2024 IEEE 5th KhPI Week on Advanced Technology (KhPIWeek)

Miniature Hybrid Quantum Optomechanical Sensors for Acceleration Measurements

Marina Rezinkina
Institute for Microelectronics, Ulm University, Ulm, Germany
National Technical University "KhPI", Kharkiv, Ukraine
e-mail: maryna.rezynkina@uni-ulm.de

Oleg Rezinkin
Institute of Quantum Optics, Ulm University, Ulm, Germany
National Technical University "KhPI", Kharkiv, Ukraine
e-mail: oleg.rezynkin@uni-ulm.de

Claus Braxmaier
Institute for Microelectronics, Ulm University, Ulm, Germany
German Aerospace Center, Institute for Quantum Technologies, Department of Quantum Metrology, Ulm, Germany
e-mail: claus.braxmaier@uni-ulm.de

Fedor Jelezko
Institute of Quantum Optics, Ulm University, Ulm, Germany
e-mail: fedor.jelezko@uni-ulm.de

2024 IEEE 5th KhPI Week on Advanced Technology (KhPIWeek) | 979-8-3503-8449-9/24/$31.00 ©2024 IEEE | DOI: 10.1109/KHPIWEEK61434.2024.10877973

***Abstract*—A number of applications, particularly aerospace, require accurate, drift-free acceleration measurement with the help of miniature instruments. For such measurements, hybrid quantum optomechanical sensors are used, which provide both high speed measurements using the optomechanical part of the sensor and drift-free measurements that do not require additional calibrations using the quantum part of the sensor. It is proposed to make the quantum part of the sensor based on ensembles of negatively charged nitrogen vacancy (NV) in diamond. Configurations of optomechanical sensors and systems for creating a uniform microwave electromagnetic field applied to an ensemble of NV centers have been proposed. Using mathematical modeling, the effectiveness of the developed systems is shown.**

Keywords—acceleration sensors, optomechanical accelerometer, ensemble of NV centers, mechanical characteristics, mathematical modeling

I. INTRODUCTION

Accurate measurement of the acceleration is important for a number of applications, such as metrology and testing [1], determination of gravitational fields [2], navigation [3], measurement of the characteristics of human body motion [4], and space missions [1]. In the case of usage in space missions, it is necessary to fulfill a number of requirements, namely, the sensors must provide high measurement accuracy and long-term operation without calibration, be able to measure accelerations that quickly change over time, be miniature, and have a small weight. Also important is the absence of the influence of crosstalk, the linear dependence of the movements of the moving part of the sensor on the values of the measured accelerations, and the independence of operation from external influences, such as electromagnetic interference. Most of these requirements are met by optomechanical acceleration sensors [1,5-7]. However, these sensors do not fully ensure the absence of drift during measurements, so hybrid quantum optomechanical acceleration sensors are considered as an advanced version. Currently, cold atoms are used in the quantum part of such sensors. Bose-Einstein condensate sensors are used in such areas as fundamental physics [8,9], geophysics [10], navigation [11], and space missions [12].

However, such sensors have a number of limitations, especially when used for space missions. These restrictions are associated with the need to create a vacuum for the operation of such quantum sensors, which leads to a significant increase in their weight and size characteristics.

It is also difficult to ensure the high response speed of such sensors under dynamic conditions [13]. In order to preserve the advantages of hybrid quantum optomechanical acceleration sensors and avoid the disadvantages of currently used types of quantum sensors, it is proposed to use sensors based on NV centers in diamond [14-19] as the quantum part of hybrid quantum optomechanical sensors. The method of measuring accelerations with their help is relatively new. Still, its promise lies in the possibility of significant miniaturization of these sensors, as well as in the absence of the need to create a vacuum for their operation, which means a significant simplification of their design and a reduction in weight and dimensions.

The work aims to develop approaches to the selection of system parameters for measuring acceleration based on the modelling of mechanical and electromagnetic processes.

