A NANOMACHINED TORQUE SENSOR WITH ULTRAHIGH SENSITIVITY

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ABSTRACT

This paper reports, for the first time, a novel nanoscale torque sensor in a split ring resonator. The mechanical resonator is embedded into ring resonator and separated by 200 nm from the substrate. By taking advantage of extreme sensitivity of ring resonator, the torque sensor achieves a displacement noise floor of 80 fm/ $Hz^{0.5}$. This is corresponding to small torque as small as 0.17×10^{-18} N·m. Particularly, the platform can be used to investigate the dispersive and dissipative coupling in optomechanics for novel physical devices and opens new door for a wide range of physical measurements involving extremely small torques.

INTRODUCTION

Optical measurement and control of mechanical vibrations are at the heart of many technological and fundamental advances in physics and engineering and play an important part in the modern science [1]. Mechanical devices with small torsion constants have been designed to response to small torques, making the sensitive measurement, such as gravity, charge, the Casimir force to be possible [2]. However, it is very difficult to make the measurement effective because although the size scaled down, the detection and measurement technique is not scaled down as well [3-4].

With the development of the optomechanics, the phonon-photon coupling provides a wonderful platform to control and measure the mechanical response. Different with traditional dispersive "path change" or "gap change" induced by flexural or breath mode of mechanical structures [5-7], dissipative sensing caused by mechanical torsional motion is attracting more and more attention [8-9]. The nonlinear coupling between the mechanical structures with the optical cavity provides a good platform to investigate the dispersive and dissipative coupling in optomechanics for novel physical devices. In this paper, we demonstrate for the first time the optomechanical torque sensor in a split ring resonator. The mechanical resonator is part of the ring, making the displacement of the resonator coupled with the transmission and resonance wavelength of ring. The transmission characteristics of ring are extremely sensitive to the displacement of mechanical resonator, making thermal mechanical noise is well resolved in the power spectrum. The displacement noise floor of this optomechanical torque sensor is 80 fm/ $Hz^{0.5}$, which can be used to detect extreme small torque as small as 0.17×10^{-18} N·m.

DESIGN AND THEORY

The proposed optomechanical sensor consists of an optical racetrack resonator, an input bus waveguide and a suspended mechanical torsional beam, as shown in Fig. 1. A signal light is pumped into the bus waveguide through the input port and coupled into the racetrack resonator. Due to the evanescent wave overlapping, the attractive optical force is generated between the racetrack resonator and the suspended beam. The motion of the beam not only shift the resonance frequency of the resonator but also changes the total transmission power of the resonator. A low power signal light is then pumped into the bus waveguide to detect the mechanical motion. As the beam modulates the resonance frequency and transmission of the ring, the power spectrum density can be observed in the RF spectrum analyzer.

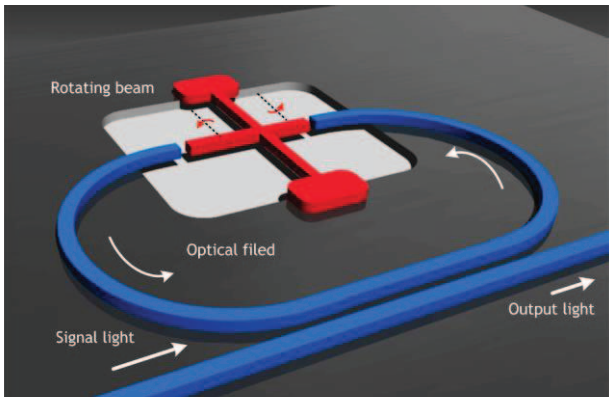

Figure 1: Schematic of the torsional sensor: a suspended beam is embedded into the racetrack resonator. The mechanical motion changes the transmission spectrum of the resonator.

The disconnected racetrack resonator is specially designed to make the dissipative sensing available. The racetrack resonator is sensitive to the torsional motion of the beam for the total resonator loss is sensitive to the out-of-plane displacement. The finite element method (COMSOL Multilphysics) simulation on the different mechanical modes (only first three modes) is shown in Fig. 2. The mechanical beam has two fundamental in-plane mode and one out-of-plane mode. The dispersive and dissipative sensing modes both exist in the mode (a) and mode (b). It should be noted that the imbalance in the beam design is to avoid the flexural mechanical mode.

The optical energy stored in the ring resonator can be expressed as [10-12]

$$|a|^2 = \frac{k_e}{(k/2)^2 + (w_c - w_r - g_{om}x)^2} P_{in} \quad (1)$$

where P_{in} is the power of the control light, k is the full-width at half-max linewidth of the optical resonance, k_e is the external coupling rate, w_c is the frequency of the control light, and w_r is the unperturbed resonance frequency of the ring, g_{om} is the optomechanical coupling coefficient and x is the mechanical deformation. The oscillator gets a random excitation from the thermal energy of the environment, which causes fluctuations in the oscillator motion known as Brownian motion. Thermal noise, which is white noise with a flat spectrum, can excite detectable displacement in the mechanical high-Q oscillator position at the oscillator resonance frequency. At resonance, the spectrum density is given by $S_{TH}(\omega) = 4k_B TQ/m\omega_0^3$, where k_B is the Boltzmann constant, T is the absolute temperature in the lab, Q is the mechanical quality factor, ω_0 is the angular mechanical resonance frequency and m is the effective mass of the resonator.

