High-Power Widely Tunable 40-GHz Pulse Source for 160-Gb/s OTDM Systems Based on Nonlinear Fiber Effects

E. Ciaramella, G. Contestabile, A. D'Errico, C. Loiacono, and M. Presi

***Abstract*—We numerically analyze and experimentally demonstrate an innovative and simple 40-GHz source for 160-Gb/s optical time-division multiplexing. The source is based on nonlinear evolution of a sine-modulated lightwave in a Raman-pumped fiber. Proper nonlinear propagation produces the simultaneous soliton generation and compression. High-power soliton-like pulses are obtained with <1-ps pulsewidth. The source can be tuned over 20 nm and it has more than 100-mW average output power.**

***Index Terms*—Optical communications, optical solitons, optical time-division multiplexing (OTDM), pulse source.**

I. Introduction

OPTICAL time-division-multiplexing (OTDM) systems could be used to transmit at 160 Gb/s and beyond. As 40-Gb/s systems will be available soon, OTDM signals will be obtained by multiplexing 40-Gb/s optical tributaries. In those systems, a short 40-GHz pulse source will play a crucial role, as it is needed at the transmitter and may be required for inline all-optical signal processing.

Several techniques were reported to produce and/or shape optical pulse trains, although most of them operate at 10 GHz. To achieve the 40-GHz repetition rate, sources based on soliton dynamics are particularly attractive because of their intrinsic stability and simplicity. As known, soliton pulses can arise in the anomalous dispersion regime due to nonlinear fiber propagation, mathematically described by the nonlinear Schrödinger equation (NLSE) [1]. Soliton sources at 40 GHz were already demonstrated, exploiting nonlinear evolution of an input sine-modulated lightwave into a regular pulse train. Either a dispersion-tailored [2] or a uniform dispersion-shifted fiber (DSF) [3] can be used as the nonlinear fiber. In the last case, 20% duty cycle is obtained [3], so that 4-ps pulses are obtained at 40 GHz. For OTDM applications, this source would need pulse compression since 160 Gb/s requires pulsewidth values lower than around 2 ps. Indeed, pulse compression might be obtained thanks to another soliton-based technique, i.e., the adiabatic soliton compression (ASC). ASC is based on the relation $\gamma P T_0^2/\beta_2 = 1$, where P and T_0 are the soliton peak power and width, while γ and β_2 are the Kerr coefficient and the chromatic dispersion coefficient of the fiber, respectively [1]. ASC may be attained via propagation along a dispersion decreasing fiber (DDF) [4]: As the dispersion $\beta_2(z)$ is made to properly decrease along the fiber, T_0 is correspondingly reduced. This technique requires careful design and realization of the DDF. As a simpler alternative, ASC could be achieved using a uniform single-mode fiber (SMF) with Raman gain. In this case, a counterpropagating Raman pump (RP) provides a power increase along the fiber, which produces pulse narrowing [5], [6]. Given the previous results, a soliton-based OTDM pulse source might, in principle, be obtained by cascading a soliton-based pulse source and a soliton compressor. However, the resulting setup would be very complex, as it would require first the soliton generation in a DSF and then the ASC in an SMF.

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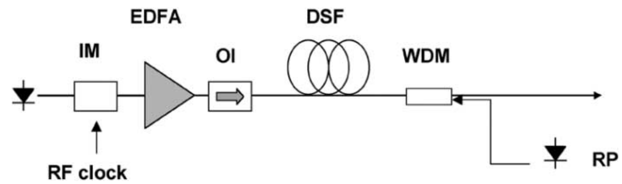

Fig. 1. Considered setup. EDFA: optical amplifier. WDM: wavelength-sensitive multiplexer for the RP.

