High-Order Amplitude Regularization of an Optical Pulse Train Using a Power-Symmetric NOLM With Adjustable Contrast

O. Pottiez, E. A. Kuzin, B. Ibarra-Escamilla, F. Gutierrez-Zainos, U. Ruiz-Corona, and J. T. Camas-Anzueto

***Abstract*—In this letter, we demonstrate high-quality amplitude regularization of an optical pulse train using a novel nonlinear optical loop mirror design, whose switching relies on nonlinear polarization evolution. Thanks to the possibility to adjust the switching contrast, second-order amplitude regularization is experimentally demonstrated using the proposed scheme. An overall suppression of about 20 dB of the initial fluctuation over all frequencies is obtained.**

***Index Terms*—Amplitude modulation (AM) noise, laser noise, nonlinear optics, optical fiber applications, optical fiber communication, optical pulse shaping.**

I. INTRODUCTION

THE GENERATION of high-repetition-rate optical pulse trains is of vital importance for ultrahigh-speed digital communication systems. Unfortunately, for most common laser sources, an upgrade of the repetition rate generally corresponds to an increase of pulse amplitude fluctuations in the form of noise (in harmonically mode-locked lasers, slow gain dynamics favors large amplitude differences between different pulses in the cavity [1]), or of periodic fluctuations if a repetition-rate multiplication technique is used (subharmonic optical injection [2], rational harmonic mode locking [3]). In order to make ultrahigh-speed pulse trains suitable for applications, amplitude fluctuations must be reduced as much as possible.

A particularly attractive way to reduce amplitude fluctuations is through the use of a nonlinear optical loop mirror (NOLM) [4]. Compared to other amplitude regularization techniques [2], [5]–[10] this one is very simple, is compatible with very high repetition rates (as the Kerr effect is extremely fast), is able to reduce amplitude fluctuations of any nature (random or deterministic), and does not require any additional pump signal.

The NOLM shows a sinusoidal power-dependent transmission, $T = P_{\text{out}}/P_{\text{in}}$ (P_{in} and P_{out} are input and output powers, respectively) [4]. Usually, the curve of transmitted power, $P_{\text{out}} = T \times P_{\text{in}}$ (or of the complementary reflected power, $(1-T) \times P_{\text{in}}$) presents extrema for particular values of P_{in} (where $dP_{\text{out}}/dP_{\text{in}} = 0$), so that amplitude fluctuations of an optical pulse train can be easily reduced if the input peak power matches one of these values. In [11], a 15-dB reduction of the initial amplitude fluctuation was obtained by this principle. Unfortunately, $d^n P_{\text{out}}/dP_{\text{in}}^n \neq 0$ for $n > 1$ at these points, and higher order harmonics of the initial amplitude modulation (AM) are created, which can be substantially higher than the residual AM at fundamental frequency (see [11, Figs. 4 and 5]). Hence, for high-quality reduction of rather large amplitude fluctuations, it is recommended that more than one of the successive derivatives of P_{out} be equal to zero.

In conventional NOLMs, the contrast is fixed by the coupling ratio of the coupler. In a recent letter, we studied in detail the operation of a particular NOLM structure [12], initially proposed in [13], and we demonstrated it experimentally [14]. With this design, the contrast is not imposed, and can be easily adjusted. In this letter, we show that, by adjusting the contrast of this NOLM, it is possible to cancel simultaneously the first two derivatives of P_{out}. We provide experimental evidence that, using this novel NOLM structure, amplitude fluctuations are efficiently reduced, while the emergence of higher order harmonics is avoided.

II. PRINCIPLE

The proposed NOLM is made of a symmetrical coupler, highly twisted fiber, and a quarter-wave plate (QWP) located close to one of the coupler output ports. Contrary to conventional NOLMs for which switching is obtained through a power asymmetry between the counterpropagating beams, the present scheme relies on the polarization asymmetry generated by the QWP. High twist is applied to maintain the polarization ellipticity constant during propagation in the loop [14].

