Effects of Size and Surrounding Medium on Whispering-Gallery-Mode Lasers in Er³⁺-Doped Silica Microspheres

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Abstract

This work reports the experimental fabrication and characterization of the Er^{3+} -doped silica microspheres (mS) and numerical investigation of the effects of size and surrounding medium on the optical properties of whispering-gallery-mode (WGM) lasers. The heat melting method of two discharge electrodes was used to produce the Er^{3+} -doped silica mS s of diameters up to several tens of micrometers. The 125- μm diameter single-mode optical fiber was tapered with a cone angle formed by chemical etching in hydrofluoric acid (HF) solutions. It was used to produce the mS s and couple the pumped laser into mS surface as well as coupled out the lasing emission. The WGM lasers at telecom regime of $\sim 1520\text{--}1570\text{ nm}$ were characterized in both clockwise (CW) and counterclockwise (CCW) propagation directions. By adjusting the coupling gap between the tapered optical fiber and the mS surface, the selectivity of the multi- or single-emitted modes of the mS laser was achieved. We performed finite-difference time-domain (FDTD) simulations to examine the size dependence and analyze the effect of the surrounding medium's refractive index on the optical characteristics, such as emission wavelength, intensity, as well as the shape of WGM lasing emission. The facile approach and quantitative investigation of this work has attracted much attention from researchers in the micro-photonic field and may be useful in many applications from tunable single-mode lasing sensing to optical micro-devices.

1. Introduction

In the last few decades, optical micro-resonators have attracted a growing interest due to their special characteristics and various promising applications for quantum electrodynamics, quantum information processing, nonlinear optics, data storages, chemical or bio-sensing, lasers, and filters [1–10]. Dielectric microspheres (μS), in which lights can be guided in the shape of whispering-gallery-modes (WGMs), can provide ultrahigh quality (Q) factors and small modal volumes (V) [4–10]. When doped with rare-earth ions, μS s can exhibit a lasing emission which acts as both gain media and resonators for emitted lasers. These lasing emissions were characterized and shown to have very narrow emission linewidths. The achieved Q -factors can be up to 10^{10} , indicating very long light storage times, achieving lasing actions at low threshold pump powers [10–16]. In recent work [10], Er^{3+} -doped silica μS s with diameters of $\sim 25\text{--}40\text{ }\mu\text{m}$ were successfully fabricated and WGM lasing emissions of single- or the multi-emitted modes in the wavelength (λ) range of $1520\text{--}1570\text{ nm}$ were quantitatively analyzed. The integration of these μS with silicon-on-insulator (SOI) slotted photonic crystal (PhC) waveguides was proposed and modelled using 3D-FDTD simulations. For μS diameter of $\sim 30\text{ }\mu\text{m}$, the integrated system deals with the challenge of confining light inside the μS with refractive index ~ 1.44 when surrounded by a higher refractive indexed medium, i.e. effective refractive index of the conducted SOI PhC (~ 2.95 at $\lambda \sim 1550\text{ nm}$). The μS was wrapped with an air ring $\sim 1.0\text{ }\mu\text{m}$, which acts as a low refractive index environment of air to prevent the WGMs inside the μS from leaking out, following the total internal reflection phenomenon. Although the proposed compact structure proved successful; it requires further research to be processed for systematic understanding and applications of ultrahigh sensitivity sensors, lasing sources, and towards the advanced quantum communications. Although several studies reported the influence of surrounding medium's refractive index on the WGMs and lasing emissions of rare-earth ions doped silica μS ; they have not provided details of the influence the refractive index has on the lights guided in the form of WGMs, as well as the intensities and linewidths of lasing emissions [7, 17–21].

