# Packaged high-Q microsphere resonator based add-drop filter

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In this letter a packaged add–drop filter composed of a silica microsphere resonator and two fiber tapers is demonstrated theoretically and experimentally. A two-step fabrication process using an UV curable polymer is shown to stabilize the microsphere resonator with a diameter of 153 μm coupled to two tapered microfibers with a diameter of 1.5 μm which are used as add and drop ports. A high loaded quality factor (Q-factor) of $0.9\times10^5$ and a free spectral range (FSR) of about 104 pm are obtained at around 1550 nm from the microsphere for the parallel coupling tapered fibers in the add–drop configuration. This device has a range of advantages, such as ease of fabrication, low-cost and compatibility with traditional and commercial fiber systems. 

An optical add-drop filter is traditionally used to insert or extract specific wavelength channels in a wavelength division multiplexed (WDM) system and has become a fundamental building block of optical communication systems [1]. To date significant efforts have been focused on designing optical add-drop filter architectures for improving spectral selectivity (i.e., quality factor) and spectral tunability [2, 3].

The past two decades have seen remarkable progress in the development of optical add-drop filters ranging from a Fiber Bragg grating (FBG) [4] to photonic crystal structures [5] and waveguide or tapered fiber coupled whispering gallery mode (WGM) microresonators, such as microsphere [6], microring [7], microdisk [8], microtoroid [9] and microbottle [10] based resonators. Traditionally it is well known that a high Q factor makes optical resonant filters attractive candidates for realizing the add-drop function because they can potentially achieve the narrowest linewidth. FBG based optical add-drop filters have the advantages of easy connectivity with all-fiber systems and high drop efficiency, but with poor quality factors of only about $10^3$, such a filter only yields a wavelength selectivity of about 0.7 nm [4]. Another all-fiber scheme can achieve a higher Q factor, for example a fiber taper coupled microfiber knot working as a resonator has been reported with a Q factor~$1.3\times10^4$ [11]. However their efficient integration into practical devices remains challenging due to the low Q factors.

Significant progress has been made in the theoretical and experimental investigation of optical microresonators with different morphologies and functionalities over the past decade [12-18]. Optical microresonators have shown potential as versatile basic building blocks capable of performing a number of key optical signal processing functions such as wavelength filtering, switching, regeneration and buffering, and also have been used as micro-lasers [19] and wavelength-division-multiplexing (WDM) components and optical add-drop multiplexers.

Microresonators have enabled the development of a range of compact channel add-drop filters [6-9] which play important roles in optical add-drop multiplexers (OADMs) and key components for modern optical networks. Traditional microresonators, such as microdisk, microring and microtoroid resonator based add-drop filters have been developed by the well-known photolithography techniques. Previously microsphere [6] and microtoroid resonator [9] based add-drop filters have been developed, with silica fiber tapers used to efficiently couple evanescent fields to and from microresonators for their characterization and use. However, it is difficult to maintain stable alignment between the microresonators and the fiber tapers for an extended period, which is a disadvantage when fabricating add-drop devices for practical, real-world applications. Packaging the microresonators and tapers is a solution to provide isolation from external environmental variations. But it is well known that a desired packaging material around a microresonator significantly influences the performance of the microresonator, such as its Q factor, extinction ratio and finesse, compared with the microresonator's performance in free space. In order to increase the mechanical stability of the microsphere resonator coupling system, recently a packaged chalcogenide microsphere resonator has been presented [20]. In that paper the packaging technique utilized a UV-curable polymer for stabilizing both the chalcogenide microsphere and the silica tapered fiber. It was shown experimentally that after the UV polymer coating process, increased phase-matching performance can be achieved between the modes propagating in the chalcogenide microsphere and in the silica fiber taper in order to ensure an ultra-high Q factor is achieved. However to date this packaging technique has not been demonstrated for the packaging of

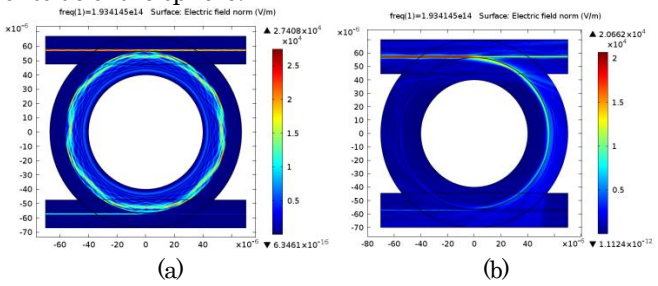
microspheres coupled with two fiber tapers for an add-drop filter application.

