Silicon Core Fibres for Nonlinear Photonics: Applications and Emerging Trends

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Abstract *This paper reviews recent advances in the development and application of silicon core fibres for nonlinear photonics. Particular focus will be placed on novel device designs that benefit from the fibre geometry and integration with existing components. ©2023 The Author(s)*

Introduction

Since their first introduction in 2006[1], silicon core fibres (SCFs) have undergone significant advancement such that they are now established platforms for nonlinear optical applications[2]. Compared to their planar counterparts, this new class of waveguide retains many of the advantageous properties of the fibre geometry and, as such, is more immediately suitable for integration with existing fibre infrastructures. In this paper I review our efforts regarding the design and optimization of SCFs for use in all-fibre nonlinear optical applications. Results will be presented over a range of wavelengths extending from the telecom band up to the mid-infrared, highlighting the potential versatility of this platform for applications spanning communications to sensing and healthcare.

Fabrication and Post-Processing

In recent years, the molten core drawing (MCD) method has become the primary fabrication approach for SCFs as it allows for the rapid production of long fibre lengths[3]. The procedure begins by sleeving a silicon rod inside a glass tube that has been coated with a CaO interface modifier layer to create a millimeter sized preform. The preform is then heated and drawn down into a fibre with micrometer dimensions using a conventional draw tower, as depicted in Fig. 1(a)[4]. The role of the interface layer is to reduce oxide contamination from the core during the high temperature drawing and also to reduce the effective expansion mismatch between the materials that can lead to residual strain and cracking of the core. To improve the transmission of the as-drawn fibres, a tapering procedure has been developed to melt and re-grow the crystalline core to increase the grain sizes, as shown in Fig. 1(b)[5],[6]. As well as reducing the transmission losses down to levels that are comparable with on-chip technologies, this approach has the added advantage of providing a route to tailor the core dimensions, as illustrated in Fig. 1(c), which is important for enhancing the nonlinear processes via dispersion engineering[7]. Moreover, by adjusting the tapering profile, it is also possible to control the longitudinal dimensions of the fibre, which can be exploited to enhance the coupling regions as illustrated in Fig. 1(d). Significantly, using these tapering methods, SCFs can now be 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[8].

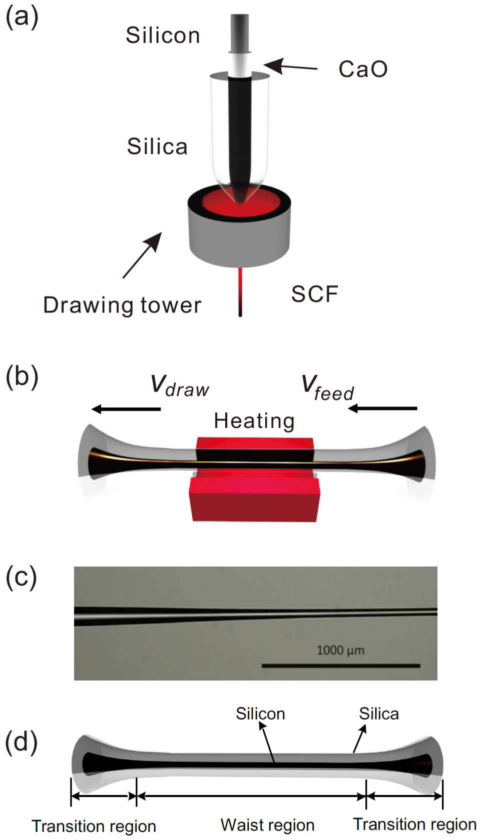

Fig. 1: (a) Schematic of the MCD fabrication process. (b) Schematic of the tapering process to control the crystallinity and dimensions of the silicon core. (c) Microscope image showing the longitudinal profile of a tapered SCF. (d) Schematic showing a tapered fibre design optimised for efficient free space coupling.

