Optical Magnetic Field Sensing based on Metamaterial Nanomechanics

Guoqiang Lan[1,2], Jun-Yu Ou[1], Eric Plum[1]

1. Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, Southampton, SO17 1BJ, UK

2. School of Electronic Engineering, Heilongjiang University, No. 74 Xuefu Road, Harbin 150080, China

Magnetic field underpins applications from navigation and mineral prospecting to data storage and brain function mapping. Therefore, small magnetic field sensors with large dynamic range, sensitivity, spatial and temporal resolution are important. Here we demonstrate a novel type of optical magnetic field sensor.

It consists of a magnetically actuated microcavity formed by a static mirror and a metamaterial (Fig. 1a). The metamaterial is supported by a flexible bridge actuator of nanoscale thickness and length L, which is displaced by the Lorentz force, $\mathbf{F}_L = L\mathbf{I}\times\mathbf{B}$, acting on an electrical current **I** flowing along the bridge in the presence of a magnetic field **B**. Such displacement changes the cavity length and thus the reflectivity of the device. Sensitivity, dynamic range and linearity of the sensor can be optimized by metamaterial design. Our metamaterial has been optimized for a quasi-linear sensor response in the near-infrared. The sensor was fabricated by thermal evaporation of gold (50 nm) on a 250 µm x 250 µm silicon nitride membrane (50 nm), followed by focused ion beam milling of bridge actuator and metamaterial (Fig. 1b). Electrical current is applied to the bridge actuator.

Magnetic displacement via the Lorentz force competes with thermal actuation via resistive heating in such a device. However, magnetic/thermal displacement does/doesn't depend on the current direction. Therefore, we measure the magnetically induced reflectivity change ΔR/R as the reflectivity difference for opposite current directions, normalized by the reflectivity without current (Fig. 1c,d). In the presence of a magnetic field, ΔR/R of the metadevice becomes strongly dependent on electrical current (Fig. 1c). We observe reflectivity changes of up to 27% at 165 mT magnetic field and 10 mA current. In this regime, the sensor's reflectivity is linearly dependent on both electrical current and magnetic field (Fig. 1c,d). Notably, the dynamic range of the sensor can be flexibly adjusted by changing the applied current. Given that the sensor is still in its linear regime at 165 mT and 10 mA, it will allow measurements of at least 1.65 T (10x larger) at 1 mA (10x smaller).

In the static regime, assuming reliable detection of 0.1% reflectivity changes with a stable laser and photodetector, the sensor has ~1 mT accuracy. This can be enhanced by resonant sensor operation with a sinusoidally oscillating current at the beam's 233 kHz fundamental mechanical resonance and lock-in detection of the resulting reflectivity modulation (Fig 1e). The mechanical resonance provides resonantly enhanced beam displacement (and thus reflectivity modulation), while detection locked to the oscillation frequency ω improves the reflectivity modulation detection sensitivity. Such detection rejects any thermal effect, as the magnetic field yields reflectivity modulation at ω, while resistive heating yields modulation at 2ω. On this basis, we estimate that sub-µT sensitivity for resonant sensor operation may be achievable. Considering that mechanical systems respond to forces that vary more slowly than their fundamental mechanical resonance, we estimate a sub-millisecond response time of the sensor.

We combine nanomechanics, photonics and metamaterials in order to realize an optical magnetic field sensor of microscale size. Here we provide an experimental proof of the sensing principle. We estimate that the sensor has the potential to provide sub-millisecond time resolution and six orders of magnitude of dynamic range.

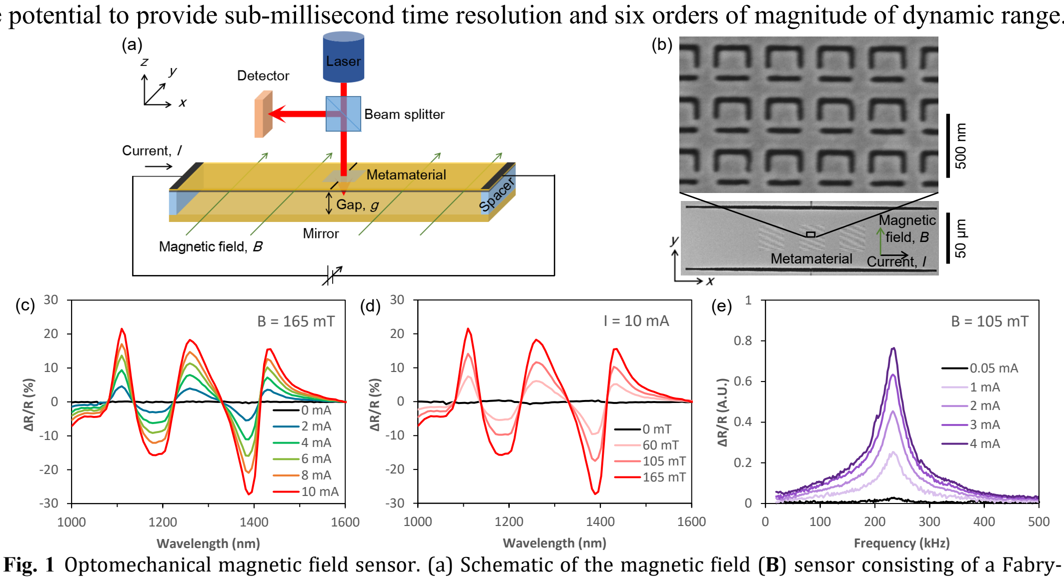

Fig. 1 Optomechanical magnetic field sensor. (a) Schematic of the magnetic field (**B**) sensor consisting of a Fabry-Pérot microcavity formed by a static mirror and a metamaterial on an elastic beam of length L that carries a current **I**. The cavity length *g* is controlled by the magnetic Lorentz force, $\mathbf{F}_L = L\mathbf{I}\times\mathbf{B}$. (b) SEM images of the metamaterial and the supporting beam. (c,d) Magnetically-induced reflectivity change for different (c) static currents and (d) magnetic fields. (e) Reflectivity modulation as a function of current modulation frequency at 1310 nm wavelength.