All-Fibered High-Quality Stable 20-GHz and 40-GHz Picosecond Pulse Generators

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I. El Mansouri, J. Fatome, S. Pitois, C. Finot, and M. Lintz

***Abstract*— In this work, we investigate the generation of stable 20- and 40-GHz pulse trains through the nonlinear compression of an initial beat-signal in a cavity-less optical-fiber-based device. Enhanced temporal stability is achieved by generating the sinusoidal beating thanks to a commercial $LiNbO_3$ intensity modulator driven by a half repetition-rate external RF clock. We also show that the residual timing jitter induced by the RF phase modulation imposed to suppress Brillouin back-scattering can be reduced by managing the cumulated dispersion of the compression line, whereas complete polarization stabilization is obtained owing to a modified setup involving a Faraday rotator mirror. Finally, a high-quality 160-Gbit/s signal is generated from our low duty-cycle 40-GHz pulse source through optical time-division multiplexing.**

***Index Terms*— Lasers sources, Nonlinear optics in fibers.**

I. Introduction

Optical sources emitting picosecond pulses at very high repetition rates are now widely employed in many scientific applications such as waveform measurement, ultra-high capacity telecommunication systems, clock generation, metrology or component testing. Among all the so far reported techniques, those based on the nonlinear reshaping of an initial signal propagating in optical fiber were proved to be attractive and efficient ways to generate such high repetition pulse trains [1]-[7]. Especially, the method based on the progressive compression of an initial beat-signal through a multiple Four-Wave Mixing (FWM) process taking place in an anomalous dispersion fiber has been successfully implemented for the generation of high quality pulses with repetition rate ranging from 20 GHz up to 2 THz [2]-[3]. In these previous experiments, the initial sinusoidal signal was originally synthesized through the superposition of two continuous waves frequency separated by the desired repetition rate. The key advantage of this all-optical method is that the repetition rate, which is simply determined by the frequency separation between the two diodes, can be widely tunable and as high as several THz, far beyond the electronic bandwidth limits. Unfortunately, in such a configuration, large synchronous instability is observed, essentially due to rapid fluctuations of the relative frequency separation between the two free-running diodes. Therefore, practical applications where stable clock reference is required can be jeopardized. To overcome this issue, relatively complex setups have to be implemented, which involves for instance stabilized optical combs [6] or phase-locking of the two laser diodes against a RF reference [8]. In this work, we use a single laser diode combined with a commercial standard $LiNbO_3$ intensity modulator driven at its zero-transmission working point by a half repetition-rate RF clock. This technique enables us to generate a twofold frequency carrier-suppressed initial beat-signal and thus to minimize repetition rate fluctuations in the generated 20- and 40-GHz pulse trains [9]. Moreover, we demonstrate that the RF phase modulation, usually imposed to prevent from stimulated Brillouin back-scattering, induces temporal fluctuations, which can be simply reduced by compensating for the global chromatic dispersion of the system. In a next section, we also introduce a modified scheme implying the return of light in a half-long segment of fiber ended by a Faraday mirror, which allows to efficiently vanish polarization fluctuations. Finally, we report the generation of a 160-Gbit/s OTDM (Optical Time-Division Multiplexing) signal from a low duty-cycle 40 GHz pulse train.

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II. Experimental setup

A schematic of our pulse generator is provided in Fig. 1. An external cavity laser diode (ECL) is used to generate a continuous wave centred around 1555 nm. A $LiNbO_3$ intensity modulator, driven by a 10-GHz (20-GHz) external RF clock around its zero-transmission point, is then employed to double the repetition rate and therefore to generate the initial beat-signal at 20 GHz (40 GHz). A programmable liquid-crystal-based optical filter, centred on each of the dual pumps is also added in order to eliminate half-repetition rate undesirable residual spectral bands. A phase modulator, driven at 100 MHz, is then inserted to increase the stimulated Brillouin scattering (SBS) threshold well above the power involved in our experiments. The resulting beat-signal is amplified to the desired average power by means of an Erbium doped fiber amplifier (EDFA) before injection into the compression fiber: 21-dBm, 7.8-km (26-dBm, 2.1-km) of standard single mode fiber (SMF-28) for 20-GHz (40-GHz) pulse source, respectively. At signal wavelength, the compression fiber provides a chromatic dispersion D of 17 $ps.nm^{-1}.km^{-1}$ and a nonlinear Kerr coefficient γ of 1.3 $W^{-1}.km^{-1}$. At the output of the fiber, the generated pulse train is finally characterized in the time domain by means of an optical sampling oscilloscope

(OSO) as well as in the spectral domain thanks to an optical spectrum analyzer (OSA).