The transmission characteristic of the NOLM can be tuned very conveniently by adjusting the angle α of the QWP. In the case of circular input polarization, this transmission is written as [12]

$$T(P_{\text{in}}, \alpha) = \frac{1}{2}\left[1 - \cos(2\alpha)\cos\left(\pi\frac{P_{\text{in}}}{P_\pi} + 2\alpha\right)\right] \quad (1)$$

where P_π is the critical power. It appears from (1) that by tuning α, the contrast C (ratio between maximal and minimal transmission) can be set to any value, between $C = 1$ for $\alpha = \pi/4 + k\pi/2$ (T independent of P_{in}), and $C = \infty$ for $\alpha = k\pi/2$, k integer.

Fig. 1(a) shows T as a function of P_{in}, for several values of α, and Fig. 1(b) the corresponding curves of $P_{\text{out}} = T \times P_{\text{in}}$. For $\alpha = 0$ ($C = \infty$), P_{out} shows up a maximum, before decreasing

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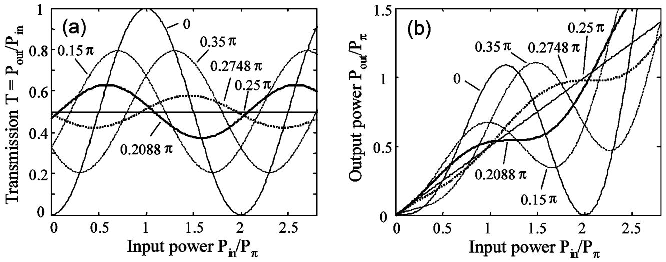

Fig. 1. (a) Transmission and (b) output power of the NOLM versus input power for several values of the QWP angle α (indicated as curve labels).

to zero. This maximum ($dP_{\text{out}}/dP_{\text{in}} = 0$) can be exploited to reduce amplitude fluctuations of an optical pulse train, by adjusting the input peak power to $P_{\text{in}} \approx 1.2P_{\pi}$. The high concavity observed at this point introduces, however, a substantial second harmonic in the resulting signal. The situation is very similar to a conventional NOLM. These conclusions are still valid if α is slightly increased (Fig. 1 for $\alpha = 0.15\pi$). Note that the nonzero minimum of P_{out} observed for $\alpha = 0.15\pi$ can be chosen as well for AM reduction, at the price, however, of a severe distortion of the pulse profile (a dip appears in the center of the transmitted pulse). Let us also observe that, between the maximum and minimum of P_{out} (points of high concavity), a point exists where $d^2P_{\text{out}}/dP_{\text{in}}^2 = 0$ (point of inflection).

By further increasing α (decreasing C), maximum, minimum, and inflexion point merge into one single point, for $\alpha \approx 0.2088\pi$ [Fig. 1(b)]. At this point (corresponding to $P_{\text{in}} \approx 1.25P_{\pi}$), the first two derivatives of P_{out} vanish so that high-quality amplitude regularization is expected for this particular value of α.

For $\alpha = 0.25\pi$, transmission is constant, $T = 0.5$ ($C = 1$), and $P_{\text{out}} = 0.5P_{\text{in}}$ is linear (Fig. 1). Above this value, for $\alpha \approx 0.2748\pi$, another point is found where the first two derivatives of P_{out} vanish [Fig. 1(b)]. Again, high-quality amplitude regularization can be expected from this point, corresponding to $P_{\text{in}} \approx 2P_{\pi}$. When α (and C) is further increased, this point splits into distinct maximum, minimum and point of inflection (Fig. 1 for $\alpha = 0.35\pi$).

Due to the extremely fast switching dynamics, some distortion will affect the pulse profile at the NOLM output. In the case of high-order amplitude regularization, the main effect is a flattening of the pulse peak. This causes an increase of the pulse duration, up to ~30% ($\alpha = 0.2088\pi$) and 10% ($\alpha = 0.2748\pi$) for initially Gaussian pulses. In the spectral domain, the 3-dB bandwidth is practically not modified by the NOLM, although side lobes appear up to ~25 ($\alpha = 0.2088\pi$) and 30 dB ($\alpha = 0.2748\pi$) below the main peak.

