All-Optical Ternary Stability in Uniform Nonlinear Chalcogenide Fiber Bragg Gratings

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ABSTRACT— In recent decades, fiber Bragg gratings (FBGs) have been very much considered for their many applications in optical communication systems, as well as due to their bistability and multi stability properties. In this paper, the formation of ternary stability (TS) in nonlinear chalcogenide fiber Bragg gratings (NCFBGs) is investigated via numerical simulations. Effective parameters on TS such as the FBG length, input wavelength and nonlinear property (or nonlinearity) on TS formation are introduced and studied. It is found that there exists a minimum length for each third order nonlinear coefficient that TS phenomena can be observed. Also, the threshold intensity for TS formation is calculated with respect to the length, input wavelength and third order nonlinearity. In addition, the relevance between the minimum length for TS formation and the third order nonlinearity in the range of chalcogenide nonlinearities are looked into. It is numerically confirmed that increasing the input wavelength (in a valid FBG input wavelength range) increases the TS formation threshold intensity, while decreases the needed FBG length. Because of using experimental values in this paper, it has valuable information about designing the all-optical device with three - level stability which makes NCFBG a suitable option for all-optical ternary switching and all-optical memory in the integrated optical circuits.

KEYWORDS: All-Optical devices, Chalcogenide fiber Bragg grating, Multistabiltiy, Nonlinear optics.

I. INTRODUCTION

Today fiber Bragg gratings (FBGs), because of the having shining features on optical communication systems, are highly considered all over the scientific and industrial world. Their various applications are known in the linear optical communication systems such as pulse dispersion compensation [1], optical filters [2], wavelength division multiplexing (WDM), optical limiters [3], and optical sensors [4]. They are also well-regarded for their nonlinear effects such as optical switching [5] and optical bistability [6, 7] which is applicable in all-optical memories and all-optical signal processing devices which has become a significant interest for research recently [8-10]. Chalcogenide glasses offer such opportunity because of their nonlinear parameter, n_2, which is about 100 to 1000 times larger compared with silica [11-14]. This type of FBGs shows bistability characteristics [15, 16] in suitable conditions as well as multistability characteristics like ternary stability (TS) which provides a good platform for speeding up the information transfer rate compared to that of the binary logic [17].

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In the present study, we consider a uniform nonlinear chalcogenide glass [10] made FBG taking into account its third order nonlinearity. We solve the governing coupled mode equations numerically and find special initial values to obtain TS as a kind of multistability. After that, we study this TS diagram which has three stable branches in input-output intensity diagram and introduce its characteristics. Finally, we investigate the effects of some important parameters like: FBG length, input wavelength (λ_0) and third order nonlinearity on the TS formation. This paper is a part of the first leading work on three level stabilities in FBG to design the suitable FBG for different applications in all-optical ternary memory and integrated optical circuits.

II. THEORY AND NUMERICAL CALCULATIONS

The schematic diagram of a typical lossless uniform FBG with length L is shown in Fig. 1. Its refractive index varies along the length periodically and can be formulated as follows [8]:

$$n(z) = n_0 + n_1 \cos\left(\frac{2\pi}{\Lambda} z\right) + n_2 \mid E \mid^2, \tag{1}$$

where E is the electric field in the FBG, Λ is the grating period, n_0, n_1 and n_2 denote the linear refractive index, refractive index modulation amplitude and third order nonlinear refractive index coefficient, respectively.

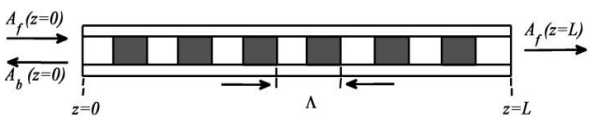


Fig. 1. The schematic diagram of the FBG with length L. The forward and backward waves are shown [10].

The electric field in the FBG can be described as combining the forward and backward waves [8]:

$$E(\mathbf{r},t) = \frac{1}{2} F(x,y)\Big[A_f(z,t) e^{i\beta_B z} + A_b(z,t) e^{-i\beta_B z} \Big] e^{-i\omega_0 t} + c.c., \tag{2}$$

where ω_0 is the carrier frequency, A_f and A_b represent the slowly varying amplitude of forward and backward waves respectively, and $F(x,y)$ is the transverse variations of two counter propagating waves.

