Broad-Band High-Repetition-Rate Source for Spectrally Sliced WDM

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***Abstract*— A uniform 35-nm-wide spectrum is generated by broadening the output from a 2.5-GHz mode-locked femtosecond fiber laser in dispersion shifted fiber. The obtained spectrum is suitable for spectral slicing and wavelength-division-multiplexed applications. The spectral broadening in dispersion shifted fiber is optimized as a function of the launched pulse chirp parameter.**

***Index Terms*— High-repetition-rate mode-locked laser, mode-locked fiber laser, optical fiber dispersion, optical fiber nonlinearity, pulse propagation in optical fiber, spectral slicing wavelength-division multiplexing, wavelength-division multiplexing.**

BROAD-BAND transmitters with multigigahertz data rates operating in the 1550-nm fiber-optic communications band are key enabling technologies for future wavelength and time division multiplexed (wavelength-division multiplexing and time-division multiplexing) networks. As the number of wavelength channels and data rates grow, using a separate stabilized source for each channel may become less practical. The individual CW sources must be tuned and aligned with the specific wavelength grid of the system. The use of a single, high repetition rate mode-locked erbium-doped fiber (EDF) laser simplifies wavelength stabilization and provides a potentially attractive alternative since its broad output spectrum can be partitioned into a large number of WDM channels [1], [2]. The wavelength channels are selected by passive filtering which facilitates the addition of new channels, and minimizes the affect of wavelength drift on system performance [3], [4]. In comparison with broadened incoherent sources such as those based on amplified spontaneous emission or supercontinuum generation, mode-locked sources do not suffer from beat noise between different portions of the spectrum within a channel, which can limit transmission capacity [5]–[7]. The coherence of the mode-locked source can be used to increase the channel information capacity by techniques such as those used in code-division multiple-access (CDMA) networks [8]. Even higher bitrates per channel can be achieved by time multiplexing the short transform limited (picosecond) pulses generated in each of the spectrally sliced channels.

In this letter, we report the generation of a uniform and flat, 35-nm-wide spectrum centered at 1549 nm from a 2.5-GHz repetition rate, femtosecond fiber laser. For channel spacing of 100 GHz, this spectrum can support over 40 wavelength channels. Our design for the spectral broadening was optimized with numerical simulations and employs commercially available single-mode fiber (SMF), dispersion-shifted fiber (DSF), and an Er-doped fiber amplifier (EDFA). Since the initial femtosecond pulses generated by the mode-locked source have a relatively wide optical bandwidth and high power, additional stages for amplification and pulse compression performed with EDFA's and specialty dispersion decreasing fibers are unnecessary in our scheme [2]–[7].

Spectral broadening in optical fibers is achieved via self-phase modulation (SPM), typically with propagation in the normal group velocity dispersion (GVD) regime to avoid any modulation instabilities, which may occur in the anomalous regime. To prevent discontinuities from forming in the broadened spectrum that typically occur in supercontinuum generation [6], [7], all frequency components must remain within the normal GVD region. This is accomplished with the use of DSF for spectral broadening. Further, to maximize the amount of SPM, the magnitude of the GVD is kept small such that the propagating pulse remains short with high peak intensity [9].

To accumulate the maximum amount of SPM in the presence of nonzero GVD in the DSF, the pulse should propagate the longest possible distance when its peak power is largest or pulsewidth is the narrowest. In a simple approach this could be accomplished by providing the pulse with an initial anomalous chirp prior to injection into the DSF and assuming the pulse would reach its shortest duration some distance into the DSF before broadening again. However, we show that an initial anomalous chirp cannot be completely compensated in the DSF if the SPM is significantly stronger than the GVD. In fact, spectral narrowing rather than broadening occurs during the initial pulse propagation in the DSF. We find that the optimum spectral broadening is achieved when the pulse launched into the DSF is transform limited with minimal initial chirp.

The experimental setup is schematically shown in Fig. 1. A passively mode-locked fiber laser generates 420 fs pulses at a fundamental repetition rate of 180 MHz which can be harmonically mode-locked to 4 GHz with average output powers of approximately 1–2 mW [10], [11]. The experiments reported here were performed with the laser operating at 2 GHz generating an output spectrum centered at 1549 nm with a 3-dB bandwidth of 6 nm. The fiber laser's output propagates through 10 m of SMF, labeled SMF1 in Fig. 1, in the anomalous dispersion regime ($D = 16.0$ ps/nm·km). It is then amplified to 70 mW in a 20-m-long Er-doped fiber amplifier with normal dispersion ($D = -25.2$ ps/nm·km). A second SMF