III. MEASUREMENTS

Fig. 2 shows our experimental setup. The NOLM consists of a 0.501/0.499 coupler, 500 m of highly twisted (7 turns/m) standard single-mode fiber (SMF-28), and a QWP made by coiling the fiber, and whose angle can be adjusted. The NOLM critical power was about 27 W. For the demonstration, we used a 1-mW average power, 800-kHz train of subnanosecond pulses from a figure-8 fiber laser, which was amplified by an erbium-doped fiber amplifier (EDFA) (gain ~ 10) and polarized circularly before entering the NOLM. Through gain modulation, we applied to the pulse train a sinusoidal AM at 400 Hz (frequency was limited by the slow gain dynamics), with a constant magnitude of 4 W (8 W peak to peak). By sweeping the average gain level, thus, the average pulse peak power, we investigated the effect of the NOLM transmission on the AM for several values of the QWP angle. Note that, due mainly to the gain nonlinearity, a second harmonic of the AM was observed in the signal at the NOLM input. However, its level always remained low enough to have a negligible contribution in the higher order harmonics observed at the NOLM output.

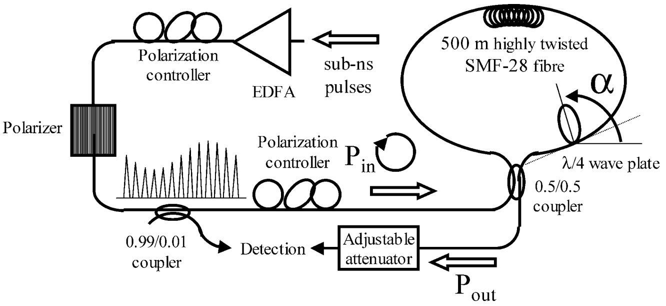

Fig. 2. Experimental setup. Average pulse power and modulation strength were adjusted through the dc and ac components of the current driving the 980-nm laser diode used to pump the EDFA.

Fig. 3 shows the magnitudes of the first three harmonics of AM at the NOLM output, a function of the average pulse peak power P_{in}, measured for three different values of the QWP angle. At all harmonics, the magnitudes are normalized to the magnitude of the initial 400-Hz modulation. These figures were obtained through time-domain demodulation in amplitude of the detected input and output pulse trains, using a vector signal analyzer [15]. The curves of P_{out} are also shown in the figures.

In Fig. 3(a), P_{out} shows a maximum and a minimum, where a reduction of more than 20 dB of the first harmonic is observed (curve for $n = 1$). Unfortunately, these points also correspond to high values (> -10 dB) of the second harmonic (curve for $n = 2$), as it was confirmed by the observation of a ripple at 800 Hz on the output pulse train. A point exists, however, between these two extrema where $d^2P_{\text{out}}/dP_{\text{in}}^2 = 0$. By adjusting the QWP angle, it was possible to make the two extrema of P_{out} coincide with this point [curves for $n = 1$ and 2 in Fig. 3(b)]. The first two harmonics were then simultaneously minimized down to ~ -20 dB, for $P_{\text{in}} \approx 30$ W $\approx 1.1P_{\pi}$, a value close to the expected value of $1.25P_{\pi}$. The performances were limited, however, by the third harmonic, at about -15 dB for $P_{\text{in}} = 30$ W (curve for $n = 3$), which was associated with a small ripple at 1.2 kHz. By rotating further the QWP slightly beyond the position of constant transmission, a plateau appeared at the upper end of the input power range [Fig. 3(c)]. Optimal AM reduction was obtained for $P_{\text{in}} \approx 48$ W $\approx 1.8P_{\pi}$, a value again coherent with the theoretical value of $2P_{\pi}$. At this point, not only the first two harmonics of P_{out} are minimized down to -20 dB (curve for $n = 1$ and 2), but the third one as well (curve for $n = 3$). In addition, harmonics of order four or higher were below the detection threshold, and no periodic ripple was observed on the output pulse train. This unexpected result may be due to the damping of the NOLM transmission characteristic for increasing P_{in}. [16]