We assume that the incident wave is continuous. Substituting Eqs. (1) and (2) into the Maxwell's equations and using slowly varying amplitude approximation, the nonlinear coupled mode equations for both forward and backward wave amplitudes are obtained in as follows [8]:

$$\frac{\partial A_f}{\partial z} + \frac{\alpha}{2} A_f = i\delta A_f + i\kappa A_b + i\gamma\left(\mid A_f \mid^2 + 2 \mid A_b \mid^2\right) A_f, \tag{2}$$

$$-\frac{\partial A_b}{\partial z} + \frac{\alpha}{2} A_b = i\delta A_b + i\kappa A_f + i\gamma\left(\mid A_b \mid^2 + 2 \mid A_f \mid^2\right) A_b, \tag{4}$$

where α is the FBG loss that is neglected, δ, κ and γ account for the detuning from the Bragg wavelength, coupling coefficient and nonlinear coefficient, respectively. The numerical solution of nonlinear coupled mode equations is derived by using Runge-Kutta methods. We do these calculations for the FBG as it is discussed in [10, 18] by doing our simulation from end to the beginning of the FBG with appropriate boundary conditions. It is done by MATLAB software.

III. OPTICAL TERNARY STABILITY CHARACTERISTICS

As shown in Fig. 2, a typical TS diagram is a kind of hysteresis diagram that has five branches; odd branches are stable while even ones are unstable as shown in Fig. 2. To study the characteristics of TS, five parameters are introduced, namely TS interval, first and second on-off switching ratios, and first and

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second TS threshold intensities which are clearly introduced in Fig. 2. Also, the typical data used in this work is shown in Table 1.

Table 1. Typical data which are used in this article.

$\lambda_B = 1550\,\text{nm}$	$n_0 = 2.45$
$\lambda = 1550.015\,\text{nm}$	$n_1 = 1.5\times10^{-4}$
$\Lambda = 3.16\times10^{-7}\,m$	$n_{2silica} = 0.273\times10^{-19}\,m^2/W$ [19]
$n_2 = 220\,n_{2silica}$ [11]	

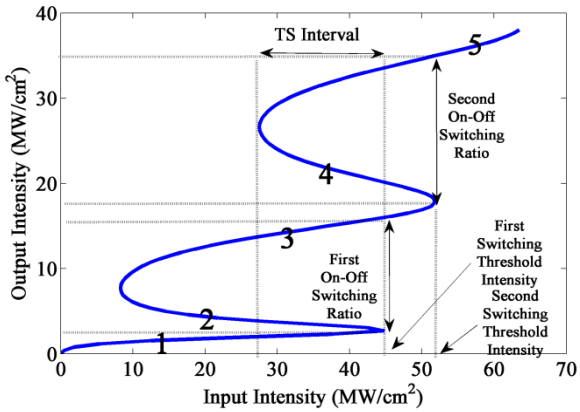


Fig. 2. An illustrative definition of five parameters of TS, first and second on-off switching ratios, first and second switching threshold intensities and TS interval. Five branches of the TS are also clearly depicted.

The two most important parameters which can be criteria for TS formation are: TS interval and second switching threshold intensity. The TS interval is an input intensity overlapping area between branches 1, 3 and 5 in typical TS diagram which is shown in Fig. 2. It means that in TS interval, for each intensity point there are three output points. If the TS diagram has a minimum TS interval that means the TS is formed i.e. with no TS interval there exist no TS curve. Also, it is clear that the second switching threshold intensity is a critical and minimum value of input intensity to form the TS diagram via these characteristics (as shown in Fig. 2). Therefore, the second switching threshold intensity should have certain values for TS formation which is also related to the TS interval. In this state when the TS diagram starts to form, "second switching threshold intensity" can also be called "minimum TS intensity" or "TS formation threshold intensity".

In the next sections, we investigate the minimum values of input intensity for TS formation with considering the effects of FBG length, input intensity, third order nonlinearity and input wavelength. Also it is obtained that by varying those parameters and selecting good values, the TS interval can be reachable.

IV. How Is a Ternary Stability Formed?

TS is not obtained in nonlinear chalcogenide FBG unless the necessary conditions are maintained. Parameters like FBG length, third order nonlinearity and input power are important for TS to be observed. Two main parameters which can considerably affect the TS formation for a given nonlinearity are "the FBG length" and "the input pulse intensity".

As it is already known, chalcogenide materials have a range of nonlinearities about 100 to 1000 times of silica glasses. Table 2 shows the linear and third-order nonlinear refractive indices for some of the chalcogenide materials which we have used for simulating the behavior of TS formation.

Table 2 Measured linear refractive index n_0 and third-order nonlinear refractive index n_2 of chalcogenide glasses [11].

