2013

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Recommended Citation

Wang, P. et al (2013) Packaged Chalcogenide Microsphere Resonator with High Q-factor. *Applied Physics Letters*, 102, 131110 (2013). doi:10.1063/1.4801474

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Funder: Irish Research Council, Science Foundation Ireland, IRC, Royal Society London FP7

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Citation: *Appl. Phys. Lett.* **102**, 131110 (2013); doi: 10.1063/1.4801474

View online: <http://dx.doi.org/10.1063/1.4801474>

View Table of Contents: <http://apl.aip.org/resource/1/APPLAB/v102/i13>

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Packaged chalcogenide microsphere resonator with high Q-factor

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(Received 8 February 2013; accepted 26 March 2013; published online 4 April 2013)

The fabrication and characterization of a packaged As_2S_3 microsphere resonator coupled to a tapered fiber using a low refractive index UV-curable polymer are reported. Embedding provides an efficient means to remove the highest order whispering gallery modes in the microsphere resonator, thus cleaning the resonator spectrum. At wavelengths near 1549.5 nm, high-Q modes up to 1.8×10^5 can be efficiently excited in a $110 \mu\text{m}$ diameter chalcogenide microsphere via evanescent coupling from a $2 \mu\text{m}$ diameter tapered silica fiber. The device photosensitivity, useful for tuning, is still present and useable after the packaging process. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4801474>]

Microsphere resonators have increasingly attracted interest because they have the potential to become key components in a variety of active and passive photonic circuit devices, while also offering a range of significant functionalities for planar lightwave circuits, such as wavelength selectivity, energy storage to allow dispersion control, enhanced nonlinearity, resonant filtering, and ultralow threshold lasing.^{1–5} The use of glass microsphere resonators in photonic circuit devices offers great flexibility in terms of material composition and properties, such as nonlinearity and gain. Nonlinear optical materials have been exploited for the direct implementation of several key functions such as wavelength conversion, optical switching, and signal regeneration, which have the potential to radically transform future optical communication networks. Most studies on microsphere resonators have utilized silica microspheres fabricated by melting the tip of an optical fiber with the resulting stem used as a tool to position the sphere while it is being characterized.^{6,7} Microresonators realized from highly nonlinear chalcogenide glasses have recently been studied because of their high optical nonlinearity.^{8–10} Chalcogenide glasses also offer a wealth of other active properties such as wide and varied photoeffects, including photosensitivity,¹¹ low phonon energy matrix, the ability to be doped with active elements including lanthanides and transitional metals, and the possibility to form detectors, lasers and amplifiers. A chalcogenide microsphere resonator showing high-Q whispering gallery mode (WGM) up to 1×10^5 has been recently fabricated.¹² In addition to microspheres, chalcogenide microrods coupled to silica microtaper with Qs up to 2×10^5 have also been reported recently.¹³

To date, most studies on microresonators have utilized silica fiber taper evanescent fields to efficiently couple light to and from microspheres for their characterization.^{14,15} However, it is difficult to maintain stable alignment between

the microresonator and the fiber taper for an extended period, which is a disadvantage when fabricating devices for many practical applications. In order to increase the mechanical stability of the microsphere resonator coupling system and to use it for real applications, recently a packaged silica microsphere resonator has been presented for a temperature sensing application.¹⁶ In that paper, the packaging technique utilized a UV-curable polymer. It was shown experimentally that after UV polymer coating, good phase-matching can be achieved between the silica microsphere and the silica fiber taper while still retaining an extra-high Q factor. However to date this packaging technique has not been demonstrated for the packaging of high index materials, such as compound silicate and chalcogenide glasses where optical nonlinearity and photosensitivity are useful attributes. More importantly, the effect of packaging on spectral cleaning has never been reported to date.