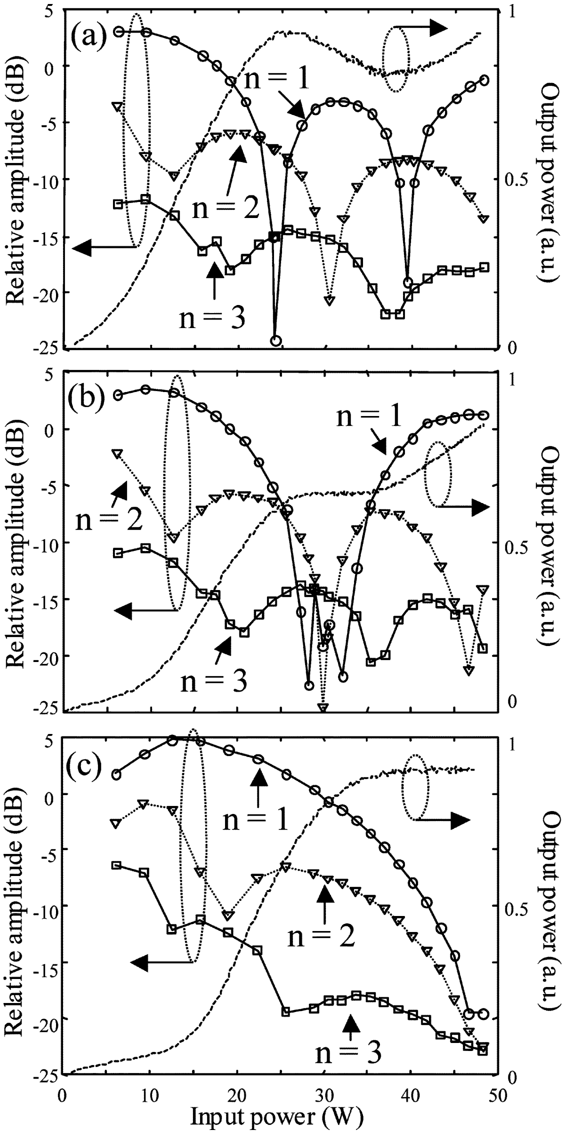

Fig. 3. Magnitude of harmonics of the sinusoidal modulation relative to first-harmonic at input, in function of P_{in} (n = harmonic order), for three different adjustments of the QWP. Curves of P_{out} (in linear scale, arbitrary units) are also shown on the figure. Experimentally measured values of the QWP angle are (a) $\alpha^* = 0$, (b) 0.23π, and (c) 0.30π, and correspond to theoretical values $\alpha = 0, 0.2088\pi$, and 0.2748π of Fig. 1, respectively, through the relation $\alpha = k\alpha^*$, where $k \approx 0.91$ (see [14] for more details on the correspondence between rotating fiber coil and bulk wave pate).

This demonstration was made using subnanosecond pulses at a repetition rate of 800 kHz, yet high-speed communications employ picosecond pulses at multigigahertz rates. In this case, the group-velocity mismatch between both circular polarization components in a twisted fiber imposes a lower limit to the pulse duration. With the present setup, we expect proper NOLM operation for durations down to about 20 ps. Making the loop shorter (e.g., 100 m, at the expense of a higher critical power), and reducing the twist rate (2–3 turns/m should be sufficient in practice), the limit becomes 1–2 ps. With short pulses, loop dispersion and soliton effect (if dispersion is anomalous) will also modify substantially the NOLM operation. Finally, for very high repitition rates, nonlinear interactions between counterpropagating beams have to be considered. A careful numerical investigation including all these effects should, thus, be carried out for applications of the proposed scheme in ultrafast photonic systems.

IV. CONCLUSION

We have proposed the use of a novel fiber NOLM structure, including a symmetrical coupler, highly twisted fiber, and a QWP, for high-quality amplitude regularization of optical pulse trains. The key feature of this architecture is the possibility to tune the contrast simply by adjusting the QWP angle. Starting with a peak-to-peak modulation of 20%–30%, a reduction of about 20 dB of this AM was measured over the whole spectrum. We believe that the proposed device will be extremely useful for the conception of reliable high-speed sources to be used in ultrafast photonic transmission networks.

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