Demonstration of an Ultra-Low Threshold Phonon Laser with Coupled Microtoroid Cavities in Vacuum

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Abstract: *We report an ultra-low threshold phonon laser using coupled microtoroid cavities in vacuum with a novel coupling method. The measured lasing threshold is as low as 1.3 μW.*
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I. INTRODUCTION

Over decade efforts, cavity optomechanics has now become a very active research field with focus on the interaction between electromagnetic radiation and mechanical motions in optical cavities [1]. In this research activity, silica microtoroid cavities have been established as a powerful platform partly due to their high quality optical [2] and mechanical [3] properties. To name a few, silica microtoroids have been largely exploited in the studies of mechanical oscillation [4], optomechanically induced transparency [5] and optomechanical cooling [6] with single microcavity.

Only a few years ago, with the use of a compound microcavity system in air, the Vahala's group reported the realization of a phonon laser [7], the phonon analog of an optical laser in a two-level system. However, in their work two microresonators were all located at the chip edges which lead to the asymmetry of the silicon pillars. As a result, such asymmetry deleteriously influenced the mechanical mode and prevented the possibility of fabricating ultra-thin pillars. Consequently, a low mechanical quality factor is typically associated with this type of coupling geometry.

To achieve a higher mechanical quality factor as well as to stabilize the system, here we demonstrate a two-level phonon-laser action with two coupled microtoroid resonators in vacuum by employing a different but new coupling method. In comparison with the previous work, our system not only exhibits a number of new features but also yields the lasing threshold of 1.3 μW, which is 5 times lower than that reported in Ref. [7].

II. SAMPLE AND MEASUREMENT

A. Sample Preparation

As schematically shown in figure 1(a), the coupled microtoroid system consists of a microtoroid A and an inverted microtoroid B. In the experiment, the microtoroid A, fabricated by two times XeF_2 dry etching, has an ultra-thin silicon pillar (Fig. 1(b)) which ensures a high mechanical Q-factor [3]. The microtoroid B with a normal silicon pillar is fabricated at the corner of a silicon chip (Fig. 1(c)). The position and temperature of the two microcavities are further controlled by attocube nanopositioners and thermoelectric cooler (TEC) elements for precision control and stabilization.

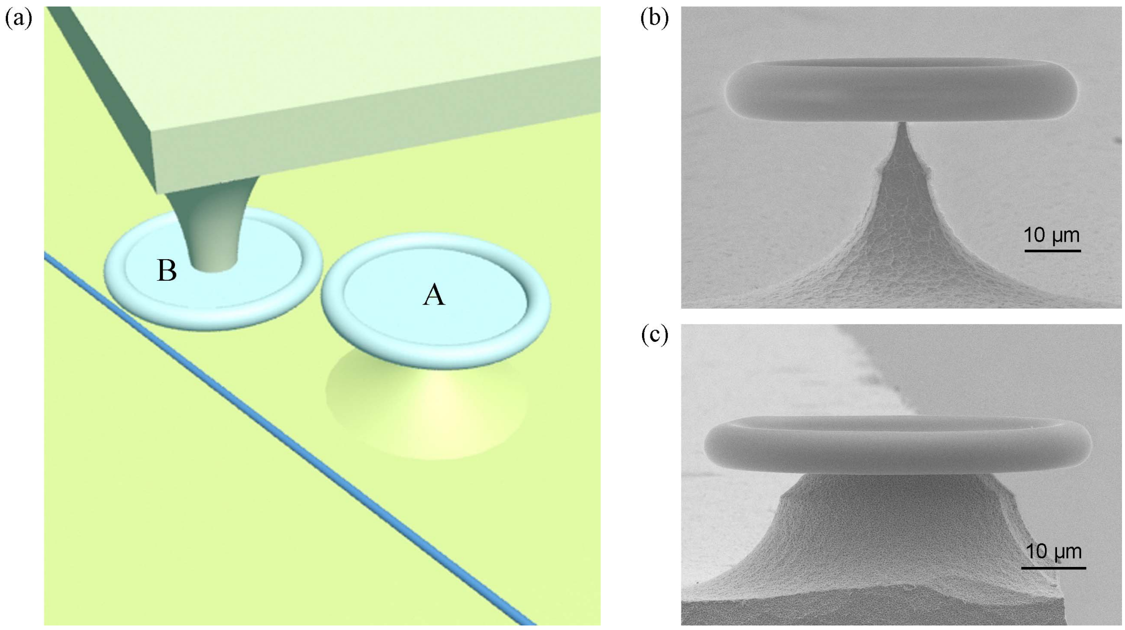

Fig.1. (a) Schematic diagram of the coupling geometry between two microtoroid resonators. (b) and (c) Scanning electron microscope images of the microtoroid with tiny silicon pillar and the microtoroid at the corner of a silicon chip, respectively.

