Control of whispering-gallery-mode spectrum from erbium-doped silica microsphere lasers

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High-power whispering-gallery modes (WGMs) emitted from microcavity lasers have attracted attention for many applications, such as optical signal processing, spectroscopy, optical sensors, and large-bandwidth optical communications. In this paper, we present a simple approach for controlling the output WGMs of erbium-doped silica microsphere lasers. With the presented scheme, accurate adjustment of the coupling gap between the collection fiber taper and the spherical surface allows us to select different single modes of the microsphere laser or different multimode configurations (also functions of the waist diameter of taper and the Er-doped concentration). The nonlinear frequency shift of the microsphere cavity as a function of intracavity power has also been studied. The high intensity and high side mode suppression ratio of the obtained single WGM are suitable for spectroscopy, optical sensors, and communications.

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1. INTRODUCTION

In recent years, laser sources based on microresonators have received a great deal of attention because of their low pump thresholds, supernarrow spectral lines, strong nonlinear effects, possible realization of frequency combs, and coupling with an external medium via evanescent waves, with many possible applications for spectroscopy, sensors, optical switches, and dense wavelength division multiplexing (DWDM) communications [1–6]. However, the use of a narrow-linewidth emission for spectroscopy and sensors has remained challenging, owing to the low power per emission line and the difficulty of resolving features that are smaller than the emitted mode spacing [7]. In addition, an independent optical channel for a simple affordable high bandwidth of DWDM requests a low relative-intensity noise of each longitudinal mode; i.e., the side mode suppression ratio (SMSR) should be large. In our previous work [8], we successfully developed microspherical cavity lasers, which can emit the whispering-gallery mode (WGM) with a high optical power of –3.5 dBm. In practice, the spectral linewidth of one WGM from the microsphere lasers obtained by the optical spectrum analyzer (OSA) depends upon the resolution of the equipment (about 0.01 nm in our experiments), but in this detected mode there is a series of peaks of optical lines, each with narrow linewidth (in the range of megahertz) [9].

In this paper we present an easy-to-use method to obtain single-mode lines of high power, narrow linewidth, and high SMSR of the WGMs in the wavelength range of 1530–1610 nm emitted from the microsphere silica lasers with different erbium (Er) concentrations. For an application, we show a technique for controlling the quantity of the collected WGMs from the microcavity lasers using half-taper fiber with the effect of dipole-field interaction between the fiber and the sphere surface. In addition, we study the nonlinear frequency shift inside the microsphere cavity depending on the intracavity power at a spatial position of a certain optical mode. In the literature on microresonator lasers (microsphere, microdisk, microbottle, etc.—which cannot be all cited here) with various glasses and various dopants, most papers show multimode operation—or single-mode operation at low pump power and multimode operation at higher pump power—or they show wavelength shifts due to thermal effects [10,11], or use the microresonator in order to select and stabilize a mode in a fiber laser [12]. Modification of the spectrum of an Er-ZBLAN microsphere with a prism coupler laser has been reported with a change in the prism-MS distance, with one mode at zero separation and more modes as separation is increased [13]. Regarding the coupling to and from microspheres, a good review is found in [14], and coupling is also discussed in [15].

Our results, as far as we know, are the only ones allowing not only the change from single-mode to multimode operation of the fiber output, but also—more importantly—the ability choose a desired single mode among several, with a simple, reproducible, and reversible procedure. The combination of the waist diameter of the half-taper, Er-doped concentrations and the coupling gap makes this technique promising for a wide range of control of the output optical lines for applications in spectroscopy, sensing, and communications.

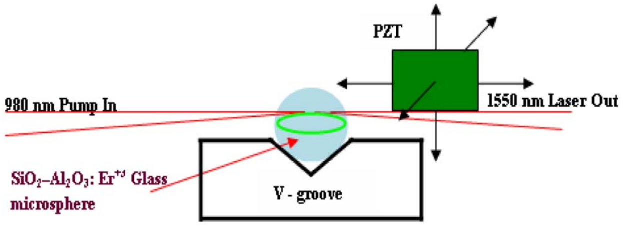


Fig. 1. Experimental setup for pumping and collecting WGMs from the microsphere laser.

