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The use of the nonlinear polarization self-rotation for the optical switching in the nonlinear loop mirror.

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ABSTRACT. For the first time the effect of the nonlinear rotation of the polarization in the fiber Sagnac interferometer configuration with a twisted fiber in the loop was examined. We have shown by numerical simulation, that it provides very high contrast switch of the reflection coefficient, from 1 to 0. The switch can be provided even in the configuration with a 0.5/0.5 coupler. By appropriate choosing of the fiber parameters both normal and inverted characteristics of the interferometer can be achieved.

RESUMEN. Por primera vez, se examinó el efecto de la rotación no lineal de polarización en la configuración del NOLM (nonlinear optical loop mirror), con una fibra birefringente en el lazo. Hemos mostrado numericamente que esto proporciona la conmutación del coeficiente de reflexión de 1 a 0 en la configuración del NOLM con un acoplador de 0.5/0.5. Por la elección apropiada de los parámetros de la fibra pueden ser activadas tanto las características normales como las de inversión.

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1. INTRODUCTION

Nonlinear optical loop mirror (NOLM) is used for fiber laser mode locking, for optical switch, etc. [1–4]. Various modifications of the design were proposed [5–7]. The concept of the conventional NOLM is based on the nonlinear phase shift between the counter-propagating linearly-polarized light beams in the loop interferometer [5]. Such interferometer operates as a nonlinear mirror with high reflectivity at low intensity of the input beam. In operation it is necessary to use an asymmetrical coupler *i. e.* one in which coupling coefficient differs from 0.5/0.5 to provide nonlinear switch of the reflection at high-intensity input signal. This leads to nonzero transmission of low power signals and, as a consequence, to the deterioration of the parameters. It is possible to modify properties of the NOLM by using of the loop with a birefringent fiber in which orthogonally polarized beams propagate in opposite directions. The possibility to invert the characteristic in this case was noted [8, 9]. But, to date only the self-phase modulation effect was considered for switch. The possibility to use the nonlinear polarization rotation was not discussed.

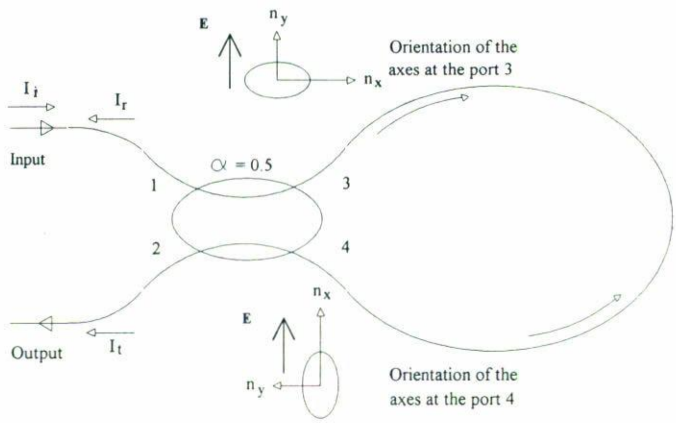

FIGURE 1. Schematic of the NOLM under discussion.

Here we, for the first time, numerically examine the effect of the nonlinear, polarization rotation in a loop mirror configuration with birefringent fiber to provide the nonlinear switch of the NOLM transmission. The controllable nonlinear transmission and reflection characteristic is shown.

The discussed NOLM is presented in Fig. 1. It consists of the fiber coupler with the power coupling ratio 0.5/0.5 with two ports joined by a birefringent fiber. The fiber is twisted by $\pi/2$ to provide the different polarization orientation of the counter-propagating beams with respect to the principal axes. In Fig. 1, for example, clock-wise beam is polarized parallel to the principal axis y and counter clock-wise beam is polarized parallel to x. For the same purpose it is possible to use a polarization rotator placed at one end of the loop. The operation of the loop interferometer with a birefringent bias at low intensity have been discussed in details in Ref. 10. It have been shown, that in this case reflection coefficient of the interferometer depends on the fiber length and birefringency.