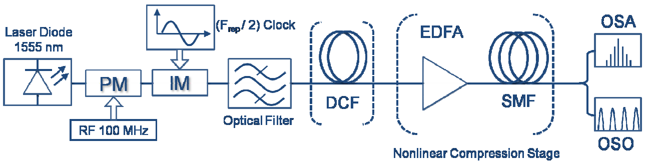

Fig. 1. Experimental setup. PM: Phase Modulator, IM: Intensity Modulator, DCF: Dispersion Compensating Fiber, EDFA: Erbium Doped Fiber Amplifier, OSA: Optical Spectrum Analyzer, OSO: Optical Sampling Oscilloscope.

III. Impact of the RF Phase Modulation

We have first studied the impact of the MHz phase modulation used to prevent SBS on the temporal features of the generated pulses. To this aim, let us consider the electrical field at the output of the phase modulator as:

$$E_1 = E_0 \exp(i\ M \sin(\Omega_M\ t))\,, \qquad (1)$$

where M and Ω_M are the amplitude and frequency of the RF phase modulation, respectively, and

$$E_0 = A_1 \exp(-i\ \Omega_0\ t/2) + A_2 \exp(i\ \Omega_0\ t/2) \qquad (2)$$

represents the initial sinusoidal beating at frequency Ω_0. By using simple physical arguments, it can be shown that this phase modulation translates into fluctuations of the time-period all along the pulse train, whose magnitude is:

$$\Delta T_0 = 2\int_{z=0}^{L}\left[\sum_{n=1}^{\infty}\frac{1}{(2n-1)!}\beta_{2n}(z)\,(M\Omega_M)^{2n-1}\right]dz \quad (3)$$

where $\beta_k(z)$ is the k-order chromatic dispersion coefficient at distance z. By taking into account only the group-velocity dispersion β_2, the resulting timing jitter can be expressed as:

$$\Delta T_0 = 2\ M\ \Omega_M \int_{z=0}^{L} \beta_2(z)\ dz\,. \qquad (4)$$

The most important point here is that these timing fluctuations are directly proportional to the cumulated dispersion of the compression line. Consequently, they can be significantly reduced in our setup by inserting a segment of normally dispersive fiber so as to pre-compensate for the global dispersion of the device, for instance a dispersion compensating fiber (DCF).

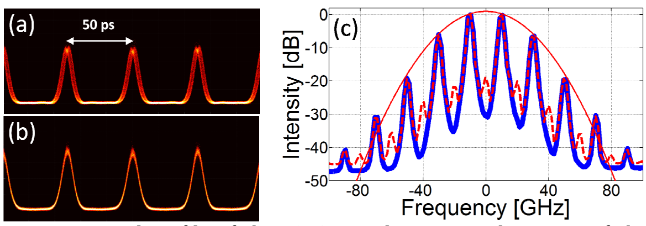

Fig. 2. Temporal profile of the 20 GHz pulse train at the output of the compressor line, without (a) and with (b) DCF (c) Optical spectrum without (red dashed line) and with optical filter (blue solid line). The red solid line is a Gaussian fit of the spectral intensity profile.