2. EXPERIMENTS

The fabrication of Er-doped silica microsphere lasers was shown in our previous work [8]. We formed two kinds of Er-doped silica glass microspheres: for the first kind, the homogenous Er-doped glass bulk was used to fabricate microspheres, and for the other, Er-doped solgel silica glass film was used to cover the regular silica microsphere with a thickness of 1.5–2 μm. The Er concentration of silica glasses was 1000–4000 ppm, and the diameters of the spheres were 40–150 μm for both kinds of glass microspheres.

The optical coupling to the spherical microcavity for pumping and for laser output extraction was performed with two different half-taper optical fibers made by the chemical etching method. The waist diameters of the half-taper were 1 μm, and the angle of the taper tip was 0.72°. We used a 976 nm laser diode with output optical power up to 170 mW in single-mode emission (SDLO-2564-170) for excitation of the Er ions. The coupling gap was adjusted by a system composed of a 3D micropositioner and a lead zirconate titanate (PZT) piezoelectric stack AE0203D08F with accuracy of 10 nm (see Fig. 1). The spectral characteristics of the WGMs were analyzed by the OSA (Advantest Q8384 with a resolution of 0.01 nm).

3. RESULTS AND DISCUSSION

In a 1000–4000 ppm Er-doped silica microsphere laser with diameter of 90 μm, we can observe the laser oscillation modes of the microsphere cavity in the large wavelength range from 1510 to 1610 nm. In our experiment, the lasing emission was often a single mode at threshold, and the laser intensity strongly depended upon the Er concentration in the silica glasses and the diameters of the microspheres. Table 1 shows the single-mode laser intensity at the threshold of the 90 μm diameter microsphere lasers with the Er concentration changing from 1000 to 4000 ppm. The WGM lasing spectra at threshold can be controlled by Er-doped concentration, and the laser intensity will be enhanced with the Er-ion concentration into silica up to 2500 ppm [16].

Table 1. Laser Intensity at Threshold from 90 μm Diameter Microsphere Lasers with Different Er Concentrations

Er Concentration (ppm)	Optical Pump Threshold (mW)	Laser Intensity (dBm)	Lasing Wavelength Range (nm)
1000	1.6	–53	1550–1580
2500	2.0	–51	1570–1600
3000	2.5	–55	1580–1610
4000	3.5	–68	1530–1560

Figure 2(a) shows the quantity of the lasing modes extracted from the 2500 ppm Er-doped silica microsphere laser when the coupling gap was of (2 ± 0.05) μm. We observed the multiwavelength lasing emission of WGMs with a free spectral range of about 2–3.4 nm and an SMSR of 15–32 dB. When the coupling gap was 0.18–0.6 μm, we often detected a single mode of WGMs.

Figure 2(b) shows a spectrum of the single lasing mode from the existing WGMs in the microspherical cavity, when the coupling gap was adjusted to (0.3 ± 0.05) μm. In addition, the wavelength of a single optical line could be chosen by precise adjustment of the gap.

Figure 3 presents the single-mode spectra extracted from a 90 μm diameter microsphere laser when the coupling gap was changed from 0.18 to 0.6 μm with an accuracy of coupling gap adjustment of 0.05 μm. When the spacing gap is less than 0.15 μm, the fiber tip begins to vibrate due to the effect of the dipole-field interaction [17], and the intensity of collected WGMs is modulated.

