Easily adjustable, power-symmetric Nonlinear Optical Loop Mirror for ultrafast photonic applications

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The operation of an unconventional, power-symmetric nonlinear optical loop mirror (NOLM) is investigated. The proposed architecture substantially differs from conventional NOLM designs, as switching relies on nonlinear polarization evolution. This particularity confers specific properties to the NOLM, which are very attractive for ultrafast photonic applications. In this paper, we investigate theoretically and experimentally the NOLM behaviour. Experimental results are shown to be in good agreement with theoretical predictions. Finally, we demonstrate experimentally that high-order amplitude regularization of an optical pulse train can be obtained using the novel scheme.

Introduction

The fibre Sagnac interferometer, or Nonlinear Optical Loop Mirror (NOLM) [1], is of common use today in many applications, including optical switching and demultiplexing, passive mode locking, pedestal suppression, pulse shaping or regeneration of ultrafast data streams. This simple device, made of a coupler whose output ports are connected through a span of fibre, offers a versatile way to generate a nonlinear transmission, or switching characteristic, through the optical Kerr effect. When a polarisation controller is inserted in the loop, the bias of the switching characteristic can be adjusted to meet at best the requirements of a specific application. Unfortunately, most NOLM designs rely on self-phase modulation, and can operate only if a power imbalance exists between the beams propagating clockwise (CW) and counterclockwise (CCW) in the loop. As the power ratio between CW and CCW beams is generally imposed by construction (in general, through the fixed coupling ratio of the coupler), such designs offer very poor possibility of adjustment, especially in terms of contrast or critical power (power at which the nonlinear phase shift difference = π). In addition, when designing such a NOLM, a compromise often has to be found between high contrast, low critical power and low insertion loss, as in general the three criteria can not be met simultaneously.

A change occurred when nonlinear polarisation evolution was included in the description of the NOLM operation [2]. In fact, even if powers are equal (case of a symmetrical coupler), a polarisation asymmetry between the CW and CCW beams can still provide switching. From this study emerged a particularly promising NOLM structure (Fig. 1). The proposed setup is made of a symmetrical coupler, highly twisted fibre and a quarter-wave plate (QWP) located close to one of the coupler output ports. In such power-symmetric design, switching can only be obtained through the polarisation

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difference generated by the QWP. The high twist applied to the fibre is of primary importance to maintain this polarisation asymmetry. Indeed, twist generates high optical activity, or circular birefringence, along the fibre, as well as a rapid precession of the fibre principal axes. Both effects tend to maintain the polarisation ellipticity constant during propagation in the loop. In contrast, in conventional NOLMs, any polarisation asymmetry vanishes rapidly, as a result of residual birefringence in standard fibre.

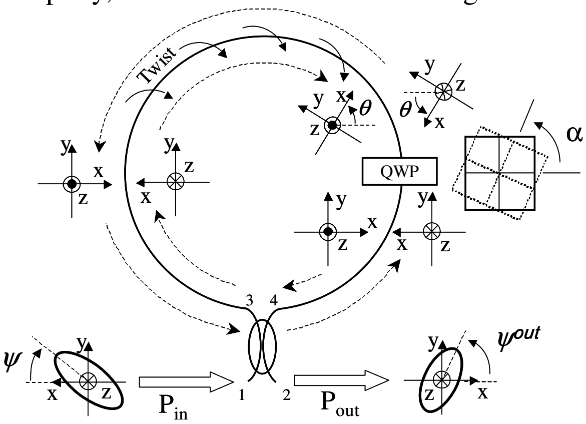

Fig. 1 - Scheme of the NOLM structure investigated in this paper, including the coordinate frames used. These frames twist along with the fibre (in a plane perpendicular to its axis). Note the $-\theta$ rotation of the frames through the QWP. Frames of CW and CCW beams only coincide at the NOLM input and output.

