All-Fibered High-Quality Low Duty-Cycle 20-GHz and 40-GHz Picosecond Pulse Sources

C. Finot, J. Fatome, S. Pitois, and G. Millot

Abstract—In this work, we demonstrate all-fibered 20-GHz and 40-GHz picosecond pulse sources with duty cycles as low as 1/14. The pulse train is achieved via the high-quality compression of an initial sinusoidal beating through four segments of optical fibers. General design rules are proposed and experimental results are in agreement with numerical predictions.

Index Terms—Nonlinear optics in fibers, parabolic pulses, pulse compression, pulse propagation and solitons.

Fig. 1. General scheme of the setup illustrating the four successive stages and their relevant parameters.

I. INTRODUCTION

GENERATION of very low duty-cycle high-quality optical pulse trains at repetition rate of tens of gigahertz around 1.5 μm has become of great interest for many scientific applications such as optical sampling or ultrahigh capacity transmission systems based on optical time-division multiplexing (OTDM). Unfortunately, the current bandwidth limitations of optoelectronic devices do not allow the direct generation of optical pulses having a temporal width below a few picoseconds. Nethertheless, actively mode-locked fiber lasers were found to be an efficient way to overcome this limitation, although they still remain an onerous option. As an alternative issue to conventional mode-locking operation, several techniques have been suggested, such as the conversion of a sinusoidal beating into a train of well-defined, pedestal-free pulses. For instance, the use of dispersion decreasing fibers [1], step-like or comb-like fiber setups [2], [3], or Raman amplification [1] have been successfully shown to be all-optical approaches to generate such high repetition rate pulse trains. Recently, a technique based on multiple four-wave mixing has also demonstrated its efficiency for the generation of optical pulse trains with repetition rates ranging from 20 GHz to 1 THz [4]. However, those different schemes have the common feature to generate pulse trains with a high duty cycle (around 1/5). Shorter pulses are clearly feasible, but at the cost of the experimental setup complexity [3], or with the development of noticeable substructures and pedestals in the recompressed pulses [5].

In this letter, we propose a new, passive and cost-effective approach allowing the generation of picosecond optical pulse trains with very low duty-cycle (around 1/15). The letter is organized as follows; we will first describe the physical principles of our approach relying on the progressive reshaping of a sinusoidal beating in a set of carefully chosen optical fibers.
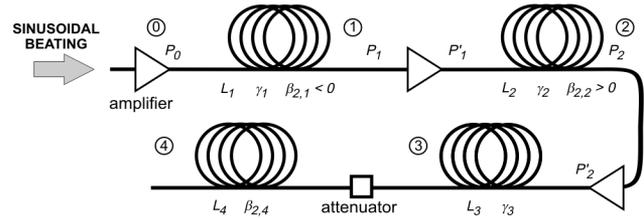
We will detail design rules enabling the rapid scaling and determination of the different elements of the setup. We will then present experimental results validating our technique at a repetition rate of 20 GHz. Other experimental data obtained at 40 GHz will demonstrate the possibility to further extend the concept to higher repetition rates.

II. PRINCIPLE AND DESIGN RULES OF THE CHAIN

Our original method is based on the temporal reshaping of a sinusoidal beating in a succession of optical fibers with lengths, dispersive, and nonlinear properties carefully chosen. The physical evolution of the beating can be simply decomposed into four stages (illustrated in Fig. 1), each having a clear physical meaning. Our technique is thus physically distinct from setups relying on step-like fiber, comb-like fiber [2], or comb-like profiled fiber [3] where the succession of numerous segments mimics a dispersion decreasing fiber.

For each stage of the setup, we have derived some semi-empirical rules to optimize and facilitate the design of our pulse train compressor. Both previously published and novel analytical formula will be presented, each one taking into account the second-order dispersion $\beta_{2,k}$ and the nonlinear coefficient γ_k of the kth fiber.

