Research article

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Tunable Brillouin and Raman microlasers using hybrid microbottle resonators

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Abstract: We realized a tunable Brillouin laser and a tunable Raman laser by using ultrahigh-quality-factor (Q) hybrid microbottle resonators. The whispering-gallery-mode microresonator-based Brillouin and Raman lasers possess unique advantages (e.g. low threshold, narrow line width, and flexible lasing wavelength region) and various potential applications. Efficient tuning of the Brillouin and Raman microresonator lasers is desirable in many cases. However, the corresponding lasing wavelength tunability is rarely reported. In this work, we realized the ultralow-threshold Brillouin and Raman lasers based on the proposed hybrid microbottle resonators with Q factors over 10^8 . Meanwhile, by feeding the control light through the axial direction of the hybrid microbottle resonators, a Brillouin lasing wavelength tuning range of 2.68 nm and a Raman lasing wavelength tuning range of 2.32 nm are realized, which are one order of magnitude and almost once larger than those reported in the previous works, respectively. Such tunable microlasers could find significant applications in light sources, microwave photonics, and optical sensing.

Keywords: tunable microlasers; whispering gallery modes; stimulated Brillouin scattering; stimulated Raman scattering; iron oxide nanoparticles.

1 Introduction

In recent years, silica whispering-gallery-mode (WGM) microresonators have become the research focus due to

their ultrahigh quality factors (Q) and small mode volumes [1–4]. Hence, they have been applied in a wide range of areas such as nonlinear optics [5–10], sensing [11–13], optomechanics [14, 15], and laser emission [16, 17]. Especially, the WGM microresonator-based laser has become an essential and powerful platform for high-sensitivity sensing [17, 18], nanoparticle detection [19], microwave photonics [20], and optical communications [21]. Generally, the silica microresonator lasers are realized by integrating the optical microresonators and specific gain materials through several different methods [22–25]. Up to now, silica WGM microresonators with different structures have been fabricated to realize the laser emission, e.g. by doping rare earth ions or quantum dots into the resonators [21, 24, 26]. Besides, Fan's group has reported a series of microlasers by injecting gain solutions into the hollow cores of the optofluidic ring resonators, which are used for biosensing and bioanalysis [27–29].

However, the doped silica microresonators mentioned above generally lase in a certain wavelength region and possess degraded Q factors, which could hinder the realization of the narrow-linewidth and ultralow-threshold microlasers. Therefore, laser emission based on stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) in silica WGM microresonators have been studied [5, 30–33]. SBS is a nonlinear optical phenomenon in which optical waves interact with acoustic waves. During this process, both energy conservation and momentum conservation are required [34]. Backward Stokes light with frequency ω_s is generated when pump light with frequency ω_p is scattered from acoustic phonons with frequency Ω_B through the equation $\omega_s = \omega_p - \Omega_B$. In order to realize the Brillouin laser, the resonant frequencies of the microresonator should be located in the Brillouin gain spectrum. The Brillouin-induced frequency redshift in silica is 11 GHz, and the gain bandwidth is 20 ~ 60 MHz, which requires an exact match between the free spectrum range (FSR) and the Brillouin frequency shift. Therefore, the Brillouin laser requires that the microresonator possesses dense WGMs, which can be realized by enlarging its diameter. Fortunately, the microbottle resonator has a large WGM density due to its

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strong-asphericity-induced degeneracy breaking [35, 36]. This unique structure enables the microbottle resonator to generate the Brillouin laser with the smaller diameter compared with other kinds of WGM resonators, such as crystalline resonator [34] and wedge resonator [37]. For another nonlinear optical process, the SRS-induced gain is derived from the interaction between pump photons and optical phonons. During this process, the phase matching is automatically satisfied. The Raman laser has been realized in silica WGM microresonators including microsphere [5], microtoroid [38], and hollow microbottle [33].

