Wavelength and Duration-Tunable 10-GHz 1.3-ps Pulse Source Using Dispersion Decreasing Fiber-Based Distributed Raman Amplification

T. Kogure, *Member, IEEE*, J. H. Lee, *Student Member, IEEE*, and D. J. Richardson

***Abstract*—We experimentally demonstrate a novel pulse compression scheme using dispersion decreasing fiber (DDF)-based distributed Raman amplification. We adiabatically compress 10-GHz 13-ps seed pulses generated using a commercially available electroabsorption modulator into high-quality 1.3-ps pulses in a 20-km DDF-based diode-pumped Raman amplifier. The usual DDF adiabatic soliton compression process is assisted by the distributed Raman gain along the fiber and by control of the input pulse chirp. Both wavelength tunability of about 30 nm and pulse-duration tunability from 1 to 5 ps are also demonstrated.**

***Index Terms*—Distributed amplifiers, nonlinear optics, optical fiber dispersion, optical pulse compression, optical solitons, Raman scattering.**

I. Introduction

ALTHOUGH the by now the mature wavelength-division-multiplexing (WDM) approach can successfully meet the foreseeable growth in demand for capacity in long-haul optical transmission systems, ultrahigh-speed optical time-division multiplexing (OTDM) technologies beyond 40 Gb/s remain of considerable research interest and significance for future optical communication systems [1]. A critical issue in the realization of such high-speed OTDM systems is the development of stable short pulse sources capable of providing high-quality pulses at high-repetition rates.

Adiabatic soliton pulse compression has been considered a simple and promising approach for the generation of high-quality short-duration pulses. This technique enables us to use established pulse carving approaches based on standard telecom qualified components which are capable of reliably generating pulses in the 10–20-ps range, and to compress these pulses down to the desired final pulse duration which ordinarily lies in the 1–5-ps range. Compression factors of 10–20 are, thus, required. A variety of adiabatic pulse compression techniques capable of these levels of compression factor have been demonstrated including those based on dispersion decreasing fibers (DDFs) [2], comb-like dispersion profiled fibers (CDPFs) [3], step-like dispersion profiled fibers [4], distributed Raman amplifiers (DRAs) using uniform fibers [5]–[7], and CDPF followed by DRA [8]. In addition, a chirped soliton compression technique using DRA combined with linear compression after an initial stage of phase modulation has also been demonstrated [9]. Although these technologies can indeed generate short pulses, special care needs to be taken to reduce unwanted pedestals [10], which can cause a fatal transmission penalty for OTDM systems. In order to achieve low pedestal levels, it is essential to make the compression process as adiabatic as possible and this can be difficult to achieve when the input pulse durations are in the 10–20-ps range. In simple DDF-based schemes, the dispersion length associated with such long pulses dictates the use of fibers with multitens of kilometers of length scale in order to reliably guarantee that adiabatic compression is achieved throughout the system. For such device lengths, background fiber loss can have a significant impact on the compression process and limit the degree of compression that can be achieved for physically reasonable ranges of dispersion variation. In pure Raman-based schemes, multitens of kilometers of fiber are also typically required to obtain the net ON–OFF gain needed for practical values of pump power. To date, most Raman-based compression schemes have required $\sim$1 W of input pump power in order to obtain sufficient Raman gain to achieve compression factors of 10–20 and, thus, have required the use of fiber laser-based pump sources rather than semiconductor pump lasers. This has an obvious impact in terms of cost, complexity, noise, and reliability of the system.

One possible way to overcome such problems is to combine the use of DRA and DDF compression in a single fiber. This approach enhances the compression factor for which high-quality adiabatic compression can be achieved for carved seed pulse sources, and reduces the pump power requirements relative to those required for pure DRA compression. Initial results in this direction were presented by Morita *et al.* in 1996 [11], however, a compression of just two was demonstrated for 14.6-ps pulses and only limited data concerning the characteristics of the DDF used and the resulting pulse quality obtained was provided. In this letter, we present detailed results on pulse compression by factors in excess of ten using Raman amplification in a DDF with a dispersion profile matched to the exponential background power loss experienced by pulses propagating through the fiber (i.e., in the absence of DRA). Using this approach, we demonstrate compression of 13-ps Gaussian pulses at a repetition rate 10 GHz from an electroabsorption modulator (EAM), followed by a 125-m dispersion compensating fiber (DCF) for input pulse chirp control, into high-quality 1.3-ps

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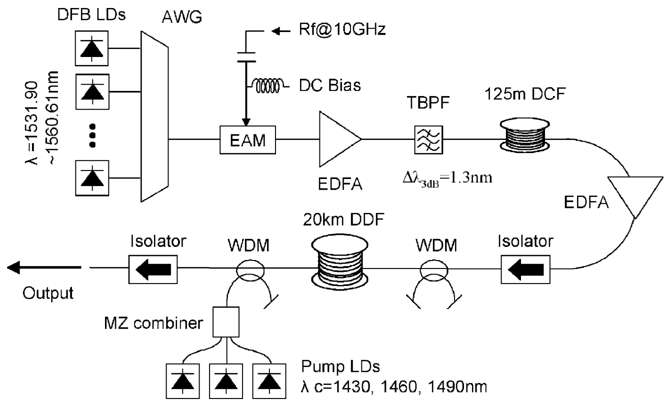

Fig. 1. Experimental setup for wavelength and pulse-duration tunable pulse sources using a DDF-based DRA.

pulses with a high-pedestal extinction ratio of up to −24 dB. Wavelength tunability over 30 nm and pulse duration from 1 to 5 ps are also demonstrated.