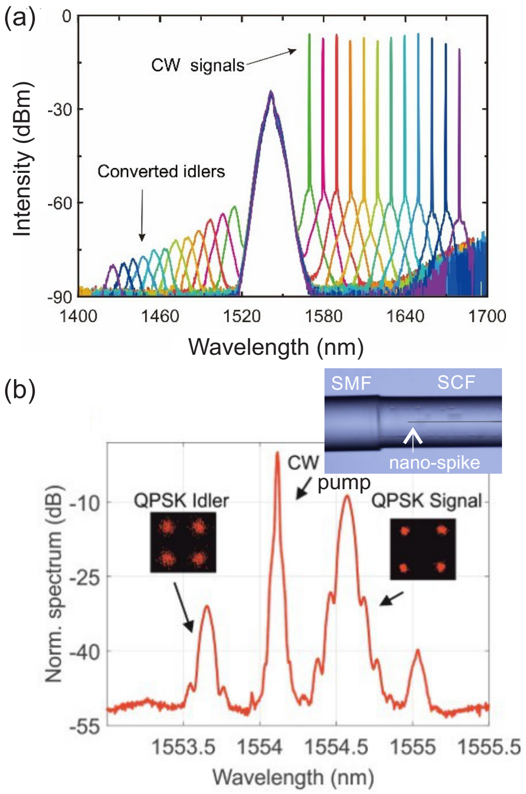

Fig. 2: (a) FWM amplification in a SCF as the signal wavelength is tuned. (b) Wavelength conversion of a QPSK data signal, with the signal and idler constellation diagrams shown as insets. Top inset shows the direct splicing of a SCF to SMF using a nano-spike coupler approach.

Nonlinear Demonstrations

As the nonlinear effects in silicon are dominated by third order susceptibility ($\chi^{(3)}$), much of our work has focused on nonlinear processing via four-wave mixing (FWM). Figure 2 highlights some of our latest results to investigate FWM for use in signal amplification and wavelength conversion in the telecommunications band. Specifically, Fig. 2(a) shows the first demonstration of parametric amplification via FWM in a SCF that was tapered to have a sub-micrometer core diameter to facilitate phase-matching with the $1540\,\mathrm{nm}$ pump[7]. Significantly, as well as demonstrating a broad conversion bandwidth ($\sim 300\,\mathrm{nm}$), this result also reported the first observation of a net optical gain obtained in a silicon waveguide in this wavelength region, where two-photon absorption (TPA) is normally a barrier to high performance. We attributed this excellent performance of the SCF to the low transmission losses, high coupling efficiency, and tailored dispersion of our tapered design. Subsequently, high efficiency FWM wavelength conversion of a $20-$Gb/s bit rate telecom signal was realized using a similar low loss tapered SCF, as shown in Fig. 2(b)[9]. However, this time the SCF was spliced to a single-mode fibre (SMF) input using a nano-spike coupler that was formed in the SCF, as shown in the inset[10]. Significantly, the nano-spike coupler not only helps to ensure efficient mode conversion between the high and low index fibre cores, but it also reduces Fresnel reflection losses, thus allowing for efficient all-fibre integration with the telecoms pump and signal.

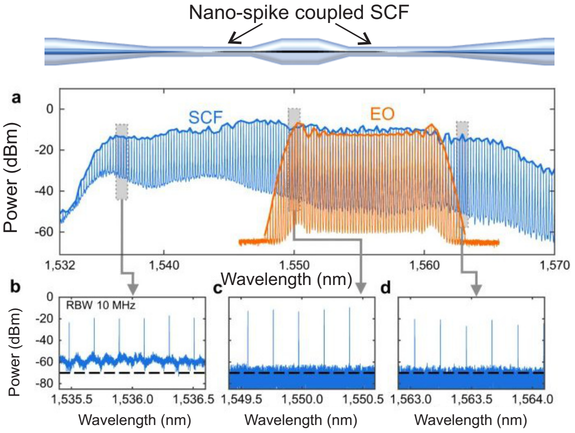

Fig. 3: (a) Spectral broadening of an electro-optic frequency comb with 26 GHz line spacing (orange) via a fully fibre integrated SCF nonlinear wave-mixer (blue). (b-d) Close-up of tone lines at selected wavelengths. Inset at top of figure shows a schematic of the integrated SCF device.

