A Stable 1550nm WGM Laser Generated by Yb\textsuperscript{3+}/Er\textsuperscript{3+} Co-doped Silica Microspheres under 1 μm ASE Source Pumping

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Abstract. The amplified spontaneous emission (ASE) light source at 1 μm was used to excite Yb\textsuperscript{3+}/Er\textsuperscript{3+} co-doped silica (YEDS) microspheres by evanescent-wave coupling through a taper optical fiber (TOF) to generate a stable 1550 nm laser. Inevitably, the experimental process was accompanied by a frequency up-conversion luminescence whose fluorescence spectrum was collected and analyzed. Pumped by the ASE light source with different power, the system of YEDS microsphere and TOF also generated single-mode laser and multi-longitudinal mode laser. Their peak wavelength, output power of the peak laser, full width at half maximum (FWHM), and side mode suppression ratio (SMSR) were respectively measured. Moreover, the characteristics of a 1550 nm whispering gallery mode (WGM) laser excited by a 1 μm ASE pumping and a tunable laser (TLS) pumping were compared under different variable conditions. It was demonstrated that the ASE pump source has polarization in all directions to excite WGMs in the microsphere cavity, which was different from and superior to the TLS. Therefore, the laser generated by the ASE pump source as an excitation source was not affected by vibration and temperature change. The results show that the 1550 nm laser pumped by ASE can stably output the microsphere WGM mode laser under the interference of vibration and temperature change, which is more suitable for the actual application environment.

1. Introduction

1550 nm optical band is the main light source for the research of optical fiber communication systems with a propagation loss of 0.20 dB/km and a long transmission distance in optical fiber. It usually includes S\textsuperscript{*}-band (1450 nm to 1490 nm), S-band (1490 nm to 1530 nm), C-band (1530 nm to 1570 nm), L-band (1570 nm to 1610 nm), and L\textsuperscript{*}-band (1610 nm to 1650 nm). This optical band can increase the optical power of the signal light through an erbium-doped fiber amplifier (EDFA) to replace the optical repeater and electrical repeater, prolong the optical fiber transmission distance or realize more optical signal shunting. As a result, it has become the main band used in optical fiber communication systems. In the meantime, the 1550 nm optical band is also the popular wavelength of gas sensors. Some toxic and flammable gases have characteristic absorption peaks in this near-infrared band, such as H\textsubscript{2}O at 1400nm, NH\textsubscript{3} at 1512nm, H\textsubscript{2}S at 1578nm, CH\textsubscript{4} at 1653.72nm, and C\textsubscript{2}H\textsubscript{2} at 1534nm[1-2].

Miniaturization and integration of optical devices are the development trend, as are lasers in the 1550nm optical band. The whispering-gallery-mode (WGM) microcavity laser with a scale of tens to
hundreds of microns is a kind of microcavity laser, which has been studied extensively in recent decades [3-5]. It has an ultra-low threshold and very narrow linewidth. SiO$_2$ microcavity can achieve extremely high-power density due to its unique WGM time limit (high-Q value) and space limit (minimum mode volume) characteristics[5], which leads to a significant reduction of the threshold power for laser generation and facilitates the generation of four-wave mixing, stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) laser[6-8]. In addition, high-Q optical microcavities are also used for gas detection and high-precision optical sensing [9].

High powerful amplified spontaneous emission (ASE) light source is frequently used in testing instruments owing to its large broadband, high power, and high stability [10]. It is also used in rural long-distance wavelength division multiplexing FTTx transmission systems to keep multiple laser tubes usage at bay [11]. Researchers conduct ASE light source as the excitation light source of microsphere cavity because of its large bandwidth and insensitive polarization. Using ASE light source as the pump source of the Yb$^{3+}$/Er$^{3+}$ co-doped silica (YEDS) microsphere has the following advantages [12] the area of absorption cross-section of Yb$^{3+}$ ion is large in the wavelength range of 900 nm to 1100 nm; 2) the ASE light source can provide a set of wavelengths resonant with the microcavity; 3) the ASE light source can adapt to the polarization-dependent characteristic of the morphology characteristic spectrum of the microsphere cavity well. One condition for using a single frequency laser source as a pump source is that its polarization should match the microsphere cavity, so a tunable laser (TLS) is always selected. However, the center wavelength of the TLS needs to be re-adjusted timely as the movement of the optical fiber made the polarization state of the transmitted light change. In contrast, the ASE pump light source provides polarized light in all directions and a wide wavelength range to make a group of light always coupled into the microsphere as excitation to meet the inherent resonant wavelength of the microsphere. This feature can overcome the mismatch between the microcavity and the pump source caused by vibration and temperature change. As a result, the microcavity pump ASE light source can produce a stable laser that better adapts to the environment. Nevertheless, ASE light source as an excitation has the disadvantage of low spectral utilization. In other words, the light of the non-resonant part is transmitted through TOF rather than coupled into the microsphere. This insufficient utilization could be made up by pumping multiple microspheres in series in future studies.

