

## Effect of Chirped Grating on Optical Bistability in $\lambda/4$ -shifted Semiconductor DFB Devices

Young-Il Kim and Tae-Hoon Yoon\*

*Research Institute of Computer Information and Communication, Department of Electronics Engineering,  
Pusan National University, Pusan 609-735, KOREA*

Seok Lee and Sun-Ho Kim

*Photonics Research Center, Korea Institute of Science and Technology, Seoul 136-951, KOREA*

(Received April 12, 2000)

In this work, we studied the effect of chirped grating on optical bistability in  $\lambda/4$ -shifted semiconductor distributed-feedback (DFB) devices, such as an etalon with nonlinear mirrors, a  $\lambda/4$ -shifted DFB waveguide, and a  $\lambda/4$ -shifted DFB laser amplifier. We found that chirped DFB devices exhibit bistable switching at a lower input power.

*OCIS codes* : 050.2770, 190.1450, 190.5970, 230.0230.

Optical bistability in semiconductor distributed feedback structures has been studied experimentally and theoretically in etalons [1,2], passive waveguides [3,4], and laser amplifiers [5,6]. Applications of optically bistable switching in these devices include optical logic, optical memory, optical signal processing, and optical switching. It was shown that  $\lambda/4$ -shifted DFB devices operate at a smaller input power than uniform grating DFB devices because of the strong light intensity near the grating phase shift [4]. In this work, we studied the effect of chirped grating on optical bistability in  $\lambda/4$ -shifted nonlinear DFB devices.

A semiconductor etalon is attractive for use in many applications because of its large nonlinearity, rapid response time, room-temperature operation, and small size. A semiconductor etalon can be fabricated monolithically by employing such growth techniques as molecular beam epitaxy or metalorganic vapor phase epitaxy. Since this device is inherently suitable to provide optical access perpendicular to the substrate, it has a great potential for application in two-dimensional array devices used for optical signal processing.

It was shown that a semiconductor etalon, whose two integrated mirrors as well as the spacer layer are nonlinear, exhibits optically bistable switching behavior with less input light intensity than that of linear mirrors [2]. A nonlinear etalon consists of two parallel reflectors and a nonlinear spacer layer between them. Each reflector consists of quarter-wave layers of alter-

nately high and low refractive index materials. For mirrors to be linear, the bandgap of each layer must be higher than the energy of input photons. This requirement may limit the choice of high-index material used. If we use a nonlinear material as the mirror material for high-index layers, the limitation caused by the bandgap of the material will be reduced, and the refractive index of the high-index layers can be higher. If the index difference between the high- and the low-index layers is higher, high reflectance can be achieved with a smaller number of quarter-wave layers. Since the same reflectance can be achieved with a thinner mirror, the time required for growth of the device will be reduced.

Optical bistability in a semiconductor etalon is usually performed at wavelengths detuned 10 nm or more below the bandgap. The index changes in this wavelength range are large enough to shift the peak by at least an instrument width and the absorption is low enough so that the Fabry-Perot finesse is not appreciably reduced. The refractive index  $n$  and the absorption coefficient  $\alpha$  depend on the light intensity  $I$  in a nonlinear medium. In this work we employed a simple saturation model for the refractive index  $n$  and the absorption coefficient  $\alpha$  in semiconductors as follows:

$$\begin{aligned} n(I) &= n_0 - \delta_n \frac{I/I_s}{1 + I/I_s}, \\ \alpha(I) &= \frac{\alpha_0}{1 + I/I_s}, \end{aligned} \quad (1)$$

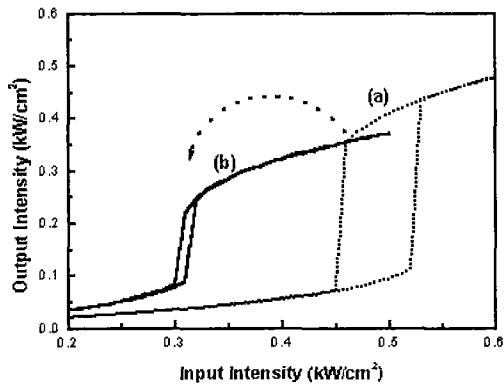


FIG. 1. Optical bistability in a GaAs/AlAs etalon with nonlinear integrated mirrors: (a) not chirped, (b) chirped.

where  $n_0$  is the linear refractive index,  $\alpha_0$  the unsaturated absorption coefficient,  $I_s$  the saturation intensity, and  $\delta_n$  the saturation value of the nonlinear refractive index change, which is negative for frequencies below the bandgap. For simplicity, the wavelength dependence is not taken into account.