In addition, the lasing wavelength tunability is a key characteristic for many applications. For the silica microresonator laser, several methods are proposed to tune the lasing wavelength, such as stretching method [33, 39], atmospheric pressure method [40], and thermal tuning method [31, 41]. In order to avoid the drawbacks of the above methods including mechanical disturbance and small tuning ranges, we have proposed an all-optical and reliable tuning mechanism in our previous work [26], which presents an excellent tuning performance. For the silica WGM microresonator, the tunable Brillouin and Raman lasers are rarely reported until now [31, 33].

In this work, we have proposed and experimentally demonstrated the tunable Brillouin and Raman lasing through the all-optical tuning mechanism based on the ultrahigh- Q hybrid microbottle resonator, which was coated with iron oxide nanoparticles on the tapered end. We have fabricated the hybrid microbottle resonators with Q factors over 10^8 . As shown in Figure 1, we fabricated an adiabatic silica microfiber to couple the pump light into the hybrid microbottle resonator. The inset of Figure 1 is

the fundamental mode field distribution of the microbottle resonator. As a result of the ultrahigh Q factor, we obtained a Brillouin laser with a threshold of 0.17 mW and a lasing wavelength tuning range of 2.68 nm by feeding the control light through the axial direction of the microbottle resonator due to the strong photothermal conversion ability of the iron oxide nanoparticles. Apart from that, we also realized a Raman laser with a threshold of 0.25 mW and a lasing wavelength tuning range of 2.32 nm. The tuning performances are obviously better than those reported in the previous works [31, 33].

2 Materials and methods

2.1 Fabrication method

The hybrid microbottle resonator was fabricated from the single-mode fiber through the two-step procedure [26, 42]. First, we fabricated the silica microbottle resonator with a microsphere on the tapered end through the fused pulling method on a carbon dioxide (CO_2) laser fabrication platform. The size of the microbottle resonator can be controlled through this method. Second, in order to realize lasing wavelength tuning, the hybrid microbottle resonator was fabricated by coating iron oxide nanoparticles on its tapered end through the precise micromanipulation. During this step, we can precisely control the coating area of the iron oxide nanoparticles.

2.2 Experimental setup

The experimental setup was illustrated in Figure 2. A tunable laser source (TLS) working in the 1550 nm band was used to measure the device performance and also acted as the pump light source. The TLS was first amplified by an erbium-doped fiber amplifier (EDFA) and then transmitted through a variable optical attenuator (VOA) and a polarization controller (PC). After that, it was split by a 10/90 optical splitter and fed into the coupling microfiber. The transmission spectrum from the other end of the microfiber was detected by a photodetector (PD) and analyzed by a digital storage oscilloscope (DSO). When we excited the Brillouin laser in the hybrid microbottle resonator, the pump light first transmitted through a circulator from port 1 to port 2, and the backward Brillouin laser outputted from port 3 was analyzed by an optical spectrum analyzer (OSA). When we excited the Raman laser, it was not necessary for the pump light to go through the

Figure 1: Schematic of the tunable Brillouin laser and Raman laser in the ultrahigh- Q hybrid microbottle resonator. The inset is the fundamental mode field distribution of the microbottle resonator with a diameter of 114 μm .

Figure 2: Schematic of the experiment setup of the tunable Brillouin and Raman lasers.

TLS, tunable laser source; AWG, arbitrary waveform generator; DSO, digital storage oscilloscope; EDFA, erbium doped fiber amplifier; VOA, variable optical attenuator; PC, polarization controller; PM, power meter; OS, optical switch; OSA, optical spectrum analyzer; PD, photodetector.

circulator. The Raman laser outputted directly from the other end of the microfiber was analyzed by the OSA. The device was placed in the clean chamber to avoid the interference of air flow and contaminants. In order to tune the lasing wavelength, another TLS was amplified by an EDFA and then transmitted through a VOA and a splitter. After that, it was fed into the hybrid microbottle resonator through its axial direction and was absorbed by the iron oxide nanoparticles.

