PHOTONICS **Research**

Demonstration of an ultra-low-threshold phonon laser with coupled microtoroid resonators in vacuum

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We demonstrate an ultra-low-threshold phonon laser using a coupled-microtoroid-cavity system by introducing a novel coupling approach. The scheme exhibits both high optical quality factors and high mechanical quality factors. We have experimentally obtained the mechanical quality factor up to 18,000 in vacuum for a radial-breathing mode of 59.2 MHz. The measured phonon lasing threshold is as low as 1.2 μW, which is ∼5 times lower than the previous result.   © 2017 Chinese Laser Press

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1. INTRODUCTION

Thanks to the rapid progress in sophisticated and advanced nanofabrication technology, cavity optomechanics [1] has become an active research field in the past few decades with focus on the interactions between electromagnetic radiation and mechanical motions in optical cavities with different platforms [2–14]. Among these research activities, silica microtoroid resonators have been established as a powerful platform mainly due to their achievable high-quality optical and mechanical properties [15,16]. For example, silica microtoroids have been largely exploited in the studies of mechanical oscillations [2,3], optomechanically induced transparency [17], and optomechanical cooling [5,18] with a single microcavity. Also, mechanical oscillations based on a single microcavity have been realized in other whispering gallery mode microcavities such as microspheres [6], microdisks [13,14], and double disks [10].

Six years ago, using a compound microcavity system (two coupled microtoroids) in air, Vahala's group reported the realization of mechanical oscillations (also called phonon laser), i.e., the phonon analog of an optical laser in a two-level system [19]. In comparison with past demonstrations using a single resonator, the compound microcavity system (often referred to as a photonic molecule) has enabled competitive optical frequency controls that affect both phononic lasing and cooling actions. Moreover, the associated level spacing is easily tunable through adjusting the optical coupling strength. The level spacing is tuned to match the mechanical frequency in order to maximize

the efficiency. In comparison with the single cavity mode phonon laser, the compound microcavity phonon laser exhibits a few impressive features, including lower threshold and insensitivity to noise. Furthermore, it does not require one to significantly enlarge the dimensions of the device to create/tune these finely spaced levels, and this advantage results in a minimal effect on enhancing the optomechanical interaction strength. In the work, the two microtoroids were placed at the edges of separate silicon chips to effectively couple their corresponding cavity modes [19]. Such a compound system has recently found interesting applications in demonstrations of the electromagnetically induced transparency (EIT)-like effect [20], parity-time symmetry [21,22], and optical isolation [21,22]. For applications in cavity optomechanics, the diameter of the silicon pillar should be made very small by using an additional XeF_2 dry-etching process [16] to ensure the high mechanical quality factor of the microtoroid. However, such a sample preparation procedure experiences certain major difficulties in achieving a centrosymmetric pillar with a small diameter, when the microtoroid is formed at the edge of the silicon chip [19]. This is because in such a case it is challenging to guarantee homogeneous etching of the silicon, and any inhomogeneous etching will limit the achievable mechanical quality factor. Besides, the defect of the silicon pillar arising from inhomogeneous etching also severely affects the mechanical modes of the microtoroid by adding harmonic peaks to the mechanical noise spectrum.

To overcome those drawbacks encountered in Ref. [19], we adopt a novel method of sample design, which enables both high optical and mechanical quality factors in this coupled-microtoroid-cavity system. In the experiment, we have achieved loaded optical quality factors around 3.7×10^7 for the supermodes of the coupled microcavities and a mechanical quality factor as high as 18,000 in vacuum for a radial-breathing mode of 59.2 MHz. The measured phonon lasing threshold is as low as 1.2 μW, which is five times lower than that reported in Ref. [19].