In this work, a high quality silica microsphere with a diameter of circa 153 μm is fabricated using a $CO_2$ laser and coupled with two low-loss tapered fibers, both with diameters of 1.5 μm and fabricated using a fire brushing technique. Their relative positioning is optimized under an optical microscope and then fixed on a microscope slide using a low refractive index UV curable polymer. The use of a coating polymer significantly increases the mechanical alignment stability of the microsphere-fiber-tapers system. At wavelengths near 1550 nm, a high-Q mode of up to $0.9\times10^5$ can be efficiently excited via evanescent coupling from the input tapered silica fiber. This Q factor reported here for a packaged microsphere resonator coupled with two silica fiber tapers is very close to the theoretical material-limited Q factor. This indicates that the extra absorption and radiation loss resulting from the polymer packaging process is relatively low.

The temperature dependence of the packaged microsphere add-drop filter has also been investigated in this paper. The packaging technique offers the potential to develop low-cost, robustly assembled fully integrated applications including WDM, sensors, ultra small optical tunable filters and also integrated micro-lasers due to the simplicity of the fabrication process compared with a conventional costly photolithographic technique.

In order to understand the spectral changes resulting from the embedding process, it is necessary to consider the modal properties of the microsphere and tapers as well as their coupling and their interaction with a surrounding packaging material. Based on the theoretical models developed in Ref. [21], since the refractive index of a silica microsphere is equal to that of a silica fiber taper (n~1.44), the phase matching constraint will favor coupling to the fundamental radial mode (propagation constant is circa $5.67\times10^6$ $m^{-1}$). For a WGM with a given mode order (*l,m,n*), increasing the refractive index of the surrounding medium $n_{surr}$ will not only shift the resonance wavelength, but also extend the evanescent field further beyond the sphere boundary and this will lead to polymer absorption loss in the packaged microsphere but on the other hand the reduction in the index contrast reduces the loss due to microsphere surface roughness. Additionally, surface scattering losses will increase due to the greater field strength at the interface, where the inhomogeneous boundary and impurities of the unfiltered polymer is prominent. Note that this is analogous to the removal of higher order modes in optical fibers by reducing the V value beyond their cut-off wavelengths.

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 silica microsphere in contact with two silica fiber tapers using commercial finite element method software (COMSOL MULTIPHYSICS 4.3b, Stockholm Sweden). The diameter of the fiber tapers and sphere were chosen to be 1.5 and 153 μm respectively, to match the geometry of the experimental sample. The chosen boundary conditions were scattering boundary [22] at both the sphere and the tapers cylindrical surfaces and port boundary at both input and output ports. The maximum mesh element sizes were 100 nm in the silica taper, 150 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.




(a) (b)

Figure 1. Simulated electric field distribution for a silica microsphere coupled with two tapered fibers in (a) air and (b) polymer, the operating wavelength is 1550 nm.

Fig. 1 shows the electric field distribution of the un-packaged and packaged silica microsphere with a λ=1.55 μm fundamental mode launched from the microfiber upper left input port. Fig. 1(a) confirms that the coupling of light from the taper into the microsphere in air excites a fundamental WGM, manifested as an interference of ray paths propagating within the sphere. 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 air as the surrounding medium is replaced by a polymer, Fig. 1(b) shows that the fundamental WGM has been drawn slightly towards the polymer. Comparison of the field profiles in Fig. 1(a) and (b) verify that the peak field strength in the packaged sphere resides approximately 5 μm further out from the surface of the microsphere when the surrounding environment is a polymer as opposed to air.

Initially, a silica microsphere with a diameter of 153 μm was fabricated using the method demonstrated in Ref. [23]. Two low loss silica tapers with a ~1.5 μm waist diameter were fabricated using standard 125 μm diameter telecommunication optical fiber (Corning SMF-28) by the modified flame brushing technique [24]. The subsequent packaging process for the silica microsphere and fiber tapers can be divided into four steps, as shown in Figure 2: a) the UV curable polymer (Efiron UVF PC363, Luvantix) is first deposited on a glass microscope slide substrate, the substrate is then placed on a spin coating machine and accelerated rapidly to the desired rotation rate of circa 500 rpm, then exposed to a UV light source, yielding a thin cured film with a thickness of circa 10 μm; b) coupling between the first optical fiber taper and silica microsphere is minimized to obtain a maximum power coupling efficiency into the sphere using high resolution 3-D translation stages; two drops of the viscous UV curable Efiron polymer are then placed on the transition regions of the first tapered fiber and cured to fix the system in place; c) the second optical fiber taper is put in place and both the microsphere and the second taper are then surrounded by a UV-curable polymer layer and coupling between the second optical fiber taper and the silica microsphere is also minimized to obtain a maximum power coupling efficiency; d) with the coupling loss minimized, the polymer material is then UV-cured.