The most easily, its operation can be described when a linearly polarized input beam is introduced. If the input polarization orientation is parallel to one of the principal axis of the fiber, clock-wise and counter-clock wise beams at the fiber inputs are polarized along the different principal axis. When the fiber twist period is longer then the fiber beat length, the beams conserve their polarization orientation with respect to the principal axes. As a consequence, the phase shift of the beams in the fiber is k_yL or k_xL for the polarization along y and x respectively. Phase difference between the counter propagating beams at the fiber outputs is $(k_y-k_x)L$. In each point of the fiber the counter propagating beams are polarized mutually orthogonal, but at the fiber outputs they are polarized in parallel, and therefore output intensity at the port 2 of the coupler depends on the phase shift between them. By change the fiber length both high and low reflection coefficient of the loop at the low input beam intensity can be achieved. At high input intensity of the linearly polarized beams the self-phase modulation effect can be observed and the nonlinear switch in this configuration is possible [9] (coupling coefficient must differ from 0.5/0.5). The nonlinear operation principle in this case is identical with those of the conventional NOLM.

When the elliptically polarized beam propagates in the fiber, the nonlinear polarization rotation may be observed [11, 12] in addition to the self-phase modulation. The operation of the NOLM in this case can be different from that of the conventional interferometer and have not been considered. As it is well known, the nonlinear polarization rotation depends on the orientation of the polarization ellipse with respect to the principal axes of the fiber. Thus, in the loop configuration with twisted fiber, at high intensity, the phase and polarization of the beams at fiber outputs will not be the same after the transmission through the fiber, even though the beam intensities are equal. Since the reflection of the interferometer depends on the phase shift between counter-propagating beams and their polarization, we can expect to provide the switch even with the 0.5/0.5 coupler. To date this possibility was not discussed. Let us consider the operation of the NOLM in this case.

The following procedure is used for numerical simulation. The relations connecting the input and output fields of the coupler are [13]

$$E_3 = \alpha^{1/2} E_1 + i(1-\alpha)^{1/2} E_2,$$
$$E_4 = i(1-\alpha)^{1/2} E_1 + \alpha^{1/2} E_2. \tag{1}$$

If the coupler is the polarization independent one, we can use these relations for beams with any polarization. The description of the self-rotation is the most convenient if two circularly polarized components with complex amplitudes C_+ and C_- are used. The orientation of the polarization with respect to the principal axes of the fiber at the port 3 differs from the orientation at the port 4 by the twist angle. It can be taken into account by multiplication of the C_+ by $\exp(i\pi/2)$ and C_- by $\exp(-i\pi/2)$. So, for the only one beam, E_1, at the loop input, the fields at the inputs of the fiber are

$$C_{\pm 3} = \alpha^{1/2} C_{\pm 1},$$
$$C_{+4} = i(1-\alpha)^{1/2} C_{+1}\, e^{i\pi/2},$$
$$C_{-4} = i(1-\alpha)^{1/2} C_{-1}\, e^{-i\pi/2}. \tag{2}$$

The evolution of the circularly polarized components with change of the fiber position z is described by coupled wave equations [11, 12]

$$dC_+/dz = ikC_- + i\beta(|C_+|^2 + 2\,|C_-|^2)C_+,$$
$$dC_-/dz = ikC_+ + i\beta(|C_-|^2 + 2\,|C_+|^2)C_-, \tag{3}$$

where $k = \pi\delta n/\lambda$ with δn being the index difference between the principal axes, $\beta = 16\pi^2 n_2 \times 10^7/ncA_{eff}$, with A_{eff} being the effective field area and n_2 the self-focusing index (1.1×10^{-13} esu for a silica fiber [14]).