More recently, we have been able to extend our integration methods to produce nano-spike couplers on both ends of the SCF, allowing for the construction of a fully SMF-integrated device that was used to demonstrate a nonlinear wave-mixer (see inset in Fig. 3)[11]. Fig. 3(a) shows the broadening of an electro-optic comb source (orange spectrum), specially designed to exhibit features such as spectral flatness, narrow tone linewidth, high tone power and low noise levels required for applications in telecommunications. The SCF comb (blue spectrum) shows a tripling of the source bandwidth from $10\,\mathrm{nm}$ to $30\,\mathrm{nm}$, obtaining 143 tone lines, whilst preserving all of the key performance features of the original comb, as illustrated by the close up views of the tone lines at three selected wavelength points.

Although the majority of our nonlinear demonstrations have focused on the telecom band, the ability to produce high quality tapered SCF designs with larger core dimensions, of several micrometers, is advantageous for application in the longer, mid-infrared wavelength region. Moreover, as the nonlinear absorption parameters of silicon, such as TPA, typically reduce for increasing pump wavelengths[12], higher power pump sources can be used. Taking advantage of this, Fig. 4(b) shows the generation of a high-brightness supercontinuum spectrum spanning almost two octaves, from the near to the mid-infrared, that was obtained using the asymmetric taper profile shown in Fig. 4(a)[13]. Specifically, the taper was designed with a short output coupling section to minimise the interaction of the long wavelength light with the lossy silica cladding, which enabled the red edge of the spectrum to be extended well beyond the previous results obtained in silica clad, silicon waveguides (by around $2\,\mu\mathrm{m}$). Moreover, thanks to the low transmission losses, and specifically the negligible TPA of the pump, a high conversion efficiency of $\sim 60\,\%$ was obtained, resulting in a supercontinuum source with sufficient power ($\sim 6\,\mathrm{mW}$ average power) for use in mid-infrared gas spectroscopy applications, as illustrated by the strong $\mathrm{CO_2}$ absorption dip. Thus, these results highlight the potential benefits of the SCFs over their planar counterparts in terms of power handling and wavelength coverage.

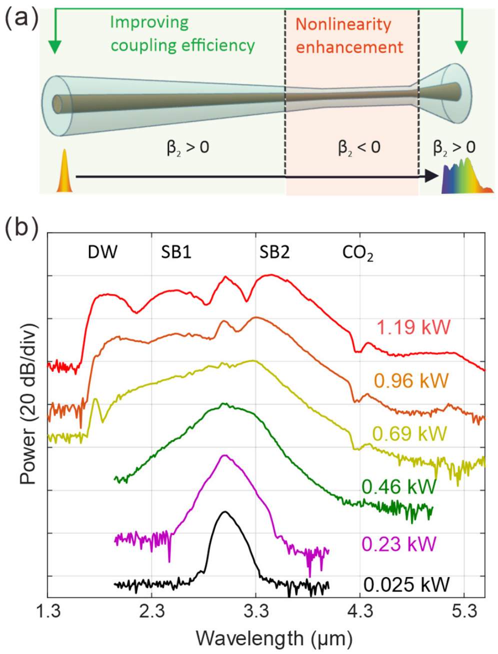

Fig. 4: Supercontinuum generation into the mid-IR using a specially designed taper. The wavelength converted peaks associated with FWM (SB1 and SB2) and dispersive wave (DW) emission are labelled. The black arrow shows the $\mathrm{CO_2}$ absorption dip.

Conclusion

The nonlinear performance of silicon core fibres has been demonstrated, firstly in the telecoms band, where they can find application for all-optical processing, but also in the mid-infrared region, where there is potential for use in spectroscopy and imaging systems. Thus this work highlights the opportunities for SCFs to find use in a wide range of practical all-fibre nonlinear optical systems.

Acknowledgements

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