High Q-factor micro-cavity laser: Fabrication and lasing emission properties

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Abstract. In this article the fabrication method and lasing emission properties of High-Q micro-cavity lasers based on High-concentration Erbium-doped silica-alumina glasses are presented in detail. The configurations of micro-cavities were spherical and/or modified toroidal forms. The lasing threshold of micro-cavity laser pumped by laser diodes was of hundred micro-watts and Q-factor of cavity had been achieved up-to $10^8$ in experiment. The emission power of one whispering-gallery-mode (WGM) lasing from micro-cavity laser was of 0.05-0.5 mW that would be enough for applying in the quantum information and optical sensor techniques. The modified toroidal micro-cavity permits to decrease the polar-mode of WGMs, which help to obtain the single-mode emission from micro-cavity lasers.

Keywords: Micro-cavity laser, whispering-gallery-mode emission, high-concentration Er-doped materials.

1. Introduction

Dielectric micro-cavities have attracted much attention due to their ability to entrap photons in the visible and NIR regions of the electromagnetic spectrum via total internal reflection [1]. Such photon confinement can be used for various purposes, ranging from fundamental studies on Quantum Electrodynamics (QED) [2] to more applied fields, such as the development of microscopic laser sources, tunable filters, and transducer mechanisms for optical sensing [3]. Due to the total internal reflection condition, photon entrapment works best for those cavity modes that propagate along the circumference of the cavity. Such modes are often referred to as Whispering-Gallery-Modes (WGMs) in analogy to an acoustic phenomenon discovered by Raleigh more than a hundred years ago [4]. As a glass spherical microcavity providing Q-factors in excess of $10^8$, silica toroidal microcavity resonators provide both long photon storage times and improved spatial confinement over microsphere resonators of comparable size [5]. Furthermore, with highly ideal, tapered-fiber coupling, efficient pumping and laser emission extraction are possible [6]. Among the solid-state microcavity lasers with ultrahigh-Q performance, Rare-earth doped glass microsphere lasers have been successfully demonstrated in last
The optical modes of spherical dielectric cavity can be calculated by solving Helmholtz equations in spherical coordinates. A significant simplification occurs if the sphere consists of a homogeneous dielectric, and if the optical modes reflect with grazing incidence upon the dielectric-air boundary, such that the polarization can be assumed to be constant along the optical trajectories. Under this assumption the optical modes can be solved by the scalar wave equation approximation and solutions fall into TE \( n, m, l \), and \( p \) and TM \( n, m, l \), and \( p \), where \( n \) is radial mode number, \( m \) is azimuthally mode number, \( l \) is polar mode number, and \( p \) is polarization state of mode [11]. In an ideal sphere cavity the optical modes possess \((2l+1)\) degeneracy with respect to the azimuthally mode number \( m \). The toroidal microcavity, which creates dense arrays of ultrahigh-Q microcavity structures in equatorial planes, can reduce modal spectra in comparison with microsphere cavity. In particular, single-mode operation was possible in these devices [12]. Recently, a toroidal microcavity has enabled access to Q-factors is excess of \(10^8\), which was the highest value reported on a planar substrate. These toroidal microcavities were silica based and fabricated on silicon chips combining standard silicon technology with ultrahigh-Q fabrication techniques [13].

In this paper, we used surface-tension-induced structure of High Er-doped silica-alumina glass made by molten method to form spherical and/or modified toroidal microcavity laser and study the lasing characteristics when these devices are coupled to a half-tapered optical fiber. Our experiments are focused on high Q-factor microcavity (with ultra-narrow spectra of laser emission) and reduction of lasing-modes in the Er-doped silica-alumina glass modified toroidal lasers in comparison with microsphere lasers in previous studies [10, 14].

2. Experiments

2.1. Fabrication of Er-doped silica-alumina glass microcavity lasers

The microcavity lasers have been fabricated by multi-component Er-doped silica-alumina glasses (90SiO2 - 6Al2O3 - 4Y2O3 - xEr2O3, where \( x = 0.065-0.3 \) is a molar percent of Er\(_2\)O\(_3\)). This kind of glass material was made by sol-gel method, that we had shown in our previous paper [14]. We formed Er-doped silica-alumina glass microcavity in the form of spheres and/or modified toroid by the following steps: first step is making Er-doped glass microsphere with diameters in the range of 30–120 \( \mu \)m by molten method using electrical arc discharge or by \( \text{CO}_2 \)-laser beam and second step is forming modified toroidal cavity by irradiation of \( \text{CO}_2 \)- laser beam with pressure on microspheres via the silicon substrate. From high thermal conductive coefficient of silicon, the area of Si-substrate is an important factor for making glass toroid. In our experiment, the area of Si-substrate was 1-2 mm\(^2\).

![Figure 1. FE-SEM images of glass microsphere (left) and dielectric boundary of microsphere (right) made by thermal molten method.](image)

Using molten method, the solid glass spheres and/or toroids rely upon surface tension to create perfect smooth dielectric boundary, along which the WGMs are confined. Figure 1 shows the dielectric boundary with surface perfection up to nanometer scale. The diameters of spheres were of...
30-120μm and the equatorial diameters and thickness of glass modified toroids was of 90-160μm and 20-30μm, respectively.

