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Single-longitudinal-mode, narrow bandwidth double-ring fiber laser stabilized by an efficiently taper-coupled high roundness microsphere resonator

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ABSTRACT

This paper proposes and demonstrates a single-longitudinal-mode, narrow bandwidth fiber laser, using an ultra-high roundness microsphere resonator (MSR) with a stabilized package as the single-longitudinal-mode selector inside a double-ring fiber cavity. By improving the heating technology and surface cleaning process, MSR with high Q factor are obtained. With the optimized coupling condition, light polarization state and fiber taper diameter, we achieve whispering gallery mode (WGM) spectra with a high extinction ratio of 23 dB, coupling efficiency of 99.5%, a 3 dB bandwidth of 1 pm and a side-mode-suppression-ratio of 14.5 dB. The proposed fiber laser produces single-longitudinal-mode laser output with a 20-dB frequency linewidth of about 340 kHz, a signal-to-background ratio of 54 dB and a high long-term stability without mode-hopping, which is potential for optical communication and sensing applications.

1. Introduction

Single-longitudinal-mode (SLM), narrow linewidth fiber lasers attract interests in various scientific research areas such as optical sensors, coherent communication and high-resolution spectroscopy, etc, due to their excellence in high coherence, compact structure and wavelength flexibility [1–3]. Linear short cavity and ring cavity are the two common cavity structures. Fiber lasers with linear cavity are divided into distributed feedback (DFB) fiber lasers and distributed Bragg reflector (DBR) fiber lasers [4,5]. For most of them, the reflective mirrors are formed by imprinting Gratings in the gain fiber or docking Gratings with the gain fiber [4–7]. The length of the active fiber is usually limited to several centimeters, requiring that the gain fiber has a high gain coefficient [8]. Compared with short linear cavity, ring cavity increases output power by utilizing longer gain fiber. As to achieve SLM operation, narrow band filters were developed and embedded into fiber ring cavity, such as fiber gratings [9–10], saturated absorber [11,12], tandem all-fiber Fabry-Pérot microcavities and the gain-controlled active compound cavity we proposed in [13,14], etc. In Ref. [15], a polarization-maintaining chirped fiber Bragg grating (PM-CFBG) filter with ultra-narrow transmission band of 0.1 pm is used to achieve stable single polarization SLM operation. However, most of the common fiber gratings and FP cavities have a filtering bandwidth larger than 0.1 pm, which limits further compression of laser bandwidth. There still need efforts as to further compress laser output bandwidth with improved stability and compactness, as well as a reduced cost for SLM laser operation.

In this paper, we propose a SLM, narrow band fiber laser using an ultra-high roundness microsphere resonator (MSR) in a packaged manner as the mode selector inside a double-ring fiber cavity. By controlling laser heating parameters (spot size and power) and using clean processing technology, we obtain MSR with high spherical symmetry and high surface quality, which ensures high quality (Q factor). WGM transmission spectra with different coupling conditions (distance and position), light polarization state, taper diameters and MSR roundness are investigated theoretically and experimentally. A SLM laser output with narrow bandwidth, high signal-to-background ratio and high stability is achieved when the high-roundness MSR and taper are coupled with ultra-high efficiency.

2. Theoretical analysis

2.1. Geometric optical analysis

Fig. 1 shows the geometrical analysis of light transmitting in the MSR. Fig. 1(a) illustrates the total internal reflection (TIR) light

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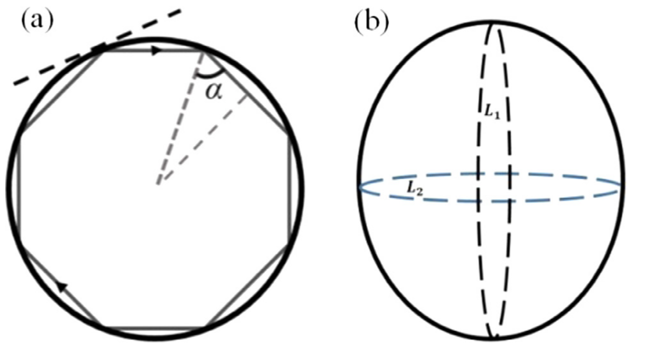

Fig. 1. Geometric optical path of light transmission in the MSR: (a) TIR of light propagation; (b) Different equatorial planes with different circumferences.

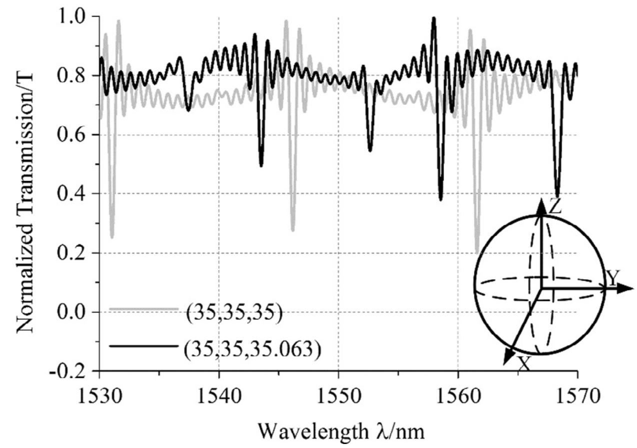

Fig. 2. Simulation of the WGM transmission spectra of MSR with different roundness, Inset: 3D coordinate map of the MSR.