In term of the relationship between the WGM resonances and the μS diameters, a dimensionless size parameter has been introduced as $x = 2\pi R/\lambda = kR$ (1), where R is the radius of the μS and k indicates the wavenumber. When the radius of the μS is much larger than the resonant wavelength ($R \gg \lambda$ or $x \gg 1$) and the light ray is at the glancing incidence of the surface of μS , the condition to have WGM resonance is equal to the optical path length. The optical path length should correspond to an integer number (l) of the wavelength, called the angular number as discussed in Sect. 2. In order to remain in phase l must be almost equivalent to the perimeter of the μS : $2\pi N R = l\lambda$ (2), where N is the refractive

index of the material of the μS [22–25]. To (i) fit much larger wavelength of WGM lasing emissions and (ii) obtain the smaller integrated size scale $\sim 100 \times 100 \mu\text{m}^2$ for minimizing the loss of the photonic integrated circuits (PICs), the Er^{3+} -doped silica μS with controlled diameter of $\sim 25\text{--}40 \mu\text{m}$ was presented and discussed in our previous work [10]. The other studies of integration systems between the μS and different platforms have been continuously studied.

Although there numerous papers have reported the experimental capability of rare-earth ions doped silica μS in generating optical signals or the numerical investigation of the WGM characteristics of the μS resonators [10–16, 22–25]; only few works have comprehensively performed experimental, characterization, and numerical simulations. Accurate numerical simulations are required to predict device performance, design and rectification as well as to obtain unexpected properties that may be exploited in the fabrication of the complex optical systems. In this paper, the heat melting method of two discharge electrodes was used to fabricate the Er^{3+} -doped silica μS with diameters of $\sim 30\text{--}80 \mu\text{m}$. Using a $125 \mu\text{m}$ diameter single-mode optical fiber, the tapered fiber tip of several micrometers were formed by chemical etching in hydrofluoric acid (HF) solutions and used to produce the μS as well as couple the pumped laser onto the μS surface and the lasing emission. The WGM lasing emission wavelength in the range of $\sim 1520\text{--}1570 \text{ nm}$ was characterized in the clockwise (CW) and counterclockwise (CCW) propagation directions. The selectivity of multi- or single-emitted modes of the μS laser was achieved by adjusting the coupling gap between the collection tapered fiber and the μS surface. The FDTD simulations [26–28] calculated the size dependence and analyzed the refractive index of surrounding medium on the optical characteristics, such as emission wavelength, and intensity of WGM lasers in Er^{3+} -doped silica μS . The facile approach and investigation of this work has attracted much attention from researchers in micro-photonic field and in applications from tunable single-mode lasing sensing to optical micro-devices.

2. Fabrication, Characterization, And Simulation Details

2.1 Fabrication

We developed the electrical discharge method to produce the μS s at the end of Er^{3+} -doped silica tapered fibers. The silica fibers with Er^{3+} concentration of $\sim 2000 \text{ ppm}$ were etched in hydrofluoric acid (HF) solutions at 25% v/v for 120 min and then 3% v/v for 45 min in order to dissolve the cladding to the naked core parts as illustrated in Fig. 1(a). The achieved diameters of the tapered fiber tips were $\sim 1.7\text{--}6.1 \mu\text{m}$ as depicted in Figs. 1(b) and 1(c). The same procedures were used for the single-mode collection tapered fibers.

The schematic of the electrical discharge equipment that was used to produce the μS s is shown in Fig. 2(a). It includes three main parts: controllable voltage source, electrodes, and 3D micro-precision stage. The discharge system driving voltage is controlled by a DC power supply. The potential difference between the electrodes must be larger than the breakdown voltage for a given electrode spacing and influence the heating of the fiber tip. The E-field strength and melting time are the dominant parameters that affect the size and surface roughness of the μS s. The first arc's strength and duration, i.e., the one that forms the μS , were $\sim 300 \text{ V/mm}$ and $\sim 750 \text{ ms}$, respectively. For the subsequent arcs, the arc strength remained unchanged but the duration time was reduced to $100\text{--}200 \text{ ms}$. A detailed procedure of the heat melting method used in this work has been reported previously [10, 29, 30]. In this work, the Er^{3+} -doped silica μS s with diameters of $\sim 30\text{--}80 \mu\text{m}$ have been controlled as shown in Fig. 3 in order to (i) fit much larger wavelength of WGM lasing emissions ($\lambda \sim 1520\text{--}1570 \text{ nm}$) and (ii) obtain the photonic integrated circuit at size scale $\sim 100 \times 100 \mu\text{m}^2$ for minimizing the loss.

