Rate Multiplication by Double-Passing Fabry–Pérot Filtering

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***Abstract*—We present a new technique for extending the decay time of the impulse response function of a Fabry–Pérot filter while simultaneously maintaining a large bandwidth. It involves double passing through the filter and it can be used for the easy multiplication of the repetition rate of optical sources. We apply the concept to a 10-GHz pulse train to demonstrate experimentally the rate quadruplication to 40 GHz.**

***Index Terms*—Fabry–Pérot resonators, optical transmitters.**

I. Introduction and Concept

PHOTONICS technologies have improved vastly over the past decade and significant inroads have been made toward the realization of lightwave networks. For fiber transmission systems, research efforts are focusing to help 40-GHz and higher line rate transmission systems to reach maturity [1], [2]. Given the current negative market conditions, telecommunication carriers are likely to consider upgrading to these new systems only if they are proven to be efficient and of low cost. Laser sources with their associated electronic drivers are key components that are used in large numbers in optical transmission systems and contribute significantly to overall system cost. As such, careful consideration is required regarding their upgrade path from 10 to 40 GHz, especially given the possibility of modulation format change from nonreturn-to-zero to return-to-zero [3]. To this end, several techniques have been demonstrated that can optically multiply the repetition rate of laser sources and that do not require changes in the microwave driver circuits. These techniques include rational harmonic mode-locking of fiber lasers [4]–[7] and the use of Fabry–Pérot (FP) filters with a free spectral range (FSR) that equals the desired line rate [8], [9]. Even though mode-locked fiber lasers have provided impressive results, they have been confined to laboratory uses primarily due to the environmental sensitivity that they display. On the other hand, rate multiplication with FP filters is likely to lead to pulse trains with amplitude modulation, unless a filter of high finesse is employed. FP filters of high finesse are very sensitive to line-rate detuning due to their narrow passband. Consequently, such devices may be costly and difficult to manufacture. Recently, we have demonstrated a repetition rate multiplication technique up to 40 GHz, which uses an FP filter of moderate finesse followed by a semiconductor optical amplifier (SOA) [10]. It takes advantage of the exponentially decay impulse response of the FP filter to generate an amplitude modulated 40-GHz pulse train, and the saturation property of the SOA is used for reducing the amplitude modulation to 0.25 dB.

In the present communication, we develop a method by which it is possible to achieve rate multiplication with negligible amplitude modulation using a single low-finesse FP filter by effectively extending its decay time. The method involves double passing through the FP filter, so that its impulse response is no longer the regular exponentially decaying sequence of pulses. Instead, the impulse response of the double-pass FP filter acquires a short rising edge and a slow exponentially decaying trailing edge, which effectively enhances its $1/e$ lifetime. Despite this lifetime increase, the effective bandwidth and finesse of the filter remain practically unchanged. In what follows, we develop the theoretical background needed to describe the proposed filter and apply the concept to demonstrate rate multiplication from 10 to 40 GHz. The resulting 40-GHz pulse train had less than 0.12-dB amplitude modulation, timing jitter of less than 500 fs, and was thoroughly stable. The proposed scheme is simple and even though in the present implementation the FP filter used was a bulk component, this can be easily replaced by a fiber FP filter. On the assumption that the initial laser source has enough bandwidth to support rate increase, this scheme can be used for its easy upgrade. Similarly, by appropriate filter choice, it can also be used for the upgrade of several wavelength-division-multiplexing sources simultaneously, thus sharing the cost of the filter between them.

II. Theory

In this section, we derive useful relationships between the bandwidth and the $1/e$ lifetime of a double-pass FP filter with respect to the filter mirror reflectivity R and its FSR, and we prove that the proposed filter possesses an extended lifetime and a large bandwidth. The bandwidth can be readily calculated in the frequency domain by use of the transfer function. The transfer function of a single-pass FP filter is

$$T_{\rm sp}(f) = \frac{1}{1+\left(\frac{2\sqrt{R}}{1-R}\cdot\sin\left(\frac{\pi\cdot f}{\rm FSR}\right)\right)^2}. \tag{1}$$

Manuscript received January 7, 2003; revised April 11, 2003.

