Parametric frequency comb generation using silicon core fiber

Ronit Sohanpal[1], Haonan Ren[2], Li Shen[3], Callum Deakin[1], Alexander M. Heidt[4], Thomas W. Hawkins[5], John Ballato[5], Ursula J. Gibson[6], Anna C. Peacock[2] and Zhixin Liu[1]

[1] *Department of Electronic and Electrical Engineering, University College London, London, U.K.*
[2] *Optoelectronics Research Centre, University of Southampton, Southampton, U.K.*
[3] *Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, China*
[4] *Institute of Applied Physics, University of Bern, Switzerland*
[5] *Center for Optical Materials Science and Engineering Technologies, and the Department of Materials Science and Engineering, Clemson University, Clemson, USA*
[6] *Department of Physics and Porelabs, Norwegian University of Science and Technology, Trondheim, Norway*

ronit.sohanpal.14@ucl.ac.uk, zhixin.liu@ucl.ac.uk

Abstract: We demonstrate all-fiber frequency comb generation using a 10-mm-length silicon core fiber as the parametric mixer. We achieved 8 dB spectral flatness over 20 nm bandwidth, generating 90 lines at 26 GHz line spacing.

1. Introduction

Optical frequency comb generators (OFCGs) are emerging as promising light sources for optical communications, spectroscopy, and microwave signal processing [1]. For dense wavelength division multiplexing (DWDM) communication systems, they offer many potential advantages including the elimination of optical guard bands for improved spectral efficiency [2], efficient compensation of fiber nonlinearity [3], and joint digital signal processing (DSP) that greatly reduces the DSP complexity [4]. To enable these benefits in practical systems, a frequency comb is required to have a flat spectrum within the telecom transmission window (e.g. telecom C-band 1535-1565 nm), high optical signal-to-noise ratio (OSNR), and stable operation over a wide temperature range.

A popular OFCG is the microresonator-based soliton frequency comb, which has been employed to demonstrate C+L band coherent communications with >30 Tbit/s data rate over a single 75-km span [5]. However, due to its bandwidth significantly exceeding that of the standard C+L telecom bands, the output power and OSNR-per-tone are limited, constraining its applications in long distance DWDM transmission. Mode-locked lasers can achieve higher OSNR within the telecom wavelength range [6]. Nevertheless, the need for a cavity makes them inherently sensitive to temperature variation, a property also apparent in the soliton microcomb. A third method of generating a wide-band frequency comb is optical parametric mixing, either by a nonlinear planar waveguide or a dispersion flattened highly nonlinear fiber (HNLF) [7, 8]. Planar waveguide mixers have the advantage of high nonlinearity and short lengths, which improves stability and significantly reduces the size of the comb generator. However, compared to the HNLF counterparts, they suffer from low output powers and poor coupling due to their small dimensions. An alternative approach is to make use of the silicon core fiber (SCF) platform, which elegantly combines the key advantages of the planar and fiber structures, such as compactness, high power handling, as well as efficient and robust integration with other fiber components [9, 10].

In this paper, we propose and demonstrate frequency comb generation using a 10-mm-long SCF as the parametric mixer. We fabricate a SCF featuring a nonlinear coefficient γ of more than 41 $\mathrm{W^{-1}\,m^{-1}}$, several thousand times that of conventional highly nonlinear fiber, thus requiring a length of only 10 mm for parametric mixing. This short length removes the need for accurate dispersion engineering, significantly simplifying implementation complexity versus conventional HNLF-based parametric comb generators. Moreover, involves direct splicing of the SCF to standard SMF, allowing for robust application in practical systems. Our SCF-based OFCG was optimized to not only reach the target bandwidth of 20 nm, but also to achieve spectral flatness for DWDM transmission.

2. Silicon core fiber (SCF) based parametric mixer

To achieve stable performance, the SCF based parametric mixer is spliced to standard single-mode fibers (SMF-28) by introducing nano-spike couplers at both facets. The as-drawn SCF is fabricated by the molten core drawing technique. [9]. During the process, a silicon rod is inserted inside a high purity silica tube and drawn into fibers using a conventional drawing tower, as shown in Fig. 1(a). To convert the as-drawn SCFs into low loss nonlinear parametric mixer that are robust and user-friendly, a multi-step tapering and splicing approach is employed. This is necessary both to obtain low loss and small core structures required for nonlinear processing, as well as to produce nano-spike mode couplers on each end to facilitate splicing to SMF. The process is illustrated in the schematic of Fig. 1(b). In the first step, the SCF is slightly heated while a small tension is applied along the fiber axis. Owing