2.2 Characterization

The sketch of in-house setup for characterizing the WGM lasers of μS is illustrated in Fig. 2(b). Our experiment focuses on the optical emission at *L*-band from Er^{3+} -doped silica μS s. The laser diode with output power $\sim 180 \text{ mW}$ at $\lambda = 1470$

nm (SLA5653-QD-71/CV1) was polarized at TE mode for excitation of the Er^{3+} ions. The pumped laser and the emitted lasers to/from the μS were guided by different single-mode optical tapered fibers, to ensure that the pumped light does not change the effective pumped power that contributes to lasing. This technique, which show simple, reproducible, and reversible procedure, has allowed for flexibility in controlling the coupling gap between the collection fiber and μS surface, when the position of excited fiber is fixed. It allows not only changing from multi- to single-emitted modes of the collection fiber, but also-more importantly-the ability chooses a desired single-emitted mode among several. The spectral characteristics of the lasing emissions were characterized by the optical spectrum analyzer (OSA)-Advantest Q8384 with 0.01 nm resolution. The coupling gap was adjusted by a 3D micro-precision stage (PZT-AE0203D08F) with the accuracy of 0.10 μm . Two propagation directions were measured (CW and CCW).

In the measured configuration depicted in Fig. 2(c), pumped laser at $\lambda = 1470$ nm takes the excited state $^4\text{I}_{13/2}$ from the ground state $^4\text{I}_{15/2}$. Then the stimulated emission has been obtained in the wavelength range of $\sim 1520\text{--}1570$ nm. The mechanism of “lasing action” and laser output power versus incident pumped power characteristics have been reported previously [31–33] and are not discussed in detail here.

2.3 Theoretical approach and simulation

As in the well-known WGM resonators, light is confined in a band around of a great circle of the μS and defined as the caustic region comprised between the outer and the inner μS , to which the propagating and bouncing rays are tangent. Eq. (2) clearly shows that changes to either the radius or refractive index of the material of the μS will change the resonance of the optical mode. The resonant wavelength changes is given [7]:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta R}{R} + \frac{\Delta N_s}{N_s} \quad (3)$$

Eq. (3) indicates that any small change in the surrounding medium’s refractive index of N_s or in the radius R of the μS must be balanced by a small change in the resonant wavelength.

Several analytical models were used to realize the WGMs of the μS [22, 34, 35]. A simplified 2D model for understanding the physical and optical properties of the 3D optically coupled μS systems was considered. Schiller’s approximation was used to predict the resonant characteristics of the μS due to its high accuracy and straightforward calculation procedure [34]. It is well known that the optical WGM is formed by repeated total internal reflections of light, which is constrained on the μS surface. Three mode numbers used, are described as: angular (l), azimuthal (m), and radial (n). The angular number, l , indicates the number of modal wavelengths that fit into the circumference of the equatorial plane of the μS ; the radial number, n , presents the number of intensity maxima along the radial direction. Therefore $2l$ is the number of the field maxima in the angular variation around the μS equator. The azimuthal mode number, m , indicates the field variation in the polar direction, with the number of intensity maxima along this direction being equal to $l - |m| + 1$. In practice, we are interested in exciting low-order WGMs with small n and with $m \approx l$ for maximizing the resonant advantages of the μS . These modes have the optical field distributions near the μS surface, which are approximated to the equator and the electric fields are compressed into the smallest modal volume.

Our work uses a dielectric μS which has the refractive index and diameter of 1.44 and $2R$ in the medium of refractive index of N_s , respectively. Due to its individual nature, a cubic region with dimension of larger than $2R \times 2R \times 2R$ was used for calculation of the whole structure. The problem of the light interacting with such structure was described by Maxwell’s equations. In this work, the simulations were carried out using commercial FDTD software package LUMERICAL [26–28]. The excitation of TE polarized point-source electric dipoles in the vicinity of the μS surface have been taken for the WGM- μS lasers. To avoid unexpected noise waves reflected from the computational domain walls,

the perfectly matched layers (PML) were set at surrounding boundaries. An intensity monitor that collects the emission pattern from the μS was placed $1.0\ \mu\text{m}$ behind the surface.