3 Results and discussion

3.1 Tunable Brillouin laser

Figure 3A is the scanning electron microscopy (SEM) image of the fabricated hybrid microbottle resonator. The equatorial diameter of the microbottle resonator, the diameter of the bottleneck, and the separation between the two bottlenecks (i.e. the bottle length) are about 114 μm , 82 μm , and 176 μm , respectively. Using the equation [43] $R(z) = R(0)[1 - (\Delta k z)^2/2]$, the curvature of the microbottle geometric profile is calculated as $\Delta k = 0.0085 \mu\text{m}^{-1}$. The azimuthal FSR and the axial FSR are calculated as 603 GHz and 292 GHz, respectively [36]. Fortunately, the high-order radial and axial WGMs can easily meet the resonant frequency separation of 11 GHz for Brillouin laser emission [44]. The rough surface in the tapered area means that this area is coated with iron oxide nanoparticles. In order to further verify this point, we also measure the energy dispersive X-ray (EDX) spectroscopy of this area. As shown in Figure 3B, the evident existence of ferrum (Fe) proves a fact that the iron oxide nanoparticles are located on the

tapered end. In order to couple pump light into the microresonator efficiently, a silica microfiber with a diameter of about 2.4 μm is used as the coupling fiber [45]. In order to ensure the stability of the system, we make them get in touch with each other in the whole testing process.

As shown in Figure 3C, the measured loaded Q factor (Q_L) of 1.4×10^8 is achieved. Considering the under-coupled condition and the normalized transmission coefficient ($T = 0.16$), we obtain the intrinsic Q factor (Q_0) of 2×10^8 based on the following equation [46]: $Q_0 = 2Q_L(1/(1-T) - \sqrt{1/(1-T)^2 - 1/(1-T)})$. The ultrahigh intrinsic Q factor denotes the fact that the iron oxide nanoparticles do not introduce extra losses to the WGMs and thus the Q factor is well maintained. In order to obtain the Brillouin laser, the pump light ought to be self-locked into a resonance mode to build up the intra-cavity power. The characteristic asymmetric transmission spectrum is shown in the inset of Figure 3D when the pump wavelength is scanned with the same direction as the thermal induced resonant frequency shift due to the accumulated power in the resonator [47]. Therefore, we finely tune the pump wavelength and enable it to be self-locked into the resonance mode. The cavity-enhanced Brillouin laser emerges when at least one resonance mode is located in the SBS gain spectrum due to dense WGMs in the microbottle resonator. As the 1-mW pump light is located at 1552.07 nm, the backward spectra including the redshift Stokes laser, the blueshift anti-Stokes laser, and the reflected pump light (R -Pump) can be seen in Figure 3D. The presence of the backward pump light is due to the Rayleigh scattering, and the anti-Stokes laser is derived from SBS-coupled four-wave mixing (FWM) [48, 49].

Figure 3E illustrates the generation principle of the Stokes laser and anti-Stokes laser in the microresonator.

Figure 3: Device performance of the hybrid microbottle resonator with an equatorial diameter of about 114 μm .

(A) SEM image of the hybrid microbottle resonator. (B) Measured EDX spectroscopy of the coating area. (C) Measured transmission spectrum of a specific mode. The red line is Lorentz fitting. (D) Brillouin laser spectrum in the backward direction. The inset is the measured asymmetric transmission spectrum of the specific mode. (E) Generation principle of the Stokes and anti-Stokes light. (F) The first-order Stokes and anti-Stokes lasing powers versus the pump power.

