Advances in silicon core optical fibers: extending their reach in nonlinear applications

Anna. C. Peacock
Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, United Kingdom
*acp@orc.soton.ac.uk

Abstract: Recent advances in the fabrication and application of silicon-core fibers will be reviewed. Focus will be placed on developments directed towards achieving low-loss transmission and efficient device designs for use in broadband nonlinear fiber systems.

1. Introduction

The past two decades have seen significant advances in the fabrication and application of silicon core fibers (SCFs) [1]. Compared to their planar counterparts, this new class of silicon waveguide retains many advantageous properties of the fiber geometry, such as polarization independence, low transmission losses, and extended propagation lengths. They also offer the potential for robust integration with existing fiber infrastructures, improving their accessibility and practicality. In this paper, I review our efforts regarding the design, fabrication, and application of SCFs, with a particular focus on their use in nonlinear photonic systems. Results will be presented over a range of wavelengths, starting from the telecom band before extending up to the mid-infrared region, highlighting the versatility of this platform for applications ranging from optical communications to quantum imaging and sensing.

2. Fabrication and Post-Processing

The molten core drawing (MCD) method is now the primary fabrication approach for SCFs as it allows for the rapid production of long lengths of fiber [2]. In the MCD procedure, the initial preform is heated and drawn into a fiber, with the softened silica cladding acting as a crucible for the molten silicon core, as illustrated in Fig, 1(a). Recently, there have been several developments in the drawing methods that are helping to improve the silicon core materials. A significant advance has been to replace the traditional induction furnace with a laser heating method, allowing for more accurate control of the drawing, resulting in as-drawn SCFs with smaller cores and lower losses (see Fig, 1(b) [3]). Moreover, to complement the fiber drawing, several post-processing techniques have also been developed to further improve the silicon core quality, increasing production yields and enhancing device performance [1]. In particular, fiber tapering, as shown in Fig. 1(c), has proven to be particularly useful as the melting and stretching of the fiber not only helps to improve the core crystallinity to reduce the losses, but it also allows for tailoring of the core dimensions, important for dispersion engineering [4]. Significantly, through the various fabrication and post-processing methods, SCFs are now being regularly produced with transmission losses $\lesssim 1\,\mathrm{dB/cm}$ for core sizes ranging from sub-micron ($\sim 700\,\mathrm{nm}$) up to a few microns in diameter, facilitating their use in different wavelength regions.

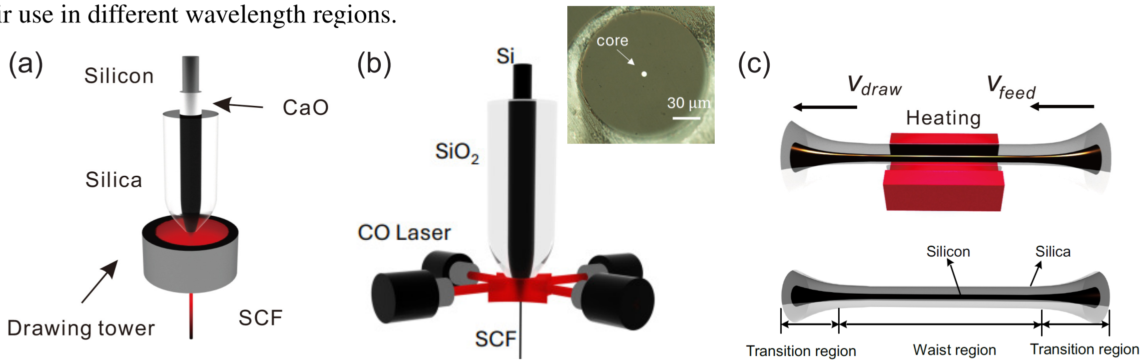

Fig. 1. (a) Schematic of the MCD fiber fabrication process. (b) Schematic illustrating the use of laser heating within the drawing process. Inset shows a cross-section of a laser-drawn SCF. (c) Top image shows a schematic of the tapering process to control the crystallinity and longitudinal dimensions of the silicon core, as illustrated by the labelled structure below.

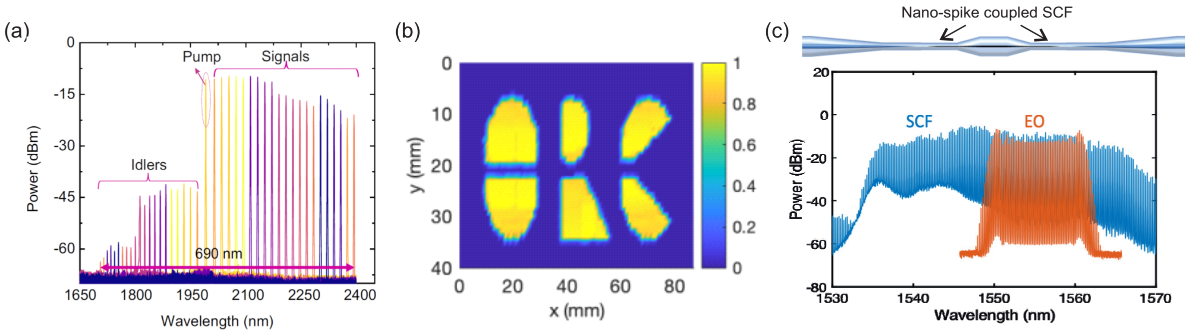

Fig. 2. (a) Broadband FWM in a SCF designed for pumping at $\sim 2\,\mu$m pump. (b) Amplitude image obtained via undetected photons generated via FWM. (c) Spectral broadening of an electro-optic frequency comb (orange) via an all-fiber integrated SCF nonlinear wave-mixer (blue). Inset at top shows a schematic of the integrated SCF device.

3. Results and Discussion

Figure 2 highlights some of our recent results in SCFs that make use of tapered waveguide designs for efficient nonlinear processing. Fig. 2(a) displays a demonstration of four-wave mixing (FWM) in a silicon fiber that was tapered to optimize the dispersion for phase-matching across a broad bandwidth [5]. The experimental results exhibited conversion across ~ 700 nm to translate signals between the mid-infrared and telecom bands, useful for applications in sensing, imaging, and broadband communications. By way of illustration, Fig. 2(b) shows an amplitude image constructed using a FWM-based system [6]. Here the results show the image obtained by detecting the FWM idler photons when only the signal photons interact with the object (in this case the ORC lettering), a process referred to as undetected photon imaging. The strong and clean image displayed here is attributed to the low loss and stability of the all-fiber system. Finally, Fig. 2(c) demonstrates the use of a SCF to spectrally broaden an electro-optic frequency comb source specially designed to exhibit features such as spectral flatness, narrow tone linewidth, high tone power, and low noise levels, as required for applications in telecommunications [7]. In this example the SCF was fully spliced to conventional fibers using nano-spike couplers that were fabricated onto each end of the high index core (as shown in the inset [8]). The resulting system was able to achieve a tripling of the source bandwidth from 10 nm to 30 nm, increasing the number of tone lines whilst preserving all of the key performance features of the original comb. Thus this work paves the way for fully integrated SCF systems that are robust, efficient, and practical.

4. Conclusion

The nonlinear performance of our unique silicon core fiber platform has been demonstrated across a broad wavelength region, highlighting its potential for use in practical all-fiber systems across a variety of applications.
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