In this paper, high quality chalcogenide (As_2S_3) microspheres with a diameter of $110 \mu\text{m}$ are fabricated and packaged using a low refractive index UV curable polymer. The use of a coating polymer not only increases the alignment stability of the microsphere-taper system but also acts as a modal filter, successfully removing some high order WGMs, as demonstrated both theoretically and experimentally. At wavelengths near 1549.5 nm, high-Q modes up to 1.8×10^5 can be efficiently excited via evanescent coupling from a $2 \mu\text{m}$ diameter tapered silica fiber. This is the highest Q factor reported to date for a chalcogenide microsphere resonator coupled with a silica fiber taper, despite the packaging with a polymer resulting in extra absorption and radiation loss. The photosensitivity of the packaged chalcogenide microsphere has also been investigated in this paper, and we show that the photosensitivity of the device, which is useful for tuning, is still present and usable after the packaging process. The packaging technique offers the potential to develop low-cost, robustly assembled fully integrated all-optical switching and tunable filter devices due to the ease of the packaging process and the retention of photosensitivity.

To understand the spectral changes resulting from the embedding, it is necessary to consider the modal properties

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FIG. 1. Simulated electric field distribution for a chalcogenide microsphere in (a, b) air and (c, d) polymer. $\lambda = 1.55 \mu\text{m}$ light is coupled into the sphere from an adjacent silica taper. The field profiles in (b) and (d) are taken along $y = 0$.

of the sphere and taper as well as their coupling and their interaction with a surrounding packaging material. Since the chalcogenide glass refractive index of $n \sim 2.4$ is significantly larger than that of silica ($n \sim 1.444$), the phase matching constraint will favor coupling to higher order WGMs rather than to the fundamental WGM. For a WGM with a given mode order (l, m, n), increasing the surrounding index n_{sur} will not only shift the resonance wavelength, but also extend the evanescent field further beyond the sphere boundary, leading to greater polymer absorption loss. Additionally, surface scattering losses will increase due to the greater field strength at the interface, as well as a reduction in smoothness due to imperfections in the polymer at the interface of between the polymer and the chalcogenide glass sphere. This has the effect of “cleaning” the spectrum as losses for higher order modes increase, as these contain a larger power fraction outside the sphere. As a consequence some modes with very high radial order n may no longer be supported, since the eigenvalue equation governing the WGMs’ resonant wavelengths contains fewer solutions for higher n_{sur} . Note that this is analogous to the removal of higher order modes in optical fibers by reducing the V value beyond their cutoff wavelengths.

Increasing n_{sur} also affects the taper mode in two ways. First, the evanescent field expands further and increases the

overlap with the WGM field inside the sphere and hence coupling (this will lead to some reduction in the external coupling Q factor). Second, the effective index n_{HE11} of the fundamental HE_{11} mode in the $2 \mu\text{m}$ taper increases from 1.35 in air to 1.40 in UV-373 polymer. Since the power coupling from the taper to the sphere falls exponentially with the square of the propagation constant mismatch between their modes, the higher n_{HE11} will thus preferentially phase match to a different set of WGMs with a higher n_{eff} closer to 1.40 (for a given wavelength), i.e., modes with lower radial n order, if the resonant wavelength is to be kept roughly the same as before.

Finally, the reduction in the index contrast of the sphere will also force the resonant wavelengths of the TE and TM WGMs closer together, although they will remain non-degenerate.

To illustrate the high order mode suppression by the UV polymer packaging, 2D simulations were carried out to evaluate the electric field distribution of a chalcogenide microsphere in contact with a silica taper using commercial finite element method software (COMSOL MULTIPHYSICS 4.1, Stockholm, Sweden). The diameter of the taper and sphere was chosen to be 2 and $110 \mu\text{m}$, respectively, to match the geometry of the experimental sample. The chosen boundary conditions were scattering boundary at both the sphere and

the taper cylindrical surfaces, port boundary at both input and output ports. The maximum mesh element sizes were 180 nm in the silica taper, 200 nm in the sphere, polymer and in air. The minimum mesh element size was set up to 25 nm on the scattering boundary outside of the sphere.

