Optical multistability in nonlinear fiber Bragg grating

SANTOSH PAWAR, SHUBHADA KUMBHAJ*, PRATIMA SEN[b], PRANAY KUMAR SEN
Department of Applied Physics, Shri G. S. Institute of Technology and Science,
23, Park Road, Indore- 452003, India
[a]*School of physics, Devi Ahilya Vishvavidyalaya, Khandwa Road, Indore- 452017, India*

Using the optical Kerr effect in nonlinear coupled mode theory, the occurrence of optical multistablity has been analytically investigated in nonlinear fiber Bragg grating for a quasi-CW laser beam. The expression for the transmittivity is obtained in nonlinear regime. It is observed that multi stable features occur near the stopband when operating wavelength is chosen in the vicinity and inside the stopband of the Bragg grating. The effect of intensity of the incident light and detuning wavelength on the multistable features of fiber Bragg grating is also studied in the present work.

(Received March 9, 2011; accepted February 20, 2012)

Keywords: Optical bistability, Multistability, fiber Bragg grating, Nonlinear coupled mode equations, Kerr nonlinearity

1. Introduction

The study of optical bistability is one of the most important areas of research in nonlinear optics due to its potential applications in all-optical computing and optical signal processing. Optical bistability (OB) characterizes as an optical system which exhibits two possible output intensities for the same input intensity. Such bistable devices have extensive interesting applications such as optical transistor, differential amplifier, optical switch, optical limiters, optical clipper, optical discriminator and optical memory elements. The principle of optical bistability was first put forward by Szoke et al [1] suggesting that bistability would occur at exact resonance if a Fabry-Perot resonator is filled with a saturable absorber in which the absorption coefficient is a decreasing function of local intensity. Later on McCall [2] numerically proved that under suitable conditions the same system can show differential gain with transistor action. The result of this work was experimentally demonstrated by Gibbs et al [3] using Na vapor filled Fabry-Perot cavity. Almost simultaneously, Felber and Marburger [4] gave the simplest explanation of dispersive optical bistability in a Fabry-Perot resonator where the optical cavity is filled with a material whose refractive index is intensity dependent. Smith et al [5] demonstrated that if a Fabry-Perot resonator contains an electro-optic element then multistability can be observed instead of bistability which has vital role in multilevel optical logic and many state optical memory operations. Later on Okada and Takizawa [6] examined theoretically and experimentally optical multistable characteristics in mirrorless electro-optic device. Miller et al [7] demonstrated optical bistability, multistability, differential gain, limiter and optical transistor in semiconductor InSb Fabry-Perot devices. Lee et al [8] experimentally realized hybrid optical multistability using a semiconductor light emitting device, a photodiode and transistor, where they presented graphical solution as well as a stability analysis to explain the occurrence of optical multistability.

The optical bistability and multistability of periodic media in the form of distributed feedback structure in integrated optics was first investigated by H. G. Winful et al. in 1979 using III-V semiconductor material [9]. Another theoretical demonstration of optical bistability in semiconductor periodic structure was reported by He and Cada [10], where they have calculated for the first time nonlinear reflectivity spectrum and obtained large OB in the vicinity of its stopband due to the optical resonance effect. Herbert and Malcuit [11] described first experimental observation of optical bistability and multistability in nonlinear periodic structure.

The multilevel optical logic operations based on multistability is important to reduce complexity of devices and interconnections since it increases the information capacity of each line and each storage element in a optical communication system as compared to the binary logic operations. The opportunities provided by fiber Bragg grating are of enormous importance for further development of fiber optic communication systems [12]. The nonlinear nature of the grating allows dynamic tuning of the band gap, the study of optical bistability and multistability in FBG has been of considerable significance in recent days. Wabnitz [13] analyzed numerically the nonlinear propagation of counterpropagating pulses in a nonlinear fiber Bragg grating and discussed bistable switching of intense optical pulses. Broderick [14] presented theoretically and numerically all-optical switching characteristics in nonlinear fiber Bragg grating using cross phase modulation. Melloni et al [15] demonstrated experimentally all-optical switching phenomena in phase shifted FBG based on a cross phase modulation induced by an intense pump pulse on a low intensity probe. Ogusu and Kamizono [16] investigated the effect of the material response time on optical bistability in a nonlinear fiber

