Repetition Rate Upgrade for Optical Sources

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***Abstract*—A novel method for the multiplication of the repetition rate of full duty-cycle return-to-zero optical sources is presented. It employs the memory property of a Fabry–Pérot filter for the multiplication task, combined with the gain saturation of a semiconductor optical amplifier for amplitude equalization. This concept has been applied to quadruplicate the rate of a distributed feedback laser source operating at 10 GHz.**

***Index Terms*—Fabry–Pérot resonators, optical transmitters, semiconductor optical amplifiers (SOAs).**

I. Introduction and Concept

EVEN THOUGH user traffic continues to rise, the recent downturn in telecommunications has forced the industry to look into transmission system solutions of lower cost but capable of gradual performance upgrades to full bandwidth utilization. In fiber links where capacity requirements justify it, current trends and technology maturity favor the deployment of systems operating at line rates of 40 Gb/s per channel [1], [2]. However, as extensive investments have been made for systems operating at line rates of 10 Gb/s, upgrading existing links to 40 Gb/s is of great importance. In this case, the transmitter units, and more precisely their laser sources, must be upgraded so that they can operate at 40-GHz repetition frequency, especially if return-to-zero (RZ) modulation format is chosen. In order to address this, several techniques for RZ repetition rate multiplication have been proposed including harmonic mode-locking [3], the temporal Talbot effect [4], and Fabry–Pérot filtering (FPF) [5], [6].

In the present work, we demonstrate a new method for multiplying the repetition rate of a local clock, laser oscillator by optical means. Our method uses a FPF followed by a semiconductor optical amplifier (SOA). The FPF is chosen so as to have a free-spectral range (FSR) that is a multiple of the laser repetition frequency and equals the desired repetition rate of the transmitter. The method relies on the property of an FPF that its time-domain impulse response is an exponentially decaying sequence of pulses at a repetition frequency equal to its FSR and whose decay constant is determined by the filter finesse (F). As a result, the pulse train at the output of the FPF displays an amplitude modulation and the role of the SOA is to reduce this amplitude modulation. The SOA is operated under heavy saturation, well into its nonlinear regime. As such, pulses with higher energy at its input receive less gain than pulses with lower energy, resulting in a reduced amplitude modulation. In the present experiment, it was found that the amplitude equalizing property of the SOA may be used successively, twice, resulting in an output pulse train with nearly zero amplitude modulation. The second pass through the SOA is particularly effective at equating the amplitudes of the pulse train because it can be used in conjunction with the gain recovery of the SOA by appropriate temporal synchronization of the two pulse trains.

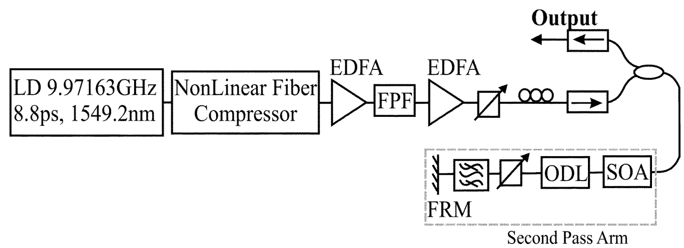

Fig. 1. Experimental Setup.

In this letter, we propose and apply the concept to multiply the repetition rate of a 10-GHz laser oscillator to 40 GHz. After filtering and amplitude equalization, the resulting 40-GHz pulse train has been found to have less than 0.25-dB amplitude modulation and timing jitter of less than 650 fs. The proposed scheme is relatively simple to implement and may help to reduce the cost of upgrading transmission systems to RZ 40-Gb/s data rate, by reducing the cost of upgrading the full duty cycle laser sources in the transmitters. The degree of amplitude modulation suppression in the SOA depends on its gain recovery time and this can be decreased to less than 10 ps by optical pumping [7]. Therefore, in principle, the advantages of our technique could be further extended if it is applied either to a single laser source to achieve a higher multiplication factor for a single channel or to simultaneously multiply the repetition frequency of several laser sources at different wavelengths with the same FPF and SOA [8], [9].

