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Single mode compound microsphere laser

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ABSTRACT

Single mode laser is demonstrated based on compound microspheres. The two coupled microspheres, corresponding to the diameters of 32.7 μm and 49.2 μm, are both made from Er^{3+}/Yb^{3+} co-doped phosphate glass. Based on the Vernier effect, single mode laser emission has been realized at 1544.43 nm with the side-mode suppression ratio of 45.1 dB and the threshold of only 163 μW. This compound microspheres scheme can effectively select one laser emission mode among various modes, which can potentially used in micro-size laser source, high precision sensor and other frontier fields.

1. Introduction

Single mode laser, which owns the merits of higher monochromaticity and better beam quality, plays a significant role in high precision measurement and manipulation research field, such as optical frequency standards [1], laser cooling [2], and single nanoparticle detection [3]. In recent years, single mode laser based on microresonators, especially whispering gallery mode (WGM) microcavities [4–12], has attracted widely interest in relevant research fields. The rotational symmetrical structure of the WGM microcavity can well confine energy by the total internal reflection law, which can be established in various shapes, such as microring [7,8], microdisk [9,10], microcylinder [11], and microsphere [12]. This principle guarantees high energy density, long photons life in WGM microcavity, which can lead to high cavity quality (Q) factor and small mode volume. For example, the microsphere can achieve high Q-factor up to 10^{10} [13], which is a highly competitive component for sensing, lasing and nonlinear optics. Therefore, WGM microcavity, especially microsphere, has been demonstrated as an excellent candidate for constructing low threshold and narrow linewidth lasers. Microcavity laser based on single active microsphere has been thoroughly and deeply researched [12–21], where the microspheres have been fabricated by using many different gain materials for various wavelength lasing emission, such as Er^{3+}/Yb^{3+} co-doped phosphate glass [14,15], Ho^{3+}/Tm^{3+} co-doped silica [16], Nd^{3+}-doped borosilicate glass [17], Bi-doped germanate glass [18] and so on. However, multi-mode emission operation and relative low side mode suppress ratio based on the single microsphere laser has restricted its further application. In order to realize single mode laser operation in microsphere, shortening cavity length for larger free spectral range (*FSR*) would be a single and direct scheme. However, microsphere for lasing is typically fabricated to be larger than 15 μm in diameter with acceptable radiation loss [19], where the corresponding *FSR* is the same order of magnitude as he gain bandwidth of the Er^{3+} doped gain materials. Although there are only a few fundamental modes within the whole gain bandwidth, tens of higher order modes will also oscillate in microsphere. As a result, both fundamental modes and higher order modes will be excited simultaneously. The single microsphere laser generally exhibits multi-longitudinal and transverse mode operation [20–22].

Therefore, assistive technology is urgently needed for effectively achieving single mode operation in microsphere laser. Conventional technologies, such as optical feedback [23] and injection seeding [24], are too complicate and bulky for the microsphere laser. Microcavity with metallic coating has been demonstrated to reduce cavity dimensions considerably smaller than the wavelength of light and achieved single mode lasing [25]. However, extremely high gain material is desired to enable lasing due to high loss in metal. Microcavities with parity-time (PT) symmetry have also been demonstrated for mode selection, where the breaking of PT-symmetry condition will induce the desired mode to have a higher gain while suppressing other modes [26]. However, elaborate manipulating the interplay between gain and loss in PT-symmetry microcavities is complicated and the use of such a structure would greatly increase the fabrication complexity. Different from the complicated schemes as mentioned above, compound microcavity structure, typically consists of two microcavities with various materials and

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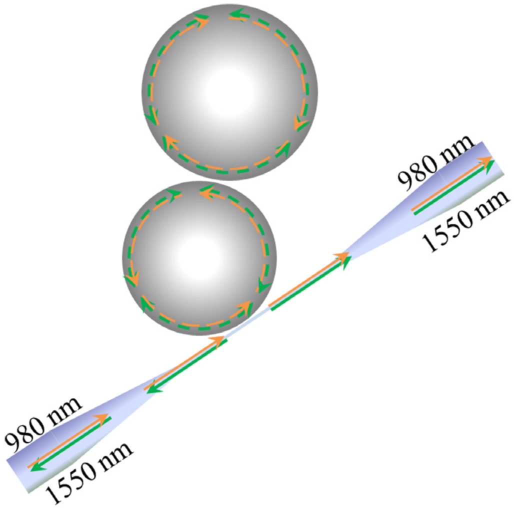

Fig. 1. Schematic diagram of compound microspheres laser. The fiber taper is used for launching the pump light (yellow arrows) and collecting the signal light (green arrows). The dashed arrows in the microsphere represent the WGM of the pump and signal light. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shapes, can realize single mode lasing operation based on the Vernier effect and intracavity modulation [27]. Vernier-scale consists of two scales with different periods and the overlap between lines on the two scales, which can be used to perform high accuracy measurement. The Vernier effect concluded from Vernier-scale, which is a compact and suitable approach for mode management, has been applied in photonic devices and various kinds of compound microcavity for single mode lasing operation [28–31].

