Ward, J.M.; Feron, P.; Nic Chormaic, S.; , "A Taper-Fused Microspherical Laser Source," IEEE Photonics Technology Letters, vol.20, no.6, pp.392-394, March15, 2008
doi: 10.1109/LPT.2008.916904

A Taper-Fused Microspherical Laser Source

Jonathan M. Ward, Patrice Féron, and Síle Nic Chormaic

***Abstract*—We report on the realization of an integrated lasing device consisting of a microsphere optical resonator fused to a tapered optical fiber. A microsphere fabricated from Er:Yb codoped phosphate glass is heated above its glass transition temperature of 375°C by pumping it at 977 nm with 70 mW via a tapered optical fiber. The onset of thermal stress in the glass at a maximum pumping power results in the sphere melting and fusing to the taper coupler, without inhibition of whispering gallery mode lasing. A taper-fused microsphere laser with ~4.5 μW of lasing power at 1593 nm is demonstrated.**

***Index Terms*—Microsphere resonator, whispering gallery modes, erbium-ytterbium phosphate glass, tapered fiber.**

I. Introduction

THE miniaturization of optical elements has been fueled by the desire for the telecommunications industry to have very compact devices. This has stimulated the development of micron-sized laser sources such as microspheres [1]. Work on the composition of rare-earth doped glasses that exploit upconversion mechanisms to produce broadband emissions has also kept apace. Microspheres fabricated from such materials are highly appealing due to their optical properties, and the broad scope of applications from bio-sensing [2] to laser engineering [3]. One main impediment for the practical use of microspheres has been the coupling of light into the resonator. To date, there are a number of techniques for achieving this, such as adiabatic single-mode tapered fibers and prisms [4] and, although efficient coupling can now routinely be achieved [5], the devices are still very fragile or too cumbersome to be of true use for the telecoms industry.

In this letter we use microspheres fabricated from IOG2 [6], an Er:Yb codoped phosphate glass. We study the maximum pump power that can be launched into an IOG2 sphere before the onset of thermal stress. A similar effect, leading to thermal damage, was reported for a microchip laser [7], but with higher pump powers. We show that this thermal effect can be used to fuse the cavity to a tapered fiber, thereby realizing an integrated coupler plus lasing source for L-band emissions. Our system facilitates the integration of microspheres into practical scenarios, and will provide more stable devices in the long term by eliminating the need for time-consuming alignment procedures. We demonstrate lasing within the device and, though the ideality of the system is reduced, the robustness compensates for any losses.

Manuscript received November 02, 2007; revised December 17, 2007. This work was funded by Science Foundation Ireland under grant 02/IN1/128.

J. M. Ward is with the Dept. of Applied Physics and Instrumentation, Cork Institute of Technology, Cork, Ireland and Tyndall National Institute, Cork, Ireland (e-mail: jonathan.ward@tyndall.ie).

P. Féron is with ENSSAT-FOTON (CNRS-UMR 6082) Université de Rennes 1, 6 rue de Kerampont, BP 80518, 22305 Lannion Cedex, France.

S. Nic Chormaic is with the Physics Dept., University College Cork and Tyndall National Institute, Cork, Ireland (e-mail: s.nicchormaic@ucc.ie).

II. Experimental Setup and Results

We used microspheres fabricated from a commercial Schott glass, IOG2, with doping levels of 2 wt% Er_2O_3 (1.7 x 10^{20} ions/cm^3) and codoped with 3 wt% Yb_2O_3 (2.5 x 10^{20} ions/cm^3). The fabrication of the spheres is described elsewhere [4]. The diameter of the spheres varies from 10-200 μm, and defect free spheres are selected and glued to the tip of a stem for ease of manipulation. The principles behind the experimental setup are discussed in [8]. Pump light is coupled into the microsphere using an adiabatic tapered fiber, made by simultaneously heating and pulling 1550 nm SMF28 fiber. The tapered fibers have waist diameters of ~1 μm, with transmission losses of 10-15%, and the same fiber is used to collect the lasing signal around 1560 nm. The taper and sphere are placed in contact such that the observed lasing signals are optimized on an optical spectrum analyzer. In this overcoupled regime, we estimate that approximately 10-20 % of launched pump power is coupled into the sphere. The low efficiency is also due to the broad linewidth of the pump laser relative to the whispering gallery modes (WGM) [9].