The first stage of our setup aims to convert an initial sinusoidal beating into a well-separated Gaussian-like pulse train with a duty-cycle of 1/5 through the multiple four-wave mixing process taking place into a standard anomalous fiber [4]. For a pulse train with a repetition rate f, it has been shown that the optimal average power P_0 at the input of the first segment is given by $P_0 \approx 12.8|\beta_{2,1}|f^2/\gamma_1$[4]. The optimal fiber length is $L_1 \approx 0.071/|\beta_{2,1}|f^2$, providing Gaussian chirp-free pulses with negligible pedestals at the output of the first stage. The full-width at half-maximum (FWHM) of the reshaped pulses is then $T_1 \approx 1/5\,f$ while their peak power is evaluated by $P_1 \approx 4.57\,P_0$.

The second stage allows the passive reshaping of Gaussian pulses into a train of linearly chirped parabolic pulses thanks to

the combined effects of self-phase modulation and normal dispersion [6]. In order to have a convenient parabolic reshaping, the optimum fiber length L_2 of the normally dispersive segment and the optimum peak power P_1' are $L_2 \approx 0.006/\beta_{2,2}f^2$ and $P_1' \approx 468\beta_{2,2}f^2/\gamma_2$, respectively.

After reshaping inside the L_2 segment, we obtain a parabolic pulse shape having an FWHM T_2 and a peak power P_2. The pulse is linearly chirped with chirp coefficient C_2 defined as the slope of the temporal chirp. The parameters of the pulses after the second stage are then given by $T_2 \approx 0.39/f$, $P_2 \approx 0.56P_1'$ and $C_2 \approx 17.3f^2$.

The purpose of the third stage is essentially to increase the linear temporal chirp of the parabolic pulses in order to enhance the final recompression process. In this aim, those pulses are launched into a highly nonlinear fiber (HNLF) where they are essentially affected by self-phase modulation without suffering any temporal broadening ($T_2 = T_3$). Due to their parabolic intensity profile, the temporal chirp induced in this third segment is strictly linear [7] and for an initial peak power P_2' and a fiber length L_3, the amount of additional linear chirp is given by $C_3 \approx 4.19P_2' L_3 \gamma_3 f^2$[8].

In this context, at the output of the third segment, the linear chirp of the parabolic pulses $(C_2 + C_3)$ can therefore be efficiently compensated by means of a usual dispersive element. A compact solution for this compensation could be a chirped fiber Bragg grating but we choose here to implement another solution by simply adding an adequate length of anomalous fiber, which constitutes the final stage of the setup. Recompressed pulses are finally transformed-limited with a shape close to a first-order Bessel function of the first kind [8] and with a temporal FWHM given by $T_4 \approx 1.85f/(C_2 + C_3)$.

Ensuring a sufficiently low power at the input of this last segment to avoid nonlinear effect, the length of fiber L_4 required to achieve such a recompression is thus given by $L_4 \approx 1/[2\pi(C_2 + C_3)\beta_{2,4}]$.

III. EXPERIMENTAL RESULTS AT 20 GHZ

We have tested our approach by generating a pulse train at a repetition rate of 20 GHz. Based on the design rules described in the above section, we have settled our experimental setup by means of commercially available devices ready for a telecom use.

The initial beating is obtained by the temporal superposition of two continuous laser diodes frequency separated by 20 GHz (external cavity laser). A phase modulator is also inserted in order to suppress the Brillouin backscattering effect. We would like to emphasize that the generation of such a beating is fully compatible with the performances of electrooptic modulators and electronic clocks commonly used in telecommunications.