In this paper, pumping the YEDS microspheres respectively with a 1 μm ASE and a 1 μm TLS, the laser at 1550 nm optical band and the green fluorescence emission were observed in both cases. And then, the output characteristics of YEDS microspheres were studied and analyzed. Therein, the frequency up-conversion part contains a fluorescence spectrum and the corresponding mechanism of the energy-level transition. The features of 1550 nm laser include the analysis of single longitudinal mode laser and multimode laser spectrum. It was found that single-mode laser and multi-longitudinal mode laser could be realized by changing the coupling position between the YEDS microsphere and taper optical fiber (later abbreviated as YEDSM-TOF structure). Finally, the YEDSM-TOF structure produced laser at 1550 nm optical band under both pumping conditions. Moreover, the effects of the polarization mode of pump light, environmental temperature, and pump power on the generation of laser were discussed. It was proved that the stability of the 1550 nm laser with the 1μm ASE light source as a pump source was better.

2. Experimental Procedure

2.1. Sample Preparation

The TOF was fabricated by stretching a standard silica single-mode fiber through the stepping motor under continuous heating of hydrogen flame. Figure 1 showed the preparation of the YEDS microspheres mainly prepared by the sol-gel method, whose Yb$^{3+}$/Er$^{3+}$-doping ratio was 2:1[13]. Pure SiO$_2$ microspheres were made by melting the optical fiber tip through electrode discharge, and then the thin gain layer of silica doped with Yb$^{3+}$ ions and Er$^{3+}$ ions was prepared by the simple sol-gel method. After that, we could obtain YEDS microspheres with smooth surface and good optical
properties, whose diameter was between 80 μm and 220 μm.

Figure 1. The preparation of the YEDS microsphere prepared by the sol-gel method. (a) The flowchart of the gain layer of SiO₂ thin film doped with rare-earth ions; (b) the preparation of microspheres by electrode discharge melting optical fiber, observed under a CCD microscope (magnification: 200×).

2.2. Experimental Setup
Figure 2 presented the schematic of the measurement system. As shown in the picture, the pump power of 1 μm ASE/TLS was adjusted by a ytterbium-doped fiber amplifier (YDFA) and a variable optical attenuator (VOA). The polarization state of the pump light was changed by a fiber polarization controller (FPC). The light was coupled into the microsphere cavity in the form of an evanescent field by the TOF. The tangential coupling position of the YEDS microsphere cavity and the TOF was accurately adjusted through a high accuracy 3D adjusting mount. The coupling process was monitored by a charge-coupled device (CCD) microscope in real-time. The 1550 nm laser spectrum was measured by the spectrum analyzer (OSA, Yokogawa-AQ6370B) with a detection range from 600 nm to 1700 nm. Furthermore, the up-conversion fluorescence spectrum was collected and measured by the grating spectrometer (GS, WGD-8A), ranging from 200 nm to 660 nm.

Figure 2. The schematic of the measurement system.

