A 36-Channel × 10-GHz Spectrally Sliced Pulse Source Based on Supercontinuum Generation in Normally Dispersive Highly Nonlinear Holey Fiber

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***Abstract*—We demonstrate a spectrally sliced pulse source which utilizes supercontinuum generated in a normally dispersive holey fiber and spectral slicing in an arrayed waveguide grating. All 36 10-GHz channels exhibit almost constant pulsewidth and excellent noise properties, as verified by bit-error-rate measurements.**

***Index Terms*—Nonlinear optics, optical fiber communication, optical fiber devices, supercontinuum (SC), wavelength-division multiplexing (WDM).**

I. INTRODUCTION

SUPERCONTINUUM (SC) generation in holey fibers (HFs) has attracted considerable interest in the recent years [1]. Most of the work reported so far has used femtosecond pulsed sources operating in the visible regions of the spectrum and have exploited the fact that HFs, unlike conventional single-mode fibers, can have zero dispersion wavelengths in this wavelength regime. Applications for SC generation include, among others, optical coherence tomography [2] and frequency metrology [3]. High capacity optical communications can also benefit from the availability of a broad-band coherent optical source. An SC pulse source is capable of generating short pulses with a broad spectral content which can be efficiently sliced to provide multiple short pulse wavelength-division-multiplexing (WDM) channels. Previous demonstrations have shown excellent performances [4]–[7], but the relatively long length of fiber used can give rise to issues related to polarization/environmental stability as well as synchronization of the generated pulse trains relative to the seed laser. The use of a much shorter length of polarization-maintaining fiber is essential to avoid these problems. In order to reduce the lengths of fiber required for efficient SC generation, it is necessary to increase the fiber nonlinearity (and/or to increase the input pulse powers). It has recently been experimentally demonstrated that the HFs can have an effective nonlinearity per length coefficient γ as high as 70 $W^{-1}km^{-1}$ in pure silica [8] and more than 640 $W^{-1}km^{-1}$ in compound glass [9]. These values of nonlinearity are more than 20 and 200 times larger than standard dispersion-shifted fiber for silica and compound glass fibers, respectively. This allows the use of much shorter lengths of fiber for this application than had hitherto been possible. Moreover, it has been shown that such fibers can readily be made polarization maintaining by introducing some form of structural asymmetry into the fiber. Fibers with beat lengths of less than 0.3 mm have been obtained in this way [10].

It has been shown that SC generation in the normal dispersion regime has the advantage of allowing the generation of flatter spectra relative to that than can be achieved in anomalously dispersive fiber [11] and less amplitude noise associated with coherence degradation [12]. (It should also be appreciated that the seed pulse shape also influences both SC spectrum flatness and its noise characteristics [13]). In this letter, we demonstrate SC generation and subsequent slicing of the spectrum of a 2-ps soliton pulses from an actively mode-locked laser operating at 10 GHz, using just 20 m of a highly nonlinear polarization-maintaining pure silica HF with normal group velocity dispersion (GVD) around 1550 nm. Using an arrayed waveguide grating (AWG) with 100-GHz channel spacing we were able to generate 36 10-GHz channels in the 1536–1565-nm wavelength range. The pulses of each individual channel were subsequently characterized using second-harmonic generation frequency-resolved optical gating (FROG). Good pulse quality was achieved for all the channels measured and bit-error-rate (BER) measurements confirmed the excellent noise performance of the system.

II. EXPERIMENTAL SETUP AND RESULTS

Our experimental setup is shown in Fig. 1(a). Our source comprises a 10-GHz regeneratively mode-locked erbium fiber ring laser (EFRL) operating at 1553 nm and generates 2.1-ps soliton pulses. These pulses were amplified by an Er–Yb doped fiber amplifier before being free-space coupled onto the HF. (Note that it is possible to splice HFs directly to conventional fibers using standard splicing techniques although it is to be appreciated that attention needs to be paid to mode-matching issues if excessive insertion losses are to be avoided when using such small core fibers). The average power of the pulses launched into the HF was ∼390 mW. This corresponds to a peak power-fiber length product of ∼0.4 W · km which is a factor of 5–10 lower than those used in previous SC source demonstrations [4]–[7].