In this paper, compound microspheres exploiting the Vernier effect are composed of two coupled Er^{3+}/Yb^{3+} co-doped glass microspheres with different diameters. The single mode lasing operation is achieved at 1544.43 nm with side-mode suppression ratio 45.1 dB and laser threshold of 163 μW. This single mode compound microspheres laser can be potentially used in bio-sensing, nanoprocessor and single photon light source.

2. Experiment devices

Fig. 1 shows the experimental diagram of compound microspheres laser configuration. The fiber taper is selected for launching the pump light and collecting the signal light [32]. The condition of phase-matching can be obtained by adjusting the diameters of microfiber and microsphere in coupling area. Meanwhile, proper distance between them will enhance coupling efficiency. The pump light can be effectively coupled into and out of the microsphere through evanescent field. This coupled method by microfiber possesses higher coupling efficiency than free space, prism and many other coupling media, which would bring the advantages of significant reduction in lasing threshold. The microfiber with 1.1 μm diameter is directly drawn from single mode fiber (HI1060, Corning) by the flame-brushing technique [33]. Through this method, the microfiber used in experiment has less than 0.1 dB/mm loss and 3 dB insertion loss.

Active microsphere is fabricated from homemade Er^{3+}/Yb^{3+} co-doped phosphate glass with concentrations of 3.0 mol% for Er^{3+} and 5.0 mol% for Yb^{3+} respectively. Its refractive index is about 1.54 around 1.55 μm wavelength. The effective gain bandwidth of this Er^{3+}/Yb^{3+} co-doped phosphate material covers the range from 1520 nm to 1580 nm. More details about this gain material can be found in our previous work [34]. Active microsphere has been fabricated by laser thermoforming technique. Firstly, Er^{3+}/Yb^{3+} co-doped glass rod is vertical hung and heated in the middle using CO_2 laser with high power, and it has been drawn to be several microns in diameter under gravity. Secondly, this microrod is cut in the middle using high power laser pulse. Finally, the end of microrod has been melted and curled to be a microsphere naturally through surface tension. The diameters of active microspheres used in experiment are 32.7 μm and 49.2 μm respectively.

3. Results and discussion

With respect to the fundamental modes in cavity, the resonant condition can be approximately written as:

$$\pi n_{eff} D = l\lambda \tag{1}$$

where n_{eff} is the effective refractive index of the resonant fundamental mode; D is the diameter of the microsphere; λ is the resonant wavelength; l is an integer giving the number of field maxima in a round trip of the resonator.

FSR is defined as wavelength spacing $\Delta\lambda_{FSR}$ of two adjacent fundamental modes in a resonator. It can be given by expression:

$$\Delta\lambda_{FSR} \approx \frac{\lambda^2}{\pi n_{eff} D} \tag{2}$$

According to Eq. (2), *FSR* will increase with R decreasing. The $\Delta\lambda_{FSR}$ is calculated to be 15.2 nm for 32.7 μm diameter microsphere used in the experiment. Theoretically, within about 60 nm gain bandwidth of the Er^{3+}/Yb^{3+} co-doped phosphate glass, there are about four fundamental modes satisfying resonant condition. Many higher order modes will also have chance to be excited. Thus, the Vernier effect based on compound microcavity is induced for enhancing *FSR* and suppressing most of laser modes. The *FSR* of each microsphere is different, and the common resonant wavelength will be selected based on the Vernier effect. The relationship of the *FSR* between compound microspheres and related single microsphere could be written as:

$$FSR_{1,2} = n_1 FSR_1 = n_2 FSR_2 \tag{3}$$

where $FSR_{1,2}$ is the *FSR* of compound microspheres; FSR_1 and FSR_2 are the *FSR* of single microsphere separately; n_1 and n_2 are integers. Combining Eq. (1) with Eq. (2), the relationship between the ratio of n_1 and n_2 and the diameters of two microspheres can be written as:

$$\frac{n_1}{n_2} = \frac{D_1}{D_2} \tag{4}$$

where D_1 and D_2 are the diameters of two microspheres. Microspheres used in this experiment are 32.7 μm and 49.2 μm. Therefore, the mode spacing in compound microspheres is at least about 45.6 nm. The Vernier effect enhanced compound microspheres are helpful for enlarging the interval of lasing modes and offering much higher possibility for achieving single mode lasing operation.

The diameters of microspheres used in this experiment are 32.7 μm and 49.2 μm, which are marked as "microsphere A" and "microsphere B" respectively in paper for simplification. As shown in Fig. 1, the smaller "microsphere A" is directly coupled with microfiber for obtaining pump light and exporting signal light. The larger "microsphere B" is placed close enough to "microsphere A" for evanescent field coupling. These two microspheres are assembled to be compound microspheres (marked as "microsphere A + B). Fine adjustment has been executed to ensure that the microfiber and the two equatorial planes of the microspheres are located at the same plane. A 976 nm continue-wave laser with 10 MHz linewidth (DBR976S, Thorlabs corporation) is adopted as pump source, which is launched into compound microspheres through evanescent field coupling. When pump power is above the laser threshold, the laser will be oscillating and propagating along clockwise and counter-clockwise directions within microsphere. The laser emission can be coupled out from both ends of the tapered fiber and recorded by optical spectrum analysis (OSA, Anritsu MS9710C)