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Fiber-coupled microsphere laser

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We demonstrate a 1.5-μm-wavelength fiber laser formed by placement of glass microsphere resonators along a fiber taper. The fiber taper serves the dual purpose of transporting optical pump power into the spheres and extracting the resulting laser emission. A highly doped erbium:ytterbium phosphate glass was used to form microsphere resonant cavities with large gain at 1.5 μm. Laser threshold pump powers of 60 μW and fiber-coupled output powers as high as 3 μW with single-mode operation were obtained. A bisphere laser system consisting of two microspheres attached to a single fiber taper is also demonstrated.

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Dielectric particles made from fused-glass microspheres, in which light is trapped internally by continuous reflections at the glass surface, provide a high-*Q* resonator system for use in studying a number of interesting optical effects.[1,2] One of the intriguing qualities of glass microspheres is their optical and structural compatibility with telecommunication optical fiber. In initial work, Knight *et al.*[3] showed the feasibility of forming micrometer-diameter fiber tapers by heating and pulling silica fiber for excitation of microsphere resonators. Fiber-taper-coupled microspheres have since been used to demonstrate critical coupling with 26-dB on-resonance extinction[4] and a matched dual-taper add–drop filter with less than 0.5% scattering loss and near-unity power transfer (on-resonance) between tapers through the microsphere resonator.[5]

In this Letter we use a fiber taper, placed in contact with Er:Yb-doped phosphate glass microsphere, to form a compact, low-threshold 1.5-μm-wavelength fiber laser source. Initial work on glass microsphere lasers at 1.08 (Ref. 6) and 0.54 μm (Ref. 7) used prism couplers, requiring bulk optics for focusing and alignment of the pump beam as well as collection of the laser emission. A single fiber taper is used here to guide the pump laser beam to the surface of the microsphere, resonantly couple the pump into the sphere, and then collect the resulting laser emission. The use of a fiber taper not only provides an efficient input and output coupling port but also plays an important role in producing single-mode lasing. Finally, the fiber taper forms a natural backbone for connecting a series of different active and passive microsphere devices, with each device addressing a different wavelength signal.

The microspheres used in this experiment were formed from phosphate glass heavily doped with Yb (20% by weight) and Er (0.5%). Kigre QX/Er phosphate glass has a transformation temperature of 450 °C and a refractive index of 1.521 at 1.5 μm. Absorption that is due to the $F_{5/2} \rightarrow F_{7/2}$ transition of the Yb^{3+} ions is strongly peaked around 976 nm (± 5 nm), with a value of $\alpha = 4\text{–}5\ \text{cm}^{-1}$ (2×10^3 dB/m).[8] The $F_{7/2}$ level of Yb^{3+} resonantly couples to the Er^{3+} $I_{11/2}$ level, which then relaxes to the $I_{13/2}$ level. The 1.5-μm lasing transition is between the ground-state $I_{15/2}$ level and the $I_{13/2}$ excited-state level of Er^{3+}, with a fully inverted gain per unit length exceeding 200 dB/m in the 1500-nm band. Fabrication of the microspheres and the fiber tapers is described in Refs. 3 and 5.

The resonant modes of nearly spherical dielectric particles can be classified according to their polarization index *p*, radial mode number *n*, and angular mode numbers *l* and *m*. Of special interest in this Letter are resonances with small radial mode number and large angular mode number, or so-called whispering-gallery (WG) type modes. Excitation of WG modes within glass microspheres has been performed with a variety of devices and methods.[3,9–11] Fiber-taper coupling has several distinct advantages in that alignment is built in, fabrication is relatively simple, and ideal matching to the WG modes of the sphere is possible.[4] A magnified image of a taper–sphere coupler is shown in Fig. 1(a).

Microspheres with diameters ranging from 50 to a few hundred micrometers were formed. For the microsphere laser studied here the diameter and eccentricity were determined by analysis of its resonant

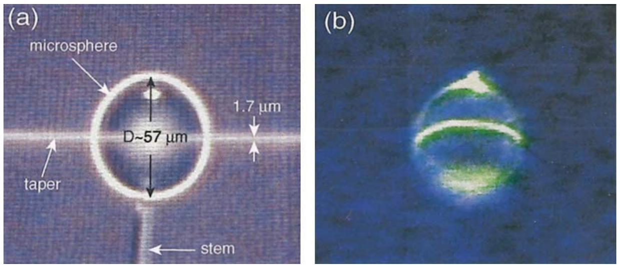

Fig. 1. (a) Image of the taper in contact with the equator of the microsphere. (b) Color image of the green upconverted photoluminescence from the taper-pumped microsphere, where the pump wavelength is tuned close to a fundamental ($|m| = l$) WG mode.

