Upconversion Lasing for Index Sensing and Strong Amplitude Modulation of WGMs in Er-Yb Co-doped Tellurite Spheres

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Abstract: We fabricated Er-Yb codoped tellurite spheres for strong upconversion WGM lasing with Q up to 27,000 for 15µm diameter and achieved the index sensitivity of 8.8nm/RIU. Strong amplitude modulation in the modes was also observed.
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1. Introduction

Microspherical resonators are one of the best cavities in terms of their ability to store energy for long periods of time within small volumes [1]. Spheres made from high index materials are particularly interesting for studies of nonlinear coupling of light with matter due to their high nonlinearity. The whispering gallery modes (WGMs) of spherical cavities have been studied in a range of high refractive index materials including chalcogenide glass and germanate glasses [2-3]. Tellurite (Te) glasses have been widely investigated for their applications in fiber lasers and amplifiers due to their capacity to be doped with high concentrations of rare earth ions without clustering. Their high refractive index (n=2.0 at 700nm) and high nonlinearity (100 times higher than silica glass [4]) suggests the possibility of forming high Q cavity structures for sensing and nonlinear applications. Currently the tellurite spherical cavities with rare earth doped have been studied only for infrared lasing, which showed poor resonance probably caused by rough surface quality [5]. Here we report the fabrication of high quality Er-Yb codoped Te spheres with sizes as small as 9 µm, strong upconversion WGM lasing with Q over 27,000, and index sensitivity of 8.8nm/RIU. We also observed that the individual WGMs were strongly modulated for some critical fiber taper coupling conditions, and the modulating subpeaks are strongly dependent on pump power.

2. Fabrication and characterisation of the Te glass spheres

The base tellurite glass (TeO2-ZnO-Na2O-La2O3) was fabricated in-house using the melt-quench technique [6]. The loss of the fiber without doping was 1dB/m in the spectrum range of 700nm to 1400nm. The ratio of Er to Yb was selected to be 1:10 for the Er-Yb codoped Te glass with Er ion concentration of 1.0×10^{19} ions / cm^3 (0.022 mol %). The doped glass was firstly extruded into a rod, which was drawn into an unstructured fibre. Two methods have been tested to make spheres by heating and stretching a length of the fiber. One method used a commercial Vytran splicer with a "Ω" shape graphite filament. The other method used a CO_2 laser. The spheres made using the CO_2 laser showed lower eccentricities compared to those made using the graphite filament shown in the inset of Fig. 1.

Figure 1 shows the experimental setup used to excite and observe the WGMs. A tapered SMF-28 fiber with a waist diameter of 1.5µm was fabricated using the Vytran splicer and used to couple light into the microsphere and to collect the evanescent field of the WGMs for spectrum analysis. The relative positions of the taper and sphere were observed from the top using a CCD camera. A 980nm short pass filter from Semrock (FF01-842/SP-25) was used to remove 975nm pump laser. A coverslip was positioned below the sphere to hold the solvent to change refractive index of the environment of the spheres.

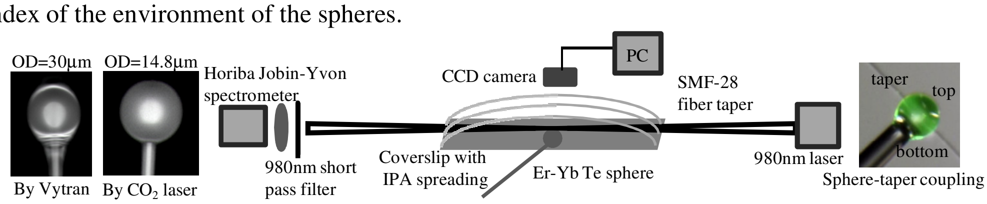

Fig.1 Experimental apparatus used for microsphere resonance characterization.

The fiber taper was located above the equator of the sphere to study resonance shift with changed environmental index. Fig. 2a shows the upconversion WGM spectrum excited in a 14.8µm diameter sphere in air. Due to the high index of the Te glass, many higher order modes were excited. However, when the sphere was dipped into isopropanol (IPA, n=1.3772 at 580nm), the lasing with less number of the modes were excited with their Q as 27,000 (Fig. 2b). Note that the resonant green light circulated along the equator of the sphere as shown in the inset of Fig. 2b. Fig. 2c displays the resonance shift of the WGMs (with Q=8300) when another sphere with a diameter of 12μm was dipped into the IPA and Methanol, respectively. The free spectral range of 4nm for this sphere was in agreement with theoretical calculation [1]. The index difference between IPA and Methanol led to resonance shift of 0.43nm, corresponding to the index sensitivity of 8.8nm/RIU. This was the first demonstration of the Te sphere used as index sensing. The index sensitivity can be increased by further reducing the sphere size.

