We report production of air-clad tapered chalcogenide fibers by directly drawing bulk glasses between cleaved tips of tapered silica fibers. Exploiting these tapered fibers with nanoscale waists as evanescent optical couplers, we demonstrate phase-matched coupling of light into on-chip whispering gallery mode chalcogenide microresonators with coupling efficiencies as high as 95%. To the best of our knowledge, this is the first-time demonstration of critical coupling into high-index microresonators by using high-index tapered fibers. The tapered chalcogenide fibers can also be utilized as optical couplers for microresonators made of various high-index materials, as well as for nonlinear optical applications.

1. INTRODUCTION

In recent years, whispering gallery mode (WGM) resonators [1] have been exploited in numerous applications ranging from ultralow-threshold Raman lasers [2] and optical frequency comb generators [3] to biological sensors for single virus detection [4] because of their very efficient spatial and temporal confinement of light resulting in enhanced light–matter interactions. One of the most critical issues for practical applications of WGM resonators is yet to find a way for a robust optical coupling enabling efficient power transfer between couplers and resonators. So far, the majority of coupling schemes are based on tapered silica fibers, which have been extensively utilized for evanescent coupling of light into WGMs of microresonators not only because of their easy and low-cost production [5] but also because of their remarkable performance as the most efficient and ideal optical coupler [6]. However, tapered silica fibers are most convenient for microresonators made of materials with refractive indices similar to that of silica [7]. As an optical coupler, tapered silica fibers cannot be used to efficiently transfer optical power both to and from microresonators made of higher-index materials (n > 1.44) because coupling efficiency is exponentially decreasing with the square of phase mismatch between propagating modes, i.e., the difference between effective refractive indices $n_{\text{eff}}$ [8]. Besides, higher order modes are more likely to be excited rather than the fundamental modes of interest as shown in chalcogenide glasses (ChG) [9], germanium [10], and bismuth silicate microsphere resonators. The coupling efficiency of tapered silica fibers is a lot worse for fundamental WGMs of higher index resonators with diameters $D > 50 \, \mu m$. To improve the coupling efficiency, although compromising practicality, loading of silica tapered fibers with Si waveguides has been proposed [12]. Other strategies have also been developed for optical coupling, some of which are high-index prism couplers for diamond sphere resonators [13], Si waveguide couplers for ChG sphere resonators [14], and LiNbO$_3$ waveguide couplers for LiNbO$_3$ disk resonators [15]. Unfortunately, these techniques still require bulky optics or pigtailed fibers at the last phase of device integration.

As an alternative, tapered fibers made of ChGs, which have unique optical properties including higher indices ($n = 2.2 - 3.4$), wide transparency window ($2 - 20 \, \mu m$), high nonlinearity, and low two-photon absorption [16], can provide phase-matched couplers convenient for critical coupling of light into high-index WGM resonators. Tapered ChG fibers are usually drawn from step index ChG fibers, as is the case for silica fiber tapering. So far, leveraging their higher nonlinear
refractive indices $n_2$ with reduced effective mode area $A_{\text{eff}}$ due
to tapering [17], ChG tapered fibers have only been utilized in
nonlinear optical applications, such as supercontinuum gener-
ation [18,19], optical parametric oscillators [20], and photon
coupled pair generation [21].

Although tapered ChG fibers are promising candidates as an
optical coupler for resonators made of high-index materials,
they suffer from mechanical instability in air-clad tapered form
with nanoscale waist diameter when tapering length is long
($>10$ mm), due to their inferior mechanical properties com-
pared to those of silica. In addition, splicing them to silica fi-
bers, which are often the external connectors, is very difficult
and requires mechanical splices with UV-cured epoxy support.
In fact, ChG fibers with polymer claddings have been fabri-
cated and shown to be robust tapers [22,23]; however, their
evanescent field is inside the cladding polymer, which has a
high absorption in the mid-IR region. Tapering of a ChG core
polymer cladding fiber is also vulnerable to Plateau–Rayleigh
(Pr) instability [24] or fragmentation during the fiber tapering
process [25].