II. Experimental Setup

The experimental setup is shown in Fig. 1. The initial pulse train was produced by a gain-switched distributed feedback (DFB) laser, operating at 1549.2 nm. The laser yielded 8.8-ps pulses at a repetition rate of 9.971 63 GHz, after linear compression through dispersion compensation fiber with total negative dispersion of 54.27 ps/nm. The laser output pulses were then amplified in an erbium-doped fiber amplifier and had their temporal width reduced in a two-stage nonlinear fiber compressor comprising of alternating sections of dispersion shifted fiber and single-mode fiber. By filtering the compressor output with a 2-nm filter, 3.2 ps nearly transform

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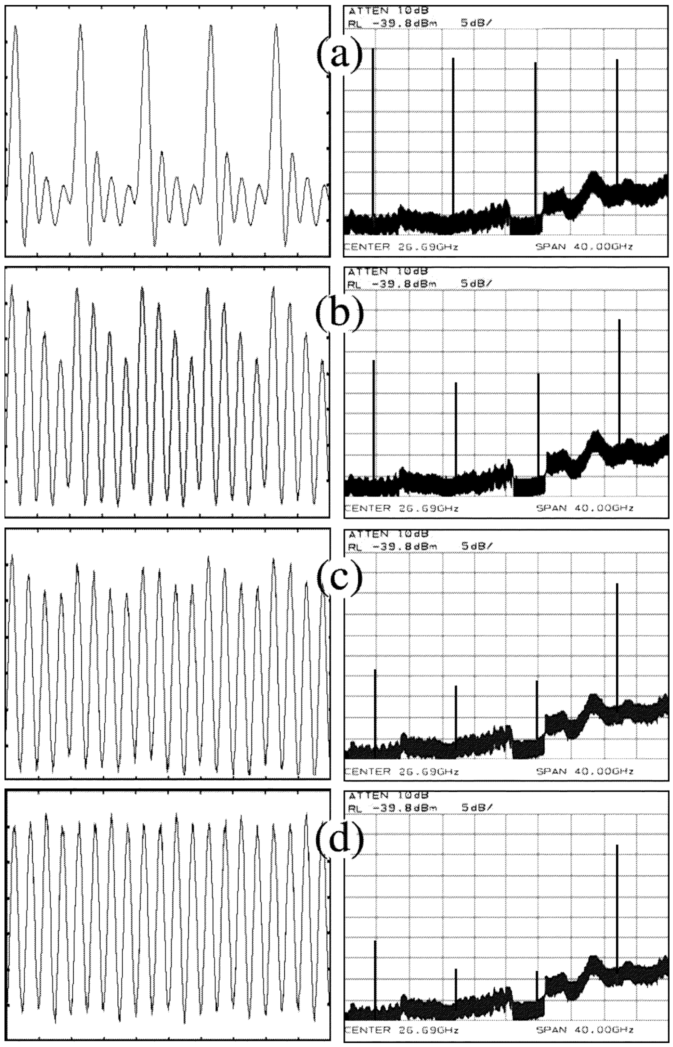

Fig. 2. Oscilloscope traces and corresponding radio-frequency (RF) spectra at the (a) compressor output, (b) FPF output, (c) output after first SOA pass, and (d) output after second SOA pass. Oscilloscope trace time base is 50 ps/div. RF spectra amplitude scale is 5 dB/div and frequency scale is 4 GHz/div.

limited hyperbolic secant pulses were obtained. The pulse train was further amplified and fed into the FPF. The FPF was an antireflection-coated fused-quartz substrate with an FSR equal to 39.886 52 GHz and a finesse of 50. After exiting from the FPF, the signal was reamplified and inserted in a 3-dB coupler used for monitoring and to provide the output of the source on its return path from the SOA amplitude equalization stage. Following the 3-dB coupler, the signal was introduced into a commercially available 1.5-mm-long SOA (Optospeed S.A.). This had small signal gain of 24 dB at 1549.2 nm, 3-dB polarization gain dependence, 10%–90% gain recovery time of 65-ps, and 10-fJ saturation energy, when driven at 700-mA dc current. After passing once through the SOA, the pulse train entered the second-pass arm. Here it was filtered in a 2.8-nm bandpass filter and was reflected back again into the SOA by a Faraday rotator mirror (FRM). The FRM defines a fixed relation between the polarization states of the input and feedback signals in the SOA and simplifies the adjustment procedure. An optical delay line (ODL) was used in the second-pass arm to provide adjustment of the temporal synchronization between

