Characteristics of Er and Er–Yb–Cr doped phosphate microsphere fibre lasers

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\textbf{Abstract}

In this paper both Er and Er–Yb–Cr doped phosphate microspheres have been successfully created through precise melting of the ends of fibre tapers, drawn, respectively, from Er and Er–Yb–Cr doped phosphate glasses. When coupled with a fibre taper, a microsphere fibre laser cavity can thus be configured creating a system pumped by a 980 nm laser diode and using an optical spectrum analyzer to monitor the spectral characteristics of the laser output. The performance and characteristics of the Er and Er–Yb–Cr microsphere lasers thus created are discussed in detail and cross-compared in this paper. Both lasers have shown low-threshold in terms of the pump power and the laser output wavelengths and a close investigation of the system has shown that the output power and laser stability are closely related to the size of the microsphere, the pump power and the microsphere material composition.

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1. Introduction

Microspheres have been researched extensively as promising laser cavities to allow the creation of low-threshold fibre lasers, due to their high Q factor, based on the whispering gallery modes (WGMs) caused by closed loop propagation inside the microcavity. In this research, building on this approach, work on both the theoretical modelling and associated experimental verification of microcavity-based devices has been undertaken to explore the potential of this type of micro-scale laser. This has included consideration of theoretical algorithms developed for the optimization of the coupling efficiency between the microcavity and a range of optical waveguides, including fibre tapers and bulky prisms\cite{1-3}, where the use of the optical fibre taper acts as one of the most efficient and flexible means to couple the light to and from the microsphere. In conjunction with this approach, a series of successful experimental laser systems has been reported creating Er\textsuperscript{3+} \cite{4-6} and Tm\textsuperscript{3+} doped \cite{7-9} microlasers in which the rare-earth doped microspheres discussed are used as gain media and the nature of the coupling between the fibre taper and the microsphere determines the coupled whispering gallery modes. In addition to this, Stimulated Raman Scattering (SRS) of the whispering gallery modes (WGMs) has been explored as a potential means of developing microcavity-based Raman lasers which show the advantage of high power from the pump laser \cite{10,11} not being necessary. Microspheres have also been used as feedback elements in a fibre laser structure in which both rare-earth fibre lasers and Raman lasers were demonstrated \cite{12}. Some of these lasers have been developed specifically for potential sensor applications, for example, by designing devices where the emitting laser wavelengths are centered on the absorption peaks of the specific gas species \cite{13,14} used.

In this work, both Er-doped and Er–Yb–Cr co-doped phosphate microsphere lasers using low-loss fibre taper coupling are reported. The microspheres are fabricated from a fibre which is drawn from the phosphate bulk glass material using the indirect heating method \cite{15}, where the fibre taper used in this work is fabricated using a CO\textsubscript{2} laser fabrication system\cite{16}. The performance of the microsphere laser created, including the laser stability is tested, evaluated and discussed in the sections below and this is the first time that the microsphere laser stability has been discussed in detail.

2. Experimental setup

2.1. Fabrication of fibre tapers

A CO\textsubscript{2} laser-based optical fibre taper fabrication system, as shown in Fig. 1, has been developed and used to fabricate the low-loss tapers which form the basis of the system. During the fabrication process, each end of the fibre was clamped on separate motorized stages which were controlled by a computer, allowing the fibre to be pulled into a taper when the laser beam from the CO\textsubscript{2} laser was focused onto and thus heated the fibre to beyond the glass melting point. A rotatable galvanometer mirror was used to scan the laser beam along the fibre, where the rotation angle and rotation frequency could be accurately determined and controlled.
The pulling speed of the fibre, the rotation speed and angle of the galvanometer mirror and the power of the laser were carefully controlled by software written using LabVIEW. The CO₂ laser (SYN-DAS) had a maximum output power of 20 W. Using this facility, a low-loss fibre taper with a diameter as small as 2 μm could be fabricated from a SMF28 single mode fibre. A typical fibre taper fabricated using this system is shown in Fig. 1b.

2.2. Fabrication of phosphate microspheres

By melting the end of the fibre taper, a microsphere could readily be formed at the fibre end, due to the effect of surface tension. Using a gas torch as a heat source and a SMF 28 single mode fibre as a seed fibre, a phosphate fibre can easily be drawn from the melted glass, as illustrated in Fig. 2, where the heat of the flame was transferred to the phosphate glass indirectly through a sapphire fibre to avoid any overheating of the glass [15]. In this work, both Er–Yb–Cr doped phosphate glass (wt%: 0.2Er–25Yb–0.1Cr) and Er-doped phosphate glass (wt%: 3.0Er₂O₃) were used, as developed and supplied by the Central Glass and Ceramic Research Institute (CGCRI) in India. Fig. 3 shows the glasses and the fibres drawn using the above technique. By melting the middle section of the fibre, followed by stretching slowly, a half taper can be created for the microsphere fabrication. The microspheres used are fabricated by melting back half of the fibre taper using a fusion splicer. The diameters of the microspheres thus fabricated, using this method, ranged from tens of microns to hundreds of microns.