Bragg grating and found that switch-on time depends on the material response time and the switch-off time is almost independent of it. Lee and Agrawal [17] considered both the uniform and phase shifted grating and compared their performance numerically as a nonlinear switch when optical pulses are sent to the grating. Recently, Yosia et al. [18] have observed double optical bistability in nonlinear π-phase shifted chalcogenide fiber Bragg grating (c-FBG) and suggested all optical transistor operation in such device.

In the present work, we have studied analytically the phenomena of optical multistability in fiber Bragg grating using coupled mode theory. We have solved nonlinear coupled mode equations (NLCMEs) in a simplest way and obtained the solutions for forward and backward propagating field amplitudes. The expression for transmittivity of fiber Bragg grating for a quasi-CW laser beam is obtained and optical multistability behavior is studied. The numerical results based on our analysis show that the multistable phenomenon is strongly dependent upon the applied input electric field intensity as well as on the wavelength of the incident light.

2. Theoretical model

A fiber Bragg grating couples forward and backward propagating waves with wavelength λ close to the Bragg wavelength λ_B. We have assumed that Bragg grating have Kerr type response so that the nonlinear refractive index is given by

$$n(\omega, z) = n_{eff}(\omega) + n_2|E|^2 + n_g(z) \tag{1}$$

where n_{eff} is the average refractive index of the grating, n_2 is the Kerr coefficient and $n_g(z)$ is the periodic index variation and E is the electric field propagating inside the grating and is written as [12]

$$E(z,\omega) = A_f(z,\omega)\exp(i\beta_B z) + A_b(z,\omega)\exp(-i\beta_B z) \tag{2}$$

Here, A_f and A_b are the amplitudes of the forward and backward propagating waves, respectively and $\beta_B = \pi/\Lambda$ is the Bragg wave number. Using standard assumptions of a slowly-varying envelope approximation, we have used the following pair of NLCMEs [12]:

$$i\frac{\partial A_f}{\partial z} + \delta A_f + \kappa A_b + \gamma(|A_f|^2 + 2|A_b|^2)A_f = 0, \tag{3}$$

and

$$-i\frac{\partial A_b}{\partial z} + \delta A_b + \kappa A_f + \gamma(|A_b|^2 + 2|A_f|^2)A_b = 0. \tag{4}$$

Here, δ, κ and γ are detuning parameter, linear coupling coefficient and nonlinear coefficient, respectively, and are defined as

$$\delta = 2\pi n_{eff}\left(\frac{1}{\lambda} - \frac{1}{\lambda_B}\right), \quad \kappa = \frac{2\pi n_g}{\lambda_B}$$

and $$\gamma = \frac{2\pi n_2}{\lambda_B}.$$

In the following analysis we have solved the above NLCMEs analytically by neglecting higher order terms of backward propagating mode and solutions are obtained as [19]

$$A_f(z) = A_1\exp(iSz) + A_2\exp(iTz), \tag{5}$$

and

$$A_b(z) = B_1\exp(iSz) + B_2\exp(iTz). \tag{6}$$

with

$$S = \frac{-\gamma I_0 + \sqrt{\gamma^2 I_0{}^2 + 4q_{nl}^2}}{2}$$

and

$$T = \frac{-\gamma I_0 - \sqrt{\gamma^2 I_0{}^2 + 4q_{nl}^2}}{2}.$$

Here, $I_0 = |A_f|^2 + |A_b|^2$ is the input intensity at Bragg wavelength λ_B and q_{nl} is the nonlinear dispersion relation in nonlinear Kerr regime and is defined as

$$q_{nl}^2 = q^2 + \delta X + Y, \tag{7}$$

where $q(=(\delta^2 - \kappa^2)^{1/2})$ is the linear dispersion parameter and parameters X and Y are defined as