2. SAMPLE FABRICATION AND PREPARATION

In this work, we adopt a new procedure to prepare the coupled-microtoroid-cavity system for multimode cavity optomechanics [23–25]. The essential design is schematically shown in Fig. 1(a), where the coupled-microtoroid system consists of a microtoroid A (with a principal diameter of 59 μm and minor diameter of 9 μm) and an invertedly mounted microtoroid B (with a principal diameter of 60 μm and minor diameter of 9 μm). Microtoroid A was first prepared by a combination of optical lithography, hydrofluoric etching, XeF_2 dry etching, and CO_2 laser reflow [15]. To reduce the clamping loss induced by the silicon pillar, an additional XeF_2 dry etching was employed to form an ultra-thin-silicon-pillar-supported microtoroid [Fig. 1(c)] [16]. Microtoroid B with a normal silicon pillar was fabricated at the corner of a silicon chip [Fig. 1(b)] with a fabrication process similar to the one used in previous works [20–22,26]. In those previous works [19–22], the microcavities were fabricated at the edges of separate chips. The coupling approach employed in the current work only needs one microcavity (microtoroid B) to be fabricated at the corner of a silicon chip, which can be used to couple with any microtoroids on another chip and therefore save fabrication time. This scheme might also be very useful for future scalable quantum computation systems, since one microcavity can be used to individually address many different microcavities (or cavity-quantum electrodynamics qubits) on a different chip.

To construct the coupled-microcavity system, we first select a pair of microtoroids that hold optical modes with the same polarization and close resonant frequencies. Figures 2(a) and 2(b) show the measured optical transmission spectra of
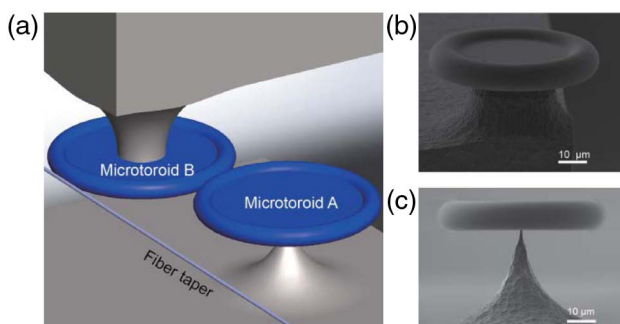
Fig. 1. (a) Physical implementation of the coupled-microtoroid cavity system. Here, only microtoroid B is coupled to the fiber taper. (b) Scanning electron microscope (SEM) image of microtoroid B with a large pillar diameter of about 20 μm. (c) SEM image of microtoroid A with a small pillar diameter of about 0.8 μm.
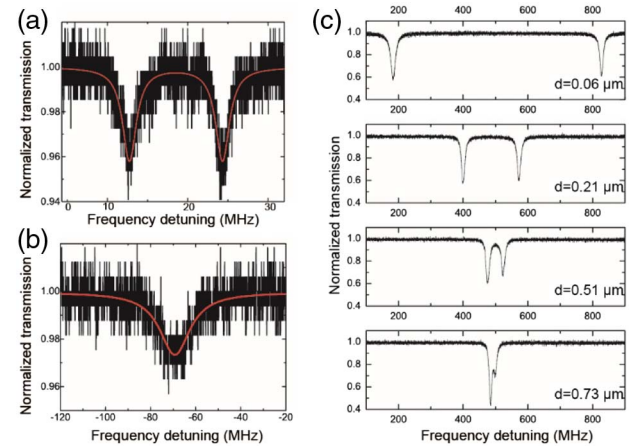

Fig. 2. (a) and (b) Normalized optical transmission spectra of microtoroids A and B with their corresponding intrinsic optical quality factors of 9.7×10^7 and 2.5×10^7 at the wavelength of 1535 nm, respectively. (c) Set of representative optical spectra taken over a range of spatial separation distance, which exhibit controllable splitting of the two supermodes in coupled microtoroids.