3. Results And Discussion

To couple light into the μS efficiently, the evanescent wave mode of the tapered fiber must match the WGM of the μS . When the Er^{3+} -doped silica μS is adequately coupled with the tapered fiber, multi-mode emission can be achieved; in which a single-mode emission can be observed [10, 13]. In the measurement, single- and multi-mode emissions were measured and the orientations of the WGM orbits have been determined by the collected tapered fiber positions. As shown in Fig. 4(a), the μS with the diameter of $\sim 29.7\ \mu\text{m}$ and coupling gap of $1.5 \pm 0.1\ \mu\text{m}$, produced multi-mode lasing emissions with spacing of $\sim 2.5\text{--}4.3\ \text{nm}$ and side mode suppression ratios (SMSR) of $\sim 14.1\text{--}27.1\ \text{dB}$. As it is shown, these emissions have the CW sense of circulation (red curve). It means that there is strong coupling and high contrast in the CW configuration, which is referred to as the in-phase matched coupling [23, 36]. For example, the lasing emission at $\sim 1547.31\ \text{nm}$: (i) the optical powers are $-30.0\ \text{dBm}$ and $-49.2\ \text{dBm}$ and (ii) the SMSRs are $27.1\ \text{dB}$ and $17.6\ \text{dB}$ for CW and CCW geometries, respectively. The optical characteristics of the multi-emitted modes from two propagation directions of CW and CCW geometries for μS diameter of $29.7\ \mu\text{m}$ are summarized in Table 1.

Table 1
Characteristics of the multi-mode lasing emissions from CW and CCW configurations for μS diameter of $29.7\ \mu\text{m}$.

CW geometry							
Emitted wavelength, λ (nm)	1540.66	1544.10	1547.31	1550.84	1554.20	1556.68	1560.93
Power (dBm)	-32.7	-35.5	-30.0	-33.5	-31.0	-39.1	-43
FWHM (nm)	0.07	0.08	0.03	0.07	0.07	0.05	0.04
SMSR (dB)	24.6	22.4	27.1	22.9	25.8	18.5	14.1
CCW geometry							
Emitted wavelength, λ (nm)	-	1544.91	1547.31	1551.34	1553.24	1554.20	-
Power (dBm)	-	-58.8	-49.2	-51.8	-62.9	-56.3	-
FWHM (nm)	-	0.07	0.07	0.05	0.06	0.06	-
SMSR (dB)	-	9.0	17.6	14.6	4.5	10.4	-
(Note: FWHM: Full-Width at Half-Maximum, SMSR: Side Mode Suppression Ratio)							

To explore the characteristics of the single WGMs, when the coupling gap g is smaller than $\sim 0.7\ \mu\text{m}$, we have collected its output power by precise adjustment of the coupling gap. Due to the vibration of the fiber tip caused from the dipole-field interaction effect and the force of the field in the tangential direction as it approaches the μS surface, it is not an effective way to make the coupling gap less than $0.15\ \mu\text{m}$ [10, 13, 37]. In the presented scheme, the diameter of μS and pumped power remained as those indicated in Fig. 4(a), while Fig. 4(b) shows the single-mode spectra extracted from the CW configuration for several coupling gaps of $0.7 \pm 0.1\ \mu\text{m}$ (black curve), $0.5 \pm 0.1\ \mu\text{m}$ (red curve), and $0.3 \pm 0.1\ \mu\text{m}$ (blue curve). As the collection tapered fiber approaches the μS surface, higher output power and SMSR could be achieved. As it is shown, the output power and SMSR are $-24.7\ \text{dBm}$ and $18.0\ \text{dB}$ for the coupling gap of $0.7 \pm 0.1\ \mu\text{m}$, while they could be as high as $-11.0\ \text{dBm}$ and $29.0\ \text{dB}$ for the coupling gap of $0.3 \pm 0.1\ \mu\text{m}$, respectively. This technique

has good reproducibility in practice and extracts most of the WGMs that can oscillate in the μS with a suitable adjustment of the coupling gap. It is important to note that the comprehension of the results is not as simple as mentioned in several published works [13, 23, 38].