In this study, we developed a direct chalcogenide fiber taper-
ing method, having been inspired by fabrication methods used
to draw micro- and nanowires directly from bulk glasses [26,27],
and demonstrated phase-matched optical coupling from a ta-
pered $\text{As}_2\text{Se}_3$ fiber to WGMs of on-chip $\text{As}_2\text{Se}_3$ microdisk res-
nators with a maximum coupling efficiency of 99.5%. The ChG
microdisk WGM microresonators were fabricated by inducing
PR capillary instability in a ChG ($\text{As}_2\text{Se}_3$) core polymer [pol-
ethersulfone (PES)] cladding resonator [28]. The microsphere cavities
formed inside the cladding were then transferred to a gold-coated
substrate, where they were trimmed into disk shape. By optical
characterization of the ChG microdisk WGM resonators with
the tapered ChG fibers, we obtained quality factors reaching
$Q = 8.2 \times 10^5$ and $Q = 3.0 \times 10^5$ in undercoupled and criti-
cally coupled regimes, respectively.

2. FABRICATION OF TAPERED CHALCOGENIDE FIBERS

Fabrication of ChG fiber tapers, steps for which are schemati-
cally shown in Figs. 1(a)–1(c), starts with conventional silica
fiber tapering. After tapering of a SMF-28 silica fiber (core/
cladding diameter of 8.2/125 μm) softened in the flame of a
hydrogen torch, the tapered silica fiber was cleaved from the
center of the waist by scoring the surface of the fiber under
tension with a sharp SiC blade. The diameter of the silica fiber
waist was kept under 40 μm to achieve a cladding guided funda-
mental mode. The next step was positioning of a material
feeding mechanism, i.e., a thin cantilever carrying a small
amount of bulk ChG (<1 mg), between separated tips of the
tapered silica fiber inside a custom-made electric heater,
which was fabricated using a chromium-nickel wire with a total
resistance of 1.3 kΩ [see Fig. 1(f)]. A picture of the setup for
the transfer and tapering process of ChG is given in Fig. 1(g),
showing the heater, the feeding cantilever, fiber holders on
moving stages, and a long-range camera. A current of
104 mA through the wire of the electric heater was applied
to reach temperatures (>300°C) high enough to melt the
$\text{As}_2\text{Se}_3$ glass on the cantilever. The ChG used for transfer
was prepared from high-purity As and Se elements (Alfa
Aesar) using a sealed-ampule melt-quenching technique [28].

Transfer of ChG to the tips of the tapered silica fiber was
obtained by immersing the tips into the molten glass and then
retracting them with some attached material, as shown in
Figs. 2(a) and 2(b). One of the tips or both can be used in
the transfer process according to the intended amount of
material to be attached. After moving the feeding mechanism
away, separated silica fiber tips were brought together to merge
the attached material and the space between via surface tension
of the glass and its surface adhesion to the silica fiber tip facets [see
Figs. 2(c) and 2(d)]. At this stage just before tapering, the tem-
perature of the system was still kept over the melting tempera-
true of the glass. Evaporation of the glass after its splicing on
both sides transforms the bottlelike shape into a uniform cy-
linder shape, as seen in Fig. 2(e), because the cleaved silica taper
tips have fixed diameters, and evaporation occurs only on the
lateral outer boundary of the glass. Tapering always starts at the
weakest point between the silica tapers including the splicing
points, where the diameter is the smallest, and the tensile stress
is at its maximum. Further evaporation results in necking of
the glass at the midpoint, which is required for symmetrical taper-
ing. Evaporation rate can be efficiently adjusted by the temper-
ure. Tapering process was initiated at a temperature of 325°C
after the current of the electrical heater was set for a steady state
temperature of 140°C, which is lower than glass transition
temperature ($T_g = 170°C$) of $\text{As}_2\text{Se}_3$. The tapering process
took 265 s. Because the temperature of the systems decays
exponentially with a time constant, the tapering was stopped
before the temperature decreased below the $T_g$ of the glass.
The set temperature can be adjusted according to different tapering durations and lengths, so final temperature is always higher than \( T_g \). As a result, a tapered ChG fiber was formed by drawing the glass bilaterally with the cleaved tips of the tapered silica fiber [see Figs. 2(f) and 2(g)], which was already connected to a laser source (Santec TLS-510) at one end and to a power meter (Newport 1935C with 918D-IR-0D3R detector) at the other end. The tapering process was monitored by a long working distance objective system (Optem Zoom 70XL) from the side opening of the heater, and the transmission of an optical input of 1 mW at a wavelength of 1550 nm was recorded during the process. A tapering loss of 9.1 dB was observed after an initial drop of power due to the nonadiabatic tapering. Multimode interference with a single-mode propagation regime achieved at the end, as seen in Fig. 2(h), is a common phenomenon also observed in silica fiber tapering [29].