The HF used was of the same design as that reported in [8]. A cross-sectional scanning electron microscope (SEM) image of the HF is shown in the inset of Fig. 1(b). The core diameter is ∼1.2 μm and the outer diameter is ∼150 μm. The measured loss was 190 dB/km at a wavelength of 1550 nm and the effective

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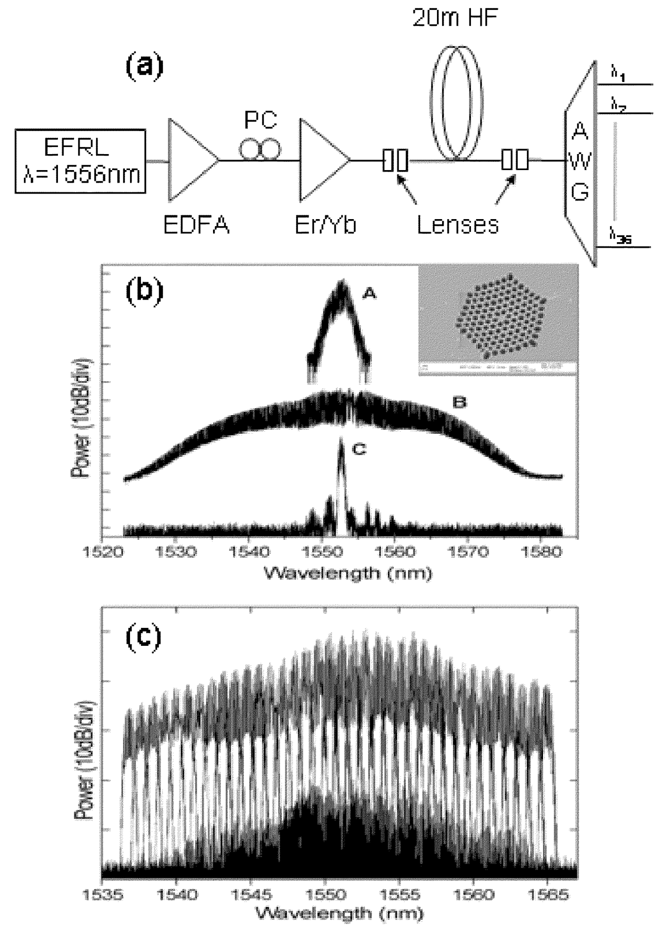

Fig. 1. (a) Experimental setup. (b) Optical spectrum traces of the input, the SC, and one of the filtered channels. Inset: SEM image of the HF. (c) Superposition of each of the sliced spectra.

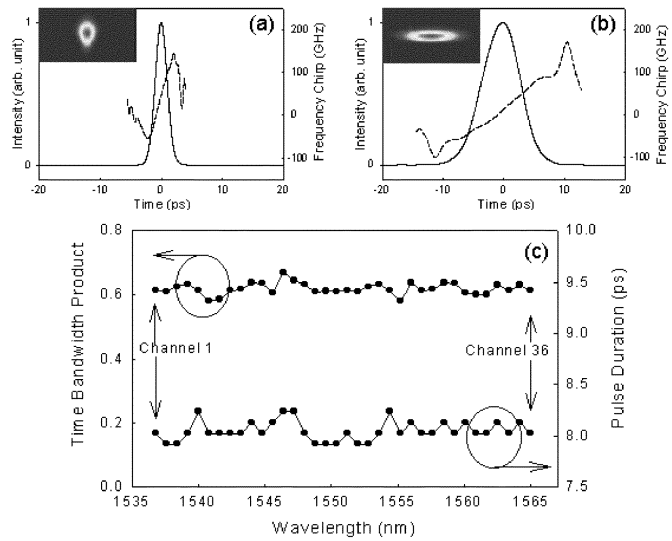

Fig. 2. FROG retrieved pulse shape and frequency chirp of the (a) original soliton pulse and (b) the filtered output. Insets show the corresponding spectrograms. (c) Measured values of the pulsewidth and time-bandwidth product for each of the filtered channels.

length of the 20-m HF was, thus, just 13 m. For this piece of fiber, we measured an effective nonlinearity coefficient γ of $\sim 70+/-10\ \mathrm{W}^{-1}\mathrm{km}^{-1}$, corresponding to an effective mode area A_{eff} of $\sim$1.5 $\mu\mathrm{m}^2$. The measured GVD was ~ -30 ps/nm/km at 1550 nm. The HF exhibited a beat length of $\sim$0.5 mm and provided a polarization extinction ratio of $\sim$17 dB over the 20-m device length. A polarization controller was used before the HF to ensure that the beam was launched onto the fiber's principal polarization axis.