Glass	n_0 at 1.55 μm	$n_2/n_{2,silica}$ (±15%)
$As_{40}S_{60}$	2.45	220
$As_{40}S_{40}Se_{20}$	2.55	300
$As_{40}S_{50}Se_{10}$	2.49	380
$As_{40}S_{30}Se_{30}$	2.62	430
$As_{25}S_{55}Te_{20}$	2.52	470
$As_{40}S_{10}Se_{50}$	2.76	560
$As_{30}Se_{61}$	2.81	660
$As_{40}Se_{55}Cu_5$	2.93	850
$As_{40}Se_{60}$	2.81	930

V. The Effect of FBG Length and Input Intensity on Ternary Stability Formation

First of all, the effect of FBG length and κL (the production of the coupling coefficient, κ, and the FBG length) on TS formation are studied for each chalcogenide glass third-order nonlinearity. Diagrams shown in Fig. 3

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illustrate these effects on the TS formation for $n_2 / n_{2,\,silica} = 220$ but for various values of κL.

As shown in Fig. 3 assuming $\kappa L = 5$ for simulation, TS is not formed even by increasing the input intensity. Although some individual bistable curves are achieved, there is no TS interval. After that, the value of κL is increased to 7 while keeping other parameters fixed. With these conditions, TS is formed well, as seen in Fig. 3 with a solid curve, such that TS interval has a considerable value.

Other simulations are carried out for various values of κL to obtain the critical one for starting the TS formation i.e. the minimum value of κL required for TS formation. The dashed curve in Fig. 3 depicts the critical situation for starting the TS formation (in fact, TS interval starts to construct), by taking $\kappa L = 5.3$, $n_2 / n_{2,silica} = 220$, and other parameters are held fixed.

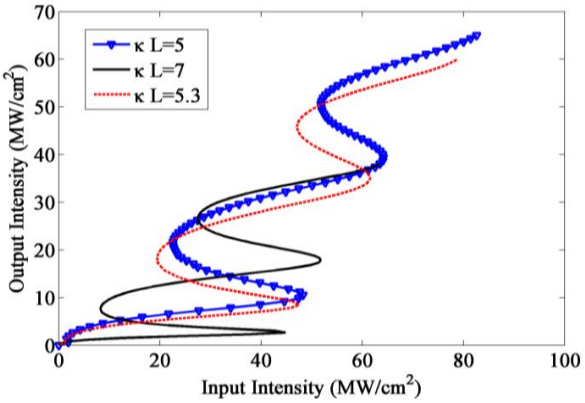


Fig. 3. The input-output diagrams for $n_2 / n_{2,silica} = 220$ and three different κL.

In the next step of our simulations, κL is fixed to 5.2 (a little lower the critical κL) while the value of third order nonlinearity is varied. We want to see if the increasing on third-order nonlinearity can compensate the lack of value of κL or not.

The results of simulations for three values of third-order nonlinearities chosen from Table 2 are presented in Fig. 4. Dashed diagram illustrates the input-output intensity diagram for $n_2 / n_{2,silica} = 300$. It shows that although TS is near to threshold formation, TS is not yet formed. It is expected that by increasing the value of third-order nonlinearity, the TS can be reached. However, as shown in Fig. 4 for $n_2 / n_{2,silica} = 660$ TS is not formed yet and even for the maximum value of $n_2 / n_{2,silica}$ i.e. 930, unpredictably TS is not formed as well.

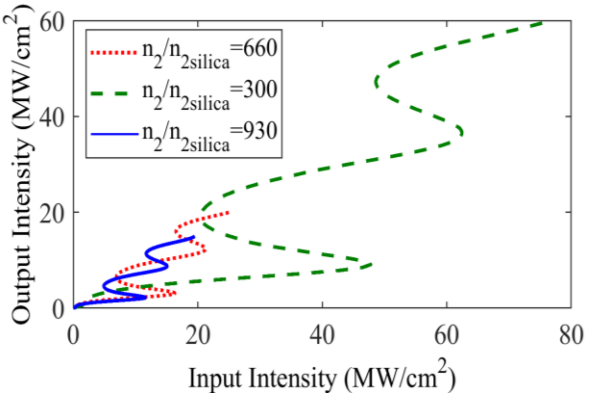


Fig. 4. The input-output diagram of TS formation in $\kappa L = 5.2$ and various $n_2 / n_{2,silica}$.

