A Tunable Narrow-Linewidth Raman Laser Based on an Ultrahigh-Q Packaged Microrod Resonator

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Abstract: We report a tunable narrow-linewidth Raman laser by using a robust packaged microrod resonator with an ultrahigh quality (*Q*) of ~1.2×10^9 . The linewidth is measured to be as low as 19 Hz.

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1. Introduction

Narrow linewidth lasers play an important part in fields such as optical atomic clocks, coherent laser communications, laser radar, and precision spectroscopy [1]. Whispering-gallery mode (WGM) microresonators with high quality factors and small mode volumes, hold promise as candidates for low-threshold and narrow linewidth lasers. Common silica microresonator lasers are typically realized through the integration of WGM microresonators and gain materials, such as the introduction of rare-earth ions or the injection of gain solutions into the resonator [2]. However, these microresonators are infused with additional substances, destroying the *Q* factors. Stimulated Raman Scattering (SRS) in silica microresonators instigates gain via the interaction between pump photon and optical phonon, obviating the need for other gain materials [3]. In addition, silica-based Raman sources also facilitate the extension of the wavelength applicability range for semiconductor lasers.

Here, we demonstrate a narrow-linewidth Raman laser based on a packaged silica microrod resonator (PSMR) with ultrahigh-*Q* of ~1.2×10^9. The achieved Raman lasing threshold is as low as 2.52 mW. By using the delayed self-heterodyne method, the 19 Hz fundamental linewidth of the Raman laser is measured. Moreover, the tunability of Raman laser is demonstrated based on thermo-optic effect. As the temperature increases from 19.04 °C to 23.71 °C, a tuning range of 0.041nm is obtained with a temperature sensitivity of 8.85 pm/°C. This work demonstrates the immense potential of ultrahigh-*Q* PSMR to become tunable narrow-linewidth Raman lasers.

2. Experimental results

The silica microrod resonator is fabricated with a 3 mm-diameter quartz rod via a CO_2 laser reflow process. The entire preparation procedure is implemented in an automated laboratory platform, which can be finished within one minute. The *Q* factor of ~1.2×10^9 is obtained by a Lorebtzian fit to the transmission spectrum, as shown in Fig. 1(a). Furthermore, the silica microrod resonator and taper fiber are packaged in a customized box, which enables the stable coupling condition and protects the microrod resonator from external pollutant, as shown in the inset of Fig. 1(a). The excited SRS spectrum is shown in Fig. 1(c). The threshold is measured by extracting the Raman lasing power under different pump power. Figure. 1(d) illustrates the dependence of Raman lasing power on varying pump power, and the threshold of is determined to be 2.52 mW through linear fitting.

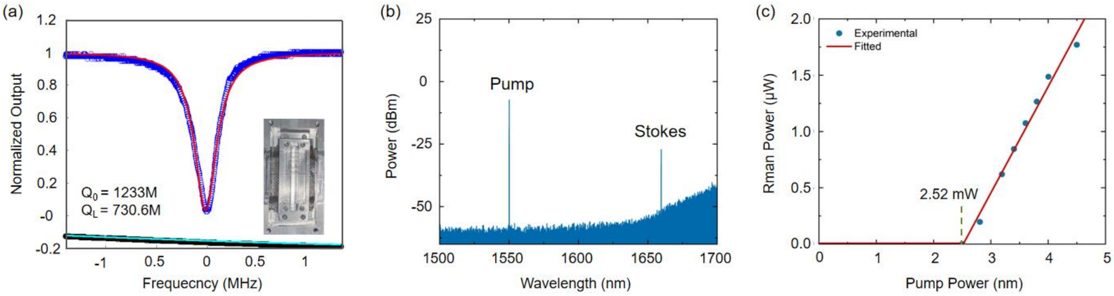

Figure. 1. (a) Transmission spectrum of PSMR, determining the Q-factor to be 1.2×10^9 via Lorenizan fitting. Inset: Physical photo of the PSMR. (b) Measured and fitted Raman spectrum. (c) The Raman lasing power versus the pump power, and the threshold of 2.52 mW is obtained.