3. Results and Discussion
3.1. Up-conversion Fluorescence in YEDS Microsphere Cavity
As shown in the up-conversion fluorescence spectrum of figure 3, the yellow-green emission visible to the naked eye was observed under the pump of the 1 μm ASE light source. Figure 3 also illustrated the
energy level transition of up-conversion luminescence of the YEDS microsphere. The mechanism of the up-conversion luminescence was analyzed as follows. Under the 1 μm ASE light source pumping, the Yb$^{3+}$ ion in the ground state transferred from the $^2F_{7/2}$ level to the $^2F_{5/2}$ level by absorbing a 1 μm photon and then to a virtual level through absorbing another photon: $^2F_{7/2}$(Yb$^{3+}$) + $\nu$ → $^2F_{5/2}$(Yb$^{3+}$), $^2F_{5/2}$(Yb$^{3+}$) + $\nu$ → the virtual state (Yb$^{3+}$), where $h$ is Planck’s constant, and $\nu$ is photon frequency. Sub-fraction of the electrons of the Yb$^{3+}$ ion in the virtual state returned to the ground state generating a 476 nm blue emission: the virtual state (Yb$^{3+}$) → $^2F_{7/2}$(Yb$^{3+}$) + 476 nm. At the same time, the excited Yb$^{3+}$ ion could transfer energy to the Er$^{3+}$ ion to cause it to transition to an excited state at the $^4F_{9/2}$ level as this virtual level matched the $^4F_{7/2}$ level of the Er$^{3+}$ ion. However, this excited state was unstable so that the electrons transferred to the $^2H_{11/2}$ level or the $^4S_{3/2}$ level in the form of non-radiative transition. After that, the electrons of the $^2H_{11/2}$ level of the Er$^{3+}$ ion transitioned to the ground state $^4I_{15/2}$, generating the 520 nm green emission: $^2H_{11/2}$(Er$^{3+}$) → $^4I_{15/2}$(Er$^{3+}$) + 520 nm. About electrons in the $^4S_{3/2}$ level, some of them transitioned to the ground state and emitted the 540 nm green fluorescence: $^4S_{3/2}$(Er$^{3+}$) → $^4I_{15/2}$(Er$^{3+}$) + 540 nm, some transferred to the $^4F_{9/2}$ level by a non-radiative decay and then radiated to the ground state $^4I_{15/2}$ with the 619 nm red emission: $^4F_{9/2}$(Er$^{3+}$) → $^4I_{15/2}$(Er$^{3+}$) + 619 nm. In addition, there was another possible way for the electron level transition: the electron of Er$^{3+}$ ion transitioned from the ground state $^4I_{15/2}$ to the excited $^4I_{11/2}$ level owing to the absorption of a 1 μm-ASE photon: $^4I_{15/2}$(Er$^{3+}$) + $\nu$ → $^4I_{11/2}$(Er$^{3+}$), then non-radiated to the $^4I_{13/2}$ level as the atomic lifetime of the excited state $^4I_{11/2}$ was short. The Er$^{3+}$ ion at the $^4I_{13/2}$ level continued to absorb a 1 μm-ASE photon to transition to the $^4F_{9/2}$ level: $^4I_{13/2}$(Er$^{3+}$) + $\nu$ → $^4F_{9/2}$(Er$^{3+}$), from which electrons returned to the ground state $^4I_{15/2}$ emitting the 619 nm red fluorescence: $^4F_{9/2}$(Er$^{3+}$) → $^4I_{15/2}$(Er$^{3+}$) + 619 nm.

**Figure 3.** Up-conversion visible light generated by Yb$^{3+}$/Er$^{3+}$ co-doped SiO$_2$ microsphere cavity excited by the 1 μm ASE light source. The left illustration: the energy level transition diagram of up-conversion luminescence of Yb$^{3+}$ and Er$^{3+}$ ions, the right illustration: the luminous physical picture of the microsphere.

### 3.2. WGM Laser In The 1550nm Optical Band Under ASE Excitation

#### 3.2.1. Single-Longitudinal Mode Laser. As shown in the figure 4 (a), the YEDSM-TOF structure output a single-mode laser pumped by 1 μm ASE light source with a wavelength of 1.6 μm, an output power of -38.58 dBm, full width at half maximum (FWHM) of 0.15 nm and a side mode suppression ratio (SMSR) of 10.58 dB. Figure 4 (b) was a schematic diagram of the energy level transition of the Yb$^{3+}$ ion by absorbing photons of 1 μm ASE light source to make electrons transition from the ground
state to the upper level and then transfer energy to the Er$^{3+}$ ion.

Figure 4. 1600.91 nm single-mode laser generated by YEDS pumped by the 1 μm ASE light source. (a) The spectral diagram, inset: the spectral detail diagram; (b) the schematic diagram of electron level transition of Yb$^{3+}$ ion and Er$^{3+}$ ion.

The principle process was analyzed as follows: the electron of the Yb$^{3+}$ ion transited from the energy level $^2F_{7/2}$ to $^2F_{5/2}$ by absorbing a 1 μm-ASE photon. Since Yb$^{3+}$ ions and Er$^{3+}$ ions were co-doped in the gain layer and the energy level $^2F_{5/2}$ of the Yb$^{3+}$ ion matched the energy level $^4I_{11/2}$ of the Er$^{3+}$ ion, an outer electron of the Er$^{3+}$ ion transited from the ground state $^4I_{15/2}$ to $^4I_{11/2}$, while the electron of the Yb$^{3+}$ ion returned to the ground state $^2F_{7/2}$. Then, the electron of Er$^{3+}$ relaxed by the nonradiative $^4I_{11/2}$ - $^4I_{13/2}$ transition, and then returned to the ground state $^4I_{15/2}$ from the $^4I_{13/2}$ level, emitting a photon with a wavelength of 1600.91 nm.

