A Microstructure-Fiber-Based 10-GHz Synchronized Tunable Optical Parametric Oscillator in the 1550-nm Regime

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***Abstract*—We demonstrate a microstructure-fiber (MF)-based supercontinuum source and a synchronously pumped optical parametric oscillator in the 1550-nm regime. By using a 12.5-m-long MF, we obtained a 10-GHz repetition-rate picosecond-pulse source that is capable of ~120-nm wavelength tunability due to the wide-gain bandwidth of the combined processes of stimulated Raman scattering and parametric four-wave mixing.**

***Index Terms*—Nonlinear optics, optical fiber communication, optical fiber devices, optical parametric oscillators, optical pulse generation, supercontinuum generation (SCG).**

I. INTRODUCTION

MICROSTRUCTURE fibers (MFs) are currently a topic of great interest owing to their high nonlinearity per unit length. An effective nonlinear coefficient of 10–100 times higher than that of standard single-mode fibers (SMFs) can be achieved in MFs due to their small effective mode area [1]. Consequently, all of the nonlinear effects that are present in standard optical fibers are expected to be observed in MFs with the latter requiring significantly reduced length and pump power. Because of this advantage, a number of MF-based telecommunication applications have recently been demonstrated, including 2R regeneration [1], Raman amplification [2], wavelength conversion [3], time-domain demultiplexing [4], and all-optical switching [5].

Many applications, particularly in the field of wavelength-division-multiplexing (WDM) communication systems, require wavelength-tunable optical pulse sources with multigigahertz repetition rate. Optical generation schemes based on nonlinear parametric effects in fibers are beneficial for this purpose for two reasons: 1) the wavelength tunability of the oscillating signal is not limited by the erbium-doped fiber amplifier (EDFA) gain band and 2) the fundamental limit on the repetition rate is the time response of the fiber's Kerr nonlinearity, which is in the femtosecond range. A simple means of implementing such a source relies on pulsed supercontinuum generation (SCG) in the fiber followed by spectral slicing. This scheme, however, suffers from reduction of the power spectral density as the wavelength detuning between the desired signal and the pump is increased. Furthermore, it has been shown that the coherence of the generated supercontinuum is limited; it leads to progressive degradation of the spectral modulation depth of the signal pulses as one moves away from the pump wavelength [6], [7]. A more promising approach for implementing a tunable pulse source is a synchronously pumped fiber-optic parametric oscillator (FOPO) [8], [9]. In this approach, the optical oscillation assures coherent light generation, while degradation of the power spectral density with wavelength detuning is avoided through energy flow from the pump to the desired oscillating signal.

Thus far, almost all demonstrations of the SCG [10], [11] and the FOPO [12] using MFs have been in the visible regime. However, for telecommuications applications, one usually requires sources in the spectral region near 1550 nm. Recently, with the use of a soft-glass photonic crystal fiber and 100-fs pulses with a repetition rate of 80 MHz, an ultrabroad SCG was reported around 1550 nm [13]. Here, we report on the operation of a 10-GHz repetition-rate synchronously pumped MF optical parametric oscillator (MFOPO) with 30-nm demonstrated tunability and with potential for over 120-nm tunability in the 1550-nm regime. This MFOPO action is achieved by using only a 12.5-m-long piece of MF with a recently reported parametric gain coefficient of $\sim$200 dB/W/km [14]. We also investigate SCG with spectral broadening that is mainly determined by the combined action of stimulated Raman scattering (SRS) and parametric four-wave mixing (FWM).

II. EXPERIMENTAL SETUP, RESULTS, AND DISCUSSION

The experimental schematic is shown in Fig. 1. The 12.5-m-long piece of MF was fabricated at Crystal-Fiber A/S. The silica core of this fiber has an average diameter of 2.4 (± 0.2) μm and is surrounded by a hexagonal array of approximately 0.8-μm diameter air voids. The total loss through the MF is 1.7 dB, including connector losses on each end of the fiber, the zero-dispersion wavelength is $\lambda_0 = 1544$ (± 3) nm, and the dispersion slope is -0.2 (± 0.05) ps/nm^2/km [14]. The MFOPO is configured as a 27-m-long ring cavity in which the remaining 14.5-m fiber in the loop is standard SMF-28. An intracavity tunable optical bandpass filter (OBF) with a 1-nm bandwidth selects the desired oscillating wavelength. The 6-ps duration pump pulses are obtained from a mode-locked fiber laser operating at 10-GHz repetition rate with wavelength of $\lambda_p = 1537$ nm. After amplification by a high-power EDFA, the