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Digital Object Identifier 10.1109/LPT.2003.816691

The transfer function for double pass through the filter is

$$T_{\mathrm{dp}}(f) = \frac{1}{\left(1+\left(\frac{2\sqrt{R}}{1-R}\cdot\sin\left(\frac{\pi\cdot f}{\mathrm{FSR}}\right)\right)^2\right)^2}. \tag{2}$$

The bandwidth of the double-pass transfer function B_{dp} is related to the bandwidth of the single-pass transfer function B_{sp} as follows:

$$\begin{aligned} B_{\mathrm{dp}} =& \frac{2\cdot\mathrm{FSR}}{\pi}\cdot\arcsin\left(\sqrt{\sqrt{2}-1}\cdot\sin\left(\frac{\pi\cdot B_{\mathrm{sp}}}{2\cdot\mathrm{FSR}}\right)\right)\cong \\ \cong& \sqrt{\sqrt{2}-1}\cdot B_{\mathrm{sp}}. \end{aligned} \tag{3}$$

The approximation stands when the finesse F of the filter is more than ten. This relation shows that the bandwidths of the single- and double-pass filters are roughly equal.

Under the condition that the signal bandwidth is broad compared to the filter FSR, so that successive pulses at the output of the filter do not overlap, the time-domain analysis provides analytical results for the double-pass impulse response of the filter as

$$h(t) = (1-R)^2\cdot\sum_{n=0}^{\infty}(n+1)\cdot R^n\cdot\delta\left(t-\frac{n}{\mathrm{FSR}}\right) \tag{4}$$

and consequently, the $1/e$ lifetime of the double-pass filter is $[m]/\mathrm{FSR}$, where m is the solution to the equation

$$(m+1)\cdot R^m = \frac{1}{e}. \tag{5}$$

Correspondingly, the single-pass $1/e$ lifetime is given by $[l]/\mathrm{FSR}$, where l is the solution to the equation

$$R^l = \frac{1}{e}. \tag{6}$$

Equations (5) and (6) show that $[m]\geq[l]$ and so the lifetime of the double-pass case is larger, but the degree of enhancement can only be assessed after solving (5) numerically. Analytical results can be readily calculated when k-times rate multiplication is considered. In this case, the analysis reveals that the amplitude modulation (highest to lowest pulse peak power ratio) is given for the double- and single-pass case by

$$\mathrm{AM}_{\mathrm{sp}}(\mathrm{dB}) = 10\cdot\log R^{2(k-1)} \tag{7}$$

$$\mathrm{AM}_{\mathrm{dp}}(\mathrm{dB}) = 10\cdot\log\left(\frac{\max_i\left\{R^{2(i-1)}\cdot\left((k-i)\cdot R^{2k}+i\right)\right\}}{\min_i\left\{R^{2(i-1)}\cdot\left((k-i)\cdot R^{2k}+i\right)\right\}}\right)$$
$$i=1,\ldots,k. \tag{8}$$

Equations (7) and (8) are plotted versus the filter finesse in Fig. 1 for the specific case of $k=4$. By curve fitting, one can find that the single- and double-pass amplitude modulation is given, respectively, by

$$\mathrm{AM}_{\mathrm{sp}}(\mathrm{dB}) = 80.33\cdot F^{-0.995} \tag{9}$$

$$\mathrm{AM}_{\mathrm{dp}}(\mathrm{dB}) = 321.81\cdot F^{-1.941}. \tag{10}$$

Equations (9) and (10) show, that as far as the amplitude modulation is concerned, the filter finesse is effectively squared,