Tapering length, which was 1.5 mm for this case, can be as short as 10 μm or up to 10 mm depending on the diameter (125 μm > \( D > 5 \) μm) of the tapered silica fiber tips as determined by the cleaving of the silica fiber waist. The tapered ChG fiber is able to remain suspended without losing its integrity under the force of gravity, demonstrating a substantial mechanical stability. Scanning electron microscope (SEM) micrographs of the produced tapered ChG fiber, including waist region and left and right thermal splice points, are shown in Figs. 3(a)–3(d). The diameters of the tapered silica fiber tip and the ChG taper waist are 37 μm and 451 nm, respectively. Better contrast can be obtained at the optical microscopy image in Fig. 3(c). Thermal image showing the scattering of coupled light at the transition region is given in Fig. 3(f). A comparative result of transmissions before and after the silica fiber tapering and after the ChG fiber tapering between the tapered silica fiber tips is given in Fig. 3(g).

We obtained a broadband transmission for the tapered ChG fiber, which was drawn until we reached single-mode regime at a nanoscale waist diameter. The total insertion loss was measured to be 21.1 dB, which is the sum of 6.4 dB loss that already existed before the silica fiber tapering process and 14.7 dB loss created afterward. The initial loss consists of 3.4 dB loss due to silica-to-silica mechanical coupling on both sides of the tapered silica fiber and 3 dB loss due to a fiber coupler used for 50% splitting of the output power, which can be effectively mitigated by thermal splicing of the silica fibers, and direct reading of the output power. The subsequent loss after the process consists of 0.6 dB silica fiber tapering loss, 1 dB Fresnel loss for both ChG/silica interface, 9.1 dB ChG fiber tapering loss, and 4 dB loss due to nonperfect cleaving of the tapered silica fiber and mode mismatch. A loss under 0.1 dB can be obtained for silica fiber tapering using the flame-brushing method. As achieved recently, ChG fiber tapering loss can be reduced to at least 5 dB by tapering a longer cylinder of ChG initially spliced to the silica tapers, improving the adiabaticity. Starting ChG fiber tapering with smaller diameter silica tips (\( D < 20 \) μm) is also more favorable for adiabatic
transition of the cladding guided modes, reducing the loss of mode mismatch. In addition to nonadiabaticity, ChG fiber tapering loss is increased by surface scattering and Rayleigh scattering due to density fluctuations caused by different evaporating rates of As and Se, changing the stoichiometry of the glass. Repetitive thermal annealing of the same bulk glass after multiple material transfers was observed to adversely affect the tapering process because of the crystallization started in the material. In principle, angle cleaved silica fiber tips can eliminate the Fresnel losses, and unlike our tapering process, which occurred under ambient conditions, tapering under inert gas atmosphere can reduce oxidation effects degrading ChGs.

3. FABRICATION OF CHALCOGENIDE RESONATORS

For the exploitation of the tapered ChG fibers as evanescent couplers, we produced microdisk cavity WGM resonators made of As$_2$Se$_3$ glass ($n = 2.7$), as shown in Figs. 4(a)–4(d), extending what we developed in a previous study [28]. Starting with an As$_2$Se$_3$ core ($\phi 34 \mu m$) PES cladding ($\phi 170 \mu m$) fiber, we induced formation of microspheres in the polymer cladding at a temperature of 300°C by PR capillary instability. Later, the bottom side of the fiber was rubbed away to uncover contact surfaces for the embedded microspheres by using sheets of SiC sandpaper with a size of abrasive particles decreasing from 5 μm to 1 μm. To promote adhesion after transfer of the bottom-trimmed fiber onto a gold-coated substrate, we applied heat to increase temperature up to 240°C, which is higher than both glass transition temperature of As$_2$Se$_3$ ($T_g = 170°C$) glass and PES ($T_g = 210°C$) polymer. In addition to these steps, we trimmed the top side of the fiber to transform cavities into a disk shape with suppressed higher order polar modes. At the last step, which was the dissolution of the polymer encapsulation by organic solvents (dichloromethane) and removal of all satellite microspheres, we obtained on-chip ChG microdisk cavity resonators as seen in the SEM micrographs of Figs. 4(e) and 4(f). Average diameter of the ChG microresonators is 68 ± 0.5 μm.