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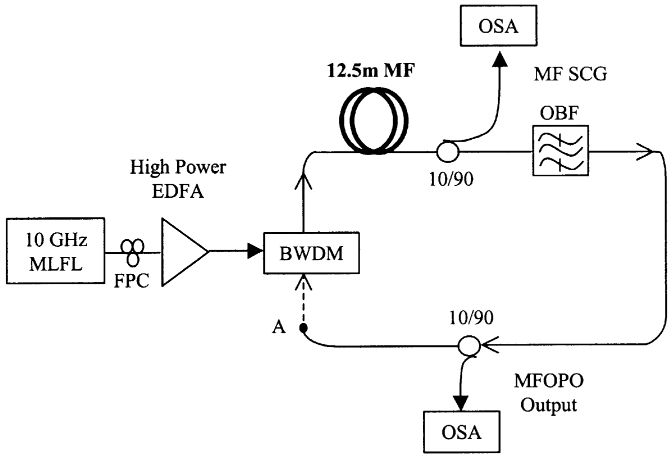

Fig. 1. Experimental setup used to demonstrate MF-based SCG (Point A disconnected) and synchronously pumped parametric oscillation (Point A connected).

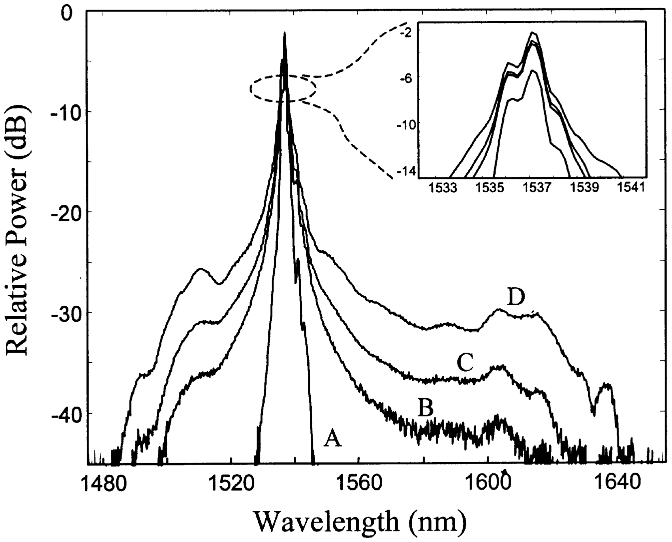

Fig. 2. Plot of the supercontinuum spectra for various pump peak powers launched into the MF. A: $P_p = 1.6$ W, B: $P_p = 3.2$ W, C: $P_p = 4.3$ W, and D: $P_p = 5.9$ W.

pump, whose polarization can be adjusted by means of a fiber polarization controller (FPC), is coupled into the ring cavity using a bandpass wavelength-division multiplexer (BWDM). When the fiber loop is open (i.e., the fiber at Point A is disconnected from the BWDM), the MF's high nonlinear coefficient $\gamma \sim 24$ $\mathrm{W}^{-1}\mathrm{km}^{-1}$ causes the generation of a broad spectrum of supercontinuum at the output of the MF. However, when the loop is closed and the pump repetition rate is adjusted equal to an integer multiple of the cavity free-spectral range (FSR), synchronous MFOPO action is established. Alternatively, an optical delay line can be used in the cavity to adjust the FSR to a subharmonic of a fixed pump repetition rate.

In Fig. 2 we show the open-loop supercontinuum spectra for various launch powers into the MF. Trace D is for 5.9 W pump peak power (354-mW average power) for which the 30-dB-down (relative to the pump) bandwidth of the continuum is 120 nm. The polarization of the input pump pulses was carefully adjusted using the FPC to maximize the SCG spectral width. As is the case for MF-based SCG in the visible regime [11], two features of the spectra shown by Trace D in Fig. 2 are worth noting. 1) The strong peak at 1537 nm (see Fig. 2 inset) that is due to the pump wave has been broadened to a spectral width of approximately 1.5 nm [full-width at half-maximum (FWHM)] owing to self-phase modulation. 2) A broad spectral feature at 1610 nm has emerged, which is down shifted from the pump frequency by ~10 THz, a value corresponding to the maximum of the Raman gain. Consistent with the SCG in the visible regime, the above two features are explained by the combined process of SRS and parametric FWM [11].

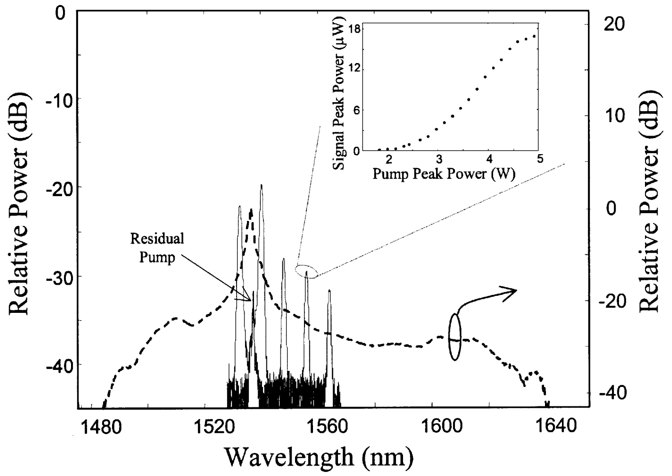

Fig. 3. Composite of the output spectra of the MFOPO for five different oscillating signal wavelengths (thin traces at 1532, 1540, 1548, 1556, and 1564 nm). The dashed curve is the corresponding supercontinuum spectrum for 5.9-W peak pump power. The inset is the measured output-signal peak power versus the pump peak power for the MFOPO oscillating at 1556 nm.