In Fig. 1 we present the fluorescence spectrum for a 95 μm diameter sphere, pumped at 977 nm, for launched pump powers varying from 13 mW to 76 mW. The signal is detected using a multimode fiber probe connected to a CCD spectrometer (Ocean Optics USB2000). Chromatic switching between the thermally coupled states, $^2H_{11/2}$ and $^4S_{3/2}$, emitting at 523 nm and 548 nm, has also been observed. IOG2 has a maximum phonon energy of 200 cm^{-1}, leading to a strong quasi-thermal population distribution between the two green emitting states, which have an energy gap of ~800 cm^{-1}. The ratio between these emissions as a function of pump power is shown in the inset to Fig. 1. From this ratio, an estimate of the effective temperature of the mode volume within the sphere can be made [7,10], providing us with an upper pump power limit before the onset of thermal damage. We assume that the detection system has an equal response at both wavelengths, and have adopted the ratio of spontaneous emission rates from earlier work on Er:Yb doped phosphate glass [7,10], with some modifications for IOG2 [6].

For a launched pump power in the range from 27 mW to 46 mW we observed a constant intensity ratio of 1.6, indicating a temperature of 210°C. When the pump power is increased the ratio jumps to 2.4, indicating a temperature just over 315°C, i.e. 60°C below the glass transition temperature, T_g [6]. Such a sudden increase in intensity is due to a portion of the pump field going into resonance with a cavity mode. This is caused by a thermally induced shift in the refractive index [11], and a change in the cavity size. The resonance condition results in a build-up of pump density in the sphere, and a corresponding increase in the intensity of emissions. From 53 mW to 69 mW the ratio again remains constant. Once 69 mW is launched into the fiber the intensity ratio increases rapidly. For example, with 72 mW launched power a ratio of 3.2 is observed, corresponding to a mode temperature of 427°C. - well above T_g. Even at this temperature there were no visible signs of thermal damage, due to the bulk of the material absorbing the heat energy and dissipating it to the surrounding air. The intensity ratio continues to increase with a value of 4.7 being observed, corresponding to 660°C, at the maximum available pump power of 76 mW. This high temperature is due to a combination of effects, namely the small mode volume and the resultant high pump density ~ GW/cm^2 [12], the quantum defect (phonon transition) between the pumping and lasing photons [7,13], and thermal feedback [14]. Note that when the intensity ratio was greater than 3.7 we observed dramatic structural changes in the sphere due to thermal damage, thereby imposing an upper limit on the pump power that should be launched into an IOG2 microsphere.

Although the high temperature region appears to be confined within the volume of the WGM, the mode itself is very close to the surface of the sphere. As a consequence, the surface temperature along the mode path rises well above T_g, and the fluidity of the material becomes evident to such an extent that the fiber sinks into the sphere, creating a fused device as shown in Fig. 2(a). As a result, the cavity symmetry breaks, and lasing action and bistable behavior are no longer achievable. Weak WGMs were, however, still observable as green bands in the spheres. T_g was reached in this particular sphere for a launched pump power of about 70 mW. High temperatures at different pump powers were observed, depending on the size and quality of the sphere used. For some spheres we found that it was not possible to reach T_g simply through coupling pump light into the sphere, due to the maximum power limit of our laser.

We explored two options for fusing a microsphere to a taper fiber, while aiming to minimize the fusing area, thereby ensuring that the cavity symmetry be preserved. The first method relied purely on heating the sphere through the pump power as described above, while trying to keep the sphere and taper in light contact to avoid complete submersion of the taper into the sphere. If one considers the image in Fig. 2(a), the taper appears to run straight through the sphere undamaged; however, even with light contact and far less submersion of the taper, the transmission through the fiber dropped dramatically from 70 mW to about 80 μW. This was probably due to the contact area between the sphere and the taper still being relatively large. It is, therefore, imperative that the sphere be fused to the tapered fiber at a single point, thus preserving the transmission; this led to a second fusing method being devised. In most cases, the glue sticking the sphere to its stem no longer adheres, due to the high temperatures involved. The sphere, therefore, separates from the stem, leaving it fused to the taper without any additional support. The unmounted sphere can pull on the fiber causing it to twist as shown in Fig. 2(a). For later experiments we used electrostatics to pick up the spheres and place them into position on the taper. Using this technique we removed the need to glue the spheres to a stem for manipulation purposes. By placing a platinum microheater ~3 mm from the taper/sphere interface - in conjunction with a very low pump power - more control over the fusing process was achievable. A taper-fused sphere fabricated using this technique is shown in Fig. 2(b); the fiber is not passing through the microsphere, but rather is stuck to the surface at a localized region. The slight bend apparent in the fiber is an imaging effect due to the differences in refractive indices. We estimate the point of contact between taper and sphere to be a few microns.