Here, we present the numerical design and the experimental assessment of a 40-GHz source based on the simultaneous soliton generation and compression in a single uniform DSF. Our scheme is illustrated in Fig. 1. It is based on nonlinear propagation in a uniform DSF with Raman gain, that transforms a 40-GHz sine-modulated wave into a train of short soliton-like pulses. The input signal is produced by external modulation of a continuous-wave (CW) source using an intensity modulator (IM). As the IM is directly driven by a radio-frequency (RF) clock, no synchronization is needed. The fiber is pumped by a counterpropagating RP, which is injected at the fiber end using a wavelength-sensitive multiplexer. An optical isolator (OI) eliminates the residual pump at the fiber input.

II. Numerical Analysis

Numerical simulations are used to check the feasibility of the technique and determine the best operating conditions. To this aim, we consider a uniform DSF 20 km long, with ${\alpha_S}^0 \approx$ 0.23 dB/km loss coefficient at the signal wavelength λ_S, and

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$\gamma = 2\ (\text{W km})^{-1}$. The 40-GHz input signal is produced by means of a Mach–Zehnder IM, as in the experimental setup (described below).

Nonlinear propagation of the signal is simulated using a similar technique as in [7]. We first calculate the time-averaged signal intensity profile $I_S(z)$ produced by the fiber loss and the RP at λ_P (thanks to the counterpropagating configuration, we can neglect the fast time-variation of the signal). To this aim, we numerically solve the usual equations coupling $I_S(z)$ and the pump intensity $I_P(z)$

$$\frac{dI_S}{dz} = g_R I_S I_P - \alpha_S I_S$$
$$\frac{dI_P}{dz} = g_R \frac{\lambda_S}{\lambda_P} I_S I_P + \alpha_P I_P \qquad (1)$$

where λ_P is the pump wavelength, g_R is the Raman gain coefficient, and α_P is the fiber loss at λ_P (around 0.35 dB/km). For the sake of simplicity, we assume that the maximum Raman gain condition ($\lambda_S - \lambda_P \approx 100$ nm [1]) is met so that the Raman gain tilt can be neglected. Solving (1), we get the (varying) gain–loss coefficient for the signal $\alpha_S(z)$ [7] and the ON–OFF Raman gain $G_{\text{on-off}}$; $\alpha_S(z)$ is then inserted into the NLSE

$$i\frac{du}{dz} = -\gamma|u|^2 u + \frac{1}{2}\beta_2 \frac{d^2u}{dt^2} - i\alpha_S(z)u \qquad (2)$$

which is eventually solved by the usual techniques [6].

Simulations are run considering a fixed signal power at the DSF input (30 mW) for a wide variety of combinations of the two most critical parameters, i.e., the dispersion and the Raman gain. For simplicity, in the following, we use D (fiber chromatic dispersion coefficient given in picoseconds/nanometers/kilometers) and $G_{\text{on-off}}$ to account for the two effects. The obtained results significantly depend on these two parameters, as indeed only a proper combination gives the desired soliton-like condition (chirp free and $\leq$1-ps pulsewidth). Namely, $G_{\text{on-off}}$ should be 11$\sim$14 dB. Lower Raman gain gives broader pulses, while excess gain typically results into higher order solitons: Indeed, close to the best operating conditions, the source pulsewidth can be slightly tuned by changing $G_{\text{on-off}}$. As far as the chromatic dispersion is concerned, the optimum value is $D \approx 2$ ps/nm/km, significantly lower compared to values used in [5] and [6] and also quite higher than for fibers with no Raman gain [4] (in the last case, 40-GHz solitons require $D \approx 1$ ps/nm/km [4]). Moreover, the D value is not as critical as in [4]. Indeed, simulations indicate that there is a quite wide range of acceptable D, so that in a practical source, λ_S could be tuned with no critical limitation due to the dispersion slope of the DSF.