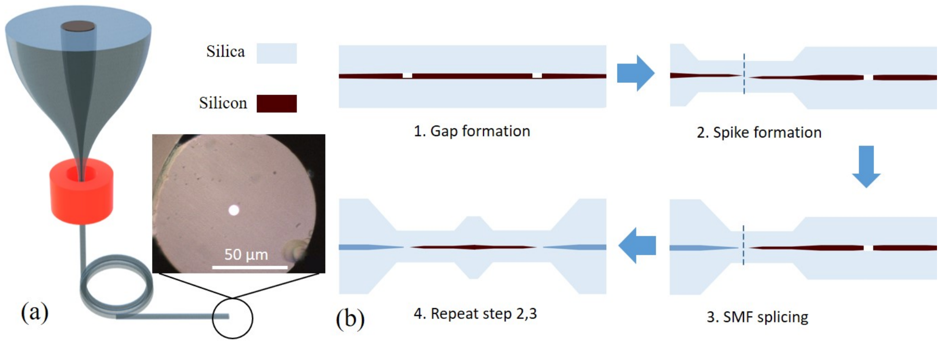

Fig. 1. (a) Schematic drawings of silicon core preform drawn into SCF with microscopy image of a drawn SCF. (b) Fabrication of the nanospike and splicing to a tapered SMF. 1. Gap formation in the core of the SCF. 2. Tapering the SCF and formation of the nanospike. 3. Splicing of the tapered SCF with a tapered SMF. 4. Spicing the other end to a tapered SMF.

to the tensile stress in the as-drawn SCF, as the heated core cools and recrystallizes, a void-gap can form around the heat zone. Another void-gap froms at the other end by repeating this heat and cooling process. Subsequently, a single sweep tapering process is used to reduce the local cladding/core ratio from $125/5\,\mu$m to $27/1.1\,\mu$m over the left-hand side of the fiber, during which the first void-gap collapses to form a spike at the end of the core. The fiber is then precisely cleaved in the core-less region and spliced with a pre-prepared tapered SMF-28 with same cladding diameter. The same procedure is then applied to the right-hand side of the fiber, creating a fully integrated fiber device. The coupling loss is about 8 dB per facet, yielding an end-to-end insertion loss of 19.5 dB. We attribute this insertion loss to the splicing loss of $27\,\mu$m clad fibers and the mode mismatch between the tapered SMF-28 patchcords and the SCF nanospike.

3. Comb generation

The schematic diagram of the OFCG is shown in Fig. 2(a). We first generate a seed comb using two cascaded phase modulators and an intensity modulator, driven with 26 GHz sinusoidal signals and seeded by a 5 kHz linewidth continuous wave (CW) laser emitting at 1555 nm. The output of the electro-optical comb consists of a 26-GHz repetition rate pulse train in the time domain, with each pulse possessing a quasi-linear frequency chirp. As shown in Fig. 2(b), the EO comb consists of 54 tones within 4 dB spectral flatness and an optical signal to noise ratio (OSNR, 0.1 nm noise bandwidth) of about 45 dB. Following the EO comb generation, a spool of 80-m SMF-28 is used to compress the pulses to about 610 fs to increase the peak power for maximized mixer figure of merit for parametric spectral broadening. The time domain pulse shape is characterized using an autocorrelator as shown in Fig. 2(c-d), with Gaussian pulse shapes assumed.