Theory

In most practical cases, the nonlinear polarisation evolution through the fibre loop can be described using the approximate, weak-nonlinearity equations introduced in [2]. These equations can be integrated over the fibre length $l = L/L_b$ (normalised with respect to beat length L_b), which allows a matrix representation of the fibre loop (in the base of circular right and left polarisations, for high twist):

$$F_{cw/ccw} = \begin{bmatrix} \exp\left\{ i\left[\mu + \frac{1}{4}\left(3 - A_s^{cw/ccw}\right)P_{in} \right] l \right\} & 0 \\ 0 & \exp\left\{ i\left[-\mu + \frac{1}{4}\left(3 + A_s^{cw/ccw}\right)P_{in} \right] l \right\} \end{bmatrix}, \qquad (1)$$

where μ represents low-power birefringence (~ ratio of circular to linear birefringence), P_{in} is the normalised input power to the NOLM (see [2]), $A_s = |C^+|^2 - |C^-|^2$ the Stokes parameter, and the superscripts CW and CCW apply to CW and CCW beams, respectively. Eq. (1) shows that the fibre produces two nonlinear effects: a phase shift $3/4P_{in}l$, and a polarisation rotation, $-1/4A_s^{cw/ccw}P_{in}l$. Considering Fig. 1, Eq. (1) and the transfer matrix of the QWP, one can determine, using matrix algebra, the Jones vector of the power-dependent output electric field, for any input polarisation defined by the Stokes parameter $A_s^{in} = A_s^{cw}$ and the orientation of the major axis of the ellipse, ψ. From this expression, the NOLM transmission can finally be determined:

$$T = \frac{1}{2} - \frac{1}{2}\cos\left(\beta - 2\alpha - \frac{1}{4}A_s^{cw}P_{in}l\right)\cos\left(\beta - 2\alpha - \frac{1}{4}A_s^{ccw}P_{in}l\right), \qquad (2)$$

where β is the total optical activity of the fibre (~5% of the total twist), and α is the QWP angle. The Stokes parameter of the CCW beam is given by A_s^{ccw} =

$-\sqrt{(1-A_s^{cw2})}\times sin2(\alpha+\psi)$. The simple expression given by Eq. (2) shows that the transmission is very flexible, as it can be adapted simply by adjusting the QWP angle α or the input polarisation. Particularly attractive situations appear if the input polarisation is circular ($A_s^{cw} = \pm 1$) or linear ($A_s^{cw} = 0$). In both cases, T is a sinusoidal function of power. In the first case, Eq. (2) shows that the contrast can be adjusted (between 1 and ∞) through the QWP angle α [Fig. 2(a)]. When $\alpha = \beta/2 + k\pi/2$ (k integer), unlike most classical NOLM architectures, we have altogether infinite contrast ($T_{min} = 0$ for $P_{in} = 0$) and no insertion loss ($T_{max} = 1$), with a moderate critical power. This very interesting behaviour of the NOLM for circular input polarisation was observed experimentally [Fig. 2(a)] [3]. In the case of linear input polarisation, Eq. (2) shows that a change of α simultaneously affects contrast and critical power. More interestingly, if α is set to $\beta/2 + k\pi/2$, fixing infinite contrast, the critical power $P_\pi = 4\pi/|sin2(\alpha+\psi)|$ is still adjustable (theoretically up to infinity) through the polarisation orientation, ψ [Fig. 2(b)].

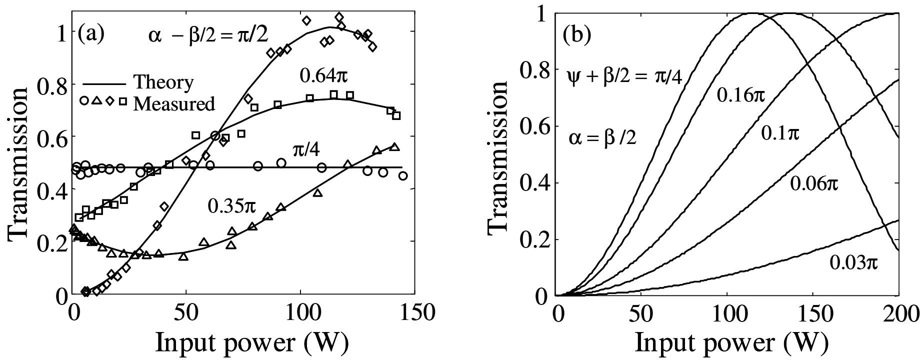

Fig. 2 - NOLM transmission for (a) circular and (b) linear input polarisations, for different values of the control parameter (α and ψ, respectively). The fibre is standard SMF-28 (length = *100 m*).