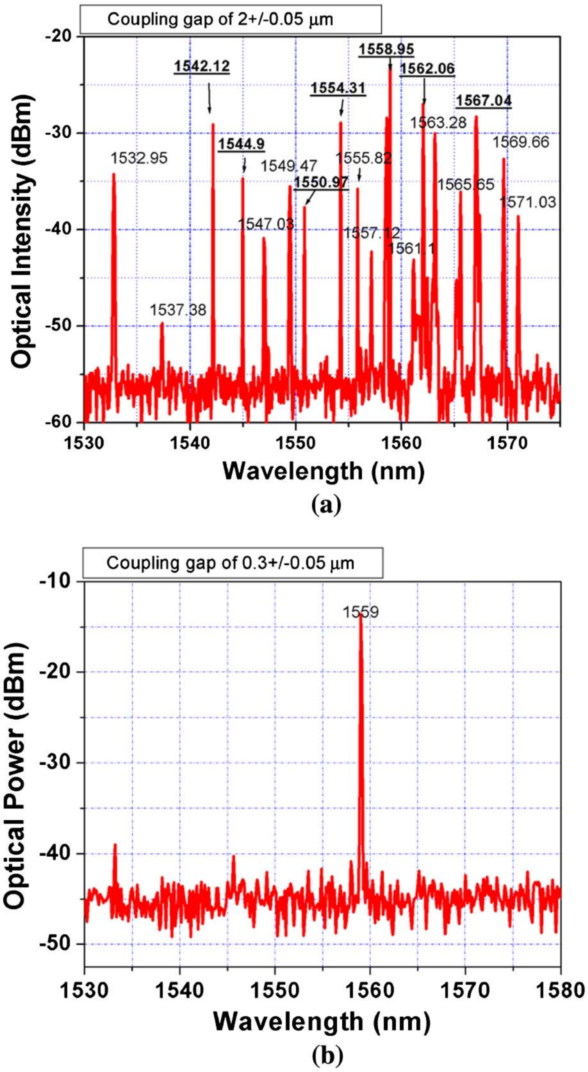


Fig. 2. Spectra and quantity of optical WGM lines extracted from Er-doped silica microcavity laser when the coupling gap between the taper fiber and the sphere surface changed from (a) 2 ± 0.05 μm to (b) 0.3 ± 0.05 μm.

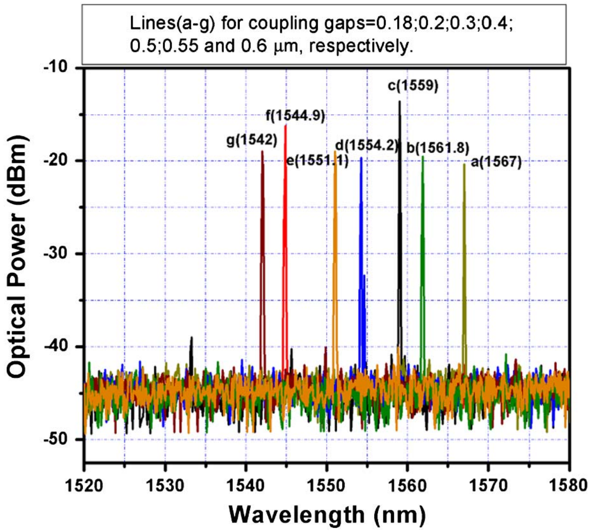


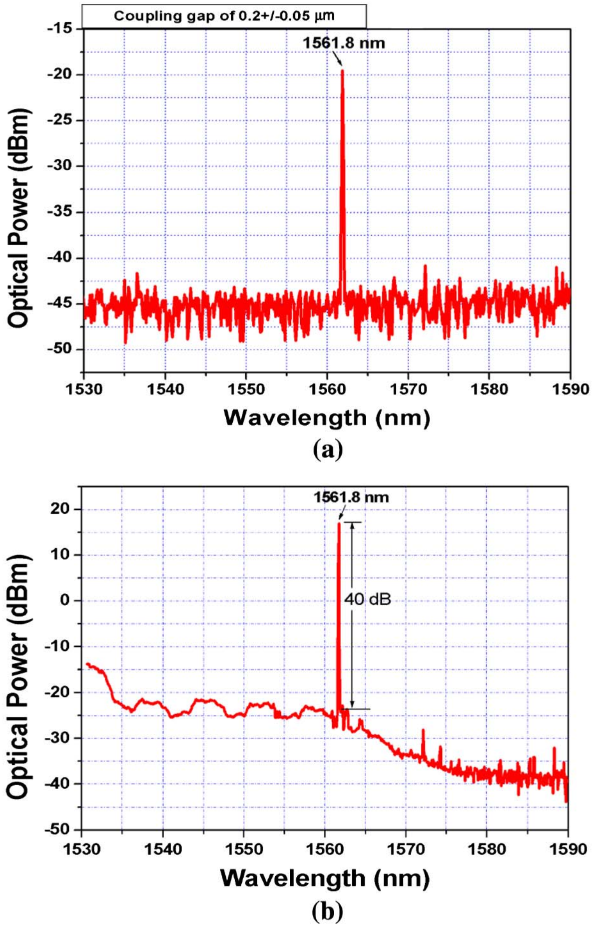
Fig. 3. Spectra of single lasing mode extracted from Er-doped silica microcavity laser when the coupling gap between the taper fiber and the sphere surface was (a) 0.18 µm, (b) 0.2 µm, (c) 0.3 µm, (d) 0.4 µm, (e) 0.5 µm, (f) 0.55 µm, and (g) 0.6 µm, respectively.