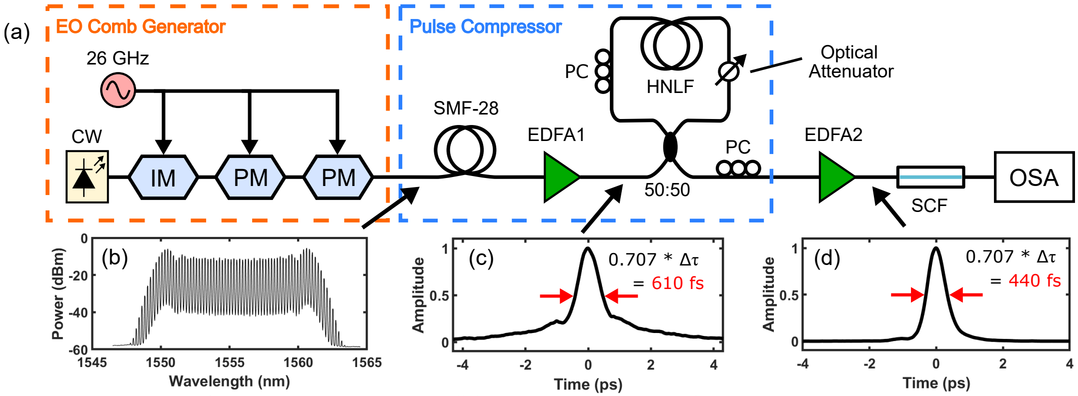

Fig. 2. (a) Optical frequency comb generator utilising spectral broadening of an electro-optic (EO) seed comb in silicon core fiber (SCF). Insets show (b) the spectrum of the seed EO comb, the autocorrelation traces of the pulse train (c) after dispersive compression and (d) after the NOLM, assuming Gaussian pulse shape. IM, intensity modulator; PM, phase modulator; PC, polarisation controller.

To obtain a flat optical spectrum, we use an attenuating nonlinear optical loop mirror (NOLM) to remove any pedestals formed as a result of the nonlinear frequency chirp in the previous stage. The removal of the undesirable pedestals also filters out the peaks at the edges of the EO comb spectrum (Fig. 2(b)), thus resulting in a flat comb after broadening. The NOLM consisted of a 3 dB optical coupler, a 5 dB optical attenuator and a 105 m length of highly non-linear fiber (HNLF), which had a chromatic dispersion of $-0.40\ \mathrm{ps\,nm^{-1}\,km^{-1}}$ at around 1555 nm. This stage acts as an intensity-discriminating gate, transmitting the high power (i.e. peak) region of each pulse while suppressing the low power leading/trailing edges and any pedestals, outputting 440 fs seed pulses into the SCF (Fig. 2(d)). Subsequently, the pulse trains are amplified to an average power of 1W using a dispersion-flattened erbium-doped fiber amplifier (EDFA2) and are launched into the 10 mm sample of tapered SCF before being measured by an optical spectrum analyzer (OSA).

4. Experimental results and discussion

The output spectrum of the SCF-based comb is shown in Fig. 3, indicating 90 lines within a bandwidth of over 20 nm with a flatness of 8 dB. The spectrum was measured by a grating-based OSA at a resolution of 0.02 nm. The close-in spectra near 1545, 1555, and 1563 nm are shown in Fig. 3(b), (c), and (d), respectively, with a resolution of 0.01 nm. We estimate that the $\text{OSNR}_{0.1nm}$ of the comb spectrum is greater than 35 dB at 1555 nm, and greater than 30 dB at 1545 nm. This variation is due to the gain asymmetry of the amplifier (EDFA1) at the NOLM input, which caused an asymmetrical increase in the noise floor.

One of the major limitations on the achievable bandwidth and power was the relatively high insertion loss. Further improvements in the fabrication and integration of the SCFs can reduce this value, allowing for comb generation with greater power efficiency and bandwidth.