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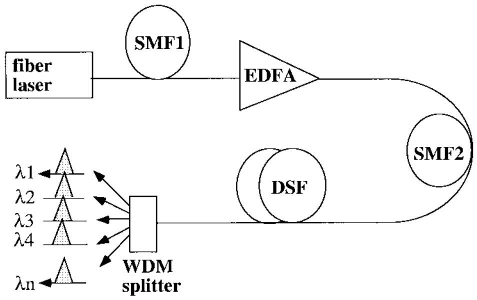
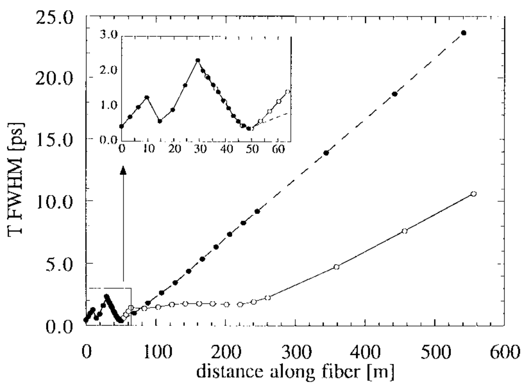
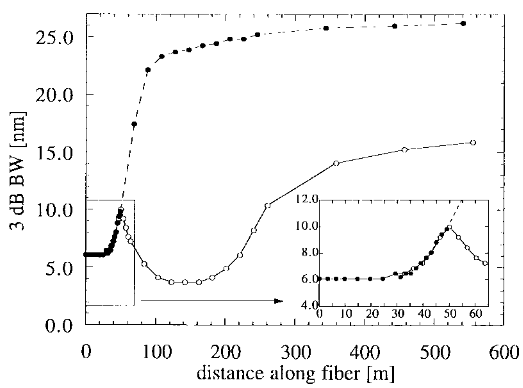


Fig. 1. Experimental setup for spectral broadening. SMF is single mode fiber, DSF is dispersion shifted fiber, EDFA is Er-doped fiber amplifier.



(a)



(b)

Fig. 2. Numerical simulation results of the evolution of the (a) temporal and (b) spectral widths of the pulse as a function of propagation distance in the fiber section for the cases of SMF2 = 35 m (open circles, solid lines) SMF2 = 20 m (filled circles, dashed lines). The insets show the evolutions in the first three fiber sections: SMF1, EDFA, and SMF2.

section, labeled SMF2 in Fig. 1, is spliced to the EDFA output to compensate the negative chirp acquired in the normally dispersive Er-doped fiber. Spectral broadening occurs in the last fiber section which is comprised of 500 m of DSF with a slightly normal GVD ($D = -1.8$ ps/nm·km) at 1550 nm.

We investigate the impact of the initial chirp of the pulse (prior to entering the DSF) on the broadening efficiency numerically and experimentally by varying the length of the SMF2 section between the EDFA and DSF. Numerical simulation results of the pulse temporal width and spectral width evolutions as a function of propagation in the fiber sections are shown in Fig. 2(a) and (b), respectively. Two cases

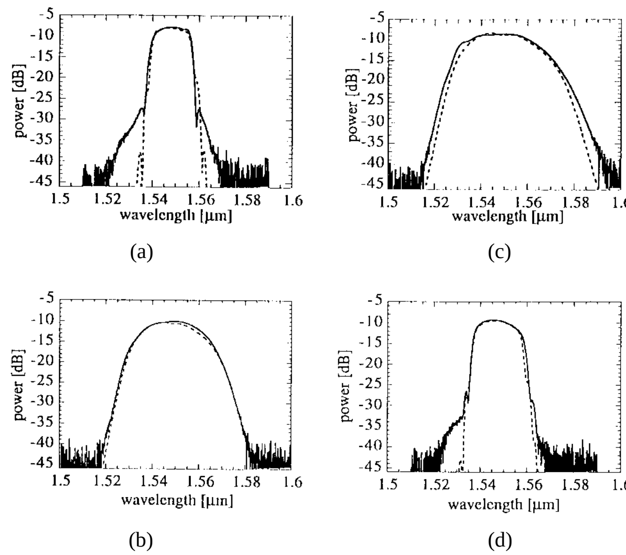


Fig. 3. Final measured spectra for (a) positively prechirped case, (b) nearly transform limited case, and (d) negatively prechirped case. The broadest spectrum achieved with the laser operated at 2.5 GHz is shown in (c). The solid lines correspond to the experimental data, and the dashed lines to the numerical results.

with SMF2 lengths of 35 m (solid lines and open circles) and 20 m (dashed lines and filled circles) are compared and plotted in Fig. 2. In the first case (SMF2 = 35 m), the pulse entering the DSF has an anomalous pre-chirp, and in the second case (SMF2 = 20 m), the pulse is nearly transform limited. As shown in the insets of Fig. 2(a) and (b), the temporal pulse width disperses linearly from 420 fs to 1.26 ps and its spectral width remains constant in the (anomalous GVD) SMF1 section common to both cases. In the following section of the EDFA also common to both cases, the pulse width initially decreases before it broadens due to the normal dispersion of the EDFA accumulating a strong negative (normal) chirp. Its spectrum broadens minimally with amplification from 6 to 6.3 nm. The fourth fiber section consists of DSF with a dispersion length that can be over an order of magnitude larger than the nonlinear length [6].