2.2. Excitation and extraction of WGMs in micro-cavity

The pump laser beam and the collected lasing WGMs are coupled to two different half tapered fibers. Efficient optical coupling to the glass micro-cavity both for pumping and for laser output extraction was performed with optical fiber tapers with waist diameter of 1÷4 μm, which were made from the standard telecommunication single-mode fiber by chemical treatment in 15 mol% -HF solution. The diameters at the waist of fiber tapers were chosen to optimize phase matching and coupling to the fundamental WGM \((n = l, m = l)\). We choose 976nm- laser diode adjusted the output power from 0 to 170 mW in single-mode emission (SDLO-2564-170) for excitation of Erbium ions. To couple light efficiently in and out of the micro-cavity laser, the half tapered optical fibers were aligned in the equatorial plane of micro-cavity. The micro-cavity laser was fixed and the half tapered fibers were attached to a micro-positioner with piezoelectric stage that allowed for their precise positioning with respect to the micro-cavity. The collected laser output fiber can go forward or backwards with respect to the pumping direction. The non-absorbed pump beam and the luminescence or laser emission corresponding to the WGMs of the micro-cavity are separated with a de-multiplexing coupler 980nm/1550nm. Thus we can analyze simultaneously the pump and the laser signals. The spectral characteristics of the emission around 1550 nm were analyzed with a 0.01 nm resolution optical spectrum analyzer (OSA: Advantest Q8384) directly after the de-multiplexing coupler.

3. Results and discussion

The input threshold pump power can be obtained directly from experiment by setting the pump power from zero. In our Er-doped silica-alumina glass micro-cavity laser, we only obtained super luminescent emission, when the pump power at wavelength of 976 nm was below 2.0 mW. The laser oscillation modes (WGMs) of the Er-doped glass micro-cavity are in the wavelength range from 1510 nm to 1610 nm (see figure 2). Depending on the gain spectral region of the highly Er-doped silica-alumina glass, the lasing wavelength of the micro-cavity lasers varied within 1540-1610 nm range, which is in the both C- and L-bands. In addition, for any equatorial diameters of the sphere and/or toroid we obtained an enhancement of the laser intensity when increasing the Er-concentration from 1,250 to 3,000 ppm in the silica-alumina glass matrix. The lasing emission could be obtained by forward and backward coupling configuration. Figure 3 shows the spectra of single-mode lasing at laser threshold obtained from 90 μm-diameter and from 110 μm – equatorial diameter of spherical and modified toroidal glass micro-cavity laser doped with 2,500 ppm of Er3+ ions, respectively.

(a) \[\text{Microsphere laser}\]

(b) \[\text{Modified Micro-Toroid laser}\]

Figure 2. Superluminescent spectra of micro-sphere (a) and micro-toroidal (b) lasers pumped by 976 nm-laser beam with light power of 2 mW (below threshold)
The WGM lasing spectra rounding 1600 nm-wavelength gives good evidence for larger gain in L-band in highly Er-doped sol-gel silica-alumina glasses. By increasing the pump power the number of lasing modes was increased and the wavelength of lasing peak could be shifted to short range.

Figure 4 presents multi-mode lasing spectra from the same modified toroidal micro-cavity lasers, when pump optical power increased up to 3 mW. We can see, the lasing mode of toroidal micro-cavity laser at wavelength 1599.349 nm was the same at threshold, and most all of the new lasing modes were shifted to the shorter band. The pump transmission was estimated about $\sim 12\%$ in this measurement, so the actual coupled threshold pump power is estimated to be approximately 0.3 mW. As we know, the lasing threshold is a sensitive function of the cavity configuration and coupling gap width between glass surface and tapered fiber. In our experiment, we can remark, that threshold optical pump power in the case of toroidal micro-cavity is the same value in comparison with micro-spherical cavity.

Figure 3. Single-mode WGM lasing from micro-sphere (1) and micro-toroid (2) lasers pumped at threshold by 976 nm-laser beam with 2.2 mW and 2.7 mW, respectively.

Figure 4. Multi-mode WGM lasing from micro-toroid cavity lasers pumped by 976 nm-laser beam with 3 mW.

Experiments show, that eventually lasing at 1600 nm can no longer be supported with increasing pump power and/or gap width because they cannot be compensated by the relatively small gain at this wavelength range. When pump power was more than 10 mW the lasing spectra of micro-cavity lasers, in general, would be shifted to short-wavelength range. In our case, the WGMs of modified micro-toroidal laser had been distributed in the wavelength range 1550-1580 nm and the number of WGMs of this one was decreased in contradiction with large WGM spectra in range of 1540-1610 nm from micro-sphere laser at the same pumped condition (see figure 5). Figure 6 demonstrates the highest WGM power lasing from micro-sphere laser with diameter of 110 μm and the WGM amplified by EDFA. The maximum lasing output power of one WGM, we achieved, are of -3.2 dBm and of -5.5 dBm from the Er-doped silica-alumina glass spherical and/or toroidal micro-cavity lasers, respectively. The high output power of lasing WGMs in our micro-cavity lasers may be caused by good tapered-micro-cavity coupling at 976 nm – pump and a homogeneous distribution of Er-ions in the silica-alumina glasses.