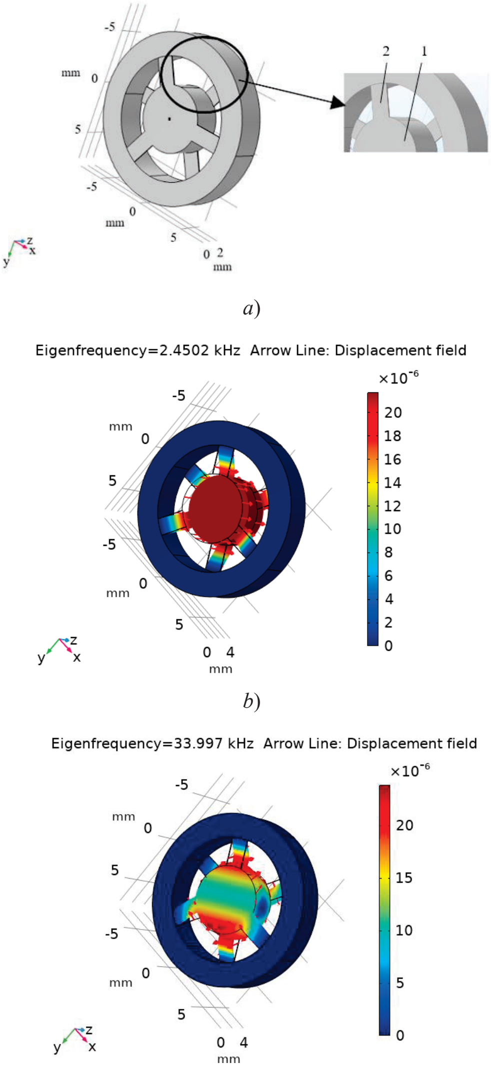
II. OPTOMECHANICAL ACCELEROMETERS

Optomechanical accelerometers (OMA) implicate using a mechanical oscillator, the moving part of which (the test mass) is displaced when acceleration is applied. The test mass serves as one of the mirrors of the Fabry-Perot cavity. The second mirror of this cavity is motionless relative to the test mass, as a result of variation in the length of the Fabry-Perot cavity, a current of photo-detector changes. It permits measuring the level of acceleration. Its magnitude is proportional to the displacement of the test mass, and this displacement is related to a known dependence on the magnitude of the applied acceleration. Thus, the applied acceleration is determined from the photocurrent measurement. To measure accelerations with frequencies of several hundred hertz and higher, mechanical oscillators of the so-called drum type are mainly used [6,20-22].

We have developed designs for such resonators and studied their mechanical characteristics. Examples of resonator configurations we have developed are shown in Fig. 1*a*, 2*a*: these mechanical resonators contain test mass 1 and thin bendable flexures 2 with thickness of the order of hundreds microns. When choosing designs, the goal was to ensure the first eigenfrequency of the order of several kilohertz. This ensures the measurement of accelerations with a frequency of several hundred hertz since the first eigenfrequency should be approximately an order of magnitude greater than the frequency of the measured acceleration [6]. As can be seen from the modelled

979-8-3503-8449-9/24/$31.00 ©2024 IEEE

distributions of the motion mode for the first eigenfrequency, its value is about 2.5 kHz, i.e. satisfies this condition (see Fig. 1*b*, 2*b*). Another goal in developing the resonator design was to reduce crosstalk levels. Crosstalk refers to the presence of movement in the direction of the measured acceleration when a load or acceleration is applied in directions perpendicular to this direction. As can be seen from Fig. 1*c*, 2*c*, the second eigenfrequency significantly exceeds the first. Since the contribution of each subsequent eigenmode to the total mode of motion is inversely proportional to the square of its eigenfrequency, the fraction of displacements in directions perpendicular to the direction of acceleration measurement will be small, which means that crosstalk is negligible.

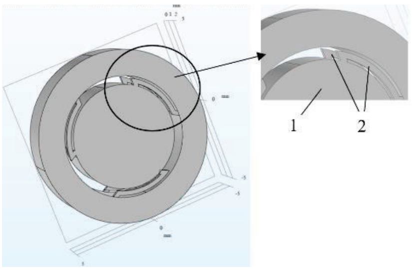


a)