4. MEASUREMENT

One of the on-chip ChG microdisk WGM resonators was positioned with a three-axis closed-loop piezo stage (NanoMax-TS) close to a tapered ChG fiber assuring alignment with the equator of the ChG microresonator as shown in Figs. 5(a) and 5(b). The tension of the tapered ChG fiber was adjusted to counterattraction between the fiber and the ChG resonator, due to electrostatic and van der Waals forces. Furthermore, we moved

Fig. 4. Production and integration of microdisk cavity ChG resonators. (a) As$_2$Se$_3$ core and PES cladding fiber. (b) In-fiber microsphere formation by inducing PR instability. (c) Attachment of the bottom-trimmed fiber containing ordered microcavities on a gold-coated substrate, and top-side abrasion of the fiber by sandpapering. (d) Dissolution of the polymer encapsulation by organic solvents. SEM micrograph of on-chip ChG microdisk WGM resonators from (e) top and (f) oblique perspectives.

Fig. 5. Optical characterizations of the ChG microdisk WGM resonators with the tapered ChG fibers. Optical microscopy images from (a) side and (b) top perspectives, showing a tapered ChG fiber coupled to a ChG microdisk WGM resonator. The tapered silica fiber tip thermally spliced to the tapered ChG fiber can also be seen in the images. (c) Wide-range optical transmission spectrum of the ChG microresonator showing two periodic families of WGM modes. (d) Optical transmission spectra of the resonant mode around the wavelength of 1551 nm in the (d) undercoupled and (e) critically coupled regimes.
the ChG microresonator along the tapered ChG fiber until we found the phase-matching diameter, and polarization was adjusted for optimum light coupling. The laser wavelength of the CW source was scanned continuously for a 10 nm wavelength range with a scan rate of 10 nm/s. We measured the wide-range transmission spectrum as given in Fig. 5(c). After setting the wavelength scan rate to 1 nm/s and scan range to 50 pm with the central wavelength at 1551 nm for a clear resonant mode, we increased the separation between the tapered fiber and the ChG resonator to measure transmission in the undercoupled regime [see Fig. 5(d)]. We then moved the ChG microresonator gradually closer to the tapered ChG fiber to reach the critical coupling regime, which is the 13 dB drop of optical transmission, as shown in Fig. 5(e). Lorentzian fits to the resonance mode in the transmission spectra show a quality factor of $Q = 8.2 \times 10^5$ in the undercoupled regime and a quality factor of $Q = 3 \times 10^5$ in the critically coupled regime. It is critical to use input powers lower than 1 µW to eliminate thermo-optic and nonlinear effects observed in ChG microresonators, which can distort the Lorentzian shape of the resonant modes.

5. RESULTS AND DISCUSSION

As a result of optical characterization of a tapered As$_2$Se$_3$ ChG fiber coupled with WGMs of the As$_2$Se$_3$ microdisk resonators of $D = 68$ µm, we obtained a maximum coupling efficiency of 13 dB (95%) and a maximum quality factor of $Q = 8.2 \times 10^5$, which is close to the intrinsic quality factor in the undercoupled regime. We previously obtained a maximum coupling efficiency of 8.7 dB and an intrinsic quality factor of $Q = 7.9 \times 10^3$ for coupling with WGMs of As$_2$Se$_3$ microsphere resonators of $D = 50$ µm with tapered silica fibers [28]. Although Q factors obtained in this study are comparable (slightly higher) to those previously obtained with silica tapered fibers, there is a remarkable increase of 4.3 dB in the maximum optical coupling efficiency observed for WGMs of the ChG microresonators with tapered ChG fibers. Maximum coupling efficiencies, which were obtained by other groups, are 10 dB for a silica tapered fiber coupled with As$_2$Se$_3$ microspheres of $D = 9.2$ µm [9], and 7 dB for silicon waveguide couplers coupled with As$_2$Se$_3$ microspheres of $D > 55$ µm [14]. We expect similar improvements in coupling efficiencies that are to be obtained for tapered ChG fibers coupled with other resonators made of high-index materials, such as Ge, Si, and LiNbO$_3$.