One interesting application of NOLMs is the reduction of amplitude fluctuations affecting optical pulse trains. If the average peak power of the input pulses matches the maximum of the transmitted power characteristic, $P_{out} = T\times P_{in}$ (point where $dP_{out}/dP_{in} = 0$), then amplitude fluctuations are significantly reduced at the NOLM output. Unfortunately, $d^nP_{out}/dP_{in}^n \neq 0$ for $n > 1$ at these points, and this reduction is generally associated to the generation of higher-order harmonics of the initial amplitude modulation (AM) (see Figs. 4 and 5 in [4]).

The story is different however if the contrast of the NOLM transmission can be adjusted, as it is the case with our architecture, for circular input polarisation. For particular values of α, points appear in the P_{out} characteristic where both first and second harmonics are zero [in bold in Fig. 3(a)]. High-quality amplitude regularisation of an optical pulse train was obtained experimentally in these cases [Fig. 3(b,c)]. For this demonstration, we used a symmetric NOLM including *500 m* of highly twisted (*7 turns/m*) standard SMF-28 fibre (critical power = *27 W*). The QWP was made by coiling a portion of the fibre. We used a 800-kHz train of sub-ns pulses at *1550 nm*, which were amplified and circularly polarised before entering the NOLM. Through gain modulation, we applied to the train a sinusoidal AM at *400 Hz*, with a magnitude of *4 W* (*8 W* peak to peak). Fig. 3(b) and (c) were obtained for $\alpha = 0.2088\pi$ and 0.2748π, respectively, by sweeping the average gain level (thus the average peak power), and measuring the magnitudes of the first three harmonics of the AM at the output (all were normalised to the magnitude of the initial 400-Hz modulation). These measurements were made through time-domain amplitude demodulation of the detected output pulse train, using a vector signal analyser. Fig. 3(b) shows that the first two harmonics are simultaneously minimised down to ~ *-20 dB* for $P_{in} \approx 30$ *W*. The performances are limited here by the third harmonic, measured at ~ *-15 dB*, and responsible for a small ripple at *1.2 kHz* in the output pulse train. In Fig. 3(c), it appears that not only the first two harmonics, but the third one as well, are minimised down to *-20 dB*, for $P_{in} \approx 48$ *W*. In addition, harmonics of order *4* and higher were not detected.

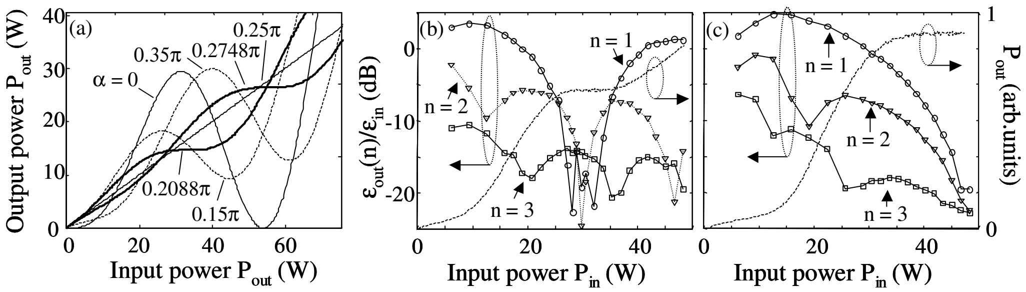

Fig. 3 - Curves of P_{out} versus P_{in} for different values of α in the case of circular input polarisation (a), and magnitude of harmonics of the 400-Hz AM versus P_{in} for $\alpha = 0.2088\pi$ (b) and 0.2748π (c). As a guide to the eyes, experimentally measured curves of P_{out} are also shown on figures (b,c). n = harmonic order.

Conclusion

We studied the operation of a power-symmetric NOLM, including a QWP and highly twisted fibre, which exploits nonlinear polarisation evolution. Using a matrix approach, we determined a general analytic expression for the NOLM transmission, which can be easily adjusted through the QWP angle and the input polarisation state. The NOLM operation is particularly attractive in the case of circular or linear input polarisation, allowing adjustment of respectively the modulation depth or the critical power. Experiments were carried out with circular input polarisation, and showed good agreement with theoretical predictions. Using this setup, we were able to perform high-order amplitude regularisation of an optical pulse train. We believe that the proposed structure will play an important role in future ultrafast photonic systems.

Acknowledgements

This work is supported by F.N.R.S. (Belgian Fund for Scientific Research), by the Interuniversity Attraction Pole IAP V/18 program of the Belgian Science Policy and by CONACyT (Mexican Council for Science and Technology). This work was also funded by CONACyT project J36135-A.

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