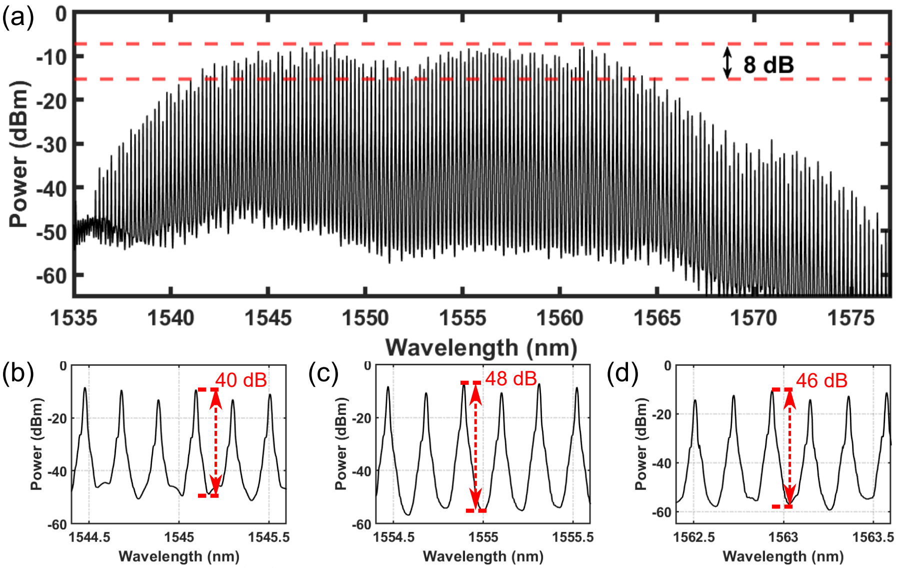

Fig. 3. (a) Measured spectrum of 26 GHz parametric frequency comb spanning more than 20nm, measured with 0.02 nm resolution. Close-in spectra measured at a resolution of 0.01nm are shown in insets below (b-d).

5. Conclusion

We generated a frequency comb via parametric broadening in an all-fiber integrated SCF. The SCF sample used was only 10 mm in length and fully integrated with SMF-28, greatly simplifying the dispersive requirements of the mixing stage and providing robustness for system applications. We achieved a comb flatness of 8 dB over 20 nm, generating 90 lines with an OSNR of greater than 30 dB across the entire bandwidth.

References

[1] V. Torres-Company, J. Schröder, A. Fülöp, M. Mazur, L. Lundberg, O. B. Helgason, M. Karlsson, and P. A. Andrekson, “Laser frequency combs for coherent optical communications,” J. Light. Technol. **37**, 1663–1670 (2019).

[2] Z. Liu, S. Farwell, M. Wale, D. J. Richardson, and R. Slavík, “Inp-based optical comb-locked tunable transmitter,” in *Optical Fiber Communication Conference,* (Optical Society of America, 2016), p. Tu2K.2.

[3] E. Temprana, E. Myslivets, B.-P. Kuo, L. Liu, V. Ataie, N. Alic, and S. Radic, “Overcoming kerr-induced capacity limit in optical fiber transmission,” Science **348**, 1445–1448 (2015).

[4] L. Lundberg, M. Mazur, A. Mirani, B. Foo, J. Schröder, V. Torres-Company, M. Karlsson, and P. A. Andrekson, “Phase-coherent lightwave communications with frequency combs,” Nat. Commun. **11**, 201 (2020).

[5] P. Marin-Palomo, J. N. Kemal, M. Karpov, A. Kordts, J. Pfeifle, M. H. P. Pfeiffer, P. Trocha, S. Wolf, V. Brasch, M. H. Anderson, R. Rosenberger, K. Vijayan, W. Freude, T. J. Kippenberg, and C. Koos, “Microresonator-based solitons for massively parallel coherent optical communications,” Nature **546**, 274–279 (2017).

[6] C. Calò, V. Vujicic, R. Watts, C. Browning, K. Merghem, V. Panapakkam, F. Lelarge, A. Martinez, B.-E. Benkelfat, A. Ramdane *et al.*, “Single-section quantum well mode-locked laser for 400 gb/s ssb-ofdm transmission,” Opt. express **23**, 26442–26449 (2015).

[7] H. Hu, F. Da Ros, M. Pu, F. Ye, K. Ingerslev, E. Porto da Silva, M. Nooruzzaman, Y. Amma, Y. Sasaki, T. Mizuno, Y. Miyamoto, L. Ottaviano, E. Semenova, P. Guan, D. Zibar, M. Galili, K. Yvind, T. Morioka, and L. K. Oxenløwe, “Single-source chip-based frequency comb enabling extreme parallel data transmission,” Nat. Photonics **12**, 469–473 (2018).

[8] B. P. . Kuo, E. Myslivets, V. Ataie, E. G. Temprana, N. Alic, and S. Radic, “Wideband parametric frequency comb as coherent optical carrier,” J. Light. Technol. **31**, 3414–3419 (2013).

[9] J. Ballato, T. Hawkins, P. Foy, R. Stolen, B. Kokuoz, M. Ellison, C. McMillen, J. Reppert, A. M. Rao, M. Daw, S. Sharma, R. Shori, O. Stafsudd, R. R. Rice, and D. R. Powers, “Silicon optical fiber,” Opt. Express **16**, 18675–18683 (2008).

[10] H. Ren, O. Aktas, Y. Franz, A. F. J. Runge, T. Hawkins, J. Ballato, U. J. Gibson, and A. C. Peacock, “Tapered silicon core fibers with nano-spikes for optical coupling via spliced silica fibers,” Opt. Express **25**, 24157–24163 (2017).