value, recalibration can be performed, that is, the magnetic field sensor 1 can be operated again in calibration mode. During recalibration, the value ranges for the variation of the operating parameters can be selected to be significantly smaller, and optimization can be performed to achieve a local optimum. Furthermore, based on the data showing how much the optimal operating point varies over time, conclusions can be drawn, if necessary, about the condition of system components, such as the excitation light source 7; for example, a drift in the optimal laser operating point. In this way, early detection of a potentially necessary replacement of the excitation light source 7 of the magnetic field sensor 1 or other components of magnetic field sensor 1 can occur.

It is understood that the method described above for calibrating the magnetic field sensor 1 can also be carried out with quantum sensors used to determine measured variables other than the strength of the magnetic field B, for example, with quantum sensors designed to determine temperature, pressure, etc. Instead of a diamond crystal with NV centers, the quantum sensor may also comprise another crystal with color centers.

Claims

1. A method for calibrating a quantum sensor, in particular a magnetic field sensor (1), comprising a crystal (2) with color centers (2a), in particular a diamond crystal with NV centers,
characterized in that, during calibration, the quantum sensor is operated in a calibration mode comprising the following steps:

a) automated adjusting of a plurality of values of at least one operating parameter (P_A, P_M, MD, f_{MW}, ...) that influences the sensitivity (η_B) of the quantum sensor,

b) automated determining of a measure of the sensitivity (η_B) of the quantum sensor for the plurality of values of the at least one operating parameter (P_A, P_M, MD, f_{MW}, ...), as well as

c) automated selecting of a value ($P_{A,OPT}$, $P_{M,OPT}$, ...) of the at least one operating parameter (P_A, P_M, MD, f_{MW}, ...) that is optimal for the sensitivity (η_B) of the quantum sensor.

2. The method according to claim 1, in which, in step a), a plurality of values of a first operating parameter (P_A) and a plurality of values of a second operating parameter (P_M) are set, and in which, in step c), an optimal value ($P_{A,OPT}$) of the first operating parameter (P_A) and an optimal value ($P_{M,OPT}$) of the second operating parameter (P_M) are selected.

3. The method according to claim 2, in which, in step a), the plurality of values of the first operating parameter (P_A) and the plurality of values of the second operating parameter (P_M) are set according to a factorial design.

4. The method according to claim 1, in which steps a) through c) are performed for a first operating parameter (P_A) and in which steps a) through c) are subsequently performed for a second operating parameter (P_M) while setting the selected optimized value of the first operating parameter (P_A).

5. The method according to any one of the preceding claims, in which steps a) through c) are performed iteratively for at least two operating parameters (P_A, P_M, MD,

f_{MW}, ...).

6. The method according to any one of the preceding claims, wherein the operating parameter or one of the operating parameters is an excitation light operating parameter (P_A) of excitation light (6) irradiated into the crystal (2) to excite the color centers (2a).

7. The method according to claim 6, wherein the excitation light operating parameter is a power (P_A) of the excitation light (6) or a pulse parameter of the excitation light (6) during pulsed operation of the quantum sensor.

8. The method according to any one of the preceding claims, wherein the operating parameter or one of the operating parameters is a microwave operating parameter (P_M , MD, f_{MW} , ...) of a microwave field (5a) coupled into the crystal (2).

9. The method according to claim 8, in which the microwave operating parameter is selected from the group consisting of: power (P_M) of the microwave field (5a), modulation depth (MD) of the microwave field (5a), modulation frequency (f_{MW}) of the microwave field (5a), a modulated variable (frequency, phase, or amplitude) of the microwave field (5a), and pulse parameters of the microwave field (5a) during pulsed operation of the quantum sensor.

10. The method according to any one of the preceding claims, wherein the operating parameter or one of the operating parameters is a demodulator operating parameter, in particular an amplifier operating parameter of a lock-in amplifier (11), of an evaluation device (10) of the quantum sensor.

11. The method according to any one of the preceding claims, wherein the operating parameter or one of the operating parameters is a discrete, in particular binary, operating parameter of the quantum sensor.

12. The method according to any one of claims 2 to 11, in which the first operating parameter is an excitation light operating parameter, in particular a power (P_A) of the

excitation light (6), and in which the second operating parameter is a microwave operating parameter, in particular a power (P_M) of the microwave field (5a), or vice versa.

13. The method according to any one of the preceding claims, in which, following the calibration mode, the measure of sensitivity (η_B) of the quantum sensor at the selected optimal value ($P_{A,OPT}$, $P_{M,OPT}$, ...) of the at least one operating parameter (P_A, P_M, ...) is determined again and compared with the measure of the sensitivity (η_B) of the quantum sensor determined during the calibration mode, wherein, based on the comparison, a decision is preferably made regarding whether to perform a new calibration operation and/or changes in the structural condition, in particular, degradation, of the quantum sensor are detected.

14. The method according to any one of the preceding claims, in which the measure of the sensitivity (η_B) of the quantum sensor is determined on the basis of a spectral intensity profile ($I(f_{MW})$) of fluorescence light (8) generated upon excitation of the color centers (2a) and/or on the basis of a demodulated signal (V_{LIA}) generated from the spectral intensity profile ($I(f_{MW})$ of the fluorescence light (8) by a demodulator, in particular a lock-in amplifier (11).

15. The method according to claim 14, in which a spectral noise density of the demodulated signal (V_{LIA}) and/or a zero-crossing slope (α) of the demodulated signal (V_{LIA}) is determined as a measure of the sensitivity (η_B) of the quantum sensor (1).

16. The method according to claim 14, in which a contrast (C_{det}) and/or a full width at half maximum (FWHM) of at least one resonance in the spectral intensity profile ($I(f_{MW})$ of the fluorescent light (8) and/or a height of the baseline of the spectral intensity profile ($I(f_{MW})$) of the fluorescent light (8) is determined as a measure of the sensitivity (η_B) of the quantum sensor (1).

17. A quantum sensor (1), in particular a magnetic field sensor, comprising:
a crystal (2) with color centers (2a), in particular a diamond crystal with NV-centers,
an excitation light source (7) for irradiating the crystal (2) with excitation light (6),
a microwave generator (5) for coupling a microwave field (5a) into the crystal (2),

a detector (9) for detecting fluorescent light (8) emitted when the color centers (2a) are excited, and

an evaluation device (10) for determining at least one measured variable, in particular a magnetic field (B), based on the detected fluorescent light (8), wherein the evaluation device (10) comprises a demodulator, preferably in the form of a lock-in amplifier (11),

characterized by

a calibration device (12) configured to carry out the method according to any one of the preceding claims.