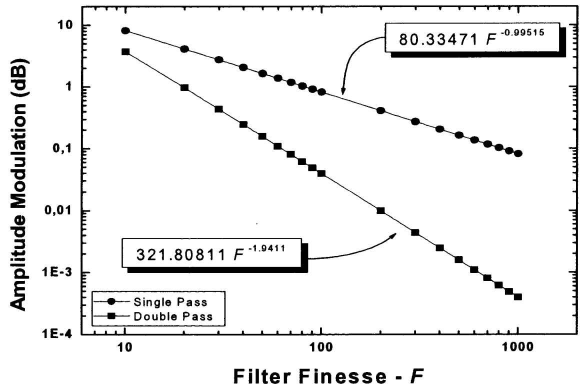

Fig. 1. Amplitude modulation versus filter finesse for single- and double-pass cases.

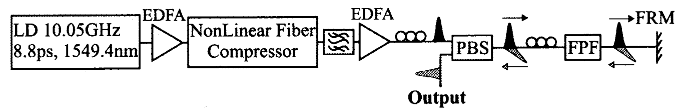

Fig. 2. Experimental setup. FPF: FP filter.

even though the filter bandwidth is reduced only by $\sqrt{\sqrt{2}-1}$, as relation (3) shows.

III. Experimental Setup

Experimental verification of this concept has been applied to a four times repetition rate multiplication experiment. The experimental setup is shown in Fig. 2. The initial pulse train was produced by a gain-switched distributed feedback (DFB) laser at 1549.4 nm. The laser diode operated at 10.05 GHz and produced 8.8-ps pulses after linear compression in a dispersion compensating fiber of total negative dispersion of 55.58 ps/nm. This pulse train was next amplified in an erbium-doped fiber amplifier and was nonlinearly compressed 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-limited hyperbolic secant pulses were obtained. This pulse train was finally amplified and fed into the FP filter through the ordinary axis of a fiber polarization beam splitter (PBS), so that a single state of polarization entered the double-pass arm. The FP filter was an antireflection-coated fused quartz substrate with an FSR equal to 40.2 GHz and a finesse of 50. For optimum performance the polarization state of the incident beam was adjusted with a polarization controller before the FP filter. At its output, a Faraday rotator mirror (FRM) was used to reflect the rate multiplied pulse train back into the FP filter so that the final output was obtained at the extraordinary axis of the PBS.

IV. Experimental Results

Fig. 3 shows the experimental results recorded on a 40-GHz sampling oscilloscope and a 50-GHz microwave spectrum analyzer. Fig. 3(a) illustrates the oscilloscope trace and the corresponding microwave spectrum of the initial 10-GHz signal. Fig. 3(b) displays the signal after its first pass through the FP filter, showing a 40-GHz clock pulse train with 1.65-dB amplitude modulation. Fig. 3(c) shows the signal after its second pass

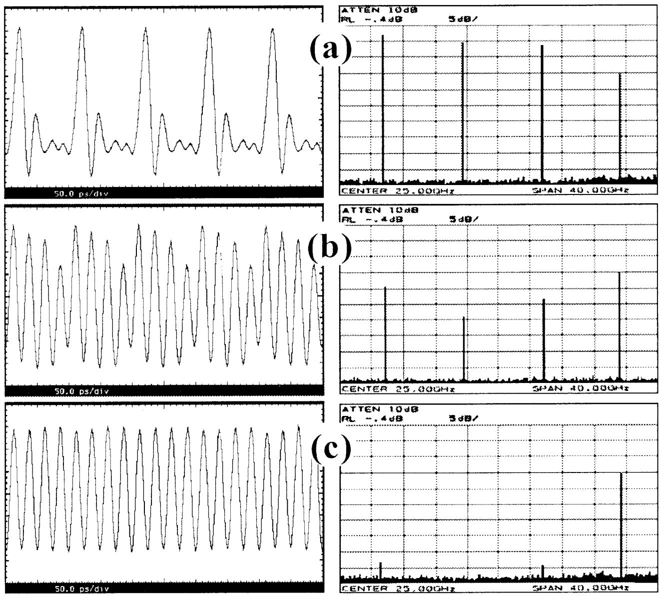

Fig. 3. Oscilloscope traces and corresponding microwave spectra at (a) compressor output, (b) first pass through FP filter, and (c) second pass through FP filter. Oscilloscope trace-time base is 50 ps/div. Radio-frequency spectra amplitude scale is 5 dB/div and frequency scale is 4 GHz/div.