microtoroids A and B (with intrinsic optical quality factors of 9.7×10^7 and 2.5×10^7, respectively), which were operated at almost the same resonant wavelength of 1535 nm. Then we tune the resonant frequency of each microtoroid cavity to be the same using the thermoelectric cooler (TEC). By fixing the coupling (distance) between microtoroid B and the tapered optical fiber to a certain value and changing the position of microtoroid A, we can precisely control the supermode splitting of the coupled microcavities. Transmission spectra at several different spatial separations between microtoroids A and B are presented in Fig. 2(c) with a tunable laser scanning in the frequency vicinity of optical resonances.
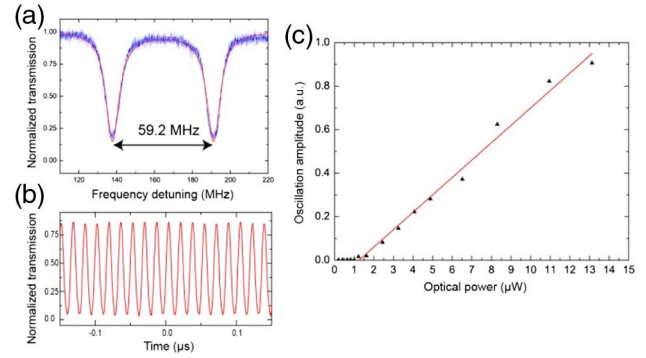
3. MEASUREMENTS OF PHONONIC LASING BEHAVIORS

We utilize the coupled-microtoroid system shown in Fig. 1(a) to demonstrate the phononic lasing action with a low threshold. Figure 3(a) depicts the experimental setup used to characterize the phonon laser with the coupled-microtoroid cavities. A narrow linewidth tunable pump beam (at the wavelength of ~1550 nm) from an external-cavity diode laser (Newport TLB-6700) is evanescently coupled to microtoroid B via a tapered optical fiber [27,28] as shown in Fig. 1(a). A wavelength meter (HighFinesse WSU10) with a PID control module is used to monitor and lock the laser frequency onto the cavity mode with a resolution of ±1 MHz. In the experiment, we place the entire system inside an ultra-high vacuum chamber (with an air pressure of 5×10^{-6} Pa) to ensure high mechanical quality factors for the microtoroids. In this vacuum environment, the sample temperature can be precisely tuned at the resolution of 1 mK through TEC. A small portion of the transmitted signal output field is injected into a low-speed and high-gain photo-receiver (Newport 2011, 1 MHz bandwidth) to characterize the optical modes of the coupled-microtoroid resonators, while the rest [after amplification by
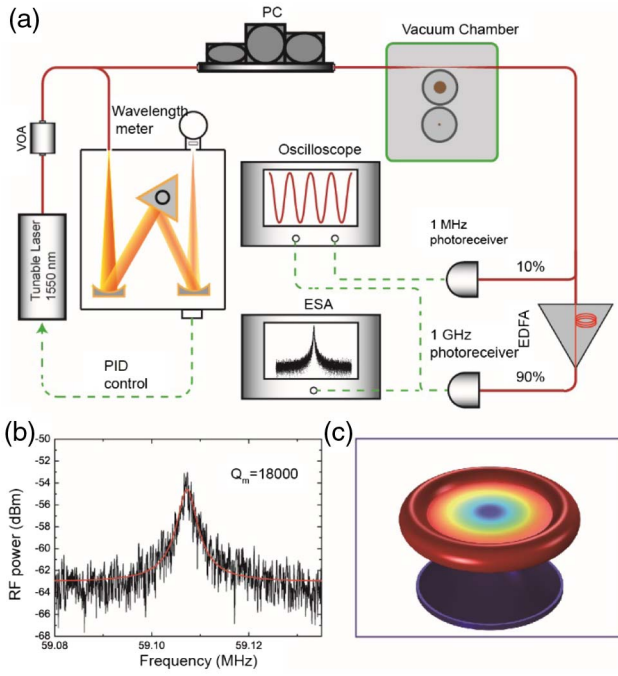
Fig. 3. (a) Schematic diagram of the phonon laser experimental setup with coupled silica microtoroid cavities. VOA, variable optical attenuator; PC, polarization controller. (b) Measured power spectrum of microtoroid A, which gives a mechanical quality factor of 18,000 in vacuum for the fundamental radial-breathing mode of 59.2 MHz. (c) Numerical FEM simulation of the fundamental radial-breathing mode.

