Milli-Tesla Level Magnetic Field Vector Detection Based on YIG Microcavity Optical Sensor

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***Abstract*—A millitesla-level magnetic field vector detection using a yttrium iron garnet (YIG) microcavity is proposed. Under the magnetic field strength of 95.49 mT, the YIG microsphere cavity-based sensor realizes the direction sensitivity of 0.0717 pm/°.**

Keywords—Optical sensing, whispering gallery mode, magnetic field vector sensor

I. INTRODUCTION

Magnetic sensors are extensively utilized in medical diagnostics, aerospace, geological exploration, and various other fields. However, most conventional magnetic sensors rely on electromagnetic induction phenomena and are prone to electromagnetic interference, which restricts their range of applications. Especially in high-intensity magnetic field environments, there are more stringent requirements for magnetic sensors. In recent years, whispering gallery mode (WGM) optical microresonators, which can support high quality (Q) factors and small mode volumes to enhance the interaction between photons and matter, play a crucial role in modern optics and have been extensively utilized in diverse sensing applications [1-5]. Moreover, optical WGM magnetic field sensors are anticipated to be an ideal platform for magnetic sensing because of their benefits such as anti-electromagnetic interference.

In previous reports, most magnetic sensors are based on composite microcavities formed by magnetic materials and WGM microcavities. In 2021, Liu et al. proposed a magnetic fluid-filled microbubble cavity magnetic sensor and investigated the effects of wall thickness and medium magnetic concentration on the sensor through theoretical and experimental analysis. By decreasing the wall thickness, a sensitivity enhancement of about 10 times is finally realized [6]. In 2022, Yu et al. achieved a sensitivity of 0.1703 dB/Oe under a DC magnetic field by using a microcapillary cavity with magnetostrictive material [7].

In this work, the detection of static magnetic fields is realized by using a magneto-optical crystal, and a magnetic vector sensor based on a yttrium iron garnet (YIG) microsphere resonator with a Q factor of $\sim 10^5$ is demonstrated. Under the external magnetic field strength of 95.49 mT, the YIG microsphere cavity with tapered fiber coupling system realizes the perception of the external magnetic field direction rotation 360°, and its direction sensitivity is 0.0717 pm/°. The magnetic vector sensor employs all-optical detection technology to detect the magnetic field, which not only enhances safety but also realizes long-distance detection. It also has the advantages of compact structure and fast response, making it more suitable for use in complex electromagnetic environments. This provides an efficient, safe, and reliable solution for magnetic field sensing.

II. RESULT AND DISCUSSION

As shown in Figure 1(a), the cavity diameter of the experimentally prepared YIG microsphere resonator is approximately 500 μm, and the diameter of the coupled microfiber is about 2 μm. The relative location between the YIG microsphere cavity and the tapered fiber can be precisely modified by the three-dimensional translation stage. It is important to note that the YIG microsphere cavity and the optical fiber are transferred to the slide respectively before coupling. To fix the position of the two glass slides, ultraviolet (UV) glue is applied to their edges, and finally fixed using a UV lamp. This design not only helps to protect the coupling system from environmental contaminants and thus maintains long-term stability, but also allows the position of the entire sensing device to be moved. Additionally, the YIG microcavity cavity exhibits low absorption loss at ~1550 nm, ensuring a higher Q factor. In the experiment, a tunable laser at ~1548 nm is coupled to the YIG microsphere cavity through the tapered fiber to excite the resonant mode. A polarization controller and an optical attenuator are used to adjust the polarization state and control the optical power, respectively. The transmission spectrum is collected by a photodetector and monitored in real-time via an oscilloscope. In the magnetic field vector sensing experiment, two static magnets are placed side by side on a rotating stage, and the YIG microsphere cavity is placed at the midline position of the two static magnets. When the magnetic field is rotated 360°, only the direction of the magnetic field changes, not its

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strength. A Gauss meter is placed above the YIG microsphere cavity to monitor the magnetic field strength. Figure 1(b) shows that the Q factor of the YIG microsphere cavity magnetic sensor is 3.99×10^5.