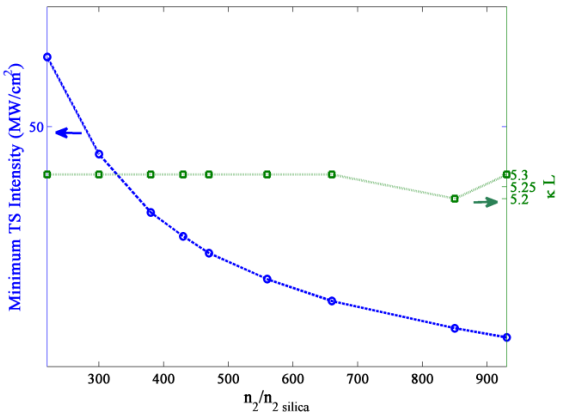


Fig. 5. The minimum intensities in the range of about 10-70 MW/cm^2 and the minimum κL (that is about 5.3) needed for TS formation in several chalcogenide third order nonlinearities.

In continue, the minimum κL for the TS formation is calculated for various chalcogenide third-order nonlinearities. The result is depicted in Fig. 5. It is worth to mention that the minimum necessary FBG length of TS formation is nearly constant (that its value is about 1.7 cm) and independent of the third-order nonlinearity. Having mentioned that the minimum input intensity, i.e. the second switching threshold intensity, which is needed for TS formation is decreased from 62MW/cm^2 to 15MW/cm^2 by increasing the

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nonlinearity (i.e. the volume of $n_2/n_{2,silica}$ from 220 to 930), as expected. Also Fig. 5 presents such behaviors. In Fig. 6, all results are compared to show the effect of minimum FBG length and minimum intensity for TS formation for different values of chalcogenide nonlinearities.

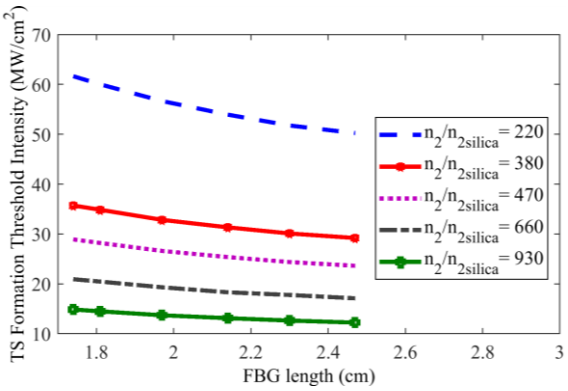


Fig. 6. Diagram of TS formation threshold intensity versus the FBG length in various third order nonlinearity for $\lambda_0 = 1550.015$ nm.

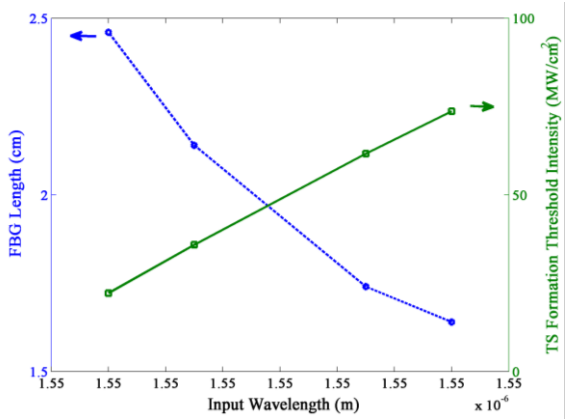


Fig. 7. The minimum length of FBG and the minimum intensity for TS formation in various input wavelengths.

VI. CONCLUSION

In this paper, the performance of the FBG is simulated by numerically solving the governing nonlinear coupled mode equations to study the ternary stability (TS). First, the special initial values are obtained in which output-input intensity diagram shows TS. Also, five parameters that represent the characteristics of TS are introduced. Usually bistability is formed in nonlinear FBGs but TS formation needs special conditions. Our simulation is conducted for the chalcogenide materials made FBG with third-order nonlinearity in the range of about 100-1000 times of the silica one. The Bragg wavelength is 1550 nm. We showed that the minimum FBG length for the TS formation is nearly constant (about 1.7 cm) and nearly independent of the third-order nonlinearity for the range of chalcogenide nonlinearities. We obtained minimum necessary intensities for each chalcogenide type for the TS formation with respect to the FBG length. There is a minimum length below which, TS will not be formed even by increasing the nonlinearity. It is also illustrated that by increasing the input wavelength in a valid range of input wavelengths, the required TS formation intensities will drop while the minimum FBG length will increase. It is worth to mention that TS can be formed in chalcogenide glasses of a few centimeters length which makes it a good alternative for all-optical ternary memory in the integrated optical circuits.

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