Tunable single-wavelength fiber laser based on a microbubble cavity

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Abstract—**A tunable fiber laser with feedback based on a high-quality factor (Q~10^7) microbubble cavity is suggested and demonstrated. The single-wavelength fiber laser output with a linewidth of ~11.68 kHz and a threshold power of approximately 35mW is achieved by incorporating a microbubble cavity-tapered fiber coupling system into an all-fiber ring laser. The tuning method of fiber lasers is achieved by the pressure variations within the microbubble cavity in the feedback loop, which has the advantages of fast tuning and continuous tuning. And a wavelength sensitivity of 0.1291 pm/kPa is obtained. This tunable fiber laser has several applications in optical fiber communications, fiber sensors, and other fields.**

Keywords—WGM resonators, microbubble cavity, tunable fiber laser

I. INTRODUCTION

Microresonators, especially whispering-gallery-mode (WGM) resonators, have received great interest in recent years as a feedback element of fiber lasers due to their high quality (Q) factor [1-3]. The wavelength tuning of fiber lasers can be achieved by external cavity feedback. As parameters such as the resonant wavelength of the WGM microcavity are highly sensitive to changes in the external environment, the method to adjust the resonant frequencies in optical microcavities is a crucial aspect of WGM-microresonator-based fiber lasers. For instance, tuning the temperature [4] or altering the excitation point [5], among other methods, can be employed. Currently, researchers have used different types of microcavities to implement fiber lasers, including MgF_2 disk cavities [6], silica microsphere cavities [7], and rare-earth-doped microsphere cavities [8]. Typically, the above solid-core microcavity controls the position of the optical fiber relative to the microcavity to achieve a fiber laser with selectable output wavelengths. This method selectively excites different modes within the microcavity, providing specific feedback for different WGMs within the microcavity [9]. However, this tuning method requires better control of the fiber taper and the position between the microcavity, and its robustness is poor in the face of external interference. It is worth mentioning that compared to solid-core microcavities, microbubble resonators (MBRs) have natural microfluidic channels in their structure, which can be easily integrated with microfluidic systems. The optical field can be distributed inside the MBRs, enhancing the interaction between internal analytes and light [10-13]. Therefore, a microbubble cavity-tapered fiber coupling system is incorporated into the all-fiber ring laser to achieve tunability of the laser through controlled microfluidics. In addition, there are two main types of fiber lasers based on the different resonant cavities: ring resonator fiber lasers and linear resonator fiber lasers. Among them, the ring resonant cavity is a gain medium added to the cavity, so that the light in a circular path is constantly circulating interference amplification. The output wavelength of a fiber laser is usually determined by the gain medium, and the doping type determines the wavelength of the output laser. For example, erbium-doped fiber has unique characteristics where erbium ions emit light close to 1550 nm when excited by a 980 nm laser. As the output wavelength of erbium-doped fiber lasers falls within the wavelength range of the communication window, they have had a significant impact on the development of optical communication.

In this work, a high Q-factor MBR-based tunable fiber laser is proposed and demonstrated. The single-wavelength fiber laser output with a linewidth of ~11.68 kHz and a threshold power of approximately 35mW is achieved by incorporating a microbubble cavity- tapered fiber coupling system into an all-fiber ring laser. The MBR with a Q-factor of 1.99×10^7 is used as external cavity feedback, while a wavelength sensitivity of 0.1291 pm/kPa is obtained. The tuning method of MBR-based fiber laser achieved by varying the magnitude of pressure inside the MBR has the advantages of fast tuning and continuous tuning. This work presents the MBR-based fiber laser as a potentially ideal

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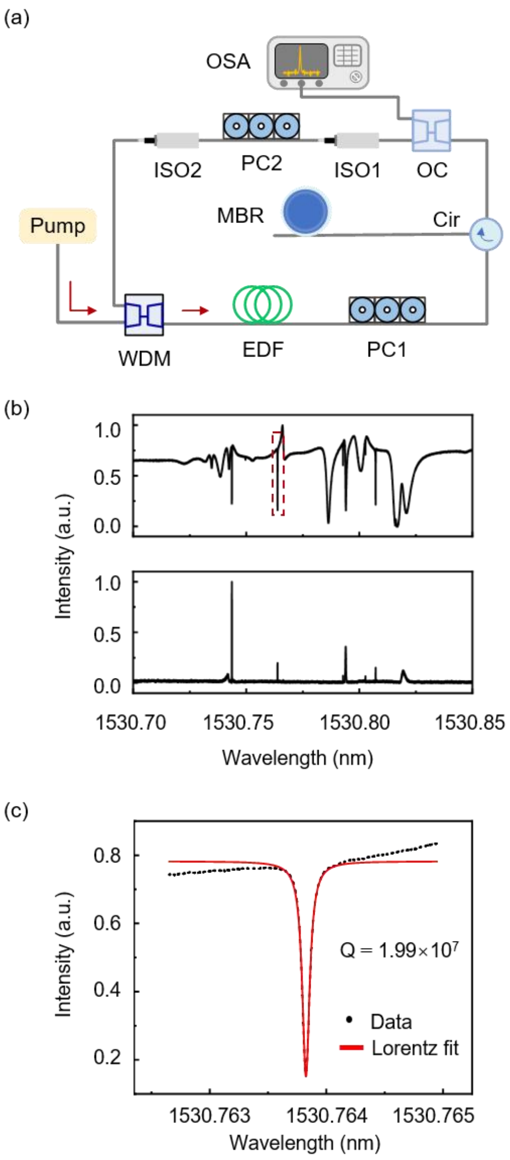