Fig. 4. (a) By carefully tuning the parameters, the system is operated to produce two supermodes with frequency splitting equal to the mechanical frequency of microtoroid A. (b) Typical optical transmitted optical power for input pump powers above the threshold. (c) Mechanical oscillation amplitude as a function of input optical pump power for the compound microtoroid resonators in vacuum, where the phonon lasing threshold is as low as 1.2 μW.
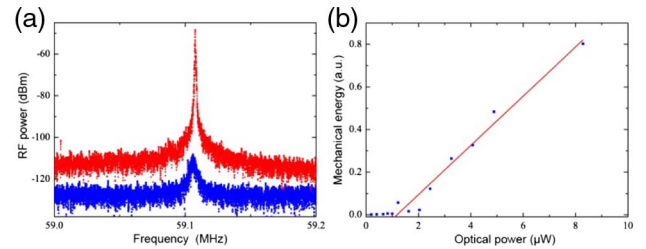
Fig. 5. (a) Typical RF spectra with optical pump power below (blue) and above (red) the threshold. (b) Mechanical energy as a function of input optical pump power.

an erbium-doped fiber amplifier (EDFA)] is sent to a high-speed photo-receiver (Newport 1611, 1 GHz bandwidth) that is connected to an oscilloscope and an electrical spectrum analyzer (ESA) for mechanical mode analysis. To obtain the mechanical quality factor of microtoroid A (in the experiment, only the mechanical mode of microtoroid A is considered), we first characterize its mechanical mode by locking an optical mode of microtoroid A to a low optical power laser with a blue detuning when microtoroid A is not coupled to microtorid B. Figure 3(b) shows the measured mechanical spectrum of the fundamental radial-breathing mode from microtoroid A, which yields a mechanical frequency of ~59.2 MHz and a mechanical quality factor of 18,000 in vacuum. This measured mechanical frequency is in good agreement with the simulated value through the mechanical finite element method (FEM) simulation [Fig. 3(c)]. Also, unlike Ref. [19], no obvious mechanical mode cluster has been found in the mechanical spectrum, due to the symmetrical silicon pillar of microtoroid A.

In the experiment, by carefully tuning the system parameters, such as the microtoroids' positions and their temperatures, we can make a supermode with a mode splitting equal to the mechanical frequency of microtoroid A, as shown in Fig. 4(a). The loaded optical quality factors for the supermodes are 3.7×10^7. To excite the phononic lasing, the pump laser is locked at the blue supermode using a wavelength meter. When the pump optical power is operated above the lasing threshold, an oscillatory transmission can be clearly observed

in the time domain [Fig. 4(b)]. The high performance of our current system allows us to have a much lower threshold value. Figure 4(c) gives the mechanical displacement amplitude, whose value is indirectly obtained through measuring optical modulation depth as a function of the optical power [29]. The measured phononic lasing threshold is about 1.2 μW, which is in good agreement with the theoretically calculated value 1.18 μW and is much lower than the threshold value of 7 μW reported in Ref. [19]. We notice that the phononic lasing threshold can also be obtained by integrating the spectral area of the mechanical spectrum [shown in Fig. 5(a)] as a function of the input pump laser power [13]. Here, as an alternative test we also used this method to retrieve the threshold value [Fig. 5(b)], which coincides with the value mentioned above [Fig. 4(c)].

4. CONCLUSION

In summary, we have experimentally realized a coupled optical microtoroid cavity system in vacuum, which exhibits excellent optical and mechanical performance. By introducing a novel coupling geometry, we demonstrated a low-threshold phononic lasing behavior for a 59.2 MHz radial-breathing mode with a mechanical quality factor of 18,000. We have achieved a lasing

threshold value as low as 1.2 μW, which is five times lower than the value obtained in Ref. [19]. Besides the phononic lasing action, such a chip-based coupled-microcavity scheme may find potential applications in multimode optomechanical cooling, multimode optomechanically induced transparency, as well as addressable quantum information processing.

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