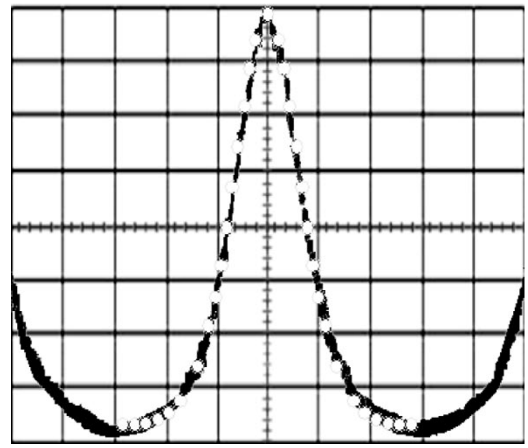

Fig. 3. Second-harmonic autocorrelation trace. The white dots indicate the fitted hyperbolic secant autocorrelation profile. Time base is 3.66 ps/div.

the counterpropagating pulses. Variable optical attenuators were used before the SOA inputs to adjust the power level of the first and second-pass signals.

III. Experimental Results and Discussion

Fig. 2 shows the experimental results at different points of the setup monitored on a sampling oscilloscope and a microwave spectrum analyzer. Fig. 2(a) illustrates the oscilloscope trace and the corresponding microwave spectrum of the initial 10-GHz clock signal. The weak ringing oscillation that appears in the oscilloscope trace is due to the photodiode used and is not present in the optical signal. Fig. 2(b) displays the signal at the output of the FPF, showing a 40-GHz clock pulse train with 1.65-dB amplitude modulation (highest to lowest pulse power ratio). Fig. 2(c) shows the pulse train after its first pass through the SOA, with its amplitude modulation reduced to 0.8 dB. Finally, Fig. 2(d) shows the signal after its second pass through the SOA. This time the amplitude modulation recorded on the sampling oscilloscope was reduced to 0.15 dB. The corresponding microwave spectrum reveals that the combination of the FPF with the double pass through the SOA, has resulted in effective suppression in excess of 26 dB of the 10-GHz component, while the 20- and 30-GHz frequency components are suppressed by approximately 35 dB. Analysis of the spectrum at the output of the source using inverse Fourier series indicates that the amplitude modulation of the signal is below 0.25 dB, which is in close agreement to the measurements made with the sampling oscilloscope. Spectral analysis also showed that the timing jitter was less than 650 fs. The temporal width of the output 40-GHz pulses was measured using a second-harmonic generation autocorrelator and Fig. 3 shows the resulting autocorrelation trace. Assuming a hyperbolic secant profile, the output pulses have a full-width at half-maximum of 3.8 ps. This is marginally increased from 3.5 ps at the input of the SOA primarily due to the polarization gain dependence and birefringence of the SOA. The output power of the source was 680 μW.

In order to achieve the results shown in Fig. 2(d), the optical power and relative timing of the signals for the two passes in the SOA must be appropriately adjusted. The input powers of the

