SPIE Newsroom

10.1117/2.1201411.005660

Robust fibers for delivering infrared light

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A new generation of robust multimaterial chalcogenide optical fibers offers transparency across the mid-IR range.

Quantum cascade lasers (QCLs) currently offer convenient access to mid-IR wavelengths in the range 3.5–12μm.[1] However, there is a lack of IR optical fibers that are transparent across this entire QCL spectrum.[2] Although fluoride[2] and tellurite[3] glass fibers can transmit light up to 5.5 and 4.5μm, respectively, chalcogenide glass fibers offer a much wider mid-IR transparency window.[4] Nevertheless, these fibers suffer from limitations that stem from the physical properties of chalcogenide glasses—especially their fragility—and difficulties in processing these glasses into fiber form.[5] Indeed, the brittleness of chalcogenides limits the fabrication processes that are suitable for producing a preform that is then drawn into a fiber.

To overcome this perennial obstacle, we recently adapted techniques developed for the fabrication of 'multimaterial fibers'[6–9] to the production of novel IR fibers. Chalcogenide glasses dictate the optical functionality of the fibers but a robust yet flexible, built-in, thermally compatible polymer jacket determines their mechanical properties.[10–12] Several other critical advantages accrue from our fabrication methodology. First, there is substantial flexibility in designing the geometry of the fiber; for example, the core diameter can be tuned from a few nanometers to hundreds of micrometers.[13] Second, large (in excess of $\sim$1) contrasts in refractive index can be achieved in an all-solid step-index fiber. This offers opportunities for dispersion engineering[14] and enhancing nonlinear optical effects[15] such as supercontinuum generation.[16] Third, the thermally compatible jacket allows tapering of the fiber without first removing the polymer, leading to robust tapers with diameters $\sim$200nm that are nevertheless easily manipulated and handled.[14–16]

Over the past few years, we have developed a suite of extrusion strategies that facilitate the production of multimaterial preforms that combine chalcogenide glasses and thermoplastic polymers.[10–12] Three examples are shown in Figure 1(a–c). In the first example, multimaterial stacked coextrusion, discs of the desired materials are stacked in a vertical sequence.[10] In the second, multimaterial disc-to-fiber co-extrusion, the billet is further structured to minimize the amount of glass needed.[11] In the third, multimaterial rod-in-tube coextrusion, the billet consists of a nested cylindrical structure.[12]

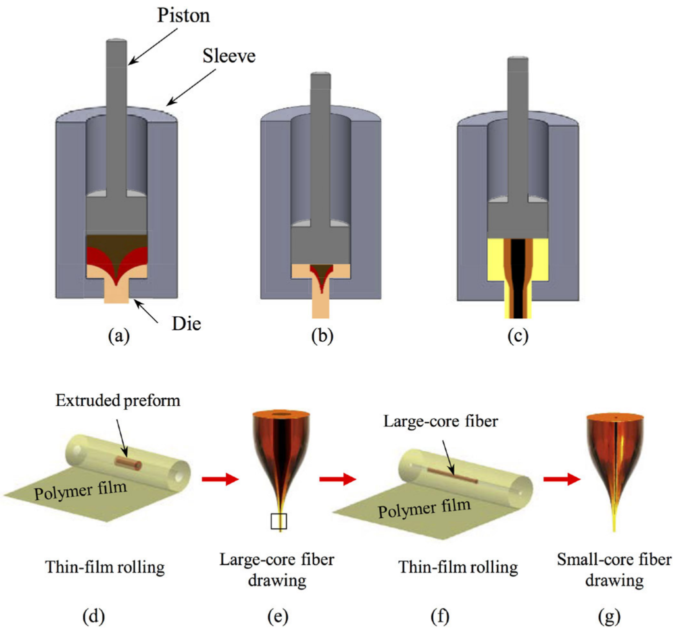

Figure 1. *Multimaterial coextrusion strategies. (a) Multimaterial stacked co-extrusion. (b) Multimaterial disc-to-fiber co-extrusion. (c) Multimaterial rod-in-tube co-extrusion. (d)–(f) Thin-film rolling and thermal drawing process to produce robust IR chalcogenide fibers.*

The multimaterial disc-to-fiber co-extrusion technique is particularly notable because it requires only $\sim$2g of glass to produce $\sim$50m of fiber.[11] This approach will hopefully enable rapid prototyping of chalcogenide fibers from the wide range of available compositions tailored for specific applications.[17] In all cases, the hybrid billet comprising chalcogenide glasses and a compatible thermoplastic polymer is heated in a metal

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sleeve and a piston forces the softened billet through a circular die. The extruded rod consists typically of a chalcogenide core, chalcogenide cladding, and a built-in polymer jacket. The diameter of the rod is then increased by rolling a thin polymer film (typically the same polymer used in the billet) followed by thermal consolidation to yield a preform. Such a preform may be thermally drawn into a continuous fiber, exploiting the principal methodology used in producing telecommunications fibers.[18] Critically, the polymer jacket—built in at the preform stage—allows thermal drawing in an ambient atmosphere.