After propagation through the HF, the 10-dB bandwidth of the soliton pulses broadened from 3 to 25 nm due to development of self-phase modulation in the presence of the normal GVD of the fiber. The broadened spectrum was then sliced using an AWG providing a 3-dB bandwidth of 0.63 nm for each of its channels. The channel separation was 100 GHz. Fig. 1(b) shows the optical spectra at different points of the experimental setup, specifically before the HF, after the HF, and at the output of one of the AWG channels (channel 18 in this instance). Fig. 1(c) shows a superposition of the spectra of all 36 channels after the AWG. The average power of the center channel was $\sim$0.5 mW. The signal-to-noise ratio (SNR) for each of the channels was better than 30 dB. Deep 10-GHz longitudinal modes are clearly resolved in all spectral measurements, indicating that the phase coherence properties of the original pulses are maintained.

We used FROG measurements to look at the quality of our pulses. The retrieved pulse shape and the corresponding frequency chirp of the original soliton pulses and one of the filtered outputs (channel 36) are shown in Fig. 2(a) and (b), respectively. The input pulses are seen to have a (slight) linear chirp with a measured time-bandwidth product of $\sim$0.39. We plot the measured pulsewidth and time-bandwidth product of each channel as a function of wavelength in Fig. 2(c). The pulse duration and time bandwidth products were almost constant at $\sim$8 ps and 0.63, respectively, across all channels (estimates were all derived from retrieved FROG data with retrieval error of less than 0.005). The pulse broadening is due largely to the narrow bandwidth of the filtered channels defined by the AWG characteristics relative to the input pulse bandwidth. The relatively high value of time-bandwidth product suggests that the output pulses are also slightly chirped. This was confirmed by FROG measurements at the system output which showed the pulses to have a reasonably linear positive chirp. The pulses should be readily compressible down to $\sim$6.4 ps using further lengths of appropriately dispersive fiber.

To assess the noise performance of the pulses, we performed BER measurements on each of the channels. This was done by modulating the filtered output with a $2^{31}-1$ pseudorandom bit sequence at a data rate of 10 Gb/s. The results for twelve of the channels are summarized in Fig. 3, and eye diagrams of four selected channels, namely channel 1, 13, 24, and 36, are shown in the inset. All channels gave error-free operation and showed similar BER curves. Only the channels furthest away from the seed wavelength showed an appreciable small penalty and even for these channels the penalty was less than 2 dB and which we attribute to the degradation of SNR in this spectral region due to the rolloff in SC efficiency for large wavelength detunings. Some slight intensity noise is also observed on the eye diagrams obtained from these channels. However, it is evident from the eye diagrams shown in the inset of Fig. 3 that high quality

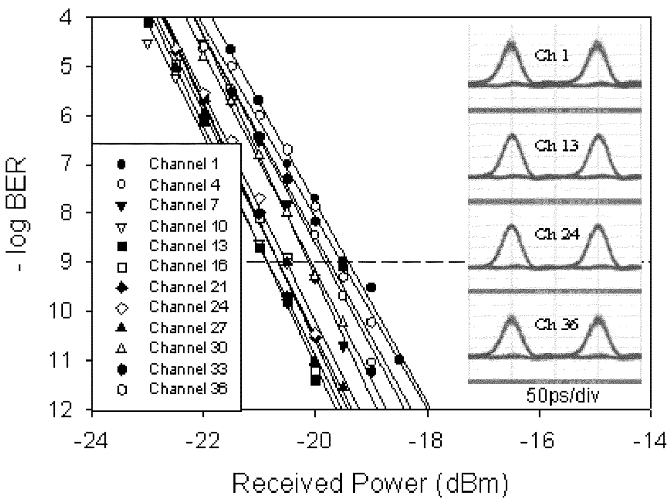

Fig. 3. BER of twelve selected channels. Inset: eye diagrams of four selected channels.

multiwavelength 10-GHz pulses trains were successfully generated. This level of system performance is comparable to that previously reported for SC experiments in more conventional fiber types [4], [5].

III. Conclusion

We have experimentally demonstrated a 10-GHz spectrally sliced pulse source based on just 20 m of polarization maintaining HF. The relatively low input power of ∼390 mW is sufficient to produce 36 channels of high quality WDM pulses. We have shown that the pulsewidth and time-bandwidth product were almost constant across the full wavelength operating range, and that error-free operation was readily achievable for all channels. The short device lengths enabled by the use of highly nonlinear HF enhances system stability and reliability and facilitates ready synchronization of all WDM channels relative to the input seed pulse train. Further extensions in SC source operating bandwidth and channel flatness along with reductions in optical power requirements/device lengths should be possible with realistic improvements in HF fabrication.

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