The average power of the initial beating launched into the first 8385-m-long section made of standard single-mode fiber (SMF) is only 21 dBm [5]. The second stage is made of nonzero dispersion-shifted fiber (NZ-DSF, dispersion $D = -1.5 \text{ ps} \cdot \text{km}^{-1} \cdot \text{nm}^{-1}$, $\gamma = 1.7 \text{ W}^{-1} \cdot \text{km}^{-1}$ with normal dispersion whose parameters ($L_2 = 7700$ m, $\beta_{2,2}$) have been carefully chosen to match the properties of the pulses generated along the SMF and thus satisfying the relation $P_1 = P_1'$. The third segment is a 500-m-long HNLF ($\gamma_3 = 13 \text{ W}^{-1} \cdot \text{km}^{-1}$) with nearly zero
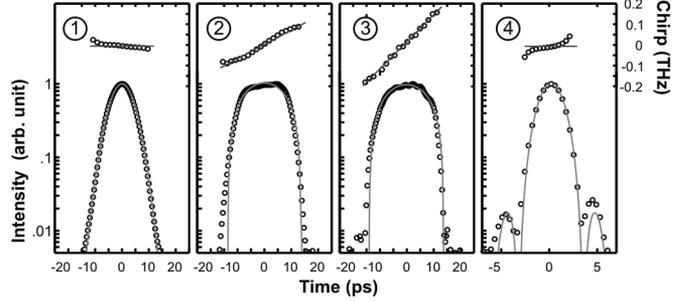

Fig. 2. Evolution of the intensity and chirp profiles (bottom and top, respectively) at different stages of the setup. 20-GHz experimental results obtained by FROG characterization (circles) are compared to various fits (solid lines). Stage 1: Gaussian fit of the intensity profile. Stages 2 and 3: parabolic fits. Stage 4: fit by a Bessel function of the first kind [8]. Chirp profiles are compared to linear fits. Note that results at stage 4 are plotted with a different temporal scale than results at other stages.

dispersion (a slight normal dispersion is used to prevent instabilities or temporal recompression). In order to achieve a significant spectral broadening and a sufficient linear temporal chirp, we have inserted an erbium-doped fiber amplifier at the input of the HNLF to reach $P_2' = 23$ dBm. The final stage is based on a 630-m-long SMF segment, preceded by an optical attenuator to ensure a linear pulse recompression without soliton recompression effect.

We have carefully characterized both in phase and intensity the pulses at the different stages of our setup by use of a frequency-resolved optical gating (FROG, based on second-harmonic generation [9]). Experimental results are represented in Fig. 2 (circles) and are also compared to various fits corresponding to the theoretical expected shapes described in part II (solid lines). After the first stage [Fig. 2①], we can check that the initial sinusoidal beating is efficiently compressed into a transform limited Gaussian pulse train with a duty-cycle close to 1/5 (FWHM = 11 ps and time-bandwith product = 0.43). In the course of the second stage [Fig. 2②], we clearly verify that those pulses have then acquired an intensity profile in good agreement with a parabolic fit. This parabolic shape is then maintained during the whole propagation in the HNLF whereas the linear chirp is further increased [stage 3, Fig. 2③]. Finally, after recompression along the SMF segment (stage 4), the output pulses [Fig. 2④], are nearly Fourier transformed-limited with a temporal duration of 3 ps (i.e., duty-cycle of 1/16) and notably exhibit only low pedestals which are characteristic of recompressed parabolic pulses [8] (peak-to-pedestal ratio larger than 17 dB). Those generated pulses are then fully suitable for 80-GHz OTDM telecommunications.