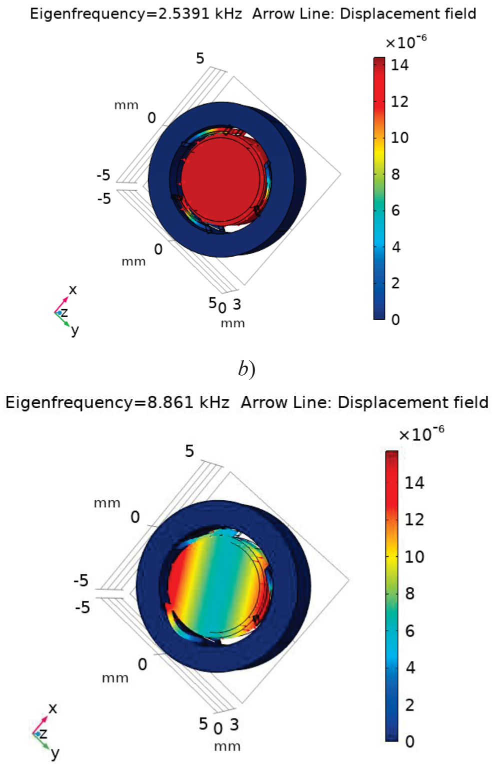
b)

c)

Fig. 1. *a*) – first OMA design; calculated displacement mode for the first (*b*) and second (*c*) eigenfrequency.



a)



b)

c)

Fig. 2. *a*) – second OMA design; calculated displacement mode for the first (*b*) and second (*c*) eigenfrequency.

The advantage of the proposed configurations is the comparative simplicity of the design, allowing manufacturing using laser cutting and etching with subsequent polishing of the surface of the test mass, which serves as one of the mirrors of the Fabry-Perot cavity so that this cavity has high finesse value.

III. USE OF NV CENTERS IN DIAMOND FOR ACCELERATION MEASUREMENTS

As noted in [14–16], mechanical resonators are promising components for quantum sensors. In such systems, mechanical stresses arising from the deformation of the resonator elements cause changes in the interaction of quantum dots with the crystal lattice, which can be detected by optical means. Quantum dots such as NV centers in diamond are very effective quantum detectors because they allow operation not only at low temperatures, but also at room temperatures. In quantum-optomechanical systems, the coherent evolution of electron spins associated with nitrogen vacancy centers in diamonds turns out to be associated with the movement of a mechanical resonator.

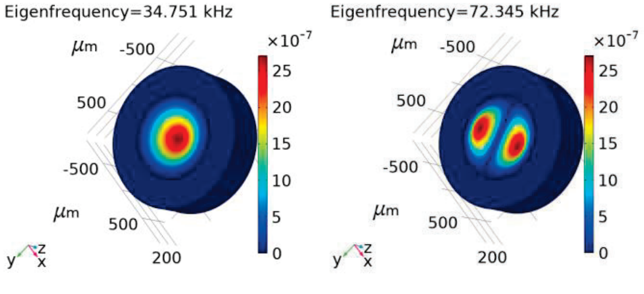
In [18], to study the mechanical properties of a thin membrane, negatively charged nitrogen-vacancy centers built under its surface are used as nanosensors. To detect membrane deflection when pressure is applied to it, confocal microscopy is used to measure the spread of fluorescence from individual nitrogen-vacancy centers. For this geometry, we simulated the mechanical processes of the distribution of the displacement mode corresponding to the first (*a*) and second (*b*) eigenfrequencies (see Fig. 3).

The coupling of a mechanical resonator with a built-in single spin and a quantum system is shown elsewhere [19]. The system under study contains a micron single-crystal diamond cantilever, in which a single spin is located in the form of a center in diamond. The device has high strength and mechanical frequency.

The mechanical processes we simulated in the described system, namely displacement mode shape for the first (*a*) and second (*b*) eigenfrequency are shown in Fig. 4.