propagation path [16]. According to the Snell law, TIR happens when the incident angle $\alpha > \arcsin(n_{air}/n_{mic})$ (n_{air} is the refractive index of air, n_{mic} is the refractive index of MSR). According to Fig. 1(a), the length of optical path along the equatorial plane L can be calculated as follows:

$$L = 2R\cos\alpha \times 2\pi/(\pi - 2\alpha) = 4\pi R\cos\alpha/(\pi - 2\alpha) \quad (1)$$

where R is the radius of MSR. Only specific wavelength that satisfies following phase matching condition can achieve resonance [17]:

$$n_{eff}L = m\lambda \quad (m = \text{integer}) \quad (2)$$

where n_{eff} is MSR's effective refractive index, λ is the resonant wavelength. As demonstrated in Fig. 1(b), if the MSR roundness is low, to say three-dimensional asymmetrical, L will be different, leading to resonance of high-order modes and reduction of the extinction ratio of the WGM transmission spectrum. Furthermore, combine formula (1) and formula (2), we get:

$$4\pi n_{eff}R\cos\alpha/(\pi - 2\alpha) = m\lambda \quad (m = \text{integer}) \quad (3)$$

Thus, the resonant wavelength depends on α, which is actually decided by the coupling position of the taper and the MSR's equatorial plane. Fiber taper deviating from the equatorial plane will results in high-order modes' resonance and reduction of extinction ratio. Therefore, it is of great significance to control the coupling position between the taper and MSR.

2.2. Finite-difference time-domain analysis

Fig. 2 shows WGM transmission spectra of the MSR with different roundness, using the finite-difference time-domain (FDTD) method: The taper diameter is 1.4 μm, and coupled at MSR's Y-O-Z plane. For phase matched coupling, the taper diameter simulated is different (1.4 μm) from that employed in the experiment, which is about 3–5 μm. The gap spacing between the MSR and the taper is set to 0.1 μm. As demonstrated in the inset of Fig. 2, diameters of the high-roundness MSR in X axis, Y axis, Z axis are 35 μm, 35 μm, 35 μm respectively (gray line). Diameter of the low-roundness MSR in X axis, Y axis, Z axis is 35 μm, 35 μm, 35.06 μm respectively (black line). The material refractive indices of the taper and MSR are 1.46. The simulated wavelength scans from 1530 nm to 1570 nm and the light source is transverse electric (TE) polarized. Fig. 2 shows the simulated transmission spectra of the MSR have a simulation grid size of 52.3 nm and the resulting spectral resolution is 0.002 nm. We define parameter $A = (z - y)/z$ as to evaluate the ellipticity of the MSR, in which z is the maximum diameter of Y-O-Z plane, y is the minimum diameter of Y-O-Z plane. By calculation, the ellipticity of high-roundness MSR and low-roundness MSR are 0 and 0.17% respectively. Larger A means lower roundness, MSR with lower roundness excites high-order modes resonance and results in WGM transmission spectrum with lower extinction ratio, broader bandwidth and larger free spectral range (FSR). Thus, MSR with high roundness is highly required for achieving WGM transmission spectrum with narrow bandwidth and high extinction ratio, as to assure SLM mode selection.

3. MSR fabrication and laser configuration

In experiments, MSR are fabricated with the diameter (D) ranging from 150 μm to 350 μm by melting the end of single-mode optical fiber using a CO_2 laser. WGMs are excited by a tunable laser (Agilent 81960A, 1550 nm wavelength resolution = 12.5 MHz) through a fiber taper and detected by a photodiode detector (Agilent 81635A). The tuning step of the Agilent laser is 0.5 pm. The gap between the MSR and the taper is controlled by electromechanical 3D X-Y-Z stages with 20 nm resolution. Fig. 3(a) and (b) give the microscopic photos of the MSR manufactured before and after improving the laser heating and cleaning technology. Our spheres were made by melting the end of a short silica fiber. Surface tension shaped the molten silica in the form of a sphere that grows at the end of the fiber. The silica fiber is cleaned several times with alcohol and an ultrasonic cleaning machine to reduce dust before fabrication of a microsphere. Then, the spheres are

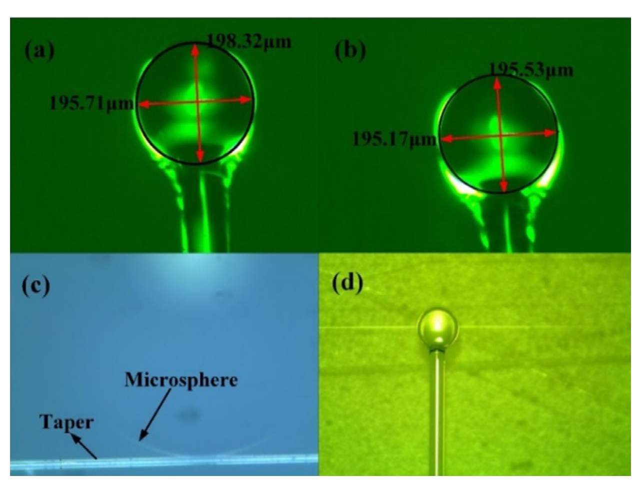

Fig. 3. Micrographs of the MSR with (a) low roundness; (b) high roundness; (c) Coupling system observed by the horizontal microscope; (d) Coupling system observed by the vertical microscope.