We used a 95 μm diameter microsphere to explore the effect of fusing the taper using only the pump power. The lasing spectra obtained before and after fusing are shown in Fig. 3. Prior to fusing, the microsphere lased at 1567 nm and had a maximum lasing intensity of ~5 μW. The inset to Fig. 3(a) shows the WGM structure of the lasing spectrum. The peak lasing power after fusing, shown in Fig. 3(b), was reduced to 0.5 μW, and the wavelength shifted to 1565 nm. If we compare the insets to Fig. 3(a) and Fig. 3(b), we see a considerable alteration to the WGM structure, indicating a large change in the size/shape of the resonator due to the fusing action. Subsequently, we studied the effects of using a microheater in conjunction with the pump power, in order to achieve better control on the fusing point. A 90 μm diameter sphere was used for these measurements. Prior to fusing, a maximum lasing intensity of 2 μW was observed. After fusing, the transmitted pump power dropped to 0.5 mW. However, a reasonably large lasing signal of 4.5 μW was observed and is shown in Fig. 4(b). When we compared the WGM structure from before and after fusing we noticed that some modes were enhanced while some were repressed. Overall, however, there was little change indicating that the shape of the cavity was largely conserved.

III. Conclusion

Tapered optical fibers are proving to be the most efficient way to pump microsphere lasers [5]. To maintain this efficiency, strict control of the gap between the taper and the cavity is required, and this can be disturbed by air currents or vibrations. In this paper we have studied the green emission ratios from an IOG2 sphere as a function of pump power and have shown that the glass transition temperature of 365°C is exceeded at a launched power of ~70 mW. Hence, we have presented a technique for fusing microspheres to tapered fibers, while maintaining WGM propagation and lasing. The onset of fusion is strongly influenced by the launched pump power, and the host material. For example, we have been unable to observe similar behavior in spheres made from ZBNA. The taper-fused microsphere offers improved robustness, with lasing observable even when the system was vibrated using air currents. The design dramatically reduces the footprint of taper coupled microspheres, and could have potential applications in cold atom experiments or biosensing. Tuning of the resonator across an atomic resonance could also be achieved by heating the sphere using a very low pump power, hence changing the size of the resonator. This is the focus of future studies.

REFERENCES

[1] M. Mortier, P. Goldner , P. Féron, G.M. Stephan, H. Xu, Z. Cai, "New fluoride glasses for laser applications" *J. of Non-Cryst. Sol.*, vol. 326-327, pp. 505-509, Oct. 2003.

[2] O. Gaathon, J. Culic-Viskota, M. Mihnev, I. Teraoka, and S. Arnold "Enhancing sensitivity of a whispering gallery mode biosensor by subwavelength confinement," *Appl. Phys. Lett.*, vol. 89, pp. 223901-1-3, Nov. 2006.

[3] A.B. Matsko, A. A. Savchenkov, D. Strekalov, V. S. Ilchenko, and L. Maleki "Review of Applications of Whispering-Gallery Mode Resonators in Photonics and Nonlinear Optics" *IPN Progress Report* 42-162, Aug. 2005

[4] P. Féron, "Whispering gallery modes as laser sources- a short review," in *Quaderni di Ottica e Fotonica*, vol. 8, p. 117, Centro Editoriale Toscano, Firenze, 2002.

[5] M. Cai, O. Painter, and K. J. Vahala "Observation of Critical Coupling in a Fiber Taper to a Silica-Microsphere Whispering-Gallery Mode System," *Phys. Rev. Lett.*, vol. 85, pp. 74-77, Jul. 2000.

[6] IOG2 phosphate laser glass specification sheet, Schott Glass Technologies, 400 York Ave., Duryea, PA 18642, USA.

[7] Z. Cai, A. Chardon, H. Xu, P. Féron, and G. M. Stéphan "Laser characteristics at 1535 nm and thermal effects of an Er:Yb phosphate glass microchip pumped by Ti:sapphire laser," *Opt. Commun*., vol. 203, pp. 301–313, Mar. 2002

[8] D. G. O'Shea, J. M. Ward, B. J. Shortt, and S. Nic Chormaic "An all-fiber coupled, multicolor microspherical light source," *IEEE Photon. Technol. Lett.*, vol. 19, pp. 1720-1722, Nov. 2007.

[9] J. C. Knight, G. Cheung, F. Jacques, and T. A. Birks, "Phase-matched excitation of whispering-gallery-mode resonances by a fiber taper," *Opt. Lett*., vol. 22, pp. 1129-1131, Aug. 1997.

[10] E. Maurice, G. Monnom, D. B. Ostrowsky, and G. W. Baxter, "High Dynamic Range Temperature Point Sensor Using Green Fluorescence Intensity Ratio in Erbium-Doped Silica Fiber," *J. Lightwave Technol*., vol. 13, pp. 1349-1353, Jul. 1995.

[11] Md. Mohiuddin Mazumder, S. C. Hill, D. Q. Chowdhury, and R. K. Chang, "Dispersive optical bistability in a dielectric sphere," *J. Opt. Soc. Am. B*, vol. 12, pp. 297-310, Feb. 1995.

[12] K. J. Vahala, "Optical Microcavities," *Nature*, vol. 424, pp. 839-846, Aug. 2003.