2.3. Coupling of fibre taper and microsphere

To allow for efficient coupling between the microsphere thus formed and a fibre taper, a configuration has been created where the fibre taper was fixed onto the fibre mounts, allowing three-dimensional controlled movement and the microsphere is clamped separately onto a three-dimensional translation stage, which allows both a wide range movement and an additional fine tuning within a shorter range. This is shown schematically in Fig. 4. A CCD camera is positioned to capture the image showing both the fibre taper and the microsphere to allow the fine tuning of the coupling.
2.4. Microsphere laser setup

Fig. 5 shows a schematic of a microsphere laser system in which a 980 nm laser diode (LD) is used as a pump light source and an Optical Spectrum Analyser (OSA) is used to capture the emission signal coupled out of the cavity. A 980/1550 nm coupler is used in the system to direct the light from the laser diode to the microsphere laser cavity and to monitor the reflected signal from the laser cavity using a photo-detector (PD).

Both Er–Yb–Cr co-doped and Er-doped phosphate microsphere fibre lasers were constructed using the configuration discussed and the results obtained are shown below.

3. Experimental results and discussion

3.1. Er–Yb–Cr co-doped phosphate microsphere laser

The Er–Yb–Cr co-doped microsphere used in this experiment has a diameter of 43 μm and the waist diameter of the fibre taper is ~2 μm. As shown in Fig. 6, the fibre taper is placed in contact with the microsphere in order to stabilize the coupling between the taper and the microsphere, to avoid any possible disturbance to the coupling caused by environmental variations.

When the 980 nm pump power is higher than ~1 mW, the microsphere laser emission, at a wavelength of 1535 nm could be observed by the OSA. With the increase of the pump power, more whispering gallery modes are supported and therefore multi-wavelength emission occurs, when the pump power is higher than 7.2 mW. Fig. 7a shows a multi-wavelength laser spectrum when the pump power is 8 mW and the OSA resolution was set to 0.2 nm. Fig. 7b shows both the single-wavelength output power and the total output power of the laser pulse generated as a function of the pump power. By considering both clockwise and anticlockwise propagation inside the microsphere, the total laser output power emitted from the cavity should be doubled over what would be achieved with unidirectional propagation.

Similar results have been achieved when the sphere diameter was increased to 125 μm. However, the pump threshold for the multi-wavelength generation has been seen to be shifted much closer to the laser threshold. Fig. 8a shows a typical laser spectrum with two output wavelengths at 1533 nm and 1537 nm, respectively, when the pump power is ~6 mW. Fig. 8b shows the total laser output power as a function of the pump power. It is noticeable that the total output power of the microsphere laser increases with the increase of the microsphere diameter, although the pump threshold for lasing has been changed and increased. This may be related to the increase of the gain medium length when the sphere diameter is larger so that more whispering gallery modes are encouraged and thus supported.

3.2. Er-doped microsphere fibre laser

Two microspheres, of diameters of 47 μm and 115 μm, respectively, have been fabricated from the high concentration Er-doped glass. Coupled with the 2 μm fibre taper discussed above and using the configuration shown in Fig. 5, a series of Er-doped microsphere fibre lasers could be created. As shown in Figs. 9 and 10, both the laser spectra and the total output power of the laser as a function of the pump power can be seen when the microsphere diameter changes from 47 μm to 115 μm. Although the microsphere composition is different from that discussed in Section 3.1, similar conclusions can be reached in terms of the laser threshold required for
single and multi-wavelength generation as the diameter of the microsphere changes. Compared to the Er–Yb–Cr doped fibre lasers using similar size microspheres, the Er-doped fibre laser produces a much higher output power. For the 47 μm microsphere Er fibre laser, the maximum output power is 600 nW when pumped by a 39 mW 980 nm laser and the total output power from a larger microsphere of 115 μm can reach 3 μW when pumped by a 23 mW 980 nm laser. However, the total output power of the Er microsphere lasers no longer changes monotonically as a function of pump power and this may be related to the power tolerance defined by the microcavity of the laser. These results obtained in this work are comparable with that reported [4], where the output power of the microsphere laser can reach 3 μW when the absorbed power is high enough.

In both cases, when the pump power is increased, the wavelength of the signal shifts slightly to the “red”. For the 125 μm diameter Er–Yb–Cr sphere, a shift as large as 0.8 nm has been observed and this is due to the material temperature increase as a result of the power, trapped inside the microsphere, increasing.
Further tests were carried out to evaluate the Er–Yb–Cr laser stability as a function of time. At room temperature, the pump power of the 125 µm Er–Yb–Cr microsphere laser was fixed at 11 mW for 35 min. Figs. 11 and 12 show, respectively, the microsphere laser output and the laser wavelength variation as a function of time. In the first 15 min the laser output is reasonably stable; however, in the following 10 min, the laser becomes unstable with a significant power drop and this is accompanied by a 0.16 nm “red” shift of the corresponding two output wavelengths, as shown in Fig. 12. This “red” shift may be caused by the increased power absorbed by the microsphere cavity resulting in an increased temperature and this may induce the variation of the microcavity characteristics, thus affecting the whisper gallery modes propagated within the cavity.

4. Summary

In this work, both Er–Yb–Cr co-doped and Er-doped microsphere lasers were successfully created, evaluated and their performance cross-compared. Both lasers have demonstrated low-threshold for single- and multi-wavelength generation and the laser performance is closely related to both the material composition and the size of the microspheres used. The long-term stability of the system has also been investigated, showing it is affected by the thermal effects inside the microsphere when no temperature control system is applied. A ‘cooling’ system may be necessary to be in place to stabilize the sphere laser performance in the future.

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References