The upper schematic diagram in Figure 3E depicts the generation principle of the Stokes light. The first-order Stokes laser is backward scattering of the pump light which is scattered from the acoustic wave and has a redshift from the pump light by about 0.09 nm (11 GHz). The lower schematic diagram illustrates the generation process of

the anti-Stokes light. The first-order Stokes light counter-propagates with the forward pump light, and R-Pump co-propagates with the first-order Stokes light. During the FWM process, R-Pump acts as the pump light and the Stokes light acts as the signal light. When the phase matching of SBS and FWM are simultaneously satisfied,

the backward anti-Stokes laser emerges based on the phase matching condition of degenerate FWM requiring $2\omega_{R-Pump} = \omega_{Stokes} + \omega_{anti-Stokes}$ and $2k_{R-Pump} = k_{Stokes} + k_{anti-Stokes}$, where ω is the angular frequency and k is the wavevector.

Figure 3F demonstrates the Stokes and anti-Stokes lasing powers as a function of the pump power. The black fitted line represents the relation between the Stokes power and the pump power. By tuning the pump power from 0 mW to 0.64 mW, we can clearly see that the Stokes power increases with the pump power and the lasing threshold P_{SBS} is as low as 0.17 mW. The anti-Stokes laser also emerges in the same pump power range. It is worthy to be noted that as the pump power exceeds 0.64 mW, the Stokes power tends to be stable while the anti-Stokes power increases faster and is larger than the former. This is because of the FWM-induced energy conversion from the Stokes light to the anti-Stokes light. When the pump power further increases, both the Stokes and anti-Stokes powers show a tendency to saturate due to the saturated SBS gain.

In the next step, we tune the Brillouin lasing wavelength by feeding the control light into the hybrid microbottle resonator through its axial direction. There are two effects responsible for the resonance wavelength tuning: the thermo-optic effect and the thermal expansion effect. The resonance wavelength shift $\Delta\lambda$ can be expressed by [50]

$$\Delta\lambda = \lambda_0 \left(\frac{1}{n} \frac{\partial n}{\partial t} + \frac{1}{R} \frac{\partial R}{\partial t} \right) \Delta t \quad (1)$$

where n is the refractive index of silica, R is the radius of the microresonator, λ_0 is the initial resonance wavelength, and Δt is the temperature change of the microresonator. The thermo-optic and thermal expansion coefficients of silica are $8.52 \times 10^{-6} \text{ K}^{-1}$ [51] and $0.55 \times 10^{-6} \text{ K}^{-1}$ [52],

respectively. The control light is absorbed by the iron oxide nanoparticles in the tapered area, and the generated heat is transferred to the WGM location to tune the lasing wavelength, due to the positive thermo-optic coefficient and positive thermal expansion coefficient of silica [36, 51, 52]. When we tune the lasing wavelength, the pump power is fixed at 1 mW. As shown in Figure 4A, the Brillouin lasing spectra present redshifts as the control power increases from 0 mW to 79.92 mW. Both the Stokes laser and the anti-Stokes laser are generated while with relatively low powers for different control powers. Figure 4B shows the Brillouin lasing wavelength shift versus the control power. The lasing wavelength increases linearly with the control power, and a tuning range of 2.68 nm is achieved, which is one order of magnitude larger than that achieved through thermal tuning in the previous work [31].

However, the Brillouin lasing power is relatively low because the diameter of the microbottle resonator is only 114 μm . As to the Brillouin gain in the microresonator, it is proportional to the resonator diameter [53]. Therefore, we fabricate the microbottle resonator with a larger size (including the bottle diameter and the bottle length). We first fabricate the microbottle resonator which has an equatorial diameter of 206 μm , a bottleneck diameter of 125 μm , and a bottle length of 564 μm using a commercial fused splicer [36]. The curvature of the microbottle resonator is calculated as $\Delta k = 0.0031 \text{ } \mu\text{m}^{-1}$, which means that the microresonator has denser WGMs compared with the previous one with a diameter of 114 μm [35, 36, 44]. This makes it easier for the microresonator to meet the resonant frequency separation of 11 GHz. As shown in Figure 5, when the pump power is 14.9 mW, we can see a cascaded Brillouin lasing spectrum with the first-, second-, and third-order Stokes lines. The backward third-order Stokes line has a redshift of about 0.27 nm (33 GHz)

Figure 4: Tuning performance of the Brillouin microlaser.