Fundamental WGMs are of interest for sensing or nonlinear optical applications, because they possess not only high-quality factors but also the smallest mode volume. Achieving critical optical coupling with the fundamental WGMs, which is the 100% power transfer both to and from a resonator, is therefore highly desired. However, this is only favorable with phase-matched couplers for high-index ($n > 2$) microresonators having diameters greater than 50 µm. Perfect phase matching for the fundamental WGMs can only be fulfilled by tapered fibers with equal or greater material index than effective indices of the WGMs in a microresonator. ChG tapered fibers with refractive index $n > 2.2$ will be a good match for most of the high-index resonators as efficient optical couplers. Moreover, starting with extremely small quantities of ChG instead of fibers, thermal splicing to silica fibers in the beginning of a tapering process and ease of tapering with electric heaters at low temperatures will be of importance for practical applications of WGM microresonators.

In this work, we also demonstrated that chalcogenide nanofibers can be obtained on the tip of tapered silica fibers. Because ChGs have large material dispersion, zero total dispersion occurs at nanoscale dimensions, so with this technique any nanoscale diameter is achievable to engineer total dispersion during tapering. Besides, the absence of long nontapered ChG fiber parts, which have high normal dispersion, can be of great advantage in terms of pre-chirp compensation required in ultrastable optical applications.

Because tapering is a thermal process based on electrical heating, the surface of the ChG nanofibers is very smooth. In addition, we observed superior mechanical endurance for the ChG nanofibers, which can be elastically transformed into loops by bringing the tapered silica fibers closer, without any mechanical and optical degradation. Being thermally spliced to silica fibers, nanofibers could be an important step for achieving in-line novel and compact fiber functional devices.

6. CONCLUSIONS

In conclusion, we demonstrated production of air-clad nanoscale waist diameter tapered ChG fibers directly drawn from bulk glasses of As$_2$Se$_3$ with extremely low starting quantities inside an electric heater. This technique can also be applied to other commonly used ChG glasses, such as As$_2$S$_3$, Ge-Sb-Te, and Ge-As-Se-Te. The tapered ChG fibers are thermally spliced to silica fibers on both sides, eliminating the need for a ChG fiber in the first place and postprocess splicing or mechanical coupling. Furthermore, noncircular tapered ChG fibers can be produced if the silica taper tips have noncircular shapes, which can be used to induce birefringence into the fibers. As an application, we demonstrated phase-matched coupling of light into on-chip As$_2$Se$_3$ microdisk cavity WGM resonators with a maximum coupling efficiency of 95% and a maximum quality factor of $Q = 8.2 \times 10^5$, verifying optical quality of our ChG microresonators and enhanced optical coupling with our tapered ChG fibers. To the best of our knowledge, this is the first time for demonstration of optical coupling into high-index WGM resonators with high-index tapered fibers. These tapered ChG fibers can be exploited as evanescent optical couplers for other resonators made of high-index amorphous glasses and high-index crystalline materials, such as CaF$_2$, Ge, Si, and LiNbO$_3$. Tapered ChG fibers can also be drawn between cleaved tips of other fibers made of high-temperature materials, such as ZnSe, Si, and Ge. In addition, owing to wide-range optical transmission of ChGs, air-clad tapered ChG fibers are very convenient for mid-IR applications. In particular, the combinations of intrinsic high nonlinearity of ChGs, the reduced effective mode area $A_{eff}$ due to nanoscale diameters, and the absence of nontapered fiber parts can be leveraged in nonlinear optical applications, such as nonlinear label-free biosensing [30], third harmonic generation [31], and generation of entangled photon triplets [32], where the promise of tapered ChG fibers is highlighted.
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