Numerical investigation of optical bistability in inhomogeneous $\mathcal{PT}$-symmetric gratings

1st S. Sudhakar
Department of Electronics and Communication Engineering
Vel Tech High Tech Dr. Rangarajan Dr. Sakunthala
Engineering College
Chennai, India
sudhakars106@gmail.com

2nd S. Vignesh Raja
Department of Physics
Pondicherry University
Puducherry, India
vickyneeshraja@gmail.com

3rd A. Govindarajan
Department of Nonlinear dynamics
Bharathidhasan University
Tiruchirappalli, Tamilnadu, India
govin.nld@gmail.com

***Abstract*—Customizing the nonlinear profile along the direction of propagation helps in the realization of low-power all-optical switches. The switching intensities are extremely low (< 0.01) in the broken regime provided that the light launching direction is right. It is believed that the switching intensities in the broken regime are always higher than that of the unbroken regime. But, the proposed system displays the lowest switching intensities in the broken regime. The interplay between inhomogeneous nonlinearity, broken $\mathcal{PT}$-symmetry and right light incidence gives rise to the switch-down mechanism at near-zero switching intensities.**

***Index Terms*—$\mathcal{PT}$-symmetry, fiber Bragg gratings, optical bistability, non-reciprocal switching**

I. Introduction

In the perspective of nonlinear fiber Bragg gratings (FBGs), several theoretical suggestions were made by researchers for reducing the switching intensities. The concept of inhomogeneous nonlinearity (INL) is arising as an apparent direction for realizing low-power all optical switches (AOS) [1], [2]. INL indicates the fluctuations in the nonlinearity (γ) as a function of propagation coordinate z. To realize such fiber based devices with INL, one needs to adjust the doping level as a function of the propagation coordinate. Thus the nonlinear coefficient becomes a function of z rather than the constant one.

Nonreciprocal steering dynamics in nonlinear FBGs under the reversal of light launching direction has been recognized as an excellent platform for fabricating low-power AOS. In the past, optical bistability (OB) in homogeneous and inhomogeneous PTFBGs were investigated in various $\mathcal{PT}$-symmetric regimes [3]–[5].

In the present work, we study the nonreciprocal switching dynamics of a PTFBG with an inhomogeneous nonlinearity for the reasons that there seem to exist hardly a few works that deal with the OB in FBGs with INL. Different kinds of nonlinear profiles exist in the form of linear, Gaussian, exponential, logarithmic, and so forth [1]. But this article deals only with the steering dynamics of PTFBGs with a linearly increasing INL.

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II. Numerical Modelling of the system

It is assumed that the fiber supports only third-order nonlinearity. The refractive index profile of the system is described as

$$n(z) = n_0 + n_{1R}cos(2\pi z/\Lambda) + in_{1I}sin(2\pi z/\Lambda) + n_2(z)|E|^2. \tag{1}$$

In Eq. (1), n_0, n_{1R}, n_{1I}, n_2 Λ, $|E|^2$ denote the refractive index (RI) of the core, modulation of real, imaginary parts of RI, third-order nonlinear coefficient, grating period and electric field strength, respectively. It should be noted that Eq. (1) obeys the $\mathcal{PT}$-symmetric condition $n(z) = n^*(-z)$ [6]. Substituting the refractive index profile and the electric field in the Helmholtz equation (governing equation for any optical medium) and by using transformation $E_{f,b}$ = $A_{f,b}\exp(\mp\delta_0 z)$, we arrive at the coupled-mode equations (CMEs) that govern the system of interest.

$$+i\frac{dA_f}{dz} + \delta A_f + (k+g)\,A_b + \gamma(z)\left(|A_f|^2 + 2|A_b|^2\right)A_f = 0, \tag{2}$$

$$-i\frac{dA_b}{dz} + \delta A_b + (k-g)\,A_b + \gamma(z)\left(|A_b|^2 + 2|A_f|^2\right)A_b = 0. \tag{3}$$

Eqs. (3) and (4) are valid for the left light incidence condition. In Eq. (3), the term $\kappa + g$ is replaced by $\kappa - g$ for the right light incidence condition. Similarly, the term $\kappa - g$ in Eq. (4) should be replaced by $\kappa + g$. The mathematical relations used in the simulations read as

$$\delta_0 = 2\pi n_0\left(\frac{1}{\lambda} - \frac{1}{\Lambda_b}\right), \quad \lambda_b = 2n_0\Lambda, \quad \kappa = \pi n_{1R}/\lambda,$$
$$g = \pi n_{1I}/\lambda, \text{ and } \quad \gamma = 2\pi n_2/\lambda \tag{4}$$

Here κ and g signify the coupling, gain and loss coefficient, respectively. The parameter δ determines the amount of detuning of the operating wavelength from the Bragg wavelength (λ_b).