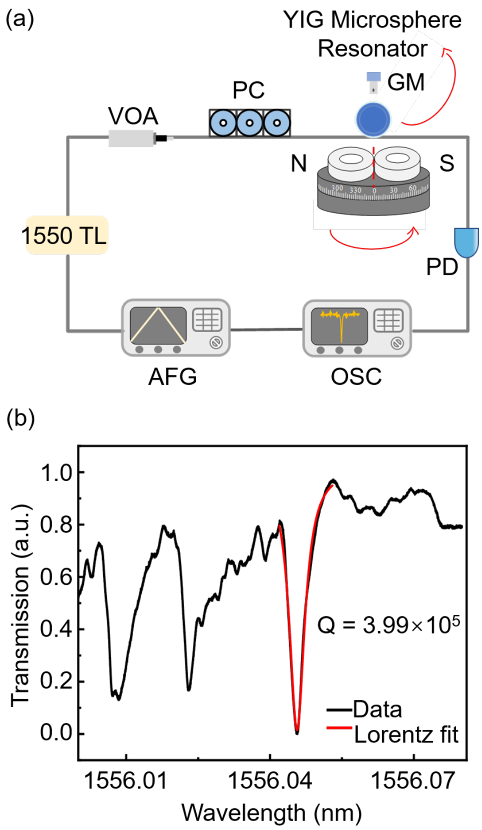

Fig. 1. (a) YIG microsphere cavity magnetic field vector sensing experimental setup. TL, tunable laser; PD, photodetector; AFG, arbitrary function generator; PC, polarization controller; OSC, oscilloscope; VOA, variable optical attenuator; GM, gauss meter (b) Typical transmission spectrum of a resonant mode in a YIG microsphere resonator.

To verify the sensing properties of the magnetic field, the external magnetic field intensity is fixed at 95.49 mT. Figure 2(a) depicts the evolution of the transmitted spectrum as the external magnetic field direction varies from 0° to 360°, with a step size of 15°. Where 0° and 90°indicate that the light propagation is parallel and perpendicular to the magnetic field direction, respectively. The location of the asterisk indicates the mode of tracking. Figure 2(b) shows the wavelength shifts with angle. The transmission spectrum exhibits blue shifts in the angle range from 0° to 90° or 180° to 270°. Conversely, the transmission spectrum shows red shifts in the angle range from 90° to 180° or 270° to 360°. A Linear fit to the experimental data yields a maximum direction sensitivity of 0.0717 pm/°. As shown in Figure 2(c), the wavelength response of the transmission spectrum exhibits a symmetrical "8" shape periodic change with the changes of the magnetic field direction in polar coordinates. The slight asymmetry of the wavelength shift relative to the magnetic field direction can be attributed to the inhomogeneity of the magnetic field and the slight displacement of the sensor from the centerline during rotation.

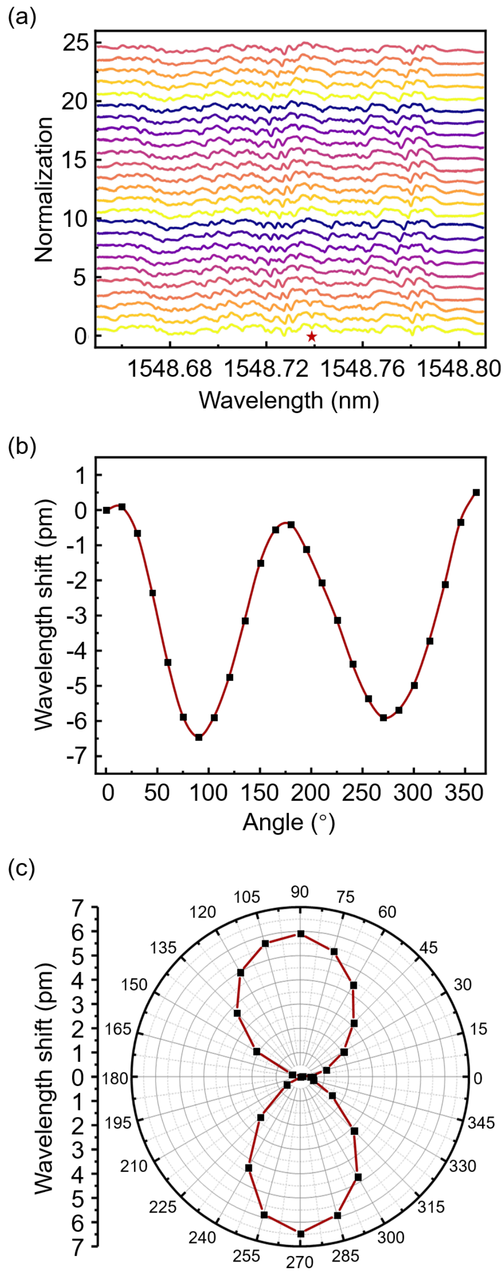

Fig. 2. (a) Transmission spectra of the YIG microsphere resonator change as the magnetic field direction from 0° to 360° in steps size of 15°. (b) The wavelength varied periodically with the magnetic field angle. (c) The correlation between the direction of the magnetic field and wavelength shift.

III. Conclusion

In conclusion, the YIG microsphere resonator-based magnetic field vector sensor is designed with a Q factor of ~10^5. Under an external magnetic field strength of 95.49 mT, the sensing of external magnetic field direction rotation 360°is realized by the YIG microsphere cavity and fiber-optic taper coupling system, and its direction sensitivity is 0.0717 pm/°. This magnetic vector sensor has the advantages of compact size and fast response, making it more suitable for use in complex electromagnetic environments. Therefore, it has potential applications prospects in industrial testing, medical diagnostics, and other fields.

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