II. Experimental Setup

Fig. 1 shows the experimental setup for our DDF-based DRA pulse source. The continuous-wave output from single conventional DFB laser diodes selected from a WDM source bank of 40 similar laser diodes with wavelengths spanning the full C-band via an arrayed waveguide grating was modulated using an EAM driven with a 10-GHz sinusoidal radio-frequency (RF) signal. The resulting 13-ps pulsed optical signal was then amplified by a low-noise erbium-doped fiber amplifier to compensate for the EAM insertion loss and filtered with a 1.3-nm tunable bandpass filter. The pulses were then passed through a 125-m length of DCF in order to obtain Gaussian pulses with a pulse duration of $12 \sim 13$ ps and a slight positive chirp which we found to be beneficial for the nonlinear compression process. These positively chirped pulses were then amplified to an appropriate level for DDF-based DRA compression.

The DDF had a length of 20 km and its dispersion at 1550 nm varied along its length according to an exponential profile, decreasing from 6.0 ps/nm · km at the input to 1.75 ps/nm · km at the output. The third-order dispersion was $0.057\ \mathrm{ps/nm^2} \cdot \mathrm{km}$. The fiber was in fact previously designed and fabricated for loss-compensated soliton transmission applications and, thus, the dispersion profile is matched to the power loss of 0.27 dB/km within the fiber. In the absence of Raman amplification, fundamental solitons propagating in the fiber undergo no change in duration or shape despite the net 5.4-dB fiber loss. Previous measurements on distributed loss and dispersion in this fiber are reported in [12] and [13], respectively.

The Raman pump source comprised three laser diodes operating at a center wavelength of 1430, 1460, and 1490 nm, respectively, and provided launched pump powers of up to 500 mW into the DDF in a counterpropagating geometry. This level of pump power was able to provide up to 8 dB of ON–OFF gain within the fiber which was sufficient to compensate for the total background fiber loss. The Raman pump power required to make the loss-compensated DDF lossless was about 150 mW. Our calculations indicate that the average power of the pulses can be kept constant to 1–2 dB over the full fiber length using a counterpropagating pump scheme. From the perspective of soliton pulses, the Raman gain provides a means to control the effect of background loss and provide compression due to the decreasing dispersion (and any excess Raman gain) along the full fiber length.

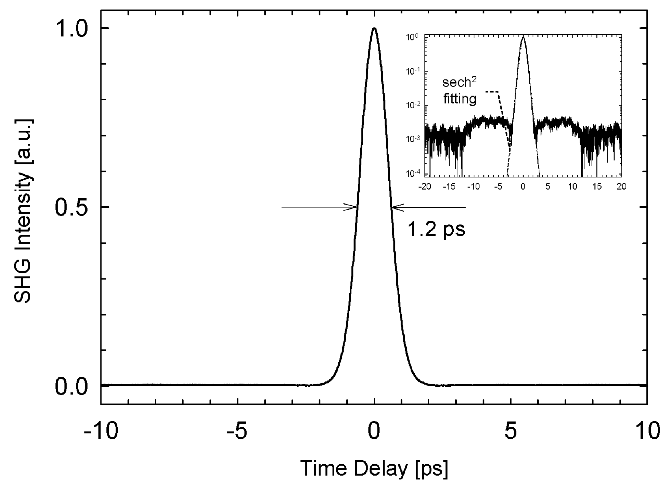

Fig. 2. Measured SHG autocorrelation trace of the output at a wavelength of 1552.19 nm. Inset shows the same figure in log scale.

It should be noted that the typical required launched power into the DDF is only about 13 dBm, and that no RF modulation of the seed DFB laser diode was needed to suppress the effect of stimulated Brillouin scattering as commonly required within many previously reported pulse compression schemes.

III. Experimental Results

Fig. 2 shows the experimental second harmonic generation (SHG) autocorrelation traces of the compressed pulses after the DDF-based DRA at an operating wavelength of 1552.19 nm with a launched Raman pump power 438 mW, which ensured maximum pulse compression. This pump power created an ON–OFF gain of about 8.0 dB. High-quality pedestal soliton pulses with full-width at half-maximum width 1.2 ps were obtained. A pedestal extinction of more than 24 dB was obtained and the pulses fitted well a sech^2 function, as shown in the inset of Fig. 2. Note that in previous DRA experiments in DSF, a pump power of ~600 mW was required to generate pulses of a similar duration although no detailed data on pedestal levels was provided. Fig. 3 shows the corresponding measured optical spectrum of the output pulses. The dashed line over the measured spectrum shows a least squares sech^2 fit, from which we calculate the spectral bandwidth to be about 2.2 nm. Based on this measurement, the time-bandwidth product of the generated pulses is 0.33, indicating that they are close to transform-limited solitons.