We show in Fig. 2 two typical results, obtained for $D =$ 2 ps/nm/km and $G_R = 13$ dB. As D and G_R are optimized, the output pulses are very similar to fundamental solitons. On the left, we report the output pulse train and on the right we show the optical spectrum. The output intensity profile is well matched with a sech^2 fitting [1] and, for each pulse, the product $\gamma P T_0^2/\beta_2$ is very close to one, i.e., the theoretical value for fundamental solitons. Furthermore, the simulated propagation along a loss-less uniform fiber (with the same γ and D) shows no appreciable distortion. These results suggest that the fiber output is very close to a regular soliton train. Finally, we checked the impact of two DSF features previously neglected, i.e., the dispersion slope (S) and polarization-mode dispersion (PMD) coefficient. Both are almost fixed in a commercial DSF and we found that, for typical values, the soliton generation is practically unaffected.

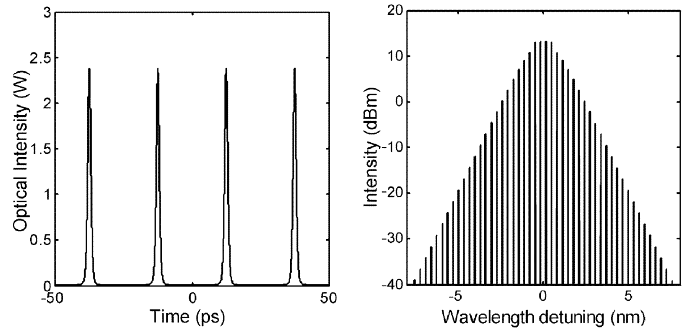

Fig. 2. Numerical simulation results. Solitons produced at 40 GHz, for $D =$ 2 ps/nm/km and 13-dB ON–OFF Raman gain. Left: pulse train. Right: optical spectrum.

III. Experimental Results

Using the above numerical results as a guideline, we experimentally assessed the validity of the technique. We used a 20-km-long DSF with zero dispersion wavelength $\lambda_0 = 1535$ nm, $S = 0.07$ ps/nm^2/km and around 0.2-ps average PMD. The CW source is a DFB laser, chosen so that it emits around 1560 nm, where the DSF dispersion D is indeed very close to the simulation optimum. The CW output source is modulated by a 40-GHz $LiNbO_3$ IM, driven by a 20-GHz RF wave. As the IM is biased at null point, a 40-GHz modulation is obtained [2] and a carrier-suppressed (CS) signal is produced. The RP is a fiber laser emitting at 1460 nm, giving the Raman peak gain around 1560 nm. The pump relative intensity noise (RIN) is around -110 dB/Hz. As we use the counterpropagating configuration, the RIN transfer to the signal is actually negligible (around -50-dB typical power fluctuation is estimated following [8]).

In this condition, we obtain high-quality $\approx$1-ps-wide soliton trains for $G_R \approx 13$ dB, with a very high output power ($\approx$150 mW). Two typical results are shown in Fig. 3. On the left, we report the intensity trace of the pulse train, which was taken by means of fast optical sampling oscilloscope (800-GHz bandwidth). As can be seen, a regular 40-GHz train of short pulses is obtained experimentally with less than 1-ps width. On the right, we show the corresponding output spectrum. As can be seen, there is a good agreement with simulation results, which is particularly apparent considering the triangular envelope of the spectrum, a clear indication of solitons [1]. Typical pulsewidth value is around 0.8 ps and the time-bandwidth product is around 0.30$\sim$0.35, very close to 0.315, i.e., the theoretical value for fundamental solitons. In the optical spectrum, we have the 40-GHz harmonics, but some 20-GHz tones are also present at quite lower intensity: These arise because we cannot bias the IM exactly at null point, which leaves a residual trace of the original 20-GHz RF. As the input lightwave, the generated sequence is CS (i.e., made of pulses with alternating phase). This feature may have positive applications, however, it can be avoided by using a conventional 40-GHz modulation scheme.