$$X = \gamma\left(I_0 + 2|A_f|^2\right)$$

and

$$Y = \gamma^2|A_f|^2\left(I_0 + |A_f|^2\right). \tag{8}$$

In the presence of Kerr nonlinearity the photonic band gap becomes $-\kappa < \delta\left(1 + \frac{X}{\delta} + \frac{Y}{\delta^2}\right)^{1/2} < \kappa,$ q_{nl} becomes purely imaginary and most of the incident field will be reflected due to the fact that the grating will not support the propagating wave. It is clear from expression of nonlinear photonic band gap that the intensity of the input beam modifies the dispersion parameter and such modification affects the reflection and transmission characteristics of the grating. On substituting parameter q_{nl} in equations (5) and (6), the fields of forward and backward propagating modes take the form

$$A_f(z) = A_1\exp(iSz) + t_{nl}B_2\exp(iTz) \tag{9}$$

and

$$A_b(z) = B_2\exp(iTz) + t_{nl}A_1\exp(iSz). \tag{10}$$

Here, t_{nl} is the effective transmission coefficient in nonlinear regime and is found as

$$t_{nl} = -\frac{\kappa}{S+\delta+\gamma\left(I_0+\left|A_f\right|^2\right)} \tag{11}$$

Applying the proper boundary conditions, the nonlinear transmission coefficient $\left(t_{ng}\right)$ for a grating of length L has been obtained by using equations (9) to (11) as

$$t_{ng} = \frac{A_f(z=L)}{A_f(z=0)} = \frac{\left(\psi^2-\kappa^2\right)\exp(iSL)}{\psi^2-\kappa^2\exp(ikL)} \tag{12}$$

where,

$$\Psi = \left(\frac{k}{2}+\tau\right),\ \tau = \delta+\gamma\left|A_f\right|^2 \text{ and}$$

$$k = \sqrt{\gamma^2 I_0^2 + 4q_{nl}^2}.$$

The corresponding expression for the transmittivity $T_{ng}\left(=\left|t_{ng}\right|^2\right)$ in the nonlinear regime is

$$T_{ng} = \frac{1}{1+\left(\frac{4\psi^2\kappa^2}{\left(\psi^2-\kappa^2\right)^2}\right)\sin^2(\Phi)} \tag{13}$$

With $\Phi = kL/2$. It is interesting to compare the transmittivity of nonlinear fiber Bragg grating obtained in Equation (13) with tranmittivity (τ) of standard electrooptic nonlinear Fabry-Perot device obtained by Smith et al in 1978 [7] as

$$\tau = \frac{1}{1+\left(\frac{4R}{(1-R)^2}\right)\sin^2(\Phi)} \tag{14}$$

A comparison of Equation (13) and (14) shows that the FBG is equivalent to an optical resonator with mirror reflectivity (transmissivity) $R = \kappa^2\Psi^2\left(T(1-R) = \Psi^2-\kappa^2\right)$ and phase shift $\Phi = kL/2$.

3. Results and discussions

On the basis of the theoretical formulations developed in the preceding sections (Equation 13), we have demonstrated the optical multistability behavior of fiber Bragg grating in nonlinear Kerr regime by plotting the transmitted intensity with input intensity in Fig. 1. The tunable quasi-CW laser source in C-band (1535 – 1565 nm) is assumed as the light source. It may be noted here that a similar order of magnitude of the pump intensity was considered by Lee and Agrawal [17] to be obtained from a quasi CW-laser of 1 ns pulse duration. Also, Taverner et al [20] used a quasi-CW Diode-seeded LA-EDFA chain radiation source at 1536 nm in their experimental work to demonstrate all-optical AND gate in an apodized FBG. All the results presented here are for chalcogenide FBG having effective index n_{eff} = 2.45, change in grating index $n_g = 3\times10^{-4}$, nonlinear Kerr coefficient $n_2 = 2.7\times10^{-17}$ m^2/W. The length of the grating L = 2 cm and Bragg wavelength λ_B = 1550 nm were chosen [18]. We have considered the chalcogenide glass FBG because it reduces the required input intensity to observe nonlinear effects as compared to silica FBG due to high value of nonlinear Kerr coefficient n_2 in such glasses.

