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Comparison of fiber-based Sagnac interferometers for self-switching of optical pulses

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Abstract

Self-switching of ultrashort optical pulses in a gain-distributed nonlinear amplifying fiber loop mirror (NALM) is investigated numerically in the soliton regime. Switching characteristics of this device is compared to those of the nonlinear optical loop mirror (NOLM) and the conventional NALM that uses a lumped gain. We show that, as compared with the NOLM or the conventional NALM, the gain-distributed NALM can produce higher-quality pulses and permits more efficient pulse compression. We also show that the gain-distributed NALM has several advantages over the conventional NALM such as sharpened switching edges, flattened switching peak, and robustness to gain variations.

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1. Introduction

Nonlinear optical loop mirrors (NOLMs) [1], capable of handling ultrashort pulses, have found many applications, such as soliton self-switching [1–3], all-optical demultiplexing [4], wavelength conversion [5], pulse pedestal suppression [6], and noise filtering [7] in all-optical fiber communication systems. Self-switching with the NOLM is achieved by placing a symmetry-breaking element in the loop and thereby causing counterpropagating pulses to acquire different amounts of nonlinear phase, so at recombination phase difference produce reflected and transmitted (switched) outputs. To break the symmetry, the original NOLM [1] uses an asymmetric coupler. Alternative schemes that can achieve symmetry breaking of the loop without resorting to an asymmetric coupler have been proposed and demonstrated to work. Examples include using dispersion-imbalanced fibers

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[8–10], asymmetrically induced nonlinear birefringence effects [11,12], or an asymmetrically located optical amplifier [13,14].

NOLMs with asymmetrically located optical amplifiers [13,14], also known as nonlinear amplifying loop mirrors (NALMs), best exploit the fiber nonlinearity resulting in the lowest threshold switching power. However, since the amplifier is much shorter than the fiber loop and is located close to the coupler, the counterpropagating pulses in the loop are not amplified simultaneously, i.e., one pulse is amplified just after entering the loop while the other experiences amplification just before exiting the loop. As a result, evolutions of the two pulses in the loop are quite different, especially in the soliton regime. When they recombine at the coupler, seriously mismatched pulse shapes lead to the poor quality of the switched pulses. It was predicted [15] that pulses switched by the conventional NALM that incorporates a lumped gain (hereinafter, we call it gain-lumped NALM) contain frequency chirp, which will affect signal propagation over long-distance, especially in soliton communication systems. Other problems with the gain-lumped NALM are that the switching curve is not sufficiently sharp and the switching characteristics are sensitive to gain variations.

In this paper we numerically study, for the first time to our knowledge, the self-switching characteristics of a gain-distributed NALM which is distinct to the gain-lumped NALM in that a distributed gain [16] rather than a lumped gain is uniformly placed along the loop while using an asymmetric coupler. We show that, as compared with the NOLM or the gain-lumped NALM, the gain-distributed NALM can produce higher-quality pulses and permits more efficient pulse compression. We also show that the gain-distributed NALM has several advantages over the gain-lumped NALM such as sharpened switching edges, flattened switching peak, and robustness to gain variations.

2. Basic equations

For simulations of pulse evolution in a fiber loop, we use the split-step Fourier method to solve the nonlinear Schrödinger equation including negative group-velocity dispersion (GVD), self-phase modulation (SPM), and gain or loss. In dimensionless form, the equation is

$$\mathrm{i}\frac{\partial u}{\partial \xi}+\frac{1}{2}\frac{\partial^2 u}{\partial \tau^2}+|u|^2u=\frac{\mathrm{i}}{2}\mu u, \tag{1}$$

where ξ, τ, and $u(\xi,\tau)$ denote, respectively, the normalized distance, time, and pulse envelope in soliton units. In real parameters

$$\xi=\frac{z}{L_\mathrm{D}}=\frac{z|\beta_2|}{T_0^2},\quad \tau=\frac{t-z/v_g}{T_0},$$
$$\mu=(g_0-\alpha)L_\mathrm{D}, \tag{2}$$

where T_0 is the half-width (at $1/e$-intensity point) of the input pulse, v_g is the group velocity, β_2 is the GVD coefficient, g_0 is the unsaturated gain, α is the attenuation constant, and $L_\mathrm{D}=T_0^2/|\beta_2|$ is the dispersion length. The term on the right-hand side of Eq. (1) accounts for gain or loss. Gain dispersion and higher-order effects such as Raman self-scattering (RSS) and third-order dispersion can be neglected for input pulses wider than 5 ps. We also neglect gain saturation, which is justified since we are only concerned with the switching of a single pulse with a typical energy (~1 pJ) much lower than the saturation energy of most amplifiers such as erbium-doped fiber amplifiers which is on the order of 1 μJ.

3. Self-switching characteristics of NOLM and gain-lumped NALM

Before we investigate pulse self-switching in a gain-distributed NALM, we discuss the switching characteristics of NOLM and gain-lumped NALM. In the case of NOLM, the loop is constructed from a piece of passive fiber, i.e., $g_0 = 0$ in Eq. (2). Fiber loss is considered with $\alpha = 0.046$ km^{-1} (i.e., 0.2 dB/km). The input pulse is assumed to be $u(0,\tau) = A\,\mathrm{sech}(\tau)$ with FWHM pulsewidth of $T_\mathrm{FWHM} = 5$ ps ($T_0 \approx 2.84$ ps), where A is related to the physical parameters by

$$A^2=\frac{\gamma P_0 T_0^2}{|\beta_2|} \tag{3}$$