To illustrate that point, Fig. 2a shows the temporal waveform of a 20-GHz pulse train generated at the output of the 7.8-km long SMF-28 when a phase modulation of amplitude M = 2.5π rad and frequency Ω_M = 180 MHz is applied. As can be seen, 11.5-ps well-separated quasi-Gaussian pulses, with low pedestals, are generated with a time period of 50 ps. However, and as theoretically predicted, a non-negligible amount of timing jitter can be observed (3 ps) due to the MHz phase modulation. Therefore, this deleterious effect can be simply managed by inserting a 1.4-km long segment of DCF (D = -88 ps.nm^{-1}.km^{-1}) just before the EDFA, so as to compensate for the cumulated dispersion of the line without altering the nonlinear compression process. The resulting eye-diagram is shown in Fig. 2b where we clearly demonstrate a significant reduction of the timing jitter (250 fs), in good agreement with the theoretical predictions.

Fig. 2c represents the corresponding optical spectrum at the output of the fiber. We observe a typical 20-GHz comb-spectrum with numerous spectral components arising from the multiple FWM process. The envelope is well fitted by a Gaussian function with a full-width at half maximum (FWHM) of 43 GHz. The time bandwidth product of 0.5, indicates that the generated pulses are nearly transform limited. On the other hand, we can also clearly see the influence of an initial filtering, with an efficient suppression of the 10-GHz sub-harmonic sidebands. Indeed, an independent measurement based on the electrical RF spectrum analysis confirms that initial filtering allows reduction of these 10-GHz sub-harmonics by 30 dB. Note however that the presence of these sub-harmonic sidebands do not modify significantly the overall output intensity profile.

IV. Management of the Polarization Fluctuations

In a second experiment, we have slightly modified the setup by cutting half of the SMF segment. Therefore and in order to conserve the same efficient length, a Faraday Rotator Mirror (FRM) as well as an optical circulator were inserted at each end so as to benefit from the inverse return of light in the fiber. The aim of this novel arrangement (illustrated in Fig. 3a) is thus to manage the unavoidable polarization fluctuations associated with the use of a non-polarization maintaining optical fiber. Note that the initial average power was slightly increased from 21.4 to 22.3 dBm so as to compensate for the insertion losses of both additional components.

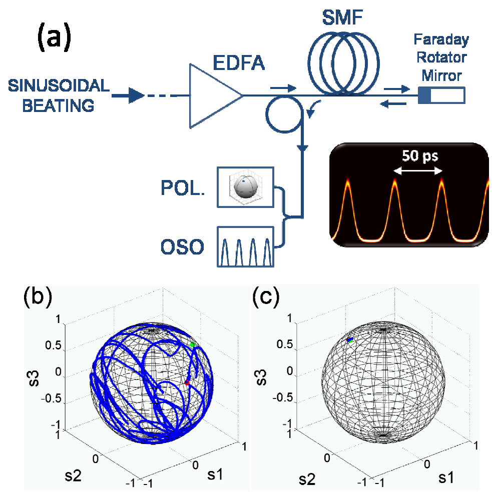

Fig. 3. (a) Experimental setup used to manage polarization fluctuations and including a Faraday Rotator Mirror, Inset shows the resulting 20-GHz temporal profile (b) Poincaré sphere obtained at the output of the 7.8-km long SMF segment (c) Poincaré sphere recorded when using the return of light in 3.9 km of SMF and a FRM.

Let us recall that using a FRM in a fibered system provides the states of polarization (SOP) of the forward and reflected light beams to be orthogonal to each other at any point of the fiber, regardless its birefringence and SOP evolution along the fiber length. In this experiment, we take advantage of this property to eliminate polarization fluctuations in our 20-GHz pulse train generator. Fig. 3b shows the evolution on the Poincaré sphere of the SOP of the pulse train at the output of the compressor when the initial 7.8-km long SMF segment (setup in Fig. 1) is used. Artificial polarization variations were introduced by means of a mechanical stress applied on the compression fiber. As can be seen, the SOP of the pulse train at the system output undergoes substantial fluctuations, which can be detrimental for number of polarization-dependent applications. On the other hand, when using the modified scheme including half of SMF and a FRM, polarization fluctuations are completely vanished (Fig. 3c), thus demonstrating the polarization stability of our pulse source. Note that the temporal profile is quasi conserved (inset in Fig. 3a) with a FWHM of 11.7 ps.