[13] J.F. Philipps, T. Töpfer, H. Ebendorff-Heidepriem, D. Ehrt, and R. Sauerbrey "Spectroscopic and lasing properties of Er^{3+}:Yb^{3+}-doped fluoride phosphate glasses" *Appl. Phys. B*, vol. 72, pp. 399-405, Mar. 2001.

[14] D. R. Gamelin, S. R. Lüthi, and H. U. Güdel, "The Role of Laser Heating in the Intrinsic Optical Bistability of Yb^{3+}-Doped Bromide Lattices," *J. Phys. Chem. B*, vol. 104, pp. 11045-11057, Nov. 2000.

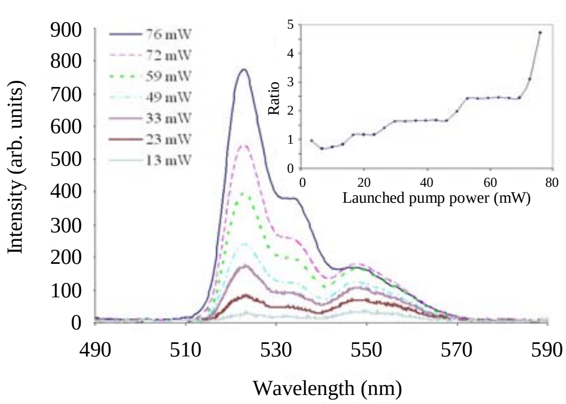

Fig. 1. Variation of the upconversion fluorescence spectrum for a 95 μm IOG2 sphere as the pump power is varied from 13 mW to 78 mW. Inset: intensity ratio for the 523 nm and the 548 nm emissions as a function of launched pump power.

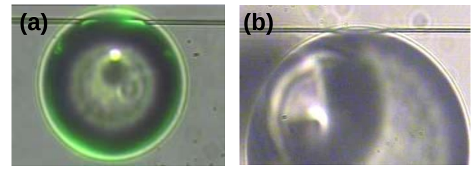

Fig. 2. Taper fused microsphere (a) using heat from the pump only and (b) using heat from a microheater in conjunction with the pump power (which is switched off for the purpose of visualization). Note that the magnification scale in both images differs.

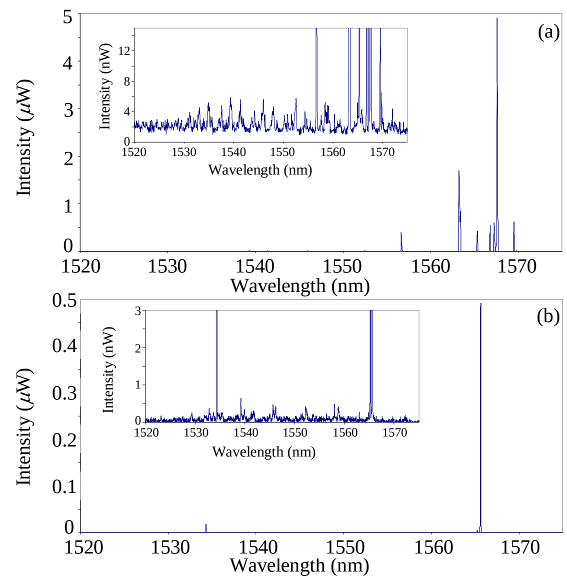

Fig. 3. Lasing spectra of a 95 μm IOG2 sphere (a) before fusing and (b) after fusing to a tapered fiber using heating via the pump power. The inset is a magnification of the spectra and shows the whispering gallery mode structure.

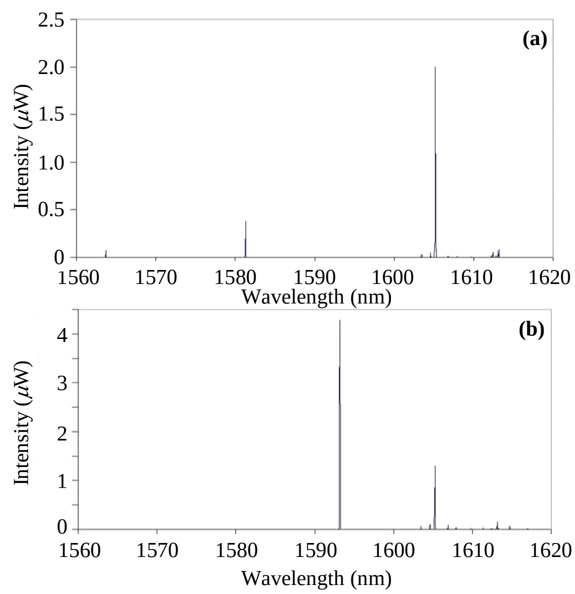

Fig. 4. Lasing spectra of a 90 μm IOG2 sphere (a) before fusing and (b) after fusing to a tapered fiber using heating via an external microheater and pump power.