IV. EXPERIMENTAL RESULTS AT 40 GHZ

We now present experimental results obtained at a higher repetition rate. Using the design guidelines described in part II, it is clear that higher the repetition rate f is, shorter should be the length of the fibers and higher should be the peak powers launched into the different fiber segments. In other words, increasing the repetition rate by a factor of 2 will globally lead to decrease the lengths of the segments L_1 and L_2 by a factor of 4 and increase by 6 dB the required input power. One inherent beneficial aspect is that the power available at the output of the
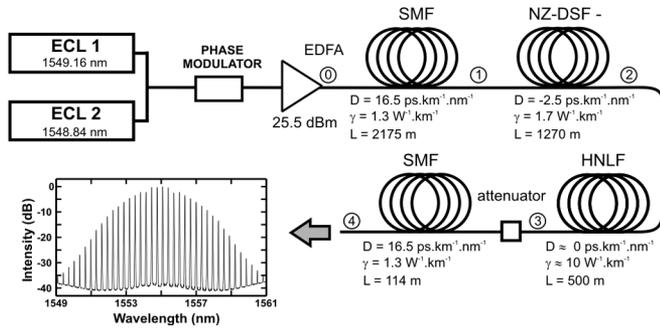
Fig. 3.   The 40-GHz experimental setup, parameters and experimental optical spectrum of the 40-GHz recompressed pulses.
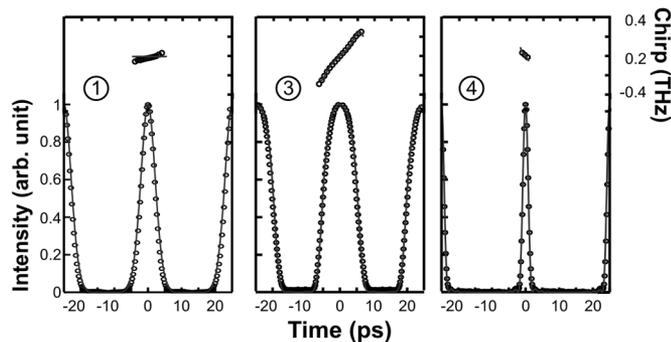

Fig. 4.   Intensity and chirp profiles at stages 1 and 3 and 4. 40-GHz experimental results obtained by FROG characterization (circles) are compared to numerical simulations of the nonlinear Schrödinger equation (solid line).

second fiber will be sufficiently high to observe a clear spectral broadening in the HNLF without any additional amplification, thus meaning a simplified experimental setup made of a single line of four spliced optical fibers, whose principal features are detailed in Fig. 3 for the 40-GHz configuration.

We have again characterized the pulses at stages 1, 3, and 4 by means of FROG measurements. In order to fairly observe the compression process, results are plotted (Fig. 4, circles) with a temporal window of two signal periods. These results demonstrate that the 4.7-ps transformed-limited Gaussian pulses derived from stage 1 [Fig. 4(1)] are efficiently reshaped into a linearly chirped parabolic shape after their successive propagations in the NZ-DSF and HNLF [Fig. 4(3)]. Final output pulses [Fig. 4(4)] exhibit a nearly sidelobe-free temporal intensity profile with a temporal width of 1.8 ps (duty cycle of 1/14). The chirp is flat over most of the central part of the pulse. The spectrum of the generated 1.8-ps 40-GHz pulse train is plotted in Fig. 3 and exhibits a symmetric good quality envelope constituted by many generated harmonics separated by 40 GHz as well as an optical signal-to-noise ratio in excess of 35 dB. The generated pulses are then fully suitable for 160-GHz OTDM telecommunication applications.

Experimental results are finally compared with those obtained from the numerical integration of the standard nonlinear Schrödinger equation (Fig. 4, solid lines). The agreement is excellent and proves the reliability of the technique. We have

also checked that higher order linear and nonlinear effects do not affect our proposed device at this repetition rate.

V. CONCLUSION

We have proposed a new and easy to implement method to generate carrier-suppressed return-to-zero pulse trains with low duty-cycles. An initial sinusoidal beating is converted into nearly transform-limited pulses with very low substructures through the propagation in only four segments of optical fiber whose dispersion and length are carefully chosen. We have derived general guidelines which facilitate the choice and speed-up the scaling of the fibers and powers involved in the nonlinear processes. Experimental results obtained at 20 and 40 GHz show that picosecond pulse trains with duty cycles as low as 1/14 have been generated, thus validating this alternative method to comb-like dispersion decreasing techniques. By reducing the number of segments, we have also relaxed the constraint of tedious splices and consequent losses. A careful characterization both in intensity and phase fully agrees with numerical simulations and confirm our approach.

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