V. Generation of low duty-cycle pulse trains

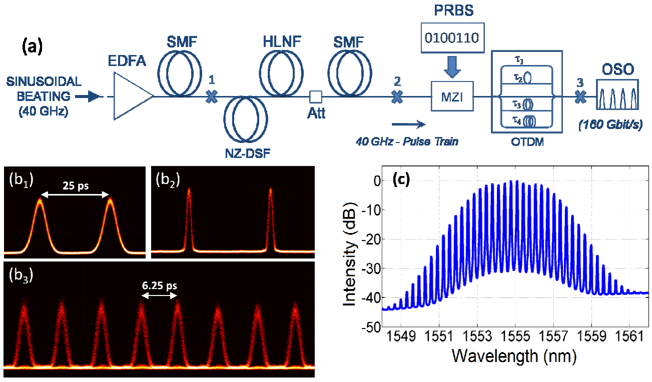

Fig. 4. (a) Experimental setup used to generate low duty-cycle pulse trains at 40 GHz and 160-Gbit/s PRBS OTDM signal. (b_1), (b_2) and (b_3): Intensity profiles of the pulse train at points 1, 2 and 3. (c) Optical spectrum at point 3.

Finally, much lower duty-cycle pulse trains were also achieved at 40 GHz by using a compressor line based on 4 segments of fiber with adequate dispersion and nonlinearity [10] (see Fig. 4a). As in the above 20-GHz experiment described in Fig. 1, an initial beat-signal at 40 GHz is first generated by means of a $LiNbO_3$ intensity modulator driven by a half repetition rate RF clock. The sinusoidal signal is then boosted to an average power of 26 dBm and nonlinearly reshaped into well-separated 5.5-ps Gaussian pulses in the first stage (2.1 km of SMF-28), as shown in Fig. 4(b_1). The second stage consists in a 1270-m long non-zero dispersion fiber (NZ-DSF) with dispersion D = - 2.5 $ps.nm^{-1}.km^{-1}$ and a nonlinear Kerr coefficient γ = 1.7 $W^{-1}.km^{-1}$. This normally dispersive fiber allows to reshape the Gaussian pulses into linearly-chirped parabolic pulses [11]. A highly nonlinear fiber (HNLF), with D = -1 $ps.nm^{-1}.km^{-1}$ and γ = 10 $W^{-1}.km^{-1}$ is then inserted to enhance the amount of linear chirp. Finally, pulses are temporally re-compressed into 145 m of SMF-28. An optical attenuator was inserted before the SMF to ensure a linear propagation regime in this last stage. As can be seen in Fig. 4(b_2), high quality pulses with duty-cycle as low as 1/17 (FWHM = 1.5 ps) can be obtained. The associated spectrum (Fig. 3c) further highlights the quality of the resulting 40-GHz pulse train. In order to assess the suitability of the source for OTDM applications, the pulse train has been encoded by a 40-Gbit/s 2^{31}–1 pseudo-random binary sequence (PRBS) in a $LiNbO_3$ intensity modulator so as to generate a 40-Gbit/s Return-to-Zero (RZ) optical data stream. An OTDM 160-Gbit/s RZ signal was then generated thanks to a (x4) bit rate multiplier (BRM). The resulting good quality eye-diagram is finally visible in Fig. 4(b_3).

VI. Conclusion

In conclusion, high quality pulse trains have been generated at 20 GHz and 40 GHz by means of the nonlinear compression of an initial sinusoidal beating obtained by a $LiNbO_3$ intensity modulator, driven in frequency at half of the desire repetition rate. Moreover, we have demonstrated theoretically and experimentally that inserting a piece of DCF before the compression line can significantly reduce the timing jitter induced by the RF phase modulation involved to suppress Brillouin scattering. By designing a modified setup including a Faraday rotator mirror, we have also successfully shown that it is possible to obtain simultaneously nonlinear compression and polarization stabilization of the light beam. Finally, we have generated a low duty-cycle 1.5-ps 40-GHz pulse train by using a compressor line based on four stages of fiber and demonstrate its high performance for 160-Gbit/s OTDM applications.

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