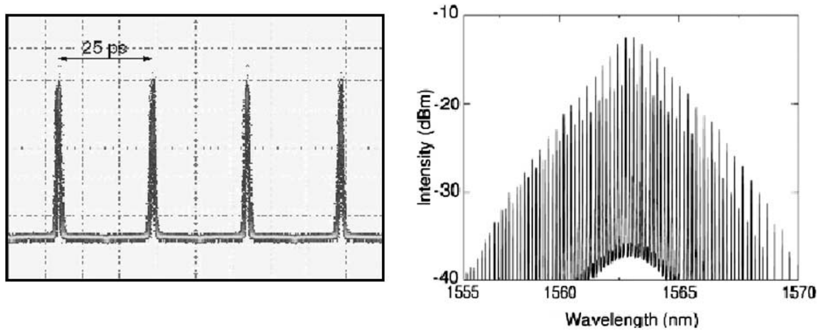

Fig. 3. Experimental results. Left: trace taken with an optical sampling oscilloscope (800-GHz bandwidth). Right: optical spectrum. Same parameters as in Fig. 2.

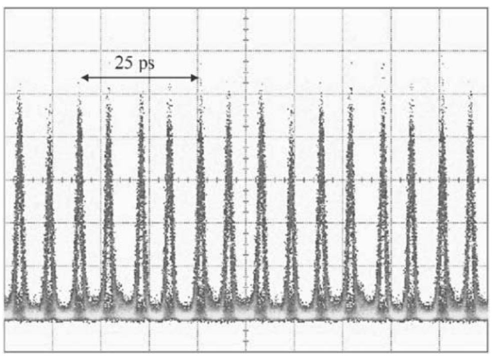

Fig. 4. Eye diagram of the 160-Gb/s OTDM signal (taken with a 800-GHz oscilloscope).

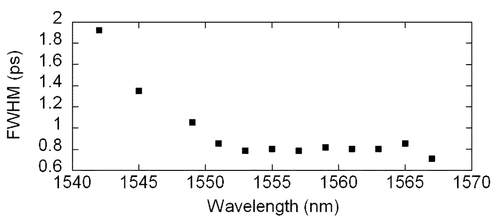

Fig. 5. Measured full-width at half-maximum (FWHM) as a function of pulse central wavelength.

We assess the validity of this source for 160-Gb/s OTDM applications. To this aim, we first modulate the source using another IM and a pseudorandom binary sequence synchronous to the RF clock. We use a commercial optical time-domain multiplexer to produce a 160-Gb/s OTDM signal. As can be seen in Fig. 4, the eye diagram at 160 Gb/s shows an high extinction ratio between pulses, indicating that no significant pulse overlap arises in the 160-Gb/s bit time. We outline that, thanks to the narrow pulsewidth and no pedestal, the same source could be used even for 320-Gb/s OTDM. The pulsewidth can be increased by lowering the Raman gain, as in [6]. On the other hand, increasing the Raman gain cannot always lead to pulse narrowing, since the adiabatic condition is no longer met. In our case, around 0.7 ps seems to be the lowest pulsewidth achievable while keeping a soliton-like shape.

Finally, we checked the source tunability. To this aim, we replaced the DFB laser with a tunable laser (TL). By moving the wavelength of the TL, the source produces pulses with an almost constant width over around 20 nm, as we show in Fig. 5. On the lower wavelength side, the source tends to produce broader pulses, due to lower Raman gain and to the gain tilt. On the other hand, on the longer wavelength side, the source operation is limited by the erbium-doped fiber amplifier (EDFA) bandwidth. Note that, according to simulations, we could have a much broader tuning range, if using EDFA with broader band together with a flat Raman gain (which can be achieved by multiple RPs).

IV. Conclusion

We presented a very simple and effective pulse source with 40-GHz repetition rate for 160-Gb/s OTDM. The source is based on nonlinear propagation in a Raman pumped DSF, which provides simultaneous soliton generation and compression. It produces a high-power (>100 mW) soliton-like pulse train with less than 1-ps pulsewidth over 20-nm tuning range. The pulse repetition rate is synchronous to an external RF clock so that no jitter control is required. A 160-Gb/s eye diagram demonstrates the effectiveness for very high-speed OTDM. In the present version, this source produces a CS pulse train: If needed, the CS feature can be removed easily.

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