3.2.2. Multi-Longitudinal Mode Laser. From figure 5, we found that the YEDSM-TOF structure also made multimode laser output when the power of the 1 μm ASE pump light increased. In the measurement results, peak wavelength was located in about 1.601 μm, the output power of the peak laser was -37.48 dBm, and the FWHM was 0.05 nm. In a separate free spectral range (FSR), the best SMR was 13.45 dB. Figure 5 showed that the laser wavelength ranged from 1595.55 nm to 1607.76 nm, and the average FSR ($\Delta \lambda_{FSR}$) covers 2.46 nm. According to the approximate calculation formula of FSR: $\Delta \lambda_{FSR} = \frac{\lambda}{2nmd}$, where $\lambda$ is the resonance wavelength, $n$ is the refractive index of the microsphere material, and $d$ is the diameter of the microsphere. Take $\lambda = 1601.18$ nm, $n = 1.456$, $d = 221.9$ nm were substituted into the formula and calculated the theoretical value $\Delta \lambda'_{FSR} = 2.52$ nm, which was close to the experimental result.
Figure 5. 1601.9 nm multi-mode laser generated by YEDS pumped by the 1 μm ASE light source. The illustration is the detailed description of peak laser, peak wavelength = 1601.18 nm, peak power $P_{\text{max}} = -37.48 \text{ dBm}$, $\Delta \lambda_{\text{FWHM}} = 0.05 \text{ nm}$, $\Delta \lambda_{\text{FSR}} = 2.46 \text{ nm}$.

3.2.3. Mode of 1550 Nm Laser Varying with the Coupling Position. During the experiment, the longitudinal mode distribution of the 1550 nm laser varied with the change of the coupling position (CP) between the TOF and the microsphere cavity. Figure 6 indicates the relationship between the longitudinal mode distribution and the CP. By adjusting the CP between the microsphere and the TOF, the laser could be transformed between the single-mode and the multi-mode laser. From coupling position 1 (CP1) to the coupling position (CP3) (corresponding to the diameter of the tapered fiber from thick to thin), the number of laser modes gradually increased, and the laser intensity increased accordingly. The reason was that the coupling efficiency depended on the strength of the evanescent wave of the TOF. The thinner the TOF, the stronger the evanescent field, the higher the coupling efficiency, the stronger the pump light entering the microspheres, and the more laser modes were produced.

Figure 6. Longitudinal laser mode distributions at different coupling positions.

4. Comparison of the Stability of Laser Pumped by ASE and TLS
The stability of laser is a critical factor to be considered in the process of use. In this paper, a 1 μm broadband ASE source and a tunable laser were selected as pump sources. By changing the polarization of pump light, environmental temperature, and pump power, the effects of various factors on the stability of 1550 nm WGM laser were investigated.
4.1. Polarization of Pump Light

Added the FPC before the pump light entered the TOF to make the polarization of the pump light vary with the state of the three fiber rings of the FPC. Figure 7 (a) and (b) respectively show the influence of the polarization change of the light pumped by ASE and TLS on the mode distributions of the laser in the 1550 nm optical band. When FPC changed in order of state 1, state 2, state 3, state 4, and state 5 (i.e., finally returned to the initial state 1), it was observed that the mode distributions of 1550 nm laser pumped by the ASE light source remained unchanged and showed excellent stability. The reason was that ASE light source has uniform polarization (i.e., contains various polarization states). It should be noted that the light source was off before the FPC transferred state 4 to state 5, and then on after the FPC turned into state 5.

![Figure 7](image-url)

**Figure 7.** Comparison of the influence of the polarization state of pump light on the output spectra of 1550 nm laser pumped by the ASE and the TLS. (a) Pumped by the ASE; (b) pumped by the TLS; (c) different states of the FPC.

As a result, there was always a set of wavelengths provided by the ASE pumping source resonant with the high-Q microsphere cavity, which met the polarization-related morphological characteristics and resonantly coupled to the microsphere cavity to excite Er$^{3+}$ ions. However, for the TLS, each change of the FPC led to significant irreversible changes in the mode distributions of the 1550 nm laser.

4.2. Environmental Temperature

To compare the resistance of 1550 nm laser pumped by ASE and TLS to the varying environmental temperature, the longitudinal mode distributions of 1550 nm laser at different temperatures were discussed. The environmental temperature was heated by an infrared lamp. Figure 8 shows the longitudinal mode distribution of 1550 nm laser pumped by ASE and TLS with the environmental temperature from 25$^\circ$C to 95$^\circ$C. It can be seen from the figure that the influence of environmental temperature on the longitudinal mode distributions of 1550 nm laser pumped by ASE and TLS is relatively slight. This is because the internal temperature of the microspheres is much higher than the external temperature due to the thermal effect of the pump light.
Therefore, the change of external temperature in the range of 25-95°C had little effect on the inherent resonance wavelength of the microsphere. However, the TLS pump source was more sensitive to the change of environmental temperature than ASE. From figure 8 (b), the number of 1550 nm laser modes produced by TLS pumping decreased as the environmental temperature increased, which was because the mode with weak resonance disappeared, and only the laser mode with strong resonance remained. On the contrary, the 1550 nm laser pumped by ASE showed good stability during the whole heating process.