During the packaging process, the input port of the first optical fiber taper was first connected to a broadband amplified spontaneous emission (ASE) source operating in the range 1540-1560 nm, while the throughout port and the drop port of the second tapered fiber were each connected to separate optical spectrum analysers (OSAs) with a resolution of 20 pm so as to allow monitoring of resonance properties in situ. When determining the most effective coupling state between the sphere and the taper fibers the resonance characteristics were recorded using a high resolution mode of the OSA. 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(c), the microsphere and fiber tapers are then coated with a larger portion of polymer material. When the alignment is optimized, the polymer is cured by exposure to a UV light for about 20 seconds and finally packaged on a glass slide, as shown in Fig. 2(d). To increase the mechanical stability of the device, the entire lengths of the tapered fibers are also packaged using the UV polymer.

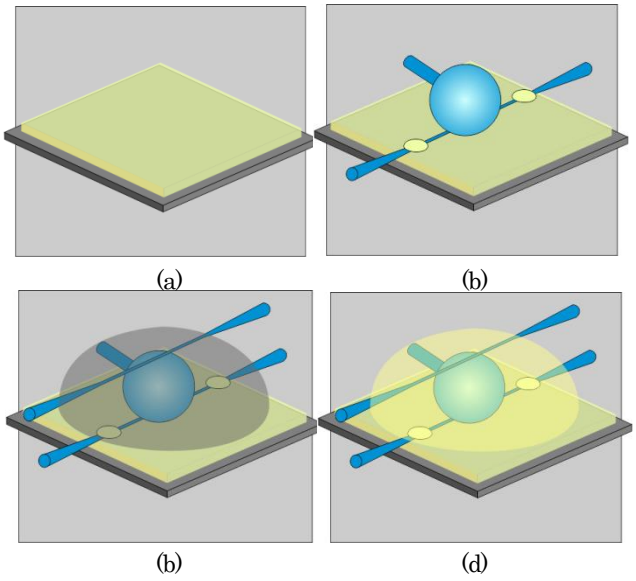



Fig. 2 Schematic of the microsphere packaging process: (a) a UV curable polymer is deposited on a glass microscope slide substrate; b) the first optical fiber taper and silica microsphere are fixed in place; c) both the microsphere and the second optical fiber taper are embedded in a layer of UV-curable polymer; d) the polymer is UV-cured.

Fig. 3(a) shows the top view of the packaged silica glass microsphere resonator with a diameter of 153 μm, in close proximity to a tapered silica optical fiber (outer coupling fiber taper) with a waist diameter d ~ 1.5 μm. Fig. 3(b) shows the magnified top view of the packaged sphere, confirming that the packaging process is free from bubbles and macro defects. However, the resolution of the optical microscopy is not sufficient to detect microdefects and imperfections at the interface.

To characterize the Q factor and the other optical properties of the packaged silica microsphere, light from a narrow-linewidth tunable laser source (Anritsu MG9638A with a wavelength tuning resolution of 1 pm) emitting ~1 mW over the wavelength range from 1549 nm to 1551 nm was launched into the packaged silica microsphere. The throughput signal was collected using an InGaAs photodetector. Fig. 4 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 ~14 pm was found for the resonance at 1550.25 nm, corresponding to a high Q-factor of ~$0.91\times10^5$ with an extinction ratio of more than 20 dB and a free spectral range (FSR) of 104 pm. Compared with the Q-factor of a silica microsphere based add-drop filter measured in air of typically $7\times10^6$ [6], the packaging process induces a degeneration of circa $10^2$ on the Q-factor. This Q-factor reported here for a packaged microsphere resonator coupled with two silica fiber tapers is very close to the theoretical material-limited Q-factor reported in Ref. [25], demonstrating that the packaging process results in only minimal increases in absorption and radiation loss.