This technique has good reproducibility in practice, and we can extract most of the WGMs that can oscillate in the microcavity with a suitable adjustment of the coupling gap. Interpretation of the results is not simple, as the oscillating modes depend on various factors: the different evanescent fields of the modes (with their radial and azimuthal dependence) and their coupling with the fiber taper, with resonances when the gain equals the coupling factor [14,15]. Further work is needed (fiber taper position and angle, polarization) in order to make a full theory of mode selection as a function of microsphere data and pump and output taper configuration (see [14]).

Figure 4(a) shows a single optical line with a linewidth of 0.2 nm (25 GHz at wavelength of 1550 nm) and an optical power of −19.4 dBm, and this one was amplified by an Er-doped fiber amplifier (EDFA) with an amplification coefficient of 40 dB [Fig. 4(b)]. The intensity of a single optical wavelength in this case can reach up to +17.2 dBm, the SMSR is 40 dB, and this selected mode is very stable by time. This means that the optical lines corresponding to different WGMs of the microcavity can be easily filtered out, separately modulated, and used as independent optical channels in DWDM networks and sensors.

Owing to the high photon confinement of the silica microsphere, the large optical energy stored in the microcavity exerts a force on the cavity sidewall that is due to radiation pressure and causes parametric instability of lasing emission [18]. The beat between the sideband and the laser line measured by the photocurrent of the high-speed detector recording the power of the laser emission is of some tens of megahertz in our case.

The single WGM spectrum shows a linewidth of 0.2 nm (25 GHz), while we expect one or several supernarrow lines within a linewidth even of the order of a few megahertz [9]. Because the splitting between adjacent Stark levels of Er ions in the silica glasses was of 2–20 nm [19], the WGM linewidth of 0.2 nm may be attributed to the frequency mismatch between the generated optical oscillation modes and the microcavity modes. We used the model through the optical Kerr nonlinearity developed by Del'Haye *et al.* [7] for explanation for this effect. The frequency shift depends on the intracavity optical power at the position of a certain optical mode and can be estimated as



(a)

(b)

Fig. 4. (a) Intensity of stable single optical line of −19.4 dBm detected from microcavity laser and (b) its amplified intensity of +17.2 dBm via EDFA.

$$\Delta\nu = \left(\frac{\Delta n}{n_0}\right)\nu_0, \tag{1}$$

$$\Delta n = \frac{n_2}{n_0}\frac{c}{4\pi^2 R A_{\mathrm{eff}}}\frac{N}{k}P_{\mathrm{in}}, \tag{2}$$

where Δn is the intensity-dependent refractive index change induced by the Kerr nonlinearity.

In our case, the optical intracavity power P_{in} of single WGM was estimated to be about 4 mW from experimental results. For a central optical mode of $\nu_0 \approx 192$ THz ($\lambda = 1561.9$ nm), $n_0 = 1.47$ and $n_2 = 2.2\times10^{-20}\ \mathrm{m}^2\cdot\mathrm{W}^{-1}$ as the linear and nonlinear refractive index of silica, a resonator radius of $R = 45$ µm, a linewidth of the resonator modes of $k = 1$ MHz, an effective mode area of $A_{\mathrm{eff}} \approx (1\ \mu\mathrm{m})^2$ and for $N = 15$–20 lines contributing to the resonance shift, we obtained a nonlinear frequency shift of $\Delta\nu \approx 19.8 - 26.4$ GHz. This calculated result is in good agreement with experimental ones.

4. CONCLUSION

In conclusion, we have presented an approach for controlling the spectrum of the WGMs emitted from the Er-doped silica microsphere cavity lasers by adjusting the precise coupling gap between the half-taper extraction fiber and the surface of the silica sphere cavity. By varying the gap, it is possible to obtain either a varying number of lines or a single line with controllable wavelength. The spacing gap should be more than 0.15 μm for prevention of the fiber tip vibration caused by the dipole-field force at the surface of a microsphere.

This technique is used to determine a single-mode lasing emission with high optical power and high SMSR within a wide range of wavelength, and this is suitable to various applications.

Additionally, the calculated nonlinear frequency shift of optical WGM in an ultrahigh-*Q* microcavity is in good agreement with experimental results.

We believe that the simplicity of this scheme for controlling the output WGM from microspherical and/or microtoroidal cavities will allow it to be widely diffused in laboratories of spectroscopy, optical sensors, and DWDM communications.

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