The fundamental linewidth of Raman lasers in microresonators is determined by the Schawlow-Townes formula as follows [4]:

$$\Delta\nu = \frac{(1+\alpha^2)\hbar\omega^3}{(4\pi P Q_T Q_{ex})}(n_T + N_T + 1) \qquad (1)$$

Where ω represents the Stokes laser angular frequency, P is the output power, Q_T and Q_{ex} denote the total and external coupling Q-factor for the Stokes lasing mode, respectively, n_T and N_T respectively are the numbers of thermal quanta in the mechanical and the Stokes field, and is the linewidth enhancement factor. It is evident that the ultrahigh-Q microresonators facilitate the achievement of narrow linewidth Raman lasers. Therefore, the silica microrod resonators with ultra-high Q factors over one billion can achieve narrower linewidths.

Figure 2(a) illustrates experimental setup for linewidth measurement based on the delayed self-heterodyne method. A tunable laser, operating at 1550 nm wavelength, serves to pump the microresonator to excite Raman lasing. The Raman laser and pump laser are split into two paths, one is directed to an acoustic-optic modulator (AOM) for frequency shifting, and the other through a 10 km fibre optic delay line. Additionally, a 1550 nm/1650 nm Raman wavelength division multiplexer is employed to separate the pump laser and Raman laser. Subsequnetly, the Raman laser and delay signal are mixed in a photodetector, resulting in the generation of beat signals. Figure. 2(b) illustrates the SSB frequency noise spectrum of the generated 34 μW Raman laser. Clearly, with the increase of frequency offset, the frequency noise decreases to the level of white noise at high frequencies [4]. It is observed that the white noise is as low as 3 Hz^2 /Hz. Considering the relationship between white noise (S_v) and fundamental linewidth (Δv_{ST}) provided by $\Delta v_{ST}=2\pi S_v$, the linewidth of the Raman laser can be calculated to be 19 Hz. Remarkably, with increasing laser power, the linewidth can reach levels as low as Hz or even sub-Hz. Moreover, the tunability of Raman laser is demonstrated using thermal tuning method, as shown in Fig. 2(c). Here, a temperature cooler and thermistor is integrated with the PSMR to control the temperature. The tunable range of 0.041 nm of Raman laser is achieved when the temperature changes from 19.04 °C to 23.71 °C in steps of ~0.5 °C.

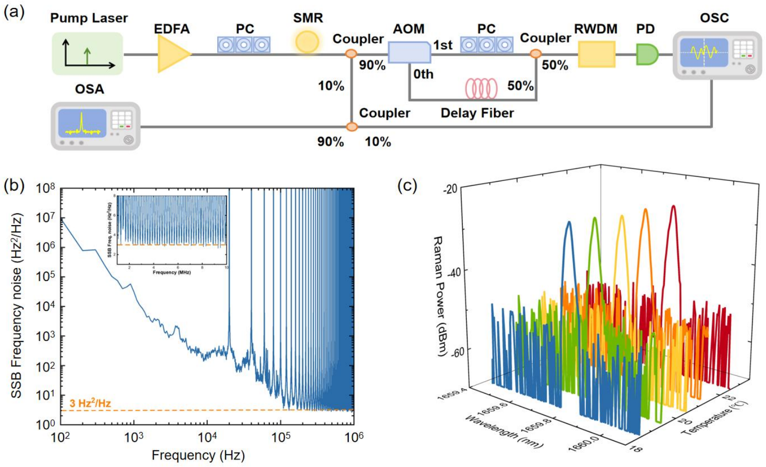

Figure. 2. (a) Linewidth measurement system. EDFA, Erbium-doped fiber amplifier; PC, polarization controller; AOM, acoustic-optic modulator; RWDM, Raman wavelength division multiplexer; PD, photodetector; OSA, optical spectrum analyzer; OSC, oscilloscope. (b) The single-sideband (SSB) frequency noise spectrum of the Raman laser. (c) The response of the packaged SMR resonator to thermal variation.

In conclusion, we report a tunable narrow-linewidth Raman laser based on a PSMR with an ultrahigh-Q over one billion. The Raman lasing with a low threshold of 2.52 mW, and the linewidth as low as 19 Hz is measured by using the delayed self-heterodyne method. Additionally, a tuning range of 0.041 nm have been attained through thermal tuning. It is worth noting that the linewidth can be further optimized by increasing Raman power, in the future to meet the needs of practical applications.

3. Acknowledgements

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