(A) Corresponding Brillouin laser spectra for different control powers. The orange dotted ellipse surrounded peaks represent the Stokes laser, and the purple dotted ellipse surrounded peaks denote the anti-Stokes laser. (B) Lasing wavelength shift as a function of the control power. The red line is linear fitting.

Figure 5: Cascaded Brillouin lasing spectrum in the backward direction.

from the pump light and a larger power (-21.34 dBm) than both the first- and second-order Stokes lines. It is because the second-order Stokes light propagates in the forward direction and both the first- and second-order Stokes light are converted to the third-order Stokes light.

After that, we fabricate the microbottle resonator possessing a comparable size with the above one. As shown in Figure 6A, the equatorial diameter, the bottleneck diameter, and the bottle length of the fabricated microbottle resonator are about $237\text{ }\mu\text{m}$, $125\text{ }\mu\text{m}$, and $648\text{ }\mu\text{m}$, respectively. Hence, we calculate the curvature of the microbottle resonator as $\Delta k = 0.003\text{ }\mu\text{m}^{-1}$. As shown in Figure 6B, we also

Figure 6: Device performance of the hybrid microbottle resonator with an equatorial diameter of about $237\text{ }\mu\text{m}$.

(A) SEM image of the hybrid microbottle resonator. (B) Measured transmission spectrum of a specific mode. The red line is Lorenz fitting. (C–H) Brillouin lasing spectra for different pump powers.

measure the loaded Q factor with a value of 1.6×10^8 and calculate the intrinsic Q factor with a value of 1.7×10^8 . The pump wavelength is located at 1551.3 nm. As shown in Figure 6C–H, by gradually increasing the pump power, we can see that when the pump power is 0.78 mW, a small Brillouin lasing peak which is about 0.09 nm (11GHz) away from the pump wavelength emerges. When the pump power exceeds the threshold (i.e. around 0.78 mW), the Brillouin lasing power proportionally rises with the pump power and is much larger than that generated in the microbottle resonator with a diameter of 114 μm , but the threshold for the latter is lower. It can be explained by the equation [37] $P_{\text{SBS}} = (\pi^2 n^2 V_{\text{eff}}) / (g_B Q_p Q_B \lambda_p \lambda_B)$, where n is the linear refractive index of silica, V_{eff} is the effective pump mode volume, g_B is the Brillouin gain coefficient of silica, Q_p (Q_B) is the loaded Q factor of the pump (Brillouin lasing) mode, and λ_p (λ_B) is the pump (Brillouin lasing) wavelength. It can be seen that larger V_{eff} for the microbottle resonator could lead to the higher threshold. Besides, we also realize the tuning of the Brillouin lasing wavelength. As shown in Figure 7A, the Brillouin lasing wavelengths tend to have redshifts as the control power increases, while the pump power is fixed at 1.37 mW. Figure 7B shows the lasing wavelength shift, which is linearly proportional to the control power, and a tuning range of 1.4 nm is achieved when the control power is 56.48 mW.

3.2 Tunable Raman laser

Next, the hybrid microbottle resonator is also an excellent candidate for the tunable Raman laser. The Raman threshold P_{SRS} in the microresonator is defined by [5] $P_{\text{SRS}} = (\pi^2 n^2 V_{\text{eff}} Q_e^P) / (\lambda_p \lambda_R B g_R (Q^P)^2 Q^R)$, where n is the linear refractive index of silica, V_{eff} is the effective pump mode volume, λ_p and λ_R are the pump and Raman lasing