Fig. 1 shows the electric field distribution of the un-packaged and packaged chalcogenide microsphere with a $\lambda = 1.55 \mu\text{m}$ fundamental mode launched from the microfiber's left input port. Fig. 1(a) confirms that the coupling of light from the taper into the microsphere in air excites a number of different WGMs, which are manifested as an interference of ray paths propagating deep within the sphere (rather than only along the circumference as would be expected for a fundamental WGM). Note that the maximum field strength in the sphere is only a third of that in the taper, due to the low coupling efficiency. When the surrounding air is replaced by polymer, Fig. 1(c) shows that the WGMs have been drawn slightly towards the surface of the chalcogenide microsphere. Comparison of the field profiles in Figs. 1(b) and 1(d) verifies that the peak field strength in the packaged sphere resides approximately $3 \mu\text{m}$ further towards the surface than for the sphere in air. In addition, the field strength outside the sphere (in the regions $x > 55 \mu\text{m}$ and $x < -55 \mu\text{m}$) is significantly greater, as expected.

The fabrication and packaging process for a chalcogenide microsphere can be divided into three steps, as shown in Figure 2: (a) optimization of coupling between the optical fiber taper and chalcogenide microsphere to obtain a maximum power coupling efficiency into the sphere; (b) embedding both the microsphere and the optical fiber taper in a UV-curable low refractive index material; (c) minimizing coupling loss in the low index material and UV-curing. Initially, a chalcogenide microsphere with a diameter of $110 \mu\text{m}$ was fabricated using the method demonstrated in Ref. 12. A silica taper with a $\sim 2 \mu\text{m}$ waist diameter was fabricated using standard $125 \mu\text{m}$ diameter telecommunication optical fiber (Corning SMF-28) by the modified flame brushing technique.¹⁷ The microsphere, positioned on a glass slide, was coupled to the tapered fiber as shown in Figure 2(a). The tapered fiber was then connected to a tunable laser source and an InGaAs detector. The position of the fiber taper with respect to the microsphere was controlled by nanotranslation stages to obtain the desired coupling and monitored using a microscope equipped with a CCD camera. As shown in Fig. 2(b), the microsphere and fiber taper are then coated with a drop of a UV-curable polymer (Eifron PC-373, Luvantix, South Korea). When the alignment between the sphere and the fiber taper is optimized, the polymer is cured by UV light exposure for about 20 s and finally packaged on a glass slide, as shown in Fig. 2(c). To increase the mechanical stability of the device, the entire length of the tapered fiber is also packaged using the same polymer.

Fig. 3(a) shows the top view of the packaged chalcogenide glass microsphere resonator with a diameter of $110 \mu\text{m}$, in close proximity to a tapered silica optical fiber with a waist diameter $d \sim 2 \mu\text{m}$. Fig. 3(b) shows the packaged chalcogenide microsphere with a silica fiber taper on a glass slide.

For optical characterization, the input port of the optical fiber taper was first connected to a broadband amplified

FIG. 2. Schematic of the microsphere packaging process: (a) coupling optimization between optical fiber taper and chalcogenide microsphere, (b) embedding both microsphere and optical fiber taper in a UV-curable low refractive index material, and (c) coupling optimization in the embedding material and UV curing of the polymer.

spontaneous emission (ASE) source operating in the range 1540–1560 nm, while the output fiber was connected to an optical spectrum analyzer (OSA) with a resolution of 20 pm to monitor resonance properties *in situ*. When effective coupling between the sphere and the microfiber occurs, the resonance characteristics were recorded using a high resolution mode of the OSA. Fig. 4 illustrates that the spectral response of the chalcogenide microsphere in air (black line) shows a series of complex resonances due to the excitation of many higher-order radial modes by the low effective index fiber taper and many non-degenerate higher-order angular modes associated with the microsphere ellipticity. After embedding the microsphere and taper in the UV-curable polymer, both the spectral responses (red and blue lines) in Fig. 4 exhibit “cleaner” spectral features with a more apparent periodicity compared with the spectrum in air as expected from the simulations presented above. However, the Q-factor decreases and the baseline loss increases after coating the microsphere with the UV-curable polymer, mainly due to polymer

(a)

(b)

FIG. 3. (a) Microscope image of a chalcogenide microsphere coupled with a silica fiber taper packaged in a cured polymer; (b) Packaged chalcogenide microsphere with a silica fiber taper on a glass slide.

absorption, and possibly also due to increased coupling strength with low order WGMs along with the removal of some high order modes. The effect on the composite Q-factor depends on the number of excited WGMs and their relative excitation strength.

FIG. 4. Optical fiber taper output over the wavelength ranges of 1540-1560 nm (up) and 1548-1552 nm (bottom) before embedding (black), in uncured polymer (red) and cured polymer (blue).

