Processing and Applications of Semiconductor Core Fibers

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Abstract: Optical fibers with semiconducting cores permit transmission of signals from the visible to THz wavelengths, and devices can utilize the large nonlinear coefficients of the core materials. Fabrication, post-processing, properties and devices are reviewed.

1. Introduction

Dielectric core fibers have allowed telecommunications to flourish due to their low losses, and doped material has made amplifier and nonlinear optical device development possible. More recently, exploration of semiconducting cores has allowed extension of the spectral range, and inclusion of optoelectronic effects in fibers. There has been substantial development of both chalcogenide and conventional semiconductors (primarily Group IV materials) with advantages for devices conferred by the fiber core material and the geometry. Semiconductor cores, in both amorphous/glassy and crystalline forms are being explored. For communications, these fibers have the potential to allow in-fiber modulation and even signal redirection with all-optical systems. Hybrid devices such as detectors, modulators, and broadband sources are also being realized. This paper will describe progress in the fabrication and optical properties of these fibers and will highlight a few key applications, concentrating on crystalline core materials.

2. Methods

2.1 Fabrication

Historically, both the micro-pulldown [1] and laser pedestal growth [2] techniques were used for the fabrication of crystalline semiconductor filaments with diameters of 10^2 -10^3 microns, but typical lengths that can be made are on the order of centimeters and the surface roughness is significant. These materials have not been pursued extensively for optical applications. More recently, development of methods for fabrication of optical fibers with glass cladding and semiconductor core diameters from 0.1 to 100 microns has resulted in rapid advances in the field.
For glass-clad semiconductor core fibers (SCF), chemical vapor deposition (CVD) and pressure assisted melt filling (PAMF) have been used to insert the core material into preexisting cavities in a glass fiber, with lengths of centimeters, and core diameters from submicron to tens of microns. Molten core drawing (MCD) of the semiconductor within a glass host (which acts as a deformable crucible) can fabricate hundreds of meters of fiber with either telecom or other dimensions. For scalable manufacture, the molten core draw shows the greatest promise, and is the focus of this paper.

The molten core method uses a glass preform that has a central cavity which is loaded with the desired semiconductor, or with both the semiconductor and a solvent phase metal that allows the fiber to be drawn at lower temperatures than the pure semiconductor. The preform is heated above the glass transition temperature and a fiber is drawn, with the molten semiconductor adopting the diameter imposed by the glass cladding. Both large-core cane suitable for materials studies, and small core fiber suitable for standard fiber coupling setups can be produced. An interface layer is used in some cases to reduce the interaction between the core and cladding.[3] Variations on the molten core technique include the use of small scale ovens that reduce the time that the core and cladding material interact at high temperatures, the use of a CO_2 laser to enhance the oven-induced heating[4] and a miniature drawing rig with a CO laser replacing the furnace[5]. The length of the region in which the semiconductor was molten was on the order of 10mm as opposed to conventional towers where longer hot zones are typical. Optical losses were reported to be lower for more rapidly drawn material (10m/min vs 1 m/min), strengthening the correlation between core-clad high temperature reaction time and optical losses. There are also reports[6] of preforms having air channels surrounding the semiconductor core, and a furnace with a 30mm hot zone. A two-step process was used, with the second step having a draw speed of 10 m/min. Silicon oxidation may have been reduced due to the lower thermal mass of the preform., and thus reduced heating times.

2.1 Post-processing

The utility of SCF in optical and other applications depends on the purity and crystalline order in the core. CVD materials deposited in preformed microchannels typically have high purities, but submicron crystallites. During molten core fabrication of large preforms, rapid cooling combined with gentle thermal gradients promotes formation of polycrystalline cores. Impurities collect at the grain boundaries due to the segregation coefficient between solid and liquid phases and the last regions to solidify have the highest concentration of the impurity. Different expansion coefficients of the cladding and core often introduce significant stress; most of the common semiconductors have a large increase in the specific volume when they solidify, and the cladding and core have different thermal contraction during cooling from the draw temperature. These factors make post-processing of the core a rich area of study.

Some recent results[5,6] show low optical loss (0.1-0.2 dB/cm) in high-speed drawn fiber , but most studies have employed post-draw annealing or recrystallization[7]. Methods used include oven and Bridgeman type[8] annealing, rapid photothermal processing[9] flame treatment and laser processing, including visible[10] and IR[11,12], both cw and pulsed sources. Conventional fiber tapering equipment has also been used[13]. Key aspects are time at temperature, surface tension of the core vs interaction strength with the cladding, the thermal gradients induced by the process, and reduction or increase in the stress induced in the semiconductor. These techniques have also been employed for fabrication of in-fiber devices[14], for segregation of immiscible components[15], and reshaping of the fiber[16–18] .

3. Materials

The first glass-clad semiconductor core optical fibers reported had Ge and Si cores that were chemical vapor deposited in glass with preexisting microchannels[19,20] This method is also uniquely suited to the fabrication of amorphous hydrogenated cores[21,22]. Ge core fibers have been made by PAMF[23]. The molten core draw (MCD) approach was initially demonstrated with silicon cores. Group IV elemental semiconductors (Si, Ge) and the alloy SiGe have been explored extensively, and advances have been made in drawing fibers of Group VI (Te[8], Se[24]) and of III-V materials. InP[25], GaSb[26], and recently, GaAs[27] have been drawn. The incorporation of direct bandgap core materials opens the possibility of low-cost fabrication of in-fiber light sources. A recent review article [15] describes materials used in the context of their phase diagrams and optical properties.

4. Applications

4.1 THz transmission and modulation

Pure silicon is one of the primary materials used for transmission of THz radiation, and because of the strong absorption of THz by atmospheric radiation, a fiber-based system is of great interest. Due to the potential for free carrier absorption, an analog of semi-insulating GaAs, Au-doped Si, was used to make fibers suitable for THz transmission[28]. These fibers had losses from 2-10 Thz, and in the infrared (out to 10 μm) comparable to a high resistivity silicon wafer. The short carrier lifetime induced by the gold allowed modulation of the THz signal with GHz frequencies[29].

4.2 Four wave mixing images

There is extensive activity on the use of quantum correlated photons to produce images with indirect information; this paper[30] used classical four wave mixing to generate an image where the photons that interacted with the structure to be imaged were at a different wavelength than those detected. This technique has importance for medical imaging and other applications where detectors may not be available for the photon energy most suitable for interaction with the target object.

4.3 Frequency comb generation

Silicon fibers have large nonlinearities, and octave spanning supercontinuum generation has been demonstrated[17]. Using a conventional splicer, gaps were opened in the silicon core to create a parametric mixer, and nanotapering was used to couple the structure to conventional single mode fibers. The system assembled gave a 30 nm bandwidth comb source with143 tones having 12 dB flatness, over the spectral region 1.53 to 1.57 μm.

5. References

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