In order to confirm the validity of wavelength and pulse-duration tunability of our DDF-based DRA pulse source, we performed SHG autocorrelation measurements of the output pulses by changing the DFB laser diode seed wavelength, and the launched pump power into the DDF, respectively. The results of the wavelength tunability are summarized in Fig. 4. High-quality pulses with a low-pedestal level less than −20 dB and durations as short as 1 ps were obtained over the full wavelength range tested. Note that less than 470 mW of pump power was required at all wavelengths as opposed to previous pure DRA compression schemes [5]–[8] which

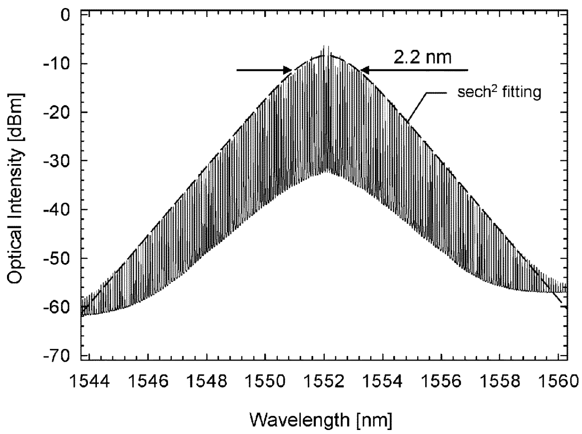

Fig. 3. Measured optical spectrum of the pulses at an operating wavelength of 1552.19 nm.

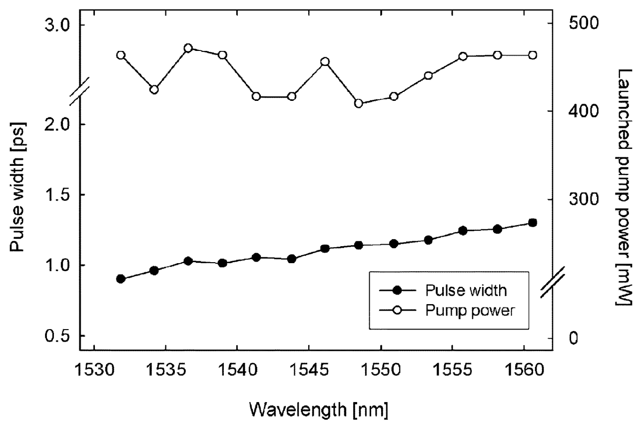

Fig. 4. Measured pulsewidth together with launched pump power as a function of wavelength at a fixed launched signal power.

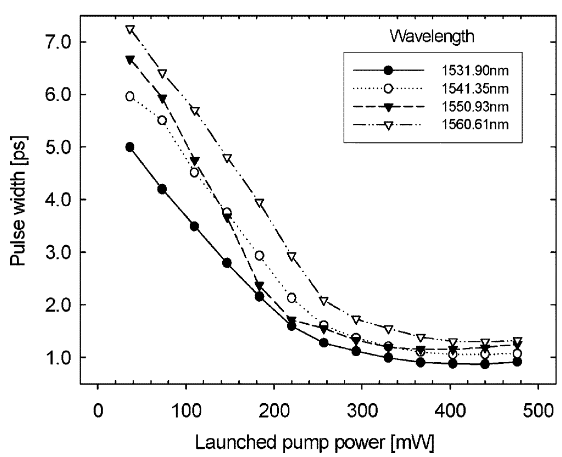

Fig. 5. Measured pulsewidth at various operating wavelengths as a function of launched pump power at a fixed launched signal power.

have required $\sim$1 W of power. The reason that the temporal pulsewidth became shorter at a shorter wavelength is due to the effect of third-order dispersion of our DDF which increases the ratio of input to output dispersion and thereby increases the contribution of the dispersive effects to the compression process. In Fig. 5, the pulse duration tunability at various operating wavelengths as a function of Raman pump power is described. As can be seen, the temporal pulsewidth can easily be varied by a factor of five or more. Both saturation of the pulsewidth and an increase in pedestal level were observed after the pump exceeds an optimum level. This behavior is accordance with our detailed simulations of the system.

IV. Conclusion

We have experimentally demonstrated a stable and reliable wavelength and pulse-duration tunable pulse source operating at a repetition rate of 10 GHz based on an EAM pulse carver followed by DDF-based DRA adiabatic soliton pulse compression. Pulse compression factors in excess of ten were achieved starting from 13-ps input pulses, and high-quality low-pedestal level pulses were obtained. Wavelength tuning over 30 nm and pulse-duration tuning in the range 1–5 ps were demonstrated and high-pulse quality was achieved across the full tuning range. This tunable versatile high-performance source uses solely telecoms qualified modulator and semiconductor pump components and should prove a suitable source for OTDM experiments at data rates of up to 160 Gb/s.

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