Interestingly, the Q-factor degradation is different for different modes. In fact, higher order modes with a stronger field at the surface of the sphere will scatter from the surface more. As scattering is strongly dependent on the refractive index difference between the microsphere and the surrounding environment, the presence of the UV exposed polymer can mitigate such a mismatch between the sphere and the microfiber.

To better characterize the Q factor of the packaged chalcogenide microsphere, light from a narrow-linewidth tunable laser source (Agilent 81600B, with tuning resolution: 0.1 pm) emitting ~ 1 mW over the wavelength range from 1549 nm to 1551 nm was launched into the packaged chalcogenide microsphere. The throughput signal was collected using an InGaAs photodetector. Fig. 5 presents the spectrum over a narrow wavelength range, showing the high-Q nature of the observed resonance dips for which a full width half maximum (FWHM) linewidth of ~ 8.6 pm was found for the resonance at 1549.46 nm, corresponding to a high Q-factor of $\sim 1.8 \times 10^5$.

It is well known that chalcogenides are photosensitive near the electronic band edge of the material, which is typically in the visible part of the spectrum. Therefore, the resonant wavelength of a chalcogenide microsphere can be easily tuned by exposing the packaged microsphere to UV light. For a WGM, the resonant wavelength shift $\Delta\lambda_R$ due to a small photosensitive refractive index change of the sphere Δn_s can be estimated as $\Delta\lambda_R \approx \Delta n_s \lambda_R / n_s$ assuming that $\Delta n_s / n_s \approx \Delta n_{eff} / n_{eff}$. Exposure to UV light which leads to increase of the refractive index would thus be expected to redshift the resonances.

To demonstrate that wavelength tuning is still possible after embedding in the UV curable polymer, the packaged chalcogenide microsphere was irradiated by a CW laser at a wavelength of 405 nm with an intensity of 3×10^4 mW/cm². The resulting resonance peak shift was monitored *in situ*. Fig. 6(a) shows that the resonance peak redshifts by 682 pm after irradiation for 1800 s, which indicates a positive refractive index change induced by the laser. Figure 6(b) shows that the

FIG. 5. Transmission spectra of the packaged chalcogenide microsphere in a wavelength range of 1549-1551 nm showing the periodic nature of the spectrum. Inset: Magnified view of the range from 1549.4 to 1549.5 nm. The resonance at 1549.46 nm has $Q \sim 1.8 \times 10^5$.

FIG. 6. (a) Transmission spectra of the packaged chalcogenide microsphere during exposure to a 405 nm laser radiation; (b) Peak shift as a function of exposure time, black dots are measured data and the solid curve is an exponential fit.

peak shift increases as a function of exposure time. The result can be fitted by a single exponential growth curve.

In conclusion, packaging of chalcogenide microspheres coupled with a silica fiber taper has been demonstrated in this paper. Whispering gallery mode resonances have been observed and a Q factor as high as 1.8×10^5 was recorded at $\lambda \sim 1.55 \mu\text{m}$. The photosensitivity of this packaged device to a 405 nm laser radiation has also been presented, which shows that the photosensitivity of the device, which is useful for tuning, is still present and usable after the packaging process. We believe that this work will provide the basis for a simple fabrication technique for chalcogenide material based microresonator devices as an ideal photonic building-block

for several applications including highly integrated optical switches, modulators, ultra small optical tunable filters, and integrated microlasers. This fabrication process is very simple and has the advantage of low cost. Efforts are underway to characterize the nonlinear properties of the packaged chalcogenide microsphere.

P. Wang is funded by the Irish Research Council (IRC), co-funded by the EU Marie-Curie Actions under FP7. L. Bo would like to thank the International Centre for Graduate Education in micro & nano Engineering (ICGEE) and the IRC for her Ph.D. funding support, Q. Wu gratefully acknowledges the support of Science Foundation Ireland under Grant Nos. 07/SK/I1200, 11/TIDA/B2051, 07/SK/I1200-STTF11, and 07/SK/I1200-ISTTF11. G. Brambilla gratefully acknowledges the Royal Society (London) for his university research fellowship.

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