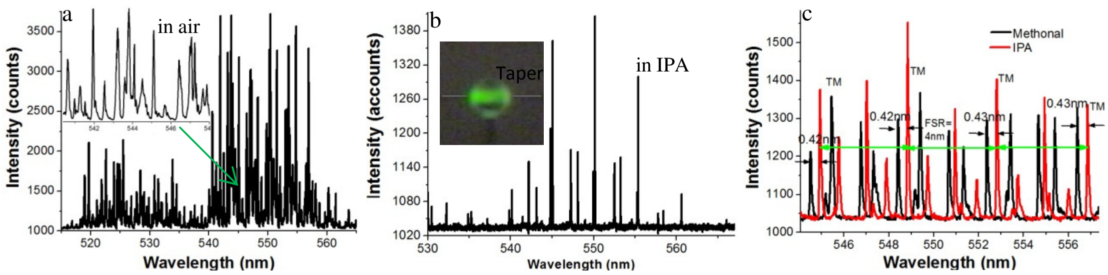

Fig.2 The WGM spectrum with the taper on the equator. a and b are the same 14.8μm diameter sphere, a in air, and b in IPA. The inset in b shows sphere image with green light circulating on the equator plane; c was obtained with a 12μm sphere in IPA and methanol separately.

We observed when the point where the taper contacted the sphere was shifted to the top of the sphere, the modes changed their circulating direction from the equator plane (Fig. 2b) to the plane vertical to the equator shown in Fig. 3a with 270 μW pump power. Our experiments showed when this contact position was finely tuned without changing the pump power, the whole sphere suddenly emitted strong light shown in Fig. 3b. At this contact point, the maximum intensity of the WGMs excited by the same power (the red curve shown in Fig. 3b) increased by a factor of 2.3 compared to Fig. 3a, and only the fundamental modes have been strongly excited. We observed that the spectrum of the individual modes was modulated by subpeaks. The gap between the neighboring subpeaks increased with increasing pump power and also with increasing wavelength. The peak positions of the fundamental modes shifted towards the red and their corresponding spectrum width increased with increasing pump power. This phenomenon was particularly clear for the WGMs of the same sphere in the red emission spectrum shown in Fig. 3c with the pump power of 51mW. When the power was increased from several milliwatts to 51mW, the resonance peak of the WGMs has changed its intensity distribution as Gauss shape (similar to Fig. 3a) to that consisting of completely separated lines.

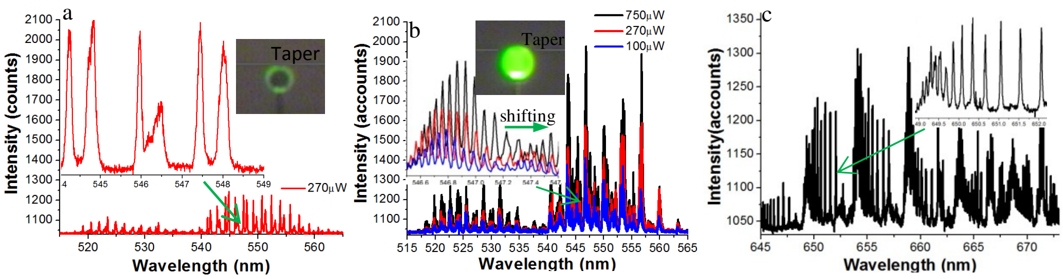

Fig.3. The WGM spectrum with the taper on the sphere top. The contact point in b and c was just finely tuned from a. b displays dependence of the WGMs on pump power. c is the subpeak modulated WGMs in the red.

The observed amplitude modulation of the WGMs may be caused by interference of some strongly resonant modes. The resonance shift, spectrum broadening, and subpeak shifting were suspected to be caused by some nonlinear processing based on their pump power dependence due to high nonlinearity and strong gain of the Er-Yb Te glass. Their generation mechanism is being investigated by analyzing single mode lasing, which could be generated by further reducing sphere size or using the pulsed laser as a pump source.

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