Fig. 1. (a) Experimental setup for fiber laser based on a microbubble cavity. WDM: wavelength division multiplexer, EDF: erbium-doped fiber, PC: polarization controller, Cir: circulator, MBR: microbubble resonator, OC: optical coupler, ISO: isolator, OSA: optical spectrum analyzer; (b) Transmission (top) and reflection (bottom) spectrum of the MBR; (c) Amplified spectrum near the wavelength of 1530.7 nm in (b).

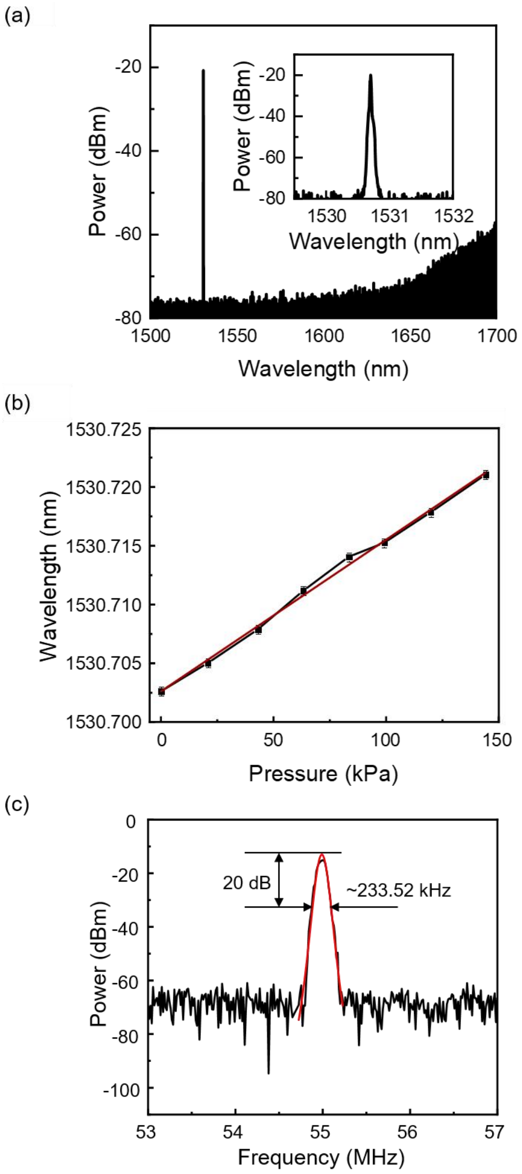

Fig. 2. (a) Fiber laser output spectrum. Inset: detailed spectrum of the fiber laser with a sweep range of 2.5 nm; (b) Fiber lasing wavelength shifts versus the different relative pressure variations (0 kPa, 20.8 kPa, 43 kPa, 63.1 kPa, 83.4 kPa, 99 kPa, 119.7 kPa, 144.1 kPa); (c) Electric spectrum of the beat signal.

platform for application in fiber sensors, optical fiber communications, and other fields.