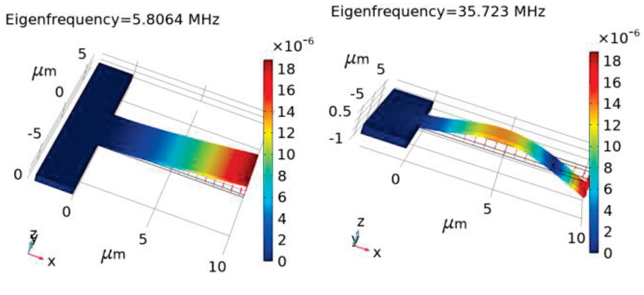
Currently, a quantum hybrid system based on spin-deformed NV centers has been proposed and implemented to measure acceleration [17]. Its advantages over existing accelerometers are that it has low power consumption, small size, frequency up to several kilohertz, and satisfactory sensitivity. The accelerometer proposed in [17] contains a mechanical oscillator fixed on both sides, which is a diamond membrane with NV centers located in the middle. The spin states of the NV electrons are initialized by laser pumping and controlled by an applied microwave electromagnetic field. As a result of the application of acceleration in a mechanical oscillator with NV centers, a deformation is created that changes the intensity and contrast of the photoluminescence read out. This provides measurements of the magnitude of the applied acceleration. The simulated distributions of displacement modes corresponding to the first (*a*) and second (*b*) eigenfrequency are shown in Fig. 5.

Fig. 6 shows the experimental setup schematic for acceleration measurements with the help of ensembles of NV centers. The advantage of using ensembles of NV centres to measure acceleration is that the measurements are based on the use of absolute physical constants. However, for measuring rapidly changing accelerations, it seems optimal to use a hybrid quantum-optomechanical accelerometers.



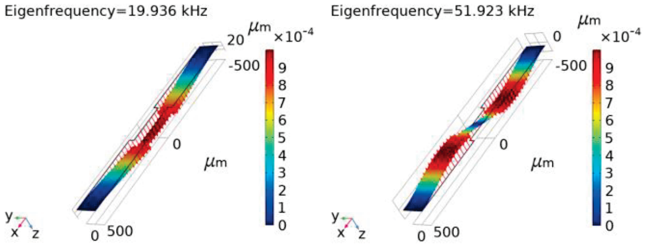
a) *b*)

Fig. 3. Modelled displacement modes shape for the first (*a*) and second (*b*) eigenfrequency (system configuration from [18]).



a) *b*)

Fig. 4. Modelled displacement modes shape for the first *a*) and second *b*) eigenfrequency (system configuration from [19]).



a) *b*)

Fig. 5. Modelled displacement modes shape for the first *a*) and second *b*) eigenfrequency (system configuration from [17]).

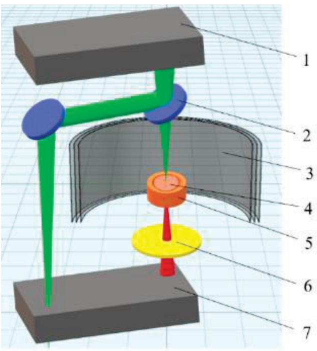
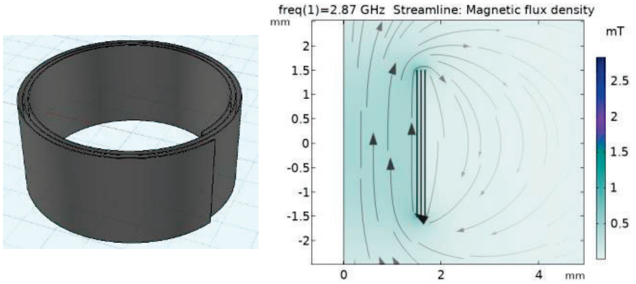


Fig. 6. Experimental setup schematic for acceleration measurements with the help of NV centers. 1 – Laser 532 nm; 2 – dichroic mirror; 3 – microwave field-forming system (shown in axial section); 4 – diamond membrane with NV centers ensemble; 5 – mechanical resonator; 6 – band-pass filter (650 to 800 nm); 7 – balanced photodetector.

The advantage of using ensembles of nitrogen vacancies to measure acceleration is that the sensitivity of measuring mechanical stress in this case will be much higher than in the case of a single NV. The dimensions of the NV centers ensemble correspond to the cross-section of the laser beam exciting its NVs. Thus, the spatial resolution of mechanical stress detection using quantum ensembles is tens of micrometers. The disadvantages of measurements based on the use of NV centers in diamond compared to the use of optomechanics are the greater noise level of the output signal of the primary transducer and the longer period required for measurement. Thus, for measuring rapidly changing accelerations, it seems optimal to use hybrid quantum-optomechanical accelerometers. In this case, you can use, for example, the inclusion of an ensemble of NV centers in flexures 2 (see Fig. 1*a*, 2*a*) of the optomechanical accelerometer, since they experience the greatest mechanical stress.