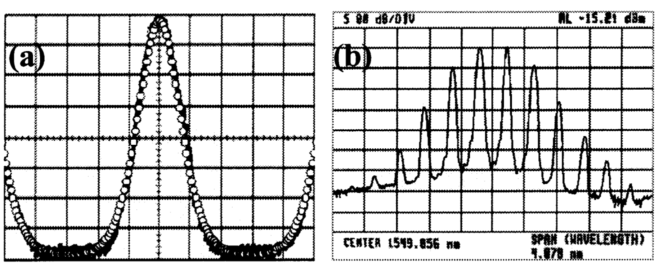

Fig. 4. (a) Second harmonic autocorrelation trace with fitted profile (white dots). Time base is 3.09 ps/div. (b) Optical spectrum trace. Amplitude scale is 5 dB/div and frequency scale is 0.4 nm/div.

through the FP filter, which displays 0.11-dB amplitude modulation as recorded on the sampling oscilloscope. This figure is very close to the 0.15-dB predicted from the theoretical analysis, as shown in Fig. 1. The corresponding microwave spectra reveal that double passing through the FP filter results in effective suppression in excess of 47 dB of the 20-GHz component and approximately 40-dB suppression for the 10- and 30-GHz frequency components. Analysis of the spectrum at the output of the source using inverse Fourier series indicates that the amplitude modulation of the signal is below 0.12 dB, which agrees well with the measurements made with the sampling oscilloscope. Spectral analysis has also shown that the amplitude jitter of the final 40-GHz signal was 3.7% and the timing jitter was less than 500 fs, and these values were the same as for the initial 10-GHz pulse train. Fig. 4(a) and (b) shows the second harmonic generation autocorrelation and optical spectrum of the 40-GHz pulse train. Assuming a hyperbolic secant profile, the output pulses have 3.2-ps and 100-GHz temporal and spectral widths (full-width at half-maximum), respectively, and

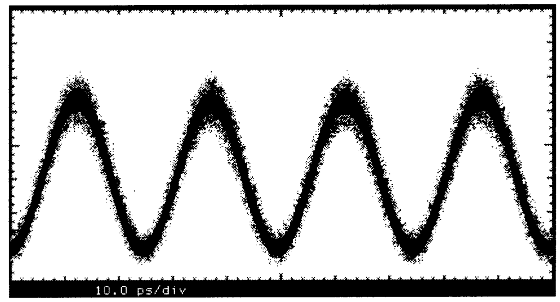

Fig. 5. Eye diagram of the output 40-GHz pulse train. Time base is 10 ps/div.

these values yield a time-bandwidth product of 0.32, which is very close to the theoretically expected 0.3148. Finally, Fig. 5 shows the eye diagram of the 40-GHz pulse train, indicating a good-quality open eye. The source was stable and did not require any adjustment for hours despite the use of a mechanically mounted FP filter, due to the fact that the double-pass technique allows for the use of a relatively low-finesse filter.

V. Conclusion

We have presented a simple technique that uses double pass through a relatively low-finesse FP filter to achieve repetition-rate multiplication. This technique has been applied to multiply by four times the repetition rate of a 10-GHz gain-switched DFB laser diode. The resulting pulse train is exceptionally stable and displays less than 0.12-dB amplitude modulation and less than 500-fs timing jitter.

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