The number of collected WGMs and the laser output power depend upon many parameters such as loading conditions (i.e. waist diameter of half-taper fiber, gap width between taper fiber and cavity), diameter and eccentricity of sphere, Er-ion concentration. In the case of well satisfying phase condition, single-mode operation can occur. In our previous results [14], the single-mode lasing spectra was obtained when the gap width was changed in the range 0.2-1 μm. Figure 7 presents a series of WGM lasing wavelengths under varying gap width between taper fiber and surface of toroidal micro-cavity laser. The multi-mode (figure7a) and single-mode lasing spectra (figure7b) with output power of -19 dBm at the same wavelength of 1561.45 nm were obtained from modified toroidal micro-cavity laser, when the gap widths were changed from 1.5 to 0.5μm, respectively.
Figure 5. WGMs measured by the fiber taper coupling, when pump power is 90 mW (Lasing peak was at 1563.09 nm). Inset: WGM spectra from microsphere laser at same pump.

Figure 6. Highest power of -3.2 dBm of WGMs from micro-sphere cavity laser. Inset: WGM signal of 19 dBm amplified by EDFA.

In practice, there are a series of peaks in the single-mode obtained from OSA-Advantest Q8384 with resolution of 0.01 nm and these peaks should be analyzed by Fabry-Perot Etalon (FPE). Using formula $Q=\frac{\omega}{\Delta \omega}$ [13] for calculation of Q-factor, we obtained $Q=5.10^7$-$10^8$ for our spherical and/or modified toroidal micro-cavities. This result was in good agreement with the other one in the papers [6-9]. Figure 8 demonstrates the pump-laser emission characteristics of microcavity laser with diameter of 90μm. Threshold of laser was about 2.5 mW of pumping power, that mean the inserted pumping power at threshold was of 0.3 mW. Figure 9 shows the spectra of amplified via EDFA optical signals lasing from DFB-laser with band-width of 0.1 nm and from spherical microcavity laser with band-width less than $10^{-5}$ nm. The saturated output power of EDFA for common DFB-laser emission, which used in the fiberoptic communication network, is of $14 \pm 0.2$ dBm. In our experiment, when the WGM’s power of about -5 dBm from microcavity laser inserted into EDFA, the amplified output power was achieved up-to 18.5 dBm. This is clear evidence that the band-width of WGM was ultra-narrow in comparison with DFB lasing emission.

Figure 7. WGM lasing spectra obtained from toroid micro-cavity laser under varying gap width changed from 1.5 micron (a) to 0.5 micron (b). The WGM single-mode power was achieved up-to -19 dBm.
For DWDM networks, the dispersion phenomenon plays a very important role. The optical signal pulse expansion $\Delta \tau$ by dispersion is given by

$$\Delta \tau = D.L.\Delta \lambda,$$

where $D$ is dispersion parameter of fiber at the working wavelength, $L$ is the fiber length and $\Delta \lambda$ is band-width of optical signal. When we use WGM with the band-width $\Delta \lambda < 10^{-5}$ nm, the $\Delta \tau$ would be decreased in four orders in comparison with band-width of 0.1 nm from common DFB lasers. That means we can increase the number of optical channels in one fiber a hundred times. On the other side, the technique of double optical transmission signals with very-closed wavelengths is used in the practical high-security optical network. The marking signal should have ultra-narrow band-width, low optical power and spacing between carrier-signal and marking signal less than 1 GHz. We propose that the WGM lasing from microcavity laser can be used as a marking signal in the high-security optical network. The high-security optical network used WGM lasing from microcavity laser will be studied next time.

**Figure 8.** Pump-signal characteristics of micro-sphere cavity laser based on Er-doped silica-alumina glasses. Inset: Up-conversion emission on the equatorial plane of microcavity laser

**Figure 9.** Amplified output power via EDFA from DFB laser with input power of 2.1 dBm (1) and from microcavity laser with input power of -5 dBm (2).

4. Conclusion
We have reviewed a method of fabrication and characterization of High Q-factor micro-cavity lasers based on Er-doped silica-alumina glasses, which has been lasing ultra-narrow spectra at 1550 nm-wavelength range. The lasing output powers of one whispering-gallery-mode were reached up to -3.2 and -5.5 dBm for spherical and modified toroid micro-cavity lasers, respectively. The Q-factor of glass micro-cavities was achieved up to $5.10^7$-$10^8$ and the reduction of lasing WGMs was obtained in the modified toroid micro-cavity laser in comparison with spherical micro-cavity under the same diameter and pumping conditions. We have successfully controlled the number of lasing WGMs by changing the gap width between taper fiber and cavity and by waist diameter of taper. The single-mode spectra of Er-doped glass micro-cavity laser has output power and ultra-narrow line-width, to the best of the authors’ knowledge, suitable for applications in the field of DWDM networks, quantum informatics and optical sensor technique.

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