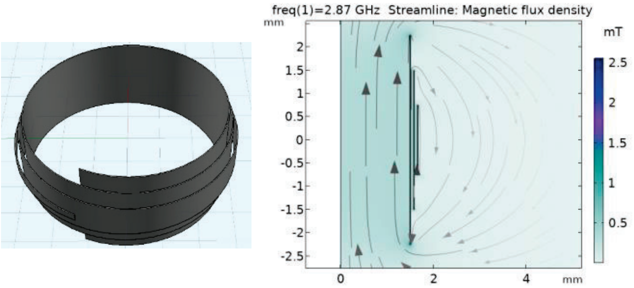
IV. MAGNETIC FIELD GENERATION FOR ACCELERATION MEASUREMENTS WITH THE HELP OF ENSEMBLES OF NV CENTERS

For spin manipulation of NV centers, a microwave electromagnetic field is applied to them. To ensure the effective use of NV center ensembles, it is necessary to provide a high degree of uniformity of the magnetic field. For this purpose, we have developed the design of field-forming systems that comprise the domain with NV centers ensemble (see Gigs. 7, 8). This design consists of three cylindrical ribbon-shaped coils of copper (see Fig. 7*a*). The calculated distribution of magnetic flux density $\boldsymbol{B}$ in this system is shown in Fig. 7*b*. The simulation of the magnetic field distribution showed that in the zone close to the axis of the turns, extending along the Z axis: -0.6 mm $\leq Z \leq$ 0.6 mm, the coefficient of



a) *b*)

Fig. 7. *a* – geometry of the first field-forming system; *b* – modeled magnetic flux density distribution.



a) *b*)

Fig. 8. *a* – geometry of the second field-forming system; *b* – modeled magnetic flux density distribution.

$$\delta_{\boldsymbol{B}} = 100\ \%\cdot(1-\boldsymbol{B}_{\min} / \boldsymbol{B}_{\max}),$$

where $\boldsymbol{B}_{\min}$, $\boldsymbol{B}_{\max}$ are the minimum and maximum $\boldsymbol{B}$ levels in the considered zone is 2.64 %. Such inhomogeneity is too large in many cases, so we have proposed another configuration of the field-forming system, in which the turns are wound from a triangular copper sheet so that the width of the inner turn of the coil is maximal and the width of the outer turn of the coil is minimal (see Fig. 8*a*). The total width of all turns is the same as for the previous field-forming system (see Fig. 7*a*). The calculated distribution of $\boldsymbol{B}$ in such a system is shown in Fig. 8*b*. In this field-forming system, in the zone close to the axis of cylindrical turns, having a dimension along the Z axis: -0.6 mm $\leq Z \leq$ 0.6 mm, the coefficient of heterogeneity of the magnetic flux density is $\delta_{\boldsymbol{B}}$ = 0.47 %.

So, a field-forming system has been proposed that ensures the magnetic field distribution that has significantly greater homogeneity of $\boldsymbol{B}$ than in the first field-forming system.

V. CONCLUSIONS

Possibilities for measuring acceleration in relation to use in space missions are considered. The use of NV centers in diamond as a quantum part of a hybrid quantum optomechanical acceleration sensor is proposed. New configurations for the mechanical resonator of optomechanical sensors are elaborated, as well as configurations for the microwave field-forming system to create a uniform magnetic field in a volume comprising an NV centers ensemble.

ACKNOWLEDGMENT

This work is supported by the German Space Agency (DLR e.V.), with funds provided by the Federal Ministry of Economic Affairs and Climate Action, under grant number 50WM2262B (HyQIS), DLR via project 50WM2170 QUASIMODO, BMBF by future cluster QSENS (project 03ZU1110JA QSPACE).

REFERENCES

[1] F. G. Cervantes, L. Kumanchik, J. Pratt, and J. M. Taylor, “High sensitivity optomechanical reference accelerometer over 10 kHz,” Appl. Phys. Lett., vol. 221111, p. 104, June 2014.

[2] T. Lévèque, C. Fallet, M. Mandea, et al., “Gravity field mapping using laser-coupled quantum accelerometers in space,” J. Geod., vol. 95:15, January 2021.