wavelengths respectively, B is the correction factor of the intracavity power due to backscattering, g_R represents the Raman gain coefficient of silica, Q_e^P is the coupling loss induced Q factor, and Q^P and Q^R are the loaded Q factors of the pump mode and the Raman lasing mode, respectively. From the above equation, we find that decreasing V_{eff} , which is determined by the size of the microresonator, is an effective approach to reduce the threshold. Therefore, we fabricate the hybrid microbottle resonator with a small diameter, as shown in Figure 8A. The microbottle resonator possesses an equatorial diameter of 47 μm , a bottleneck diameter of 31 μm , and a bottle length of 124 μm with $\Delta k = 0.0133 \mu\text{m}^{-1}$. Despite the small diameter of the microbottle resonator, it still maintains a Q factor over 10^8 . As shown in Figure 8B, the transmission spectrum of a specific mode shows a loaded Q factor of 2.7×10^8 , and its intrinsic Q factor is calculated as 3.5×10^8 . The inset of Figure 8C shows the asymmetric transmission spectrum of the specific mode. When the pump light is self-locked into one certain WGM, the Raman gain gradually increases, and the Raman lasing is generated when the gain is larger than the total loss in the resonator. Figure 8C is the Raman lasing spectrum when the pump power at 1550 nm is 0.51 mW and single-mode lasing at 1645.77 nm with a peak power of -21 dBm is achieved. Figure 8D shows the Raman lasing power as a function of the pump power, which indicates that a lasing threshold of 0.25 mW is realized. When the pump power exceeds the threshold, the Raman power is linearly related to the pump power. We also use the following parameters to calculate the theoretical threshold ($n=1.45$, $V_{\text{eff}}=7400 \mu\text{m}^3$, $\lambda_p=1550$ nm, $\lambda_R=1645.77$ nm, $B=0.5$, $g_R=0.66 \times 10^{-13}$ m/W, $Q_e^P=1.18 \times 10^9$, $Q^P=Q^R=2.7 \times 10^8$). By substituting these parameters into the threshold expression, the theoretical threshold of 0.11 mW is obtained, which is a little lower than the measured threshold. It is mainly because of

Figure 7: Tuning performance of the Brillouin microlaser.

(A) Brillouin lasing spectra (including the reflected pump light and the first-order Stokes light) for different control powers. (B) Lasing wavelength shift as a function of the control power.

Figure 8: Device performance of the hybrid microbottle resonator with an equatorial diameter of about 47 μm.

(A) SEM image of the hybrid microbottle resonator. (B) Measured transmission spectrum of a specific mode. The red line denotes Lorentz fitting. (C) Raman lasing spectrum when the pump power is 0.51 mW. The inset represents the asymmetric transmission spectrum of the specific mode. (D) Raman lasing power as a function of the pump power. The red line denotes a linear relation between the lasing power and the pump power.

Figure 9: Tuning performance of the Raman microlaser.

(A) Raman lasing spectra for different control powers. (B) Raman lasing wavelength shift as a function of the control power.

the propagation path loss of the pump light before it is coupled into the microresonator.

We also tune the Raman lasing wavelength. During the tuning process, the pump power is fixed at 0.45 mW. As shown in Figure 9A, the lasing wavelengths present redshifts as the pump power increases. Figure 9B shows the lasing wavelength shift, which linearly increases with the control power. When the control power is 112 mW, we achieve a tuning range of 2.32 nm, which is almost twice

as large as that realized through stretching in the previous work [33].

4 Conclusion

In conclusion, we have realized the tunable Brillouin and Raman lasers based on the ultrahigh- Q hybrid microbottle resonators. We have fabricated hybrid microbottle

resonators with Q factors over 10^8 and realized the Brillouin and Raman lasers with thresholds as low as 0.17 mW and 0.25 mW, respectively. Meanwhile, based on the strong tunability, we have achieved wavelength tuning of the Brillouin laser with a range of 2.68 nm and the Raman laser with a range of 2.32 nm. This work could further broaden the applications of the silica microresonator lasers.

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