For the fiber position normalized to the beat length $L_0 = \pi/k$ we have equations

$$dC_+/dZ_N = i\pi C_- + i(\pi\beta/k)(|C_+|^2 + 2\,|C_-|^2)C_+,$$
$$dC_-/dZ_N = i\pi C_+ + i(\pi\beta/k)(|C_-|^2 + 2\,|C_+|^2\,C_-, \tag{4}$$

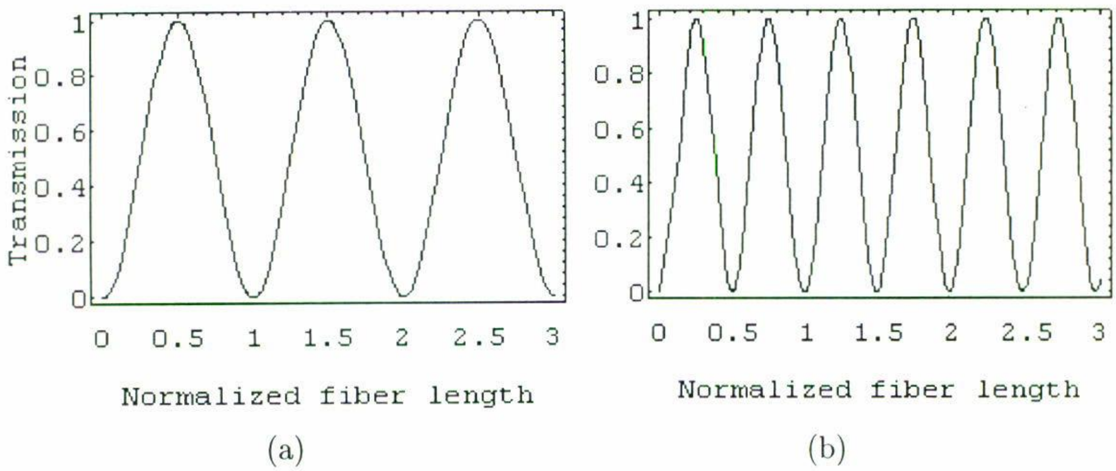

FIGURE 2. Dependencies of the transmission of the NOLM on the loop length, (a) low intensity, (b) high intensity of the beam.

where Z_N is the normalized fiber position, $(\pi\beta/k)\left|C_{\pm}\right|^2$ is the normalized intensity of the right and left circularly polarized component. Here we do not consider the nonlinear interaction of the counter-propagating beams. It is possible if the pulse length is shorter than the length of the fiber. At the same time, the pulse length must be long enough to avoid the pulse dispersion problem. So, our consideration is restricted by nanosecond and subnanosecond pulses.

The Eqs. (4) were solved numerically, and then the output field at the port 4 was multiplied by $\exp(-i\pi/2)$ for C_+ and $\exp(i\pi/2)$ for C_-, to take into account the effect of the fiber twist for the beams propagating from the port 3 to port 4. Then the relations (1) were used once again to calculate the beam parameters at the loop output (the port 1 or 2 of the coupler).

This procedure was applied to the linearly polarized input beam with polarization orientation of $\pi/4$ with respect to the principal axes of the fiber. To understand the operation of the NOLM, it is helpful to calculate the output intensity as a function of the fiber length. It is presented in Fig. 2a for the low input intensity, $|C_{\pm}| = 1$, and in Fig. 2b for the high input intensity, $|C_{\pm}| = 25$. At the low intensity the operation of the loop is straightforward and have been explained above. The counter-propagating beams in the fiber have a different wave number, the phase shift between them depends linearly on the fiber length. As result, the oscillations of the output intensity with period being equal to the beat length are observed. With increasing of the input power, the similar oscillations, but with shorter period, was found. As it can be seeing, the period of the oscillations is approximately two time shorter. From this results it is easily to understand that, at the fixed fiber length, the loop transmission have to depend on the input intensity.