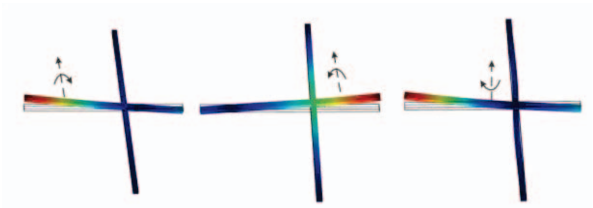
(a) (b) (c)

Figure 2: The first fundamental mechanical mode of the beam with out-of-plane mode (a), (b) and in-plane mode. The dispersive and dissipative sensing mode both exist in the mode (a) and mode (b). It should be noted that the imbalance in the beam design is to avoid the flexural mechanical mode.

The thermal noise of the beam can have an effect on the racetrack resonator, which can be used to measure the small torque. The transmission spectrum of the resonator as a function of the offset deformation and resonance wavelength is shown in Fig.3. The normalized maximum transmission occurs at 1577.17 nm with no offset deformation. When the beam is positive offset in the out-of-plane, the resonance wavelength is red shifted and the transmission is reduced. The resonance wavelength change is due to the effective index of the resonator is increased as the beam approaches the substrate. The normalized transmission is due to the total loss is changed by the separation between the resonator and the beam.

The normalized transmission as a function of offset deformation is much clearer in Fig.4. We defined the transmission changes due to the offset deformation as the transmission coupling $G_T = dT/dx$ and the resonance wavelength changes as the wavelength coupling. $G_\lambda = dT/dx$. The two coupling contributes to the power spectrum density changes in the frequency domain. In our structures, the transmission coupling plays more important part in the torsion sensing for the optical quality factor of the racetrack resonator is relative small.

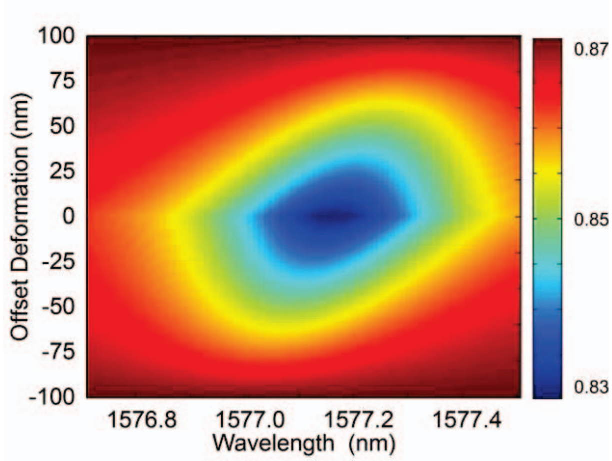

Figure 3: The normalized transmission spectrum of the resonator as a function of the offset deformation and resonance wavelength.

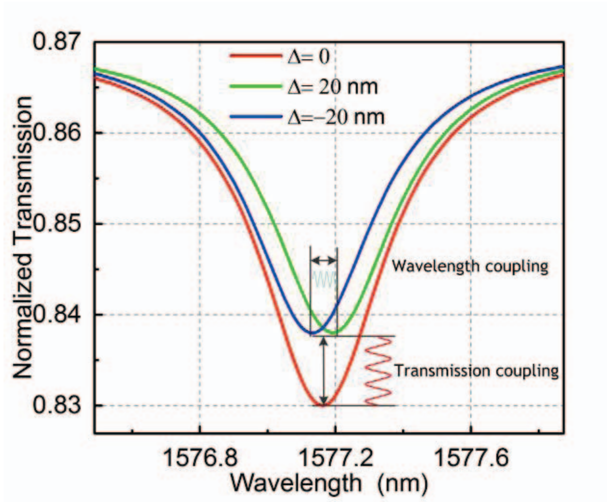

Figure 4: The normalized transmission as a function of offset deformation. The transmission coupling is due to the loss induced by the gap change with the wavelength coupling is due to the effective index change induced by the gap.

FABRICATION PROCESSES

The scanning electron microscope (SEM) graphs of the torsion sensor is shown in Fig. 5. The racetrack resonator with a footprint of 50 µm × 30 µm is fabricated on silicon-on-insulator (SOI) wafer with structure layer thickness of 220 nm. The actuator is patterned by deep UV lithography and etched by plasma dry etching. The waveguide is covered by a layer of SiO_2 cladding (2 µm thick) which is deposited using plasma enhanced chemical vapor deposition (PECVD). In the release process, a 50-nm amorphous silicon layer is used as the hard mask to protect the structures not to be released. Then the buried-oxide layer is removed using HF-vapor with precise time control. The desired gap between the silicon beam and substrate can be achieved by precisely time control. A pair of grating coupler was used to couple light into and out of the device. The device is tested in a vacuum chamber with conditions of 10^{-6}Pa. The vacuum conditions can be further improved by molecular pump. In our design, the condition is good enough to make the thermal mechanical noise resolved in the power spectrum density.