The measurements of lasing emissions of the other μS diameters of $\sim 30\text{--}80\text{ }\mu\text{m}$ were also considered and exhibited the same tendencies. As shown in Fig. 4(c), WGM emission spectra extracted from Er^{3+} -doped silica μS with $79.8\text{ }\mu\text{m}$ diameter in the CW geometry for the coupling gaps $g = 1.5\text{ }\mu\text{m}$ (red curve) and $1.2\text{ }\mu\text{m}$ (blue curve). As it is shown, the multi-mode lasing emissions for two coupling gaps have been observed. The number of lasing emissions was reduced for a narrower coupling gap. Table 2 shows the characteristics of the multi-mode emissions from CW geometry for μS diameters of $79.8\text{ }\mu\text{m}$ for coupling gaps of $1.5\text{ }\mu\text{m}$ and $1.2\text{ }\mu\text{m}$. When the coupling gap g was smaller than $\sim 0.7\text{ }\mu\text{m}$, the single-mode lasing emission was also achieved. The single-mode emitted laser of the Er^{3+} -doped μS with diameter of $79.8\text{ }\mu\text{m}$ for the CW geometry and coupling gap of $0.3 \pm 0.1\text{ }\mu\text{m}$ is shown in Fig. 4(d). As it is shown, the optical output power and SMSR could be as high as -10.2 dBm and 30.0 dB , respectively.

Table 2
Characteristics of the multi-mode lasing emissions from CW configuration for μS diameter of $79.8\text{ }\mu\text{m}$ for coupling gaps of $g = 1.5\text{ }\mu\text{m}$ and $1.2\text{ }\mu\text{m}$.

$g = 1.5\text{ }\mu\text{m}$									
Emitted wavelength (nm)	1540.67	1544.50	1551.03	1554.57	1556.25	1558.68	1563.22	1565.39	1569.49
Power (dBm)	-40.0	-31.6	-34.3	-27.6	-29.5	-39.2	-34.8	-27.8	-31.9
FWHM (nm)	0.06	0.07	0.04	0.06	0.07	0.05	0.04	0.04	0.05
SMSR (dB)	17.0	25.4	22.7	29.4	27.5	17.5	22.2	29.2	25.1
$g = 1.2\text{ }\mu\text{m}$									
Emitted wavelength (nm)	1540.87	1544.78	-	1554.85	-	-	1563.16	-	-
Power (dBm)	-26.5	-29.9	-	-24.3	-	-	-30.1	-	-
FWHM (nm)	0.06	0.07	-	0.06	-	-	0.04	-	-
SMSR (dB)	25.5	22.1	-	27.7	-	-	21.9	-	-

For visualizing the modes and fields, the 3D-FDTD method combined with PML were implemented to simulate the radiation patterns of WGMs from μS [26–28]. As mentioned above, the electric-dipole emitters located near the surface and oriented along the radials of the μS , produced the $\sim 20\text{ fs}$ sinusoidal pulses centered at emission wavelengths. Figures 5(a-c) show the WGM H -field distributions for diameters $29.7\text{ }\mu\text{m}$, $38.5\text{ }\mu\text{m}$, and $79.8\text{ }\mu\text{m}$; their refractive index of 1.44 in air, at the wavelengths of 1550.84 nm , 1550.92 nm , and 1551.03 nm , respectively. The pair of mode parameters for WGMs of $(l = 66, n = 4)$ in Fig. 5(a), $(l = 85, n = 4)$ in Fig. 5(b), and $(l = 177, n = 6)$ in Fig. 5(c) were determined by counting the number of H -field intensity maxima. Figure 5(d) demonstrates the E -field intensity corresponding to the WGM- μS for $29.7\text{ }\mu\text{m}$ diameter, where the light is well confined in the equatorial plane.

To confirm the FDTD simulations, the modes and fields of the WGMs of μS have been realized by the approximate expressions described by Schiller [34]. The spherical mode is described conventionally in terms of three integer numbers l , m , and n . The value $l - m + 1$ is the number of field maxima in the polar direction, normal to the equatorial plane and between two poles. The value of n counts the number of field maxima in the radial direction. At the equatorial plane, $m = l$, the “fundamental mode”, the resonant wavelength is determined by the value of l and n . The values of l that correspond to various n for the μS with diameters of 29.7 μm , 38.5 μm , 60.1 μm , and 79.8 μm ; refractive indices $N = 1.44$ and $N_s = 1.0$ in the wavelength of interest were calculated. For the considered diameters here, the dependence of resonant wavelength on (l, n) for TE mode can be expressed as,