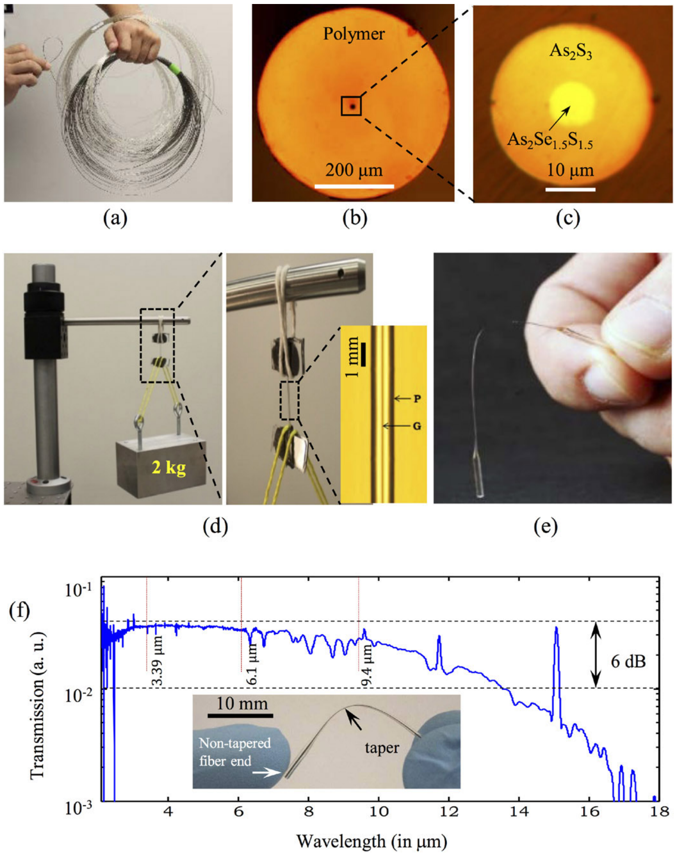

Figure 2. *(a) Drawn large-core fiber (black) and small-core fiber (gray). (b–c) Optical reflection micrographs of a small-core fiber cross-section. The diameter of the arsenic selenide sulfide ($As_2Se_{1.5}S_{1.5}$) chalcogenide core is* ∼*10*μ*m, and the diameter of the arsenic trisulfide (As_2S_3) chalcogenide cladding is* ∼*30*μ*m, and that of the built-in polyethersulfone polymer jacket is* ∼*1mm. (d–e) Superior mechanical properties of multimaterial IR chalcogenide fibers and nano-tapers. (d) A 2kg weight hanging from a 5cm-long fiber. The fiber is attached to microscope slides using epoxy while keeping the ends free for optical measurements. (e) A robust multimaterial nano-taper. (f) Transmission spectrum of a robust tellurium-based chalcogenide multimaterial fiber. The inset is a mechanically robust tellurium-chalcogenide fiber taper. (The black tellurium-chalcogenide core and cladding are visible inside the transparent polymer jacket.) a.u.: Arbitrary units.*

Subsequent iterations of the same procedure enable multiple recursive draws to further reduce the diameter of the chalcogenide core. In a typical example, a section of the extruded rod (outer diameter 5–10mm and length 20–40mm) is rolled with a polymer film to form a larger-sized preform after thermal consolidation (outer diameter 25–35mm and length 80–120mm): see Figure 1(d). This preform is then thermally drawn into a large-core fiber (outer diameter of a few millimeters and core diameter of a few hundred micrometers): see Figure 1(e). A segment of this large-core fiber (length 80–100mm) is subsequently rolled with a polymer film to form a new preform—see Figure 1(f)—which in turn is drawn into a small-core fiber (outer diameter 1mm and core diameter ∼10μm): see Figure 1(g). Figure 2(a–c) depicts examples of such a fiber. Furthermore, we have confirmed that multiple iterations of this procedure can reduce the chalcogenide core diameter in a continuous fiber to <5nm![13] The superior mechanical properties of such multimaterial fibers with respect to those of the chalcogenide glasses used in the fiber are evident in Figure 2(d–e).

Most recently, we have demonstrated that this fabrication strategy can be extended without significant modifications to tellurium-based chalcogenide glasses, which offer the broadest IR transparency window of any glass.[12] The result is robust yet flexible IR fibers and fiber tapers with a transparency window that extends across the entire QCL spectrum: see Figure 2(f). Indeed, using commercially available IR zinc selenide lenses, it was straightforward to couple light from QCLs at 6.1 and 9.4μm wavelengths, Fourier-transform IR light, and a helium-neon (He-Ne) laser at 3.39μm into these fibers. We have currently achieved this relatively flat transmission window with ∼6dB/m losses.

In summary, we have adapted the new concept of multimaterial fibers to combine thermoplastic polymers with IR-transparent chalcogenide glasses for mechanically robust IR fibers with losses of ∼6dB/m over the spectral range 2.5–12μm. We expect this strategy to pave the way to a new generation of robust IR chalcogenide fibers that could increase the accessibility and use of QCLs in applications ranging from biosensing to environmental pollution monitoring. We are now working to purify the chalcogenide glass to further reduce losses during transmission.

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