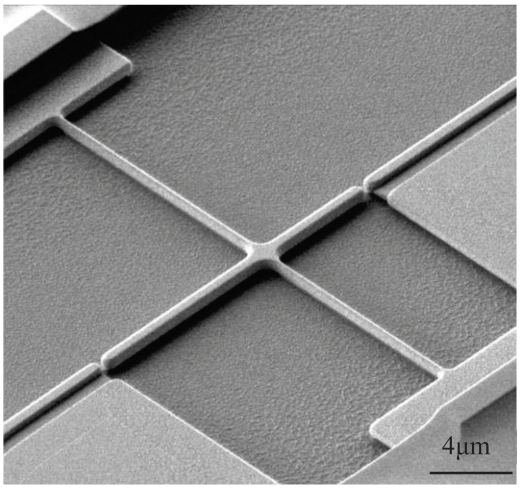

Figure 5: SEM images of the torsional sensor with a scale bar of 4 micrometers.

RESULTS AND DISCUSSIONS

A wide spectrum light from a 12-dBm ASE light source (Amonics ALS-CL-13) is pumped into the waveguide to measure the transmission spectrum of the resonator. The power and polarization state of the signal light from a tunable laser (Santec TSL 510) is controlled by the fiber polarization controller and variable optical attenuator. The output signal light is detected by the photo detector (FPD 510). The converted electrical signal.is sent to oscilloscope (MDO4104B-3) to measure the time and frequency domain response of the coupled resonators.

The fabricated racetrack resonator has an optical quality factor of 3942.5 at resonance wavelength 1577.1625nm. The optical quality factor is much lower than a complete ring. However, the quality factor is still good enough to make thermal mechanical noise resolved in our measurement. It is due to the large transmission-coupling coefficient. In our experiment, the mechanical quality factor is estimated to 440 by fitting the experimental results. More detailed parameters is listed in Table 1. The thermal mechanical noise spectrum is shown in Fig. 6. The most sensitive mode is in 4.3 MHz, which corresponds to -79 dBm in power spectrum. Other mechanical mode is also demonstrated in our experiment, which is labelled as other mechanical modes. The coupling of a mechanical oscillator to the heat bath leads to energy loss and noise according to the fluctuation–dissipation theorem. The displacement noise of mechanical resonator can be calculated by Nyquist relation. By fitting the experiment data, displacement noise floor and torque sensitivity can be calculated. The displacement noise floor of this optomechanical torque sensor is 80 fm/ $Hz^{0.5}$, which can be used to detect extreme small torque as small as 0.17×10^{-18} Nm.

The noise floor of the torque sensor can be improved by improving the optical quality factor of the racetrack resonator and mechanical quality factor of torsion beam. The structure and dimensions of the cross section of the racetrack can also be optimized to have the large optical quality factor.

Table 1: parameters that used in the simulation and figure plotted in the text.

Symbol	Parameters	Value
ω_0	Mechanical frequency (first)	2.2 MHz
Q_m(Vacuum)	Mechanical quality factor	440
m	Mechanical mass	3.07pg
λ_0	Optical resonance frequency	1577.1625 nm
Q_o	Optical quality factor	3942.5
G_λ	Wavelength coupling coefficient	1.5 pm/nm
G_T	Transmission coupling coefficient	4×10^{-4}/nm

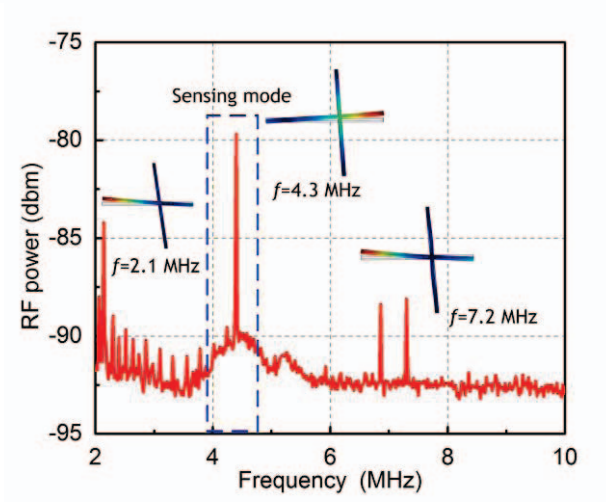

Figure 6: Thermal mechanical noise of the torsional sensor.

CONCLUSIONS

In this work, a novel nanoscale torque sensor in a split ring resonator for the first time. The mechanical resonator is embedded into ring resonator and separated by 200 nm from the substrate. By taking advantage of extreme sensitivity of ring resonator, the torque sensor achieves a displacement noise floor of 80 fm/ $Hz^{0.5}$. This is corresponding to small torque as small as 0.17×10^{-18} N·m. Particularly, the platform can be used to investigate the dispersive and dissipative coupling in optomechanics for novel physical devices and opens new door for a wide range of physical measurements involving extremely small torques.

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