$$N\lambda_l^n = l + \frac{1}{2} - \zeta_n \sqrt[3]{\frac{l+0.5}{2}} - \frac{q}{\sqrt{q^2-1}} + \frac{3\zeta_n^2}{2^{2/3}10\sqrt[3]{l+0.5}} + \frac{\frac{1}{3}q^3\zeta_n^2}{2^{1/3}\sqrt[3]{(q^2-1)^3}\sqrt[3]{(l+0.5)^2}} \quad (3)$$

where λ_l^n is resonant wavelength, which is well identified with the pair (l, n) ; ζ_n denotes the n^{th} zero of the Airy function $Ai(\zeta_n)$, the field intensity distribution or the total number of field strength spikes, either positive or negative, or in the radial direction and $q = N/N_s$ (the ratio of the refractive index of μS material and the surrounding medium). Normally for a given WGM, the n number is a small integer. In our research, Eq. (3) was used to calculate the l parameter using the resonant wavelength λ when a given n is known. The calculated (l, n) pairs are listed in Table 3. A more intuitive way to determine the pairs (l, n) is from the simulation in which the field maxima could be seen in artistic pictures and those parameters could be counted along the circumference and diameter of the μS . These values were also listed in Table 3 and are in good agreement. However, the simulation resolution and the analytical approximation condition will cause some discrepancies.

Table 3
The comparison of (l, n) WGM parameters calculated by different methods.

No	μS diameter (μm)	Schiller approximation	FDTD simulation
1	29.7	(67, 4)	(66, 4)
2	38.5	(86, 4)	(85, 4)
3	60.1	(135, 5)	(133, 5)
4	79.8	(175, 6)	(177, 6)

WGM- μS have been used extensively for temperature, humidity, and stress sensing. The working principal of WGM- μS sensor is that the emission wavelength or intensity of the output signal varies with the change in external environment. Here we consider the influence of the surrounding medium on the optical characteristics of the WGM- μS , such as the wavelength and intensity of lasing emission. As mentioned above, there is no influence of changing refractive index on the pumped light that couples to Er^{3+} -doped silica μS surface. Figure 6 illustrates the dependences of the wavelength and intensity of the emitted laser on the surrounding medium's refractive index. For the given emission mode, as the ambient refractive index increases, the displacement wavelength shall be towards longer wavelengths and the emission intensity decreases. For example, when the ambient refractive index increases from air to 1.20, the emission wavelength changes from 1554.20 nm to 1581.0 nm and from 1554.47 nm to 1565.61 nm (the variation in wavelength is 26.8 nm and 11.14 nm for 0.2 refractive index units), corresponding to the μS diameters of 29.7 μm and 79.8 μm , as shown in

Figs. 6(a) and 6(b), respectively. In addition, the emission intensity also decreases as the refractive index of the medium increases. As Fig. 6 depicts, the wavelength and emission intensity of lasing emission are quite sensitive to the surrounding environment for the small μS size. Therefore, the microscopic size of $\sim 30\ \mu\text{m}$ is suitable for sensing applications that detect small changes in the surrounding medium.

In order to see the influence of the surrounding medium on the shape and intensity of the WGM lasing emission, the field distributions in the equatorial plane were simulated as shown in Figs. 7 and 8. Figure 7 shows the field profiles in the equatorial plane for μS diameter of $29.7\ \mu\text{m}$ immersed in different refractive index media: (a) air ($\lambda \sim 1554.20\ \text{nm}$); (b) $N_s = 1.04$ ($\lambda \sim 1557.28\ \text{nm}$); (c) $N_s = 1.05$ ($\lambda \sim 1558.18\ \text{nm}$); (d) $N_s = 1.10$ ($\lambda \sim 1563.81\ \text{nm}$). The shape of WGM exists and changes little with refractive indices less than 1.05, but they change a lot when the refractive index is greater than 1.05 although the emission intensity is insignificantly low.