[3] N. El-Sheimy, A. Youssef, “Inertial sensors technologies for navigation applications: state of the art and future trends,” Satell. Navig., vol. 1:2, January 2020.

[4] C. Liu, L. Han, S. Chang, and J. Wang, “An Accelerometer-based Wearable Multi-node Motion Detection System of Freezing of Gait in Parkinson’s Disease,” 2022 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), pp. 1-5, May 2022.

[5] B. J. Reschovsky, D. A. Long, F. Zhou, et al., “Intrinsically accurate sensing with an optomechanical accelerometer,” Opt. Express, vol. 30, pp. 19510-19523, May 2022.

[6] A. Hines, A. Nelson, Y. Zhang, et al., “Optomechanical Accelerometers for Geodesy,” Remote Sensing, vol. 14(17), p. 4389, September 2022.

[7] S. Abozyd, A. Toraya, N. Gaber, “Design and Modeling of Fiber-Free Optical MEMS Accelerometer Enabling 3D Measurements,” Micromachines, vol. 13(3), p. 343, February 2022.

[8] P. Asenbaum, C. Overstreet, M. Kim, et al., “Atom interferometric test of the equivalence principle at the 10−12 level,” Phys. Rev. Lett. vol. 125, p. 191101, November 2020.

[9] C. Overstreet, P. Asenbaum, J. Curti, et al., “Observation of a gravitational Aharonov-Bohm effect,” Science, vol. 375, pp. 226–229, January 2022.

[10] Stray, B. et al., “Quantum sensing for gravity cartography,” Nature, vol. 602, pp. 590–594, February 2022.

[11] F. A .Narducci, A. T. Black, and J. H. Burke, “Advances toward fieldable atom interferometers,” Adv. Phys., vol. 7(1), 1946426, March 2022.

[12] D. C. Aveline, et al., “Observation of Bose–Einstein condensates in an Earth-orbiting research lab,” Nature, vol. 582, pp. 193–197, July 2020.

[13] J. Lee, R. Ding, J. Christensen, et al., “A compact cold-atom interferometer with a high data-rate grating magneto-optical trap and a photonic-integrated-circuit-compatible laser system,” Nat Commun., vol. 13, 5131, September 2022.

[14] M. S. J. Barson, et al., “Nanomechanical Sensing Using Spins in Diamond,” Nano Letters, vol. 17 (3), pp. 1496-1503, August 2017.

[15] J. Cai, F. Jelezko, and M. Plenio, “Hybrid sensors based on colour centres in diamond and piezoactive layers,” Nat Commun., vol. 5, p. 4065, June 2014.

[16] S. Kolkowitz et al., “Coherent Sensing of a Mechanical Resonator with a Single-Spin Qubit,” Science, vol. 335, pp. 1603-1606, February 2012.

[17] J. Lu-Min. et al., “Design and simulation of an accelerometer based on NV center spin–strain coupling,” Chinese Phys., vol. 3(1), 017301, Januar 2023.

[18] S. Ali Momenzadeh, et. al., “Thin Circular Diamond Membrane with Embedded Nitrogen-Vacancy Centers for Hybrid Spin-Mechanical Quantum Systems,” Phys. Rev. Applied, vol. 6, 024026, August 2016.

[19] J. Teissier, A. Barfuss, P. Appel, E. Neu, and P. Maletinsky, “Strain Coupling of a Nitrogen-Vacancy Center Spin to a Diamond Mechanical Oscillator,” Phys. Rev. Lett., vol. 113, 020503, July 2014.

[20] L. Kumanchik, M. Rezinkina, and C. Braxmaier, “Choice of the miniature inertial optomechanical sensor geometric parameters with the help of their mechanical characteristics modelling,” Micromachines, vol. 14(10), p. 1865, September 2023.

[21] M. Rezinkina, and C. Braxmaier, “Designs of Optomechanical Acceleration Sensors with the Natural Frequency from 5 Hz to 50 kHz,” Designs, vol. 8, no.21 2, p. 33, April 2024.

[22] M. Rezinkina, and C. Braxmaier, “Designs of Miniature Optomechanical Sensors for Measurements of Acceleration with Frequencies of Hundreds of Hertz,” Designs, vol. 8(4), p. 67. July 2024.