15 years of nonlinear semiconductor optical fibers: a review of past, present, and future

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ABSTRACT

First reported in 2006 and scaled to long and practical lengths in 2008, semiconductor core optical fibers have matured from basic material and fiber fabrication explorations to a diverse range of practical applications. The ability to bring many on-chip optoelectronic functions inside an optical fiber offers many benefits. This paper begins with a brief historical review of semiconductor fibers, the principal fiber fabrication approaches employed, and the range of material system realized. From there, the nonlinear properties and approaches to their optimization will be discussed along with a range of nonlinear in-fiber devices that have been reported in both telecom and mid-infrared spectral regions. Lastly, on-going challenges and musings on future semiconductor fiber materials, devices, and performance will be made leveraging their significant benefits in terms of their flexibility, power handling, wavelength coverage, and general ease of use over competing fiber and on-chip platforms.

Keywords: optical fiber, semiconductors, nonlinear optics, frequency combs, super-continuum generation.

1. INTRODUCTION

From humble origins in the 1980s [1,2] to expansive growth over the past 20 years in particular [3-6], silicon photonics has enjoyed global attention as a means to low cost and power efficient communication components and devices [7,8]. More recently, the marriage of silicon photonics with nonlinear and infrared fiber optics, in the form of silicon optical fiber [9,10], has emerged as a complementary platform to the on-chip, planar platforms, offering many benefits associated with waveguide design and coupling.

This brief review will highlight the past 15 years of semiconductor optical fibers, dating to the first report (2008) of silicon optical fiber produced via a drawing tower method [10]. Though not the first silicon fibers, either optical [9] or non-optical [11], these were the first to be thermally drawn, using the same low cost, high-speed, and high-volume approach employed in the fabrication of conventional (silica) telecommunications fiber. As such, this represents the birth of scalable silicon optical fiber. For the interested reader, numerous reviews have been published that thoroughly cover the range of semiconductors that can be thermally drawn into glass-clad fibers [12-15] and the myriad of high-performance photonic and optoelectronic devices that have been made and studied to date [15-18].

2. SEMICONDUCTOR FIBER MATERIALS, FABRICATION, AND POST-PROCESSING

The fibers discussed herein were all fabricated using the molten core method (also called the "melt-in-tube" approach), which is a more generalized version of the original "powder-in-tube" method first employed to directly fabricate optical fibers from glasses insufficiently stable to form bulk samples [19]. Whereas the powder-in-tube method used powder precursors to the core phase, the molten core method can use powders, wires, single crystals, ceramics, or combinations thereof. The basic premise is that the core phase melts at the temperature where the glass tube holding said powders thermally draws into fiber. In many cases, the glass tube is comprised of pure silica (SiO_2), though softer glasses have also been used or proposed, depending on the thermal and thermomechanical properties of the core phase [12,20,21]. Thermally drawn semiconductor core fibers are always crystalline. Amorphous semiconductor core fibers are possible using chemical vapor deposition (non-drawing) approaches [22].

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An important feature of the molten core method is the vast range of crystalline semiconductors (and novel inorganic glasses) phases that can be realized [12]. To-date, relevant to this paper, examples include crystalline cores of Si [10], Ge [23], SiGe [24], InSb [25], GaSb [26,27], Si-GaSb [28], biphasic metal / semiconductor (GaSb and Si) systems [29], GaAs [30], and recent preliminary efforts with ZnSe and InP [31]. A thorough review of the materials science and range of core phases can be found in Ref. [14].

As-drawn semiconductor core fibers are polycrystalline over their length, though can exhibit regions of single crystallinity that extend over several millimeters. Significant early efforts focused on methods of annealing the fibers to control / induce single crystallinity and reduce loss [32-36]. The most effective means of controlling and tailoring single crystallinity and loss is to laser post-process the fibers; akin to the zone refinement / recrystallization of bulk crystals but performed inside the glass cladding. Excellent results, i.e., single crystallinity and loss reductions, have been obtained using both CO_2 lasers [24,27,37], which heat the glass cladding, and visible lasers, which directly heat the semiconductor core [38-39]. In addition to crystallinity and loss, laser post-processing can also (i) control the microstructure and compositional gradients in the core [24,28,40,41] and (ii) taper the core size. Tapering provides an alternative method for improving the losses and tailoring the core size, and thus has been used to promote efficient coupling to conventional (telecom) fibers [42,43] as well as for dispersion engineering, which is critical for in-fiber nonlinear devices (see Section 3).