4.3. Pumping Power

The 1550nm laser generated by the YEDS microspheres at different pump powers is present in figure 9. For the ASE pump source, the longitudinal mode distribution of 1550 nm laser remained constant when the pump power decreased in steps of 3 dB in the order of P1, P2, and P3, and then increased in the order of P3, P2, and P1. As for the TLS pump source, when the pump power was reduced from P'1 to P'2 in a step of 0.5 dB, the longitudinal mode distribution changed significantly. Nevertheless, after that, whether the pump power decreased or increased, the longitudinal mode distribution remained unchanged, indicating that the change of the longitudinal mode distribution with the pump power was irreversible.
P'2 = 14.5 dBm, P'3 = 14 dBm.

5. Conclusion
In this paper, a laser at the 1550 nm optical band was obtained in the Yb\(^{3+}/\)Er\(^{3+}\) co-doped silica microsphere excited by the 1 μm ASE light source. The longitudinal mode distribution of the laser was closely related to the coupling position of the TOF and the microsphere cavity. Meanwhile, the smaller the diameter of the tapered optical fiber at the coupling position, the stronger the evanescent wave, the easier it was to produce a multimode laser. With the 1 μm broadband ASE source pumping, single-mode laser and multi-longitudinal mode laser were achieved in the YEDSM-TOF structure. The peak wavelengths of these two lasers were around 1.6 μm with a power of about -38 dBm. The SMSR of the former was 10.58 dB, and the best of the latter in a separate FSR was 13.45 dB. Furthermore, the 1550 nm laser pumped by ASE could stably output the WGM laser under the interference of vibration and temperature change that can be potentially used in unstable environments.

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References
[1] Rothman L S et al. The HITRAN2016 molecular spectroscopic database 2017 J. Quant. Spectrosc. Radiat. Transf 130 (11) 4–50.
[2] Pan W D et al. 2012 Tunable Diode Laser Absorption Spectroscopy System for Trace Ethylene Detection [J] Spectrosc. Spect. Anal 32 2875–8.
[3] Li Q L, Huang Y T et al. 2015 Ultralow-threshold laser in a Nd\(^{3+}\) doped silica microsphere [J] Opt. Commun. 356 368–72.
[4] Wu T J, Huang Y T et al. 2014 Laser oscillation of Yb\(^{3+}\)-Er\(^{3+}\) co-doped phosphosilicate microsphere [J] Appl. Opt. 53 4747–51.
[5] Vahala K J. 2003 Optical microcavity[J] Nature 424 839–46.
[6] Zhuang S J, Huang Y T et al. 2017 Realization of an O-waveband laser based on cascaded stimulated Raman scattering of microspheres [J] Appl. Opt. 56 7572–6.
[7] Zhang P J et al. 2013 Study of cascaded raman scattering laser in silica microsphere pumped by 976 nm laser[J] Acta Physica Sinica 62 224207.
[8] Guo, C L, et al. 2015 Low-threshold stimulated Brillouin scattering in high-Q whispering gallery mode tellurite microspheres Opt. Express 23 32261–6.
[9] Chen W J, et al. 2017 Exceptional points enhance sensing in an optical microcavity[J] Nature 548 192–6.
[10] Pan W W, et al. 2017 An efficient multiwavelength light source based on ASE slicing [J] Opt. Lett. 42 5162.
[11] Chang C H, et al. 2009 A broadband ASE light source based full-duplex FTTH/ROF transport [J] systemOpt. Express 17 22246–53.
[12] Huang Y T, et al. 2020 2 μm Tm\(^{3+}\) doped silica microsphere laser using amplified spontaneous emission light for pumping[J] Opt. Commun 460 125137–43.
[13] Peng L X, et al. 2017 2μm laser oscillation of Ho\(^{3+}\)-Tm\(^{3+}\) co-doped silica microspheres[J] Appl. Opt. 56 7469–73.
[14] Huang Y T, et al. 2014 Ultralow-threshold laser and blue shift cooperative luminescence in a Yb\(^{3+}\) doped silica microsphere[J] AIP Adv. 4 027113.