With the loop closed and the cavity length adjusted for oscillations, the spectrum of the pulses taken at the MFOPO output (see Fig. 1) consists of a narrow peak at the OBF passband along with a much weaker peak corresponding to the residual pump. In Fig. 3, we show a composite of the output spectra for five different settings of the OBF, plotting for clarity only the spectrum in the vicinity of the OBF passband in each case. For comparison, the spectrum in the vicinity of the residual pump, which looks similar in all cases, is also plotted for one OBF setting. The pump peak power was 5.9 W and the corresponding supercontinuum spectrum is shown by the dashed trace in Fig. 3. The inset in Fig. 3 shows an example of the measured MFOPO output peak power as a function of the pump peak power injected into the MF. An oscillation threshold is clearly seen as the pump peak power crosses 2 W. The tunability range of the signal wavelength in our setup at present is limited to 30 nm (from 1535 to 1565 nm) by the characteristics of the OBF and the BWDM. However, by using OBF and BWDM with appropriate characteristics, we expect the tuning range to be at least 120 nm. This is because the growth of the supercontinuum over the 120-nm range implies the presence of optical gain through a combination of the Raman and parametric FWM processes. Basically, in the closed-loop configuration, once a portion of the supercontinuum is filtered, the pump wave transfers energy to the signal wave, which experiences gain through the combined action of Raman and parametric FWM processes. Mode-locked

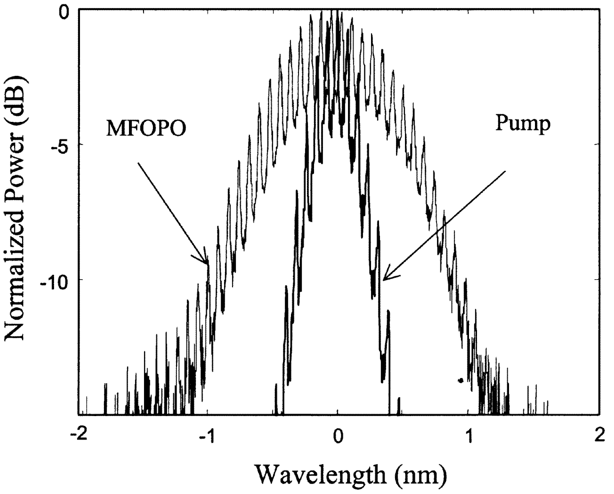

Fig. 4. Opical spectra of the 10-GHz-rate pump source and the MFOPO output (at 1556 nm) with 0.01-nm resolution.

oscillations occur when 1) the signal gain per pass exceeds the 7-dB round-trip loss in the cavity, and 2) the pump repetition rate is equal to a harmonic ($\sim$1350th) of the cavity FSR.

In Fig. 4 we show high-resolution optical spectra of the 10-GHz synchronized oscillating signal pulses at 1556 nm along with the 10-GHz repetition-rate pump pulses launched into the MF. The modulation depth of the 0.08-nm-spaced peaks in the spectrum of the signal pulses is comparable to that in the pump pulses, which is indicative of strong mode locking of the MFOPO. With use of an autocorrelator, the FWHM of the output-signal pulses was measured to be 2.2 ps, which is limited by the 1-nm bandwidth of the OBF. Use of a 3-nm bandwidth filter resulted in $<$1-ps-wide pulses. We note here that with the loop open, the sliced SCG spectrum at the same wavelength (1556 nm) showed no 0.08-nm-spaced modulation and no pulses were observed at the MFOPO output due to severe coherence degradation. The closed-loop configuration, however, results in a coherent 10-GHz-rate optical pulse train, justifying the advantage of the synchronized MFOPO for use as a widely tunable high repetition-rate optical pulse source.

III. CONCLUSION

We have demonstrated an MF synchronized optical parametric oscillator that emits 10-GHz rate picosecond pulses in the 1550-nm telecommunications band. While 30-nm tunability was demonstrated in our setup, this source is capable of more than 120-nm tunability over the entire gain band of the combined Raman and parametric processes. Such a high repetition rate, widely tunable source, would be very useful in high-capacity WDM time-division-multiplexing transmission systems.

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