II. RESULTS AND DISCUSSION

To implement a narrow linewidth single longitudinal mode fiber laser, an external cavity feedback device for mode selection is introduced. During microcavity coupling, light can be transmitted both forward and backward, so it can be used either as a narrow linewidth reflector and filter or simply as a filter using a mode selection function to achieve a narrow linewidth laser output. The proposed tunable fiber laser based on a high *Q*-factor microbubble cavity is shown in Fig. 1(a). A 980 nm pumping laser is injected into the ring cavity through a 980/1550 nm wavelength division multiplexer, and then a section of 11m erbium-doped fiber is pumped. An optical circulator is inserted in the ring cavity to circuit the reflective light from the microbubble-taper coupling system. The as-fabricated MBR has an approximate diameter of 80 μm and a wall thickness of around 2 μm, respectively, and connects with the Teflon tubes to transport gas pressure. In this case, the microbubble resonators are prepared via heating and expanding process [14]. First, the hollow silica capillary is heated with a hydrogen flame, followed by stretching its outer diameter to ~30 μm. Then, the sealed capillary is pressurized with a syringe. Finally, the capillary is heated using a CO_2 laser, and the capillary expands to form a hollow microbubble cavity. The tapered fiber for coupling is prepared from ordinary single-mode fibers by the hydrogen flame "heating and pull" method, and the diameter of the tapered area is about 2 μm. With the assistance of CCD camera for imaging, the relative positions of the tapered optical fiber and the microbubble cavity are precisely adjusted by using the micro/nano positioning technology. This allowed the evanescent wave to couple into the microbubble cavity through the extremely fine tapered waist, effectively exciting the WGM of the microbubble resonator and achieving optimal coupling. The 90% port of the optical coupler is connected with the isolator to form the ring cavity, and another port is employed to extract the laser output from the ring cavity. An optical spectrum analyzer is utilized to obtain the output spectrum of the fiber laser. The threshold power of the single-wavelength fiber laser is about 35 mW. In addition, the ring cavity utilizes two polarization controllers and two isolators to regulate the polarization state and ensure the unidirectional transmission of the laser within the ring cavity, respectively. Figure 1(b) displays the transmission and reflection spectra that are obtained by using a circulator, normalized by the input intensity. A noticeable reduction in the number of modes can be observed in the reflectance spectrum as compared to the transmission spectrum. The reflected WGM is produced due to the backscattering within the MBR, which is usually caused by surface inhomogeneity and density fluctuations. The backscattered WGM with high *Q*-factor has less loss and long photon lifetimes, which is more conductive to the establishment of a stable beam with reverse circulation and formation of feedback. To estimate the *Q*-factor of the microbubble cavity, we examined the individual resonances in the WGM spectra. Lorentz fitting of the transmission spectra at wavelengths about 1530.702 nm yields the *Q*-factor of 1.99×10^7, as shown in Fig. 1(c).

After fine-tuning the polarization controller and the coupling position of the MBR to the tapered fiber, a single-wavelength laser output is obtained. Figure 2(a) illustrates the output spectrum of the MBR-based fiber laser. Meanwhile, the stability of the laser is measured, and a maximum laser output wavelength shift of approximately 0.54 pm is obtained within 5 minutes, indicating its good stability. The inset shows the detailed spectrum of the fiber laser with a sweep range of 2.5 nm. In the gain range of the Erbium-doped fiber at 1530-1570 nm, a single-wavelength fiber laser output is realized. The optical fluidic microbubble cavities serve as wavelength tuners for fiber ring resonators, producing a tunable single-wavelength laser whose wavelength variation depends on changes in pressure. Figure 2(b) shows extracted fiber lasing wavelength shifts on gas pressure. The sampling interval of OSA is 0.001 nm, and the laser center wavelength is obtained by nonlinear fitting of the output spectrum. The pressure regulator and pressure gauge are attached to one port of the MBR, and UV glue is used to seal the other. The applied pressure to the MBR is controlled by a pressure regulator, and the pressure gauge is used for reference measurement. At room temperature, the internal relative pressure of MBR increases from 0 kPa to 144.1 kPa. When the pressure increased, the resonant wavelength appears red-shift due to strain- and stress-induced geometrical variation and refractive index change. Meanwhile, the fiber laser wavelength also shows red-shift, which is attributable to the resonance wavelength variation in the feedback loop. Consequently, a wavelength sensitivity of 0.1291 pm/kPa is obtained, showing a good linear relationship. We employ a delayed self-heterodyne scheme to measure the linewidth of a fiber laser. One path of the fiber Mach-Zehnder interferometer has a delay fiber of 50 km. The other path of the interferometer has an acousto-optic modulator that generates a frequency shift of 50 MHz. The resulting beat frequency signal is sent to an electrical spectrum analyzer through a photodetector. A Lorentzian fit of the beat frequency signal is shown in Figure 2(c). The actual linewidth is inferred as 1/20 of the 20 dB linewidth, corresponding to approximately 11.68 kHz.

III. CONCLUSION

In conclusion, we achieve a high *Q*-factor MBR-based tunable fiber laser. A microbubble cavity-tapered fiber coupling system is incorporated into the all-fiber ring laser to achieve a single-wavelength fiber laser output with a linewidth of ~11.68 kHz and a threshold power of approximately 35mw. This type of device could potentially prove useful for manufacturing low-cost and single-wavelength lasers. The microbubble cavity is used as an external cavity feedback and the *Q*-factor is kept above 10^7, while a wavelength sensitivity of 0.1291 pm/kPa is obtained. The tuning method of MBR-based fiber laser achieved by varying the magnitude of pressure inside the MBR has the advantages of fast tuning and continuous tuning. This tunable fiber laser has several applications in optical fiber communications, fiber sensors, and other fields.

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