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mode structure at 1.5 μm. The measured WG mode free-spectral range in l (FSR$_l$) for this microsphere is 1.1 THz (8.7 nm) at 1.5 μm, giving a diameter of 57 μm. The measured free-spectral range in m is 13 GHz for $|m| \approx l$, with the resonant frequencies increasing with decreasing m value. This corresponds to a slightly oblate microsphere with an eccentricity of 2.4%.

The pump wave in this experiment is launched from a 980-nm-wavelength, narrow-linewidth (<300-kHz), tunable external-cavity laser into the fundamental mode of the fiber taper. To pump the microsphere efficiently it is crucial to obtain good matching between the fundamental taper and WG modes of the sphere[4,12] and to match the input coupling strength to the round-trip resonator loss (critical coupling). By tailoring the taper diameter, one can phase match the fundamental taper mode to a given WG sphere mode, thus improving the ideality of the coupler. Owing to the large absorption within the microsphere at the pump band and the subsequent large round-trip microsphere resonator loss, maximum power transfer is obtained for the fundamental WG modes ($|m| = l$), as the spatial overlap with the taper is highest for the equatorial modes, resulting in higher input coupling strengths. For this sphere a taper diameter of 1.75 μm was used to phase match and selectively excite the lowest-order ($n = 1, 2$) fundamental WG modes of the sphere.

To determine the pump volume within the microsphere we obtained images of the visible photoluminescence. The green emission is due to spontaneous emission from the upconverted $F_{9/2}$ level to the ground state of Er^{3+} (Ref. 8) and traces the path taken by the 980-nm pump wave within the sphere. The image in Fig. 1(b) shows a micrometer-sized ring encircling the equator of the sphere. This equatorial ring corresponds to resonant pumping of a WG mode with $|m| = l$ and mode volume of approximately 1000 $\mu\mathrm{m}^3$. For this taper–sphere combination, and with resonant pumping of an equatorial WG mode, the scattering loss of the taper–sphere junction is less than 5% (as measured by the off-resonance transmission), and roughly 85% of the pump power is absorbed by the microsphere.

Lasing in the microsphere is rather complex, owing to the large number of high-Q modes that are present in the sphere, the spatial selectivity of the pump, the loading of the sphere as a result of the taper, the large spectral gain bandwidth, and the variations in the emission and absorption cross sections versus wavelength in the phosphate materials.[8] Depending on the gain region within the sphere, lasing occurred at wavelengths ranging from 1530 to 1560 nm in both multimode and single-mode fashion. By adjusting the taper contact position on the sphere and the pump wavelength, we were able to switch between multimode and single-mode lasing action. We obtained single-mode lasing by tuning the pump wavelength to a fundamental WG mode resonance that produced a narrow equatorial-ring gain region.

A typical single-mode lasing spectrum (as collected by the taper) for an equatorial-ring pump region is shown in Fig. 2. To resolve the fine spectral features of the laser (different m modes) we used a high-finesse (≈10,000) scanning Fabry–Perot cavity with a spectral resolution of a few megahertz to obtain the spectra shown in the inset of Fig. 3. The microsphere was found to lase on a single m WG mode over the entire pump range depicted in Fig. 3. In previous fused-silica microsphere laser experiments,[6] a laser diode was used to pump a nonfundamental WG mode, thus expanding the gain region within the microsphere and resulting in multi-m mode lasing. Work on millimeter-sized Nd:YAG spherical laser resonators[13] in which a narrow-linewidth pump source was focused to optimize coupling to a single fundamental WG mode within the sphere showed laser mode selection

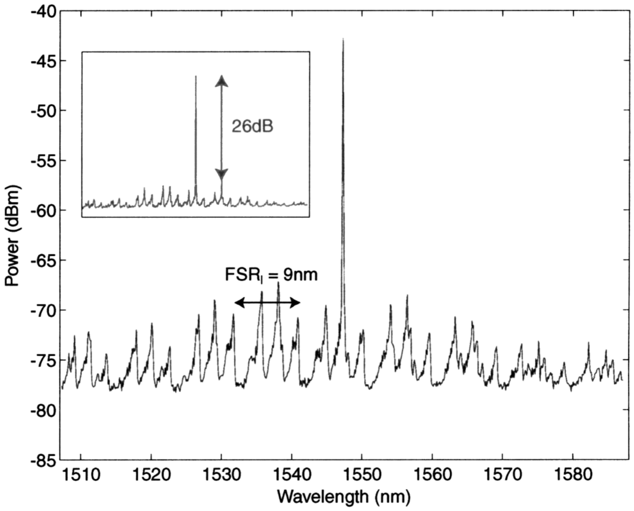

Fig. 2. Photoluminescence spectra [taken at point (a) in Fig. 3, below] of the microsphere for an annular pump region about the equator. The photoluminescence (inset) is taken at point (b) in Fig. 3 (wavelength range matching that of the main spectra), where the side-mode suppression is 26 dB.