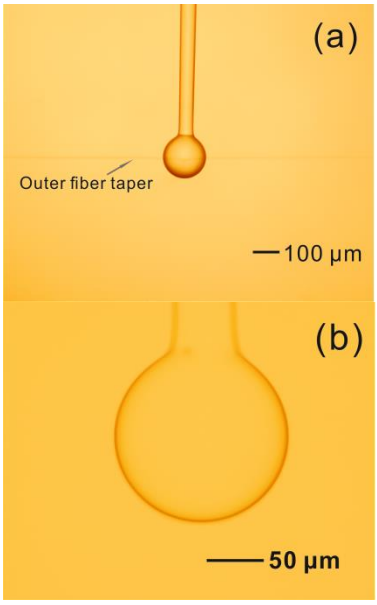



Figure 3. (a) Microscope image of a silica microsphere coupled with a silica fiber taper packaged in a cured polymer; (b) Zoom-in microscope image (we cannot see the coupling taper here because the focus is on the middle of the microsphere).

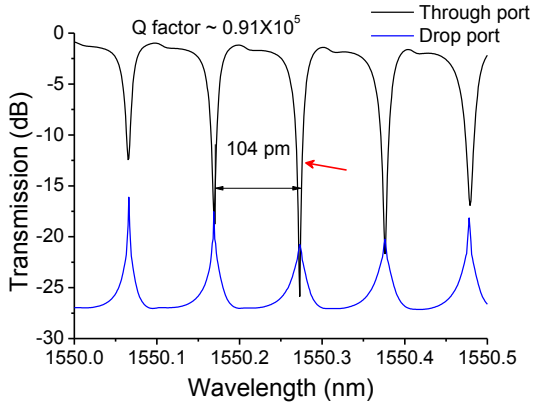



Figure 4. Transmission spectra outputted from the through port (black line) and the drop port (blue line).

To investigate the temperature dependence of the fabricated device, the packaged silica microsphere device

was placed on a heating plate, the temperature was controlled from room temperature (circa 20°C to 60°C with in intervals of 10°C). The resulting resonance peak shift was monitored in situ. The peak with the largest extinction ratio over the transmission spectrum, indicated by a red arrow in Fig. 4, was selected to be monitored for determining the peak wavelength shift. Fig. 5 shows that the resonance peak redshifts by 604 pm when the temperature increases from 20°C to 60°C, which indicates a positive refractive index change of UV polymer induced by the heating. The result can be fitted by a linear fit, which indicates an average temperature sensitivity of 15.1 pm/°C with a linear fitting coefficient of 0.9979, slightly higher than that for the measured data presented in Ref. [26]. It is worth noting that the thermo-optic coefficient (TOC) of the UV curable polymer used is circa $-3\times10^{-4}$ °C$^{-1}$, which is orders of magnitude higher than that of the conventional high purity silica (TOC $7\times10^{-7}$ °C$^{-1}$), therefore the influence from thermo optic effects induced by the microsphere and the silica tapers vary with the surrounding temperature can be very small, compared with the influence induced by the thermo optic effects of the UV polymer.

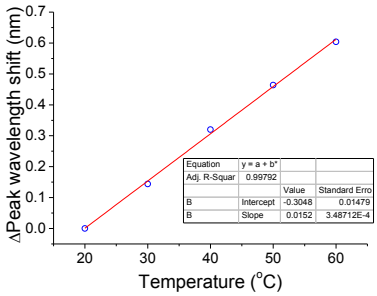



Figure 5. Temperature dependence of the packaged microsphere device.

In conclusion, we have presented a packaged silica microsphere coupled with two silica fiber tapers for application as an add-drop filter. Whispering gallery mode resonances have been observed, with a Q factor as high as $0.9\times10^5$ and an FSR circa 104 pm recorded at λ~1550 nm. The transmission spectral responses of the add and drop channels demonstrate the add–drop potential of the filter for very closely spaced DWDM channels. The filter temperature dependence has been presented and the investigation of the polarization dependence of this filter is underway. We believe that this work will provide the basis for a simple fabrication technique for microsphere coupled with fiber tapers based add-drop filtering devices as an ideal photonic building-block for several applications including DWDM, sensors, ultra small optical tunable filters and integrated micro-lasers. The proposed fabrication process is very simple and has the advantage of low cost for practical applications.

P. Wang is funded by the Royal Irish Academy Mobility Fellowship 2013 and the Irish Research Council "New Foundations". 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. G. Brambilla gratefully acknowledges the Royal Society (London) for his university research fellowship. This work was supported by the 111 project (B13015), at the Harbin Engineering University and also was supported by the National Natural Science Foundation of China (NSFC) under grants U1231201, 61275094. This publication has emanated from activity supported in part by Science Foundation Ireland (SFI) under the International Strategic Cooperation Award Grant Number SFI/13/ISCA/2845.

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