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The inhomogeneous nonlinear profile ($\gamma(z)$) is assumed to be linearly changing at a rate (σ) defined by

$$\gamma(z) = 1 + \frac{(\sigma - 1)z}{L} \tag{5}$$

where L is the normalized length of the PTFBG. The system of equations in (2) and (3) are solved by implicit Runge-Kutta fourth-order method. The boundary conditions to solve the CMEs are assigned as

$$A_f(0) = A_f^0 \quad \text{and} \quad A_b(L) = 0. \tag{6}$$

Different operating regimes of the PTFBG are defined as

$$\kappa \begin{cases} > g, & \text{unbroken } \mathcal{PT}\text{-symmetric regime} \\ < g, & \text{broken } \mathcal{PT}\text{-symmetric regime} \end{cases} \tag{7}$$

The length of the device and coupling coefficient are assumed to be $L = 2$ and $\kappa = 3$ in the numerical simulations.

III. Simulation Results

A. Unbroken regime

The gain and loss parameter (g) decreases the hysteresis width as well the switching intensities (both switch-up and down) on the grounds that the magnitude of g is closer to the coupling coefficient (κ) as shown in Fig. 1(a). This is true for both the direction of light incidences (left and right). The presence of $\mathcal{PT}$-symmetry ensures that the system posses non-reciprocal switching on the reversal of direction of light incidence. The switching intensities are pretty low for the right light launching condition. To reduce the intensities further, one can opt for the frequency detuning. It is optimal to operate the system in the negative detuning regime as shown in Fig. 1(b). Here, the magnitudes of switching intensities decrease as the magnitude of the detuning parameter ($delta$) decreases. It must be ensured that the value of negative detuning parameter ($\delta < 0$) should lie within the range as shown in Fig. 1(b). Far away from these values, the OB curves do not take place.

B. Broken regime: Right incidence

Instead of typical S-shaped OB curve, the system reveals OB with ramp-like first stable state while operating in the broken regime. The value of input intensities for which the ramp-like appear in the OB curve is called the span of the ramp. The span of the ramp is reduced when increasing the rate of the variation of INL (σ) as shown in Fig. 2(a). Also, the hysteresis width gets narrower with an increase in the value of σ. The onset of switching is indicated by the sudden jump in the output intensities from the ramp-like stable state to the next branch. The system reveals switch-down mechanism at near-zero intensities provided the value of INL (σ) is carefully manipulated in the numerical simulations as shown in Fig. 2(a). This is possible only in the case of broken PTFBG with right light launching conditions. This peculiar switching phenomenon occurs only at specific values and not for a wide range of system parameters. For other values, low-power OB curves with ramp-like states will appear. From Fig. 2(b), it is confirmed that the interplay between larger values of INL (σ) and the negative detuning parameter (δ) favors the low-power all-optical switching (< 0.01).

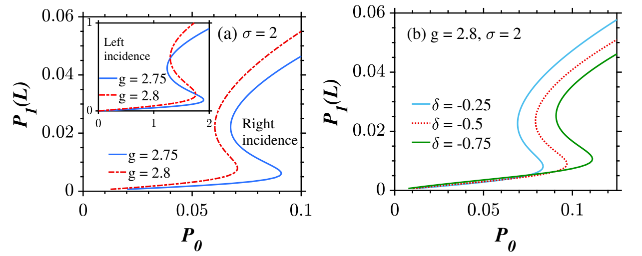

Fig. 1. (a) Comparison of switching-intensities between left and right incidences for different values of gain and loss (g). (b) Role of frequency detuning (δ) in the presence of right light incidence.

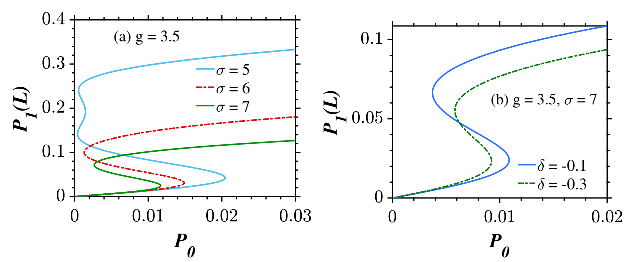

Fig. 2. Low-power OB curves with ramp-like first stable states. The system is operated in the broken regime and the direction of light incidence is right. (a) Role of INL (σ). (b) Role of frequency detuning ($\delta < 0$)

IV. Conclusions

It is found that the switching intensities can be extremely low provided that inhomogeneously increasing nonlinearity must be large. The switching intensities are lower in the broken regime than the switching intensities in the unbroken regime. Also, the OB curves display ramp-like first stable states prior to the switch-up action. In the presence of right light incidence direction, the system gives rise to OB curves with *near-zero switching* intensities when it is operated in the broken $\mathcal{PT}$-symmetric regime.

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