The plot of the transmitted intensity as a function of the input intensity is given in Fig. 1 for three different values of incident wavelengths such as λ = 1549.75 nm (Fig. 1a), λ=1549.80 nm (Fig. 1b), λ=1549.85 nm (Fig. 1c) and λ=1549.90 nm (Fig. 1d). All the incident wavelengths considered above are lying inside the stop band of the fiber Bragg grating. At low intensity these wavelength are reflected by the grating as a result the transmission of the structure is low. As the intensity of the input beam is increased the average refractive index of the grating will increases and the stop band appear to shift towards higher wavelengths side resulting in an increase in the transmission of those wavelengths which were reflected by the grating at low intensity.

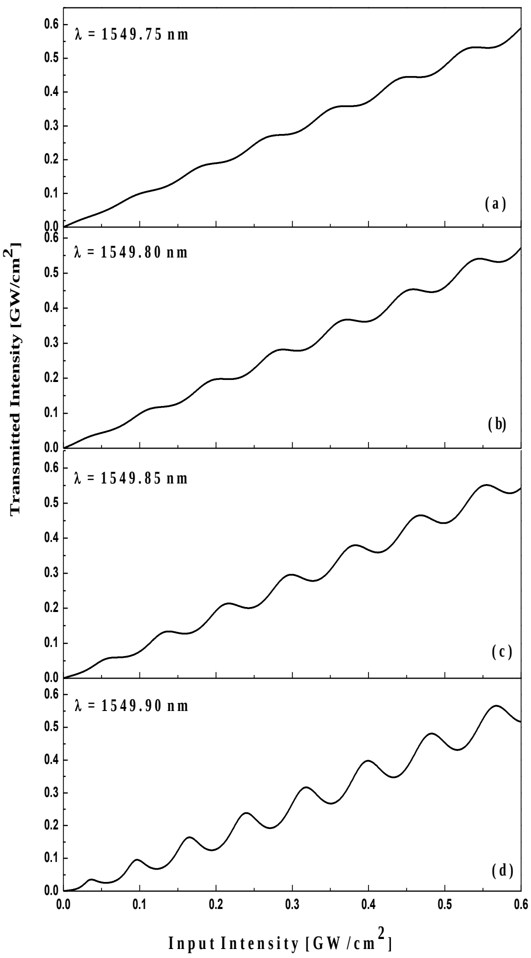

Fig. 1. Transmitted vs. incident intensity for a nonlinear fiber Bragg grating for different values of detuning wavelengths.

It is observed from Fig. 1, that when the wavelength of the incident light is tuned deeper into the stop band (very near to the Bragg resonance, Fig. 1d) the transmitted intensity shows strong oscillatory behavior. The occurrence of oscillatory behavior can be explained as follows: It is well established that reflection spectrum of FBG shows the presence of multiple sidelobes with decreasing intensity located at each side of the stop band. These sidelobes originate from the weak reflections occurring at the two grating ends where refractive index changes suddenly compared to its value outside the grating region due to which a Fabry-Perot cavity with its own wavelength dependent transmission is formed. As the input intensity increases the feedback path of the Fabry-Perot cavity increases. As a result the phase shift of the incident light is increases due to self phase modulation. This causes the strong periodic sidelobes showing multistability in the transmission. Our observations are consistent with the stability analysis of Sterke [26] who suggested that at high excitation intensity there are many regions where the high transmission states are predicted due to temporal fluctuations which become chaotic. He found that as the wavelength of the incident beam is tuned deeper and deeper into the stopgap, the system tends to become more and more unstable giving rise to many stable and unstable states at the output. Multistable behavior in nonlinear fiber Bragg grating can also be considered in terms of many gap solitons formation inside the stopband of the grating [21-24]. In 1998 Broderick et al. [25] has observed experimentally five gap soliton at a particular input intensity when the wavelength of the incident beam is tuned inside the photonic bandgap of fiber Bragg grating. They suggested that the bistable switching is associated with the formation of gap soliton inside the grating.