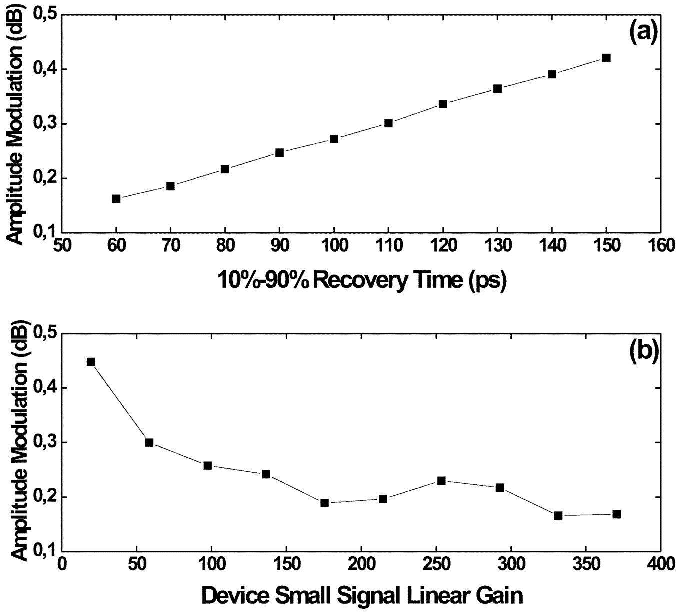

Fig. 4. (a) Amplitude modulation versus SOA recovery time and (b) amplitude modulation versus device small-signal gain.

pulse trains before entering the SOA were 850 μW for the first and 80 μW for second pass, respectively. These input powers correspond to mean energies/pulse of 25 fJ for the first and 2 fJ for the second pass. With these input powers the SOA operated in a deeply saturated regime, but the degree of saturation and recovery is primarily determined by the first-pass pulse train. In contrast, the second-pass signal has low energy value and accesses the saturated amplifier gain. Arranging the temporal adjustment of the second-pass signal with respect to the first pass using the ODL, it is possible to use the gain recovery of the SOA as an additional parameter to enhance the amplitude equalization of the SOA for the second-pass pulse train. It was found that optimized performance is obtained when the second-pass pulses enter the SOA just after their equivalents from the first-pass exit, and that is with a delay of approximately 5 ps.

In principle, rate multiplication with approximate amplitude equalization could also be achieved with a single FPF of high finesse [5]. For example, to achieve amplitude modulation of 0.25 dB in the rate multiplied pulse train with a single FPF, simulations have shown that its finesse must be equal to 325, and this figure grows more if the amplitude modulation must be further reduced. In this case, the filter has very sharp resonance peaks so that it may be harder to construct and less practical as it will display no tolerance on variations of the input line rate.

A simulation tool was developed in order to provide insight on how the gain and recovery time of the SOA affect the resulting amplitude modulation and assess whether this technique can be used for higher rates or for simultaneous multiplication of several different wavelength sources. The simulation tool was based on the equations for gain saturation and recovery derived in [10], modified to take into consideration the presence of the double-pass signal in the amplifier and was used with the parameters of the experimental setup. Fig. 4(a) shows the amplitude modulation with respect to the SOA recovery time and displays an almost linear increase of the amplitude modulation with the recovery time. This is to be expected, since in faster SOAs the gain excursions will be larger during amplification reducing the amplitude modulation. This result is, however, important because it shows that, at least in principle, this rate multiplication and gain equalization technique should be extendable to achieve higher multiplication factors to higher rates. Fig. 4(b) shows the resulting minimum amplitude modulation of an input pulse train of 1.65-dB modulation, after double pass through an SOA with saturation energy of 10 fJ and optimized synchronization of the two pulse trains. Low amplitude modulation can be achieved for a gain region between 21 and 25 dB, in close agreement with the experimental results. For small variations of the gain parameter within this regime, no significant changes on the amplitude modulation take place. This shows that a single SOA can, in principle, be used to simultaneously multiply the repetition frequency of several laser sources at different wavelengths with the same FPF and SOA, provided that the small signal gain varies within a certain range and that they are temporally synchronized in the SOA.

IV. Conclusion

We have presented a simple method that can be used to upgrade the repetition rate of a local clock laser source. The proposed technique has been applied to four-times multiply a 10-GHz DFB laser output. The multiplication task involves an FPF of moderate finesse and pulse amplitude equalization is performed by double passing this modulated 40-GHz pulse train through a heavily saturated SOA. The source has been shown to display amplitude modulation below 0.25 dB and stable operation under laboratory conditions.

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