For the first case, the pulse entering the DSF has an initial anomalous chirp, a 1.44-ps temporal width, and a 7.2-nm 3-dB spectral width. The temporal pulse width decreases only slightly as the initial chirp is compensated by the normal GVD in the DSF, however, the spectrum (3 dB) bandwidth drastically narrows from 7.2 to 3.7 nm (solid lines and open circles in Fig. 2). This spectral narrowing by a factor of two is due to the interplay between the initial chirp and the nonlinearity in the fiber [12], [13]. Further into the DSF, the chirp switches from positive to negative and the spectrum begins to broaden steadily. However, since the pulse duration is also increased the experimentally measured 3-dB bandwidth of the final spectrum measured with a resolution bandwidth of 0.1 nm, is only 16 nm, as shown by the solid line in Fig. 3(a).

In the second case, where 20 m of SMF2 is used to just compensate the chirp and a nearly transform limited 380-fs pulse is launched into the DSF, the spectrum broadens rapidly. The numerical simulation results for this case (filled circles

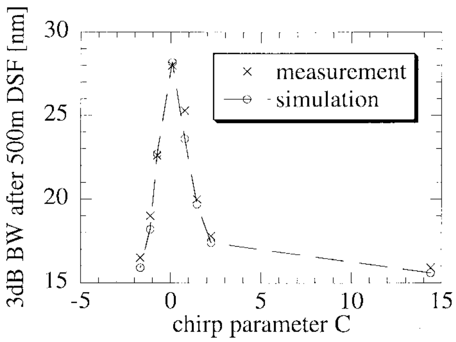


Fig. 4. Final 3-dB spectral bandwidth as a function of the pulse chirp parameter entering the DSF. Experimental values of the chirp parameter (shown by ×) were estimated from the measured pulse time–bandwidth product. Chirp parameters obtained from simulation results are shown with circles. The largest chirp corresponds to no SMF2. Adding SMF2 decreases the chirp, with the smallest value of chirp corresponding to 35 m of SMF2.

and dashed lines in Fig. 2) show that the broadening saturates after approximately 100 m of DSF. The final experimentally measured spectrum in Fig. 3(b) has a 3-dB bandwidth of 28 nm. The broadest spectrum, with a 35-nm-wide 3-dB bandwidth centered at 1549 nm in Fig. 3(c), was achieved with this configuration (SMF2 $= 20$ m) when the laser was operating at a somewhat higher harmonic repetition rate of 2.5 GHz and generated a shorter pulse (TFWHM $= 320$ fs). However, the broadening ratio, of the final to initial optical bandwidths was approximately the same.

A 1×16 WDM splitter was used to slice the broadened spectrum into channels separated by 1.6 nm yielding 16 stable 2.5-GHz pulse trains [14]. To examine the WDM channel quality across the 35-nm-wide spectrum we used a 1-nm optical filter at three different locations: the lowest wavelength channel at 1532 nm, the center channel at 1549 nm, and the longest wavelength channel at 1566 nm, and measured the output pulse autocorrelation. At all three locations the FWHM pulse width assuming a Gaussian pulse shape was 4.2 ps, indicating that the pulses are slightly chirped with an approximately 20% higher time–bandwidth product than the transform limited case.

Providing the pulse with an initial normal (negative) chirp prior to launch into the DSF is accomplished by reducing the length of SMF2 to 10 m. This diminishes the amount of broadening achieved and leads to the measured final spectrum shown in Fig. 3(d) with a 20-nm 3-dB bandwidth. Results from numerical simulations, shown with dashed lines in Fig. 3, are in good agreement with the experiments (solid lines) for all cases. In Fig. 4 the experimentally measured and numerically computed output spectrum bandwidths are plotted as a function of the pulse chirp parameter entering the DSF. The chirp parameter C is defined by fitting the phase of the pulse envelope to phase $= 2Ct^2/T_{\mathrm{FWHM}}^2$, where T_{FWHM} is the pulse full width at half maximum, and t is the time variable across the pulse [9]. The experimentally obtained values were estimated from the measured pulse time–bandwidth product and the assumption of a Gaussian pulse shape. We note that no direct experimental measurements of the pulse chirp parameter were performed. It is clear that the optimized broadened spectrum is obtained when the input pulse chirp, either positive or negative, is minimized.

Uniform spectral broadening can be achieved by propagation of short, transform limited pulses in a DSF with an effective nonlinear length that is significantly shorter than the dispersion length. The obtained smooth and flat spectral bandwidth is a suitable source for WDM applications. Spectrally slicing the broadened spectrum will lead to multiple wavelength channels each with multigigahertz data streams. Since the individual bits in each of the channels are short picosecond pulses further bandwidth utilization can be achieved by TDM techniques.

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