4. Conclusion

We have investigated the phenomenon of optical multistabilty in nonlinear chalcogenide fiber Bragg grating by incorporating Kerr effect in the coupled mode analysis. The expression for the intensity dependent transmittivity is obtained by solving nonlinear coupled mode equations analytically for quasi-CW laser beam. The theory demonstrates that the optical multistability takes place when operating wavelengths are chosen inside the stopband of fiber Bragg grating at suitable incident intensity. We believe the present analytical study will be useful in future experimental work for the exploration of optical multistability in nonlinear fiber Bragg grating and for the development of nonlinear optical components for all-optical signal processing.

Acknowledgements

The work is financially supported by University Grant Commission (UGC), New Delhi.

References

[1] A. Szoke, V. Daneu, J. Goldhar, N. A. Kurnit, Applied Physics Letters, **15**, 376 (1969).
[2] S. L. McCall, Physical Review A, **9**, 1515 (1974).
[3] H. M. Gibbs, S. L. McCall, T. N. C. Venkatesan, Physical Review Letter, **36**, 1135 (1976).
[4] F. S. Felber, J. H. Marburger, Applied Physics Letter, **28**, 731 (1976).
[5] P. W. Smith, E. H. Turner, P. J. Maloney, IEEE J. Quantum Electron. **14**, 207 (1978).
[6] M. Okada, K. Takizawa, IEEE J. Quantum Electron., **15**, 82 (1979).
[7] D. A. B. Miller, S. D. Smith, C. T. Seaton, IEEE J.Quantum Electron., **17**, 312 (1981).
[8] C. H. Lee, K. H. Cho, S. Y. Sin, S. Y. lee, IEEE J. Quantum Electron., **24**, 2063 (1988).
[9] H. G. Winful, J. H. Marburger, E. Garmire, Appl. Phys. Lett., **35**, 379 (1979).
[10] J. He, Michael Cada, IEEE J. Quantum Electron., **27**, 1182 (1991).
[11] C. J. Herbert, M. S. Malcuit, Optics Lett. **18**, 1783 (1993).
[12] G. P. Agrawal, Application of Nonlinear Fiber optics, Academic Press, San Diego, 2001.
[13] S. Wabnitz, Optics Communication, **114**, 170 (1995).
[14] N. G.. R. Broderick, Optics Commun., **148**, 90 (1998).
[15] A. Melloni, M. Chinello, M. Martinelli, IEEE Photon. Technol. Lett., **12**, 42 (2000).
[16] K. Ogusu, T. Kamizono, Optical Review, **7**, 83 (2000).
[17] H. Lee, G.. P. Agrawal, IEEE J.Quantum Electron., **39**, 508 (2003).
[18] Y. Yosia, Shum Ping, Physica B, **394**, 293 (2007).
[19] S. Pawar, S. Kumbhaj, P. Sen, P. K. Sen, Nonlinear Optics Quantum Optics, **41**, 253 (2010).
[20] D. Taverner, N. G. R. Broderick, D. J. Richardson, M. Ibsen, R. I. Laming, Optics Letter, **23**, 259 (1998).
[21] B. J. Eggleton, C. M. de Sterke, R. E. Slusher, J. E. Sipe, IEEE Electron. Lett., **32**, 2341 (1996).
[22] B. J. Eggleton, C. M. de Sterke, R. E. Slusher, J. Opt. Soc. Am. B, **14**, 2980 (1997).
[23] H. G. Winful, Appl. Phys. Lett. **46**, 527 (1985).
[24] H. G. Winful, G. D. Cooperman Appl. Phys. Lett. **40**, 298 (1982).
[25] N. G. R. Broderick, D. Taverner, D. J. Richardson, Optics Express., **3**, 447 (1998).
[26] C. M. de Sterke, Phys. Rev. A., **45**, 8252 (1992).

*Corresponding author: skumbhaj@gmail.com