3. NONLINEAR SEMICONDUCTOR FIBER DEVICES

Nonlinear devices that have to-date been fabricated from semiconductor core fibers generally fall into two broad categories: those operating at the 1.55 μm telecommunication wavelengths and those operating in the mid-infrared (MIR) spectral region. While some of the enabling nonlinearities, e.g., Raman gain, may be employed in both spectral regimes, the fiber designs will necessarily be different.

At telecommunication wavelengths, significant progress and successes have been realized. This includes several demonstrations based on four-wave mixing (FWM) such as parametric amplification (see Fig. 1(a) [44]), wavelength conversion of high-speed data signals [45,46], and undetected photon imaging [47]. More recently, by extending the fiber lengths, we have also observed Raman amplification using a low power CW pump (see Fig. 1(b) [46]) and an all-fiber integrated telecom band comb source suitable for applications such as dense wavelength division multiplexing [48]. As well as offering excellent performance metrics such as high gain, high output powers, and broad spectral coverage, the ability to integrate the silicon fibers with existing fiber infrastructures [42] can significantly improve the robustness and practicality of silicon photonic systems.

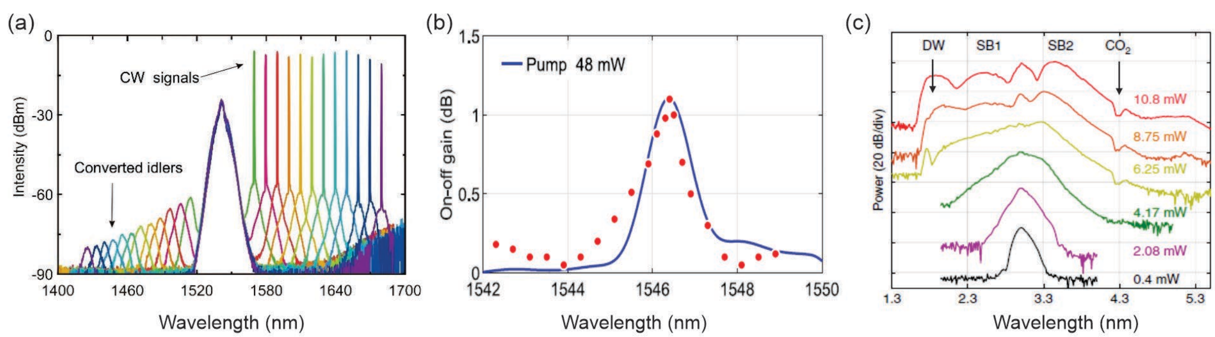

Figure 1: Examples of nonlinear processes in the silicon core fibers. (a) FWM amplification as the signal wavelength is tuned in the telecom band. (a) Raman amplification of a telecom signal. (c) Supercontinuum generation into the mid-IR.

By tuning the silicon core fiber designs to support operation at longer wavelengths, a number of important demonstrations have also been made in the MIR. This includes super-continuum generation (see Fig. 1(c) [17]), broadband FWM capable of converting between the near and mid-IR regions [49], and high gain Raman amplification [50]. Importantly, thanks to the high nonlinearity and extended transparency of the semiconductor core compared to traditional silica fibers, silicon fibers open up new avenues for exploration within the MIR region, particularly within application in areas such as sensing, imaging and free-space communications.

Prior to concluding this Section, it is worth noting that other semiconductor fiber structures and devices have been realized beyond those exhibiting nonlinear functionalities. Some examples include (chronologically) photoconductive fibers [51], solar cells [52], fiber Bragg gratings and associated temperature sensors [53,54], and THz modulators [55].

4. CONCLUSIONS

Semiconductor optical fibers offer a unique approach to marrying the needs of silicon photonics with nonlinear and infrared fibers optics. This paper has briefly reviewed 15 years of thermally drawn fiber fabrication and optimization as well as the nonlinear performance of a myriad of fibers and applications.

5. ACKNOWLEDGEMENTS

Over these 15 years, a great many people and organizations have contributed to the development of the fibers discussed herein. Of particular note are Wade Hawkins (Clemson), Stephanie Morris (Clemson, now Coherent), Tommer Zaengle (Clemson), Colin McMillen (Clemson), Meng Huang (Southampton), Dong Wu (Southampton), Shiyu Sun (Southampton), Li Shen, (Southampton), and Haonan Ren (Southampton). Special acknowledgment also goes to Prof. Ursula Gibson and Dr. Bob Rice. The authors are grateful for the financial support from The Engineering and Physical Sciences Research Council (EPSRC), Northrop Grumman, Raytheon, DARPA, and the National Science Foundation.

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