In order to get an idea of the dependence of the reflectivity on the input intensity, the period of the oscillation as a function of the input pump power was calculated. It is shown in Fig. 3. This dependence gives it possible to calculate the transmitivity of the NOLM at any fiber length. The examples the transmission coefficient as a function

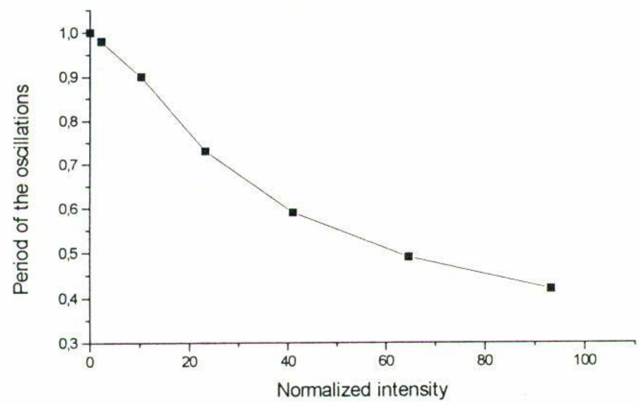

FIGURE 3. Dependencies of the transmission of the NOLM on the loop length, (a) low intensity, (b) high intensity of the beam.

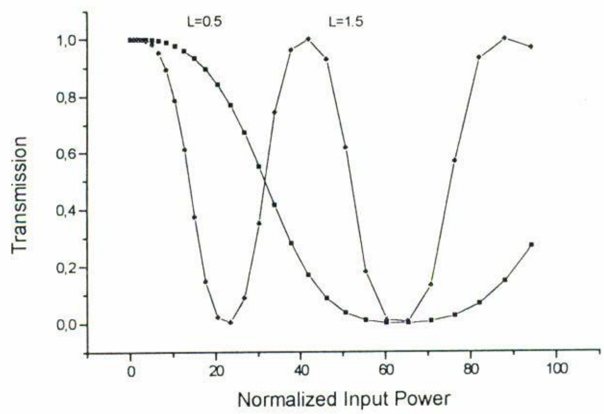

FIGURE 4. Dependencies of transmission of NOLM on the power for fiber length corresponding to first and second low intensity transmission maxima.

of the input intensity are presented in Fig. 4 for the normalized fiber length of 0.5 and 1.5, and in Fig. 5 for the normalized fiber length of 1.0. The dependencies demonstrate the switch of the transmission coefficient between one and zero as the input intensity is increased. The output beam polarization was found to be the same as the input beam polarization at any beam intensity.

It is important to note, that the nonlinear switch in this configuration is only due to the nonlinear polarization rotation effect and does not depend on the self-phase modulation. The nonlinear polarization rotation effect is due to the terms $|C_-|^2 C_+$ and $|C_+|^2 C_-$ of Eq. (4) and does not depend on the self-modulation terms $|C_+|^2 C_+$ and $|C_-|^2 C_-$. The simulation of the interferometer with Eqs. (4) from which the self-modulation terms was excluded have led to the same results exactly, as above. The presented results show that, in the Sagnac interferometer configuration with the 0.5/0.5 coupler and twisted fiber, the nonlinear polarization rotation effect provides the reflection coefficient switch

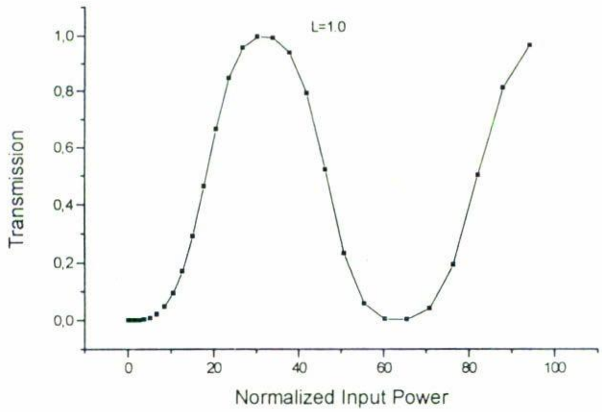

FIGURE 5. Dependencies of the transmission of the NOLM on the power for fiber length corresponding to first low intensity transmission minimum.

between one and zero. To get switch in a standard interferometer, it is necessary to use asymmetrical coupler, for which couple ratio differs from 0.5/0.5. This results to decrease of the contrast of switch. Additionally both normal and inversion transmission characteristics can be achieved in our configuration.

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