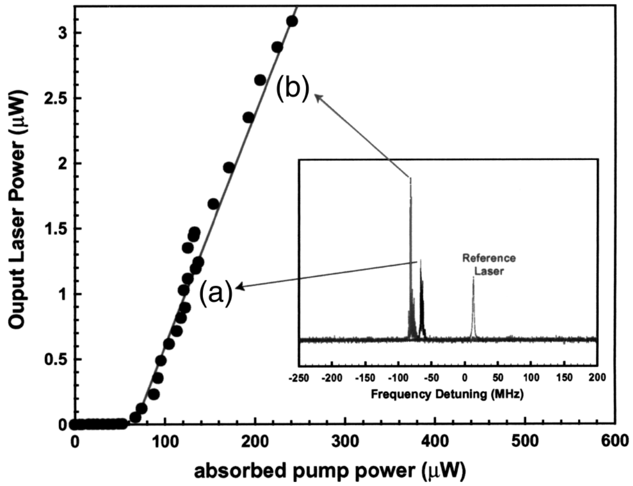

Fig. 3. Collected laser output power versus absorbed pump power in the microsphere ($L_{\mathrm{out}} - L_{\mathrm{in}}$). Inset, spectral output of a Fabry–Perot filter, showing the single-mode nature of the microsphere laser, where for reference a single-frequency laser with a known linewidth of 300 kHz is also shown.

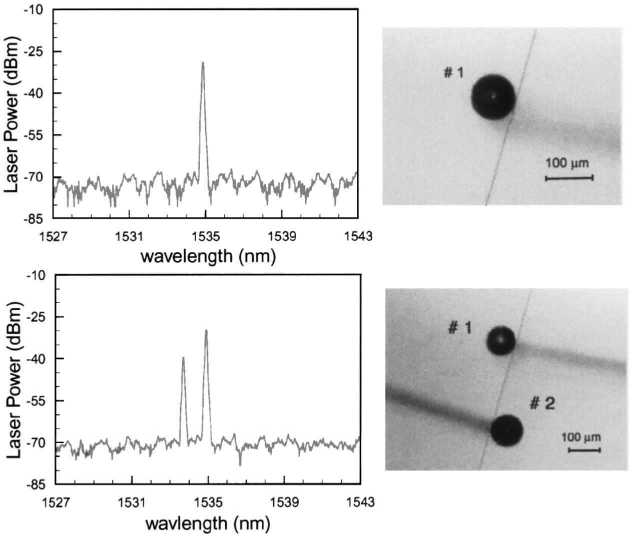

Fig. 4. Bisphere system in which two spheres have been placed on the same taper and pumped by a single 980-nm laser source, producing two separate laser lines, at 1533 and 1535 nm.

similar to that described here. The phosphate glass microsphere laser that we studied here was also found to be self-pulsing under these pump conditions, with a period of roughly 15 μs and a pulse width of 500 ns. Instability in the laser can be linked to the large unpumped highly absorbing regions within the sphere and the nonlinear dynamics associated with absorption saturation.[14]

A plot of the laser power collected in the taper versus the total pump power absorbed and scattered by the presence of the sphere ($L_{\text{out}} - L_{\text{in}}$) is shown in Fig. 3. The lasing threshold is estimated at 60 μW, and the laser reaches an output power of 3 μW while remaining single mode. A collected power as high as 10 μW was obtained in a single line at higher pump power, although the laser was multimode at this point. As we use the same taper to couple in the 980-nm pump power as that used to couple out the 1.5-μm laser power from the sphere, and since we designed the taper for phase matching at the pump wavelength to reduce the lasing threshold, the laser emission is not optimally collected by the taper (as the higher-order taper modes will be radiated away before reaching the detector). A dual-taper system, as was used in earlier work on a microsphere add–drop filter,[5] might be employed to improve the differential output efficiency.

As mentioned at the beginning of this Letter, one of the advantages of using a fiber taper to couple light into and out of a microsphere resonator is the ability to cascade a series of devices. As an example of this ability, we placed two phosphate glass microspheres, one after the other, along a single fiber taper. In Fig. 4 we show a taper with two different-sized microspheres attached. The first laser has a wavelength of 1535 nm, and after the second microsphere is placed in contact with the taper a second laser line at 1533 nm appears. In this case the first microsphere laser seems relatively unaffected by the presence of the second microsphere; however, one can imagine passive and active microsphere systems forming "photonic molecules,"[15] where coupling is provided by the fiber taper.[10]

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