Same to Fig. 7, Fig. 8 shows the distribution of magnetic fields in the equatorial plane for μS diameter of $79.8\ \mu\text{m}$ in different refractive index media: (a) air ($\lambda \sim 1555.20\ \text{nm}$); (b) $N_s = 1.10$ ($\lambda \sim 1558.40\ \text{nm}$); (c) $N_s = 1.20$ ($\lambda \sim 1565.61\ \text{nm}$); (d) $N_s = 1.30$ ($\lambda \sim 1571.70\ \text{nm}$). The shape of the WGM still exists and changes little with a refractive index of less than 1.20, but the shape of the WGM changes a lot when the refractive index is greater than 1.20.

4. Conclusions

In conclusion, the Er^{3+} -doped silica μS with diameters of $\sim 30\text{--}80\ \mu\text{m}$ were fabricated by using an electrical discharge method and their WGM lasing emissions at the telecom regime were quantitatively analyzed. In the measurement, the coupling gap between the collection tapered fiber and the μS surface resulted in the single- or the multi-emitted modes. The FDTD simulations were performed to examine the size dependence and analyze the refractive index of surrounding medium on the optical characteristics, such as emission wavelength and intensity of WGM lasers in Er^{3+} -doped silica μS , which justifies the observation of the lasing emission modes. The demonstrated approach of this work may be beneficial in applications from tunable single-mode lasing and sensing to micro-devices.

5. Declarations

Disclosures

The authors declare no conflicts of interest.

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Figures

Figure 1

(a) SEM images representing the tapered fiber tips. The fiber taper has a smooth shape and its diameter gradually reduces to $\sim 1.7 - 6.1 \mu\text{m}$ (b and c), where it forms an almost sphere.

Figure 2

Schematic illustrations of the (a) electrical discharge equipment to produce the μS at the end of Er^{3+} -doped glass silica tapered fiber; (b) tapered fiber coupled μS optical measurement system and (c) three lowest energy-level diagram of Er^{3+} ion.

Figure 3

SEM images of the Er^{3+} -doped silica glass μS s with diameters of ~ 30 - $80 \mu\text{m}$. (a) 29.7 μm , (b) 38.5 μm , (c) 60.1 μm , and (d) 79.8 μm .

Figure 4

WGM emission spectra of the Er^{3+} -doped silica glass μS with diameters of 29.7 μm (a and b) and 79.8 μm (c and d). The coupling gap between the tapered fiber and the μS surface changes from (a) $1.5 \pm 0.1 \mu\text{m}$ to (b) $0.7 \pm 0.1 \mu\text{m}$, $0.5 \pm 0.1 \mu\text{m}$, and $0.3 \pm 0.1 \mu\text{m}$; (c) $1.5 \pm 0.1 \mu\text{m}$ and $1.2 \pm 0.1 \mu\text{m}$ to (d) $0.3 \pm 0.1 \mu\text{m}$. The CW and CCW configurations are indicated in 2(b).

Figure 5

Magnetic field distributions in the WGM plane for the wavelengths (λ) and μ S's diameters (Φ): (a) $\lambda \sim 1554.20$ nm and $\Phi = 29.7$ μm; (b) $\lambda \sim 1554.70$ nm and $\Phi = 38.5$ μm; (c) $\lambda \sim 1555.20$ nm and $\Phi = 79.8$ μm. The E-field magnitude of the μ S with diameter of 29.7 μm for the wavelength of ~ 1554.20 nm is shown in (d).

Figure 6

Wavelength and real part of electric field at resonances of various refractive indices of surrounding media for the μ S with diameters of (a) 29.7 μm and (b) 79.8 μm .

Figure 7

Magnetic field distributions in the WGM plane for the wavelengths (λ) and μ S's diameters (Φ): (a) In air ($\lambda \sim 1554.20$ nm); (b) $N_S = 1.04$ ($\lambda \sim 1557.28$ nm); (c) $N_S = 1.05$ ($\lambda \sim 1558.16$ nm); (d) $N_S = 1.10$ ($\lambda \sim 1563.87$ nm).

Figure 8

Field distributions in the WGM plane for the wavelengths (λ) and μS 's diameters (Φ): (a) In air ($\lambda \sim 1555.20$); (b) $N_S = 1.10$ ($\lambda \sim 1558.41 \text{ nm}$); (c) $N_S = 1.20$ ($\lambda \sim 1565.32 \text{ nm}$); (d) $N_S = 1.30$ ($\lambda \sim 1571.70 \text{ nm}$).