B. Phonon Laser Measurement

In the experiment, two microtoroid cavities with intrinsic optical Q-factors of 9.7×10^7 and 9.3×10^7 and scattering-induced mode splittings of 11.2 MHz, 7.6 MHz, were used to form the coupled system. By carefully tuning the positions and temperature of the two microtoroids, we can obtain a supermode with a mode splitting equal to the mechanical frequency of the microtoroid A. The mechanical frequency for the fundamental radial breathing mode of microtoroid A is measured to be 57.5 MHz, and the mechanical Q-factor is 9000 in vacuum. To excite the phonon laser, the pump laser is locked at the blue supermode using a wavelength meter. When the pumped optical power is operated above the threshold, an oscillatory transmission can be clearly observed in the time domain (Fig. 2(a)). The high performance of our system allows us to have a much lower threshold. As shown in figure 2(c), the measured phonon lasing threshold is about 1.3 μW, which is much lower than 7 μW reported in the work of Ref. [7].

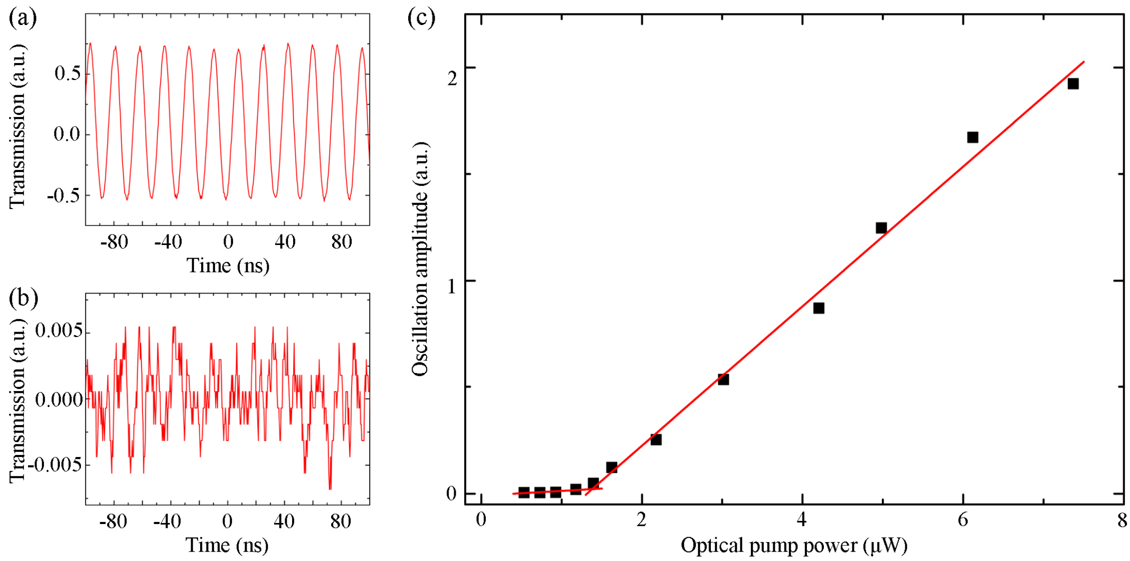

Fig. 2. (a) and (b) Optical transmitted powers above and below the threshold, respectively. (c) Measured oscillation amplitude versus optical pump power.

III. Conclusions

In conclusion, we demonstrated a compound structure of two microtoroids through a new coupling method for multi-mode cavity optomechanics. In particular, we have successfully realized an ultra-low threshold phonon laser operating in vacuum. It is expected that our system will find other applications in multi-mode optomechanical cooling.

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References

[1] M. Aspelmeyer, T J Kippenberg, and F Marquardt, “Cavity optomechanics,” Rev. Mod. Phys, vol. 86, pp. 1391-1452, December 2014.

[2] D. K. Armani, T. J. Kippenberg, S. M. Spillane, and K. J. Vahala, “Ultra-high-Q toroid microcavity on a chip,” Nature, vol. 421, pp. 925-928, February 2003.

[3] G. Anetsberger, R. Rivière, A. Schliesser, O Arcizet, and T. J. Kippenberg, “Ultralow-dissipation optomechanical resonators on a chip,” Nat. Photonics, vol. 2, pp. 627-633, September 2008.

[4] T. Carmon, H. Rokhsari, L. Yang, T. J. Kippenberg, and K. J. Vahala, “Temporal behavior of radiation-pressure-induced vibrations of an optical microcavity phonon mode,” Phys. Rev. Lett, vol. 94, 223902, June 2005.

[5] S. Weis, R. Rivière, S. Deléglise, E. Gavartin, O. Arcizet, A. Schliesser, and T. J. Kippenberg, “Optomechanically induced transparency,” Science, vol. 330, pp. 1520-1523, December 2010.

[6] A. Schliesser, R. Rivière, G. Anetsberger, O. Arcizet, and T. J. Kippenberg, “Resolved-sideband cooling of a micromechanical oscillator,” Nat. Physics, vol. 4, pp. 415-419, May 2008.

[7] I. S. Grudinin, H. Lee, O. Painter, and K. J. Vahala, “Phonon laser action in a tunable two-level system,” Phys. Rev. Lett, vol. 104, 083901, February 2010.