Analysis of a nonlinear etalon can be performed by the iteration method as follows. First, we calculate the light intensity distribution inside the etalon for a given input by using the characteristic matrix method, assuming a linear media. Once the light intensity distribution is known, we can calculate the refractive index change using Eq. (1). In the calculation of intensity-dependent index distribution, we have assumed that the carrier density in the spacer or each quarter-wave layer is made uniform by the diffusion of carriers and confined by the neighboring higher bandgap quarter-wave layers. Then, the refractive index  $n$  and the absorption coefficient  $\alpha$  will be uniform in each layer. Thus, the average intensity is inserted into Eqs. (1) and (2), rather than the light intensity at each point. With the new index distribution, we can calculate light intensity distribution by using the characteristic matrix method. We repeat the iteration until we achieve the required accuracy. The detailed numerical procedures are described in [2].

Consider an etalon that consists of 10 periods of GaAs/AlAs quarter-wave stacks for each mirror and a bulk GaAs spacer layer between the two quarter-wave mirrors. We assume that the GaAs substrate has been removed. The parameters used in our numerical calculation are as follows: the operating wavelength  $\lambda_0 = 0.887 \mu\text{m}$ , GaAs ( $n_0 = 3.606$ ,  $\delta_n = 0.0035$ ,  $\alpha_0 = 100 \text{ cm}^{-1}$ ,  $I_s = 16 \text{ kW/cm}^2$ ) for spacer and high-index layers, AlAs ( $n_0 = 2.99$ ) for low-index layers. We studied the effect of chirped grating in a semiconductor etalon with nonlinear mirrors. In an etalon with nonlinear mirrors, the optical thickness decreases

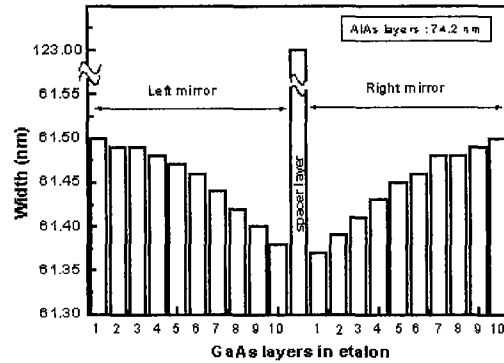


FIG. 2. Width distribution of GaAs layers in a chirped GaAs/AlAs etalon.

with the increase of the light intensity at the spacer and the mirror layers near the spacer because of the decrease of the refractive index. In order to provide the device equal amount of spatial chirp at a lower input power, we introduced structural chirp to the device. As shown in Fig. 1, a GaAs etalon with chirped GaAs/AlAs mirrors exhibits optical bistability at a lower input power than that with no chirping. Width distribution of GaAs (high-index) layers of a GaAs/AlAs etalon is shown in Fig. 2. We also found that the switching power can be reduced further by introducing both asymmetry [1] and chirping simultaneously in the etalon structure.

Guided-wave structures are attractive to construct nonlinear optical devices with low operational power because of long device length and high optical power density in waveguides due to the confinement of light in a small cross-sectional area. Although we can fabricate a device in a Fabry-Perot type, distributed Bragg reflectors are especially useful as optical feedback elements in single-substrate photonic circuits because integration can be achieved without requiring facets.

It was demonstrated experimentally as well as theoretically that passive DFB waveguide devices can exhibit optically bistable switching. It was also shown theoretically that  $\lambda/4$ -shifted DFB waveguide devices can be operated at a lower input power [4]. Although analytic results are provided in [4], effect of carrier diffusion that cannot be neglected in semiconductor devices is not taken into account. The transmission characteristics of a semiconductor DFB waveguide device that includes the effect of carrier diffusion can be calculated numerically by following the transfer-matrix method described in [7]. The nonlinearity of the waveguide is modeled simply by the optical Kerr effect, the intensity-dependent refractive index  $n(I) = n_0 + n_2 I$ , where  $n_0$ ,  $n_2$  and  $I$  are the linear refractive index, the intensity-dependent refractive in-

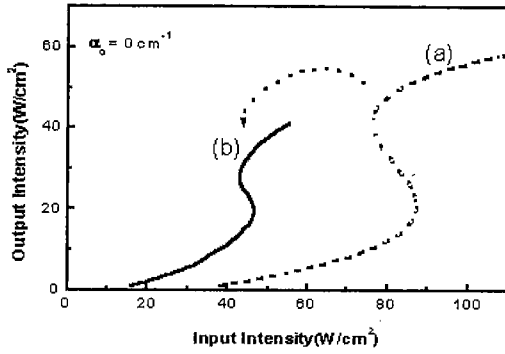


FIG. 3. Optical bistability in  $\lambda/4$ -shifted DFB waveguide ( $\alpha_0 = 0 \text{ cm}^{-1}$ ): (a) not chirped, (b) chirped.

dex, and the intensity of the light, respectively. The parameters used in our numerical calculation are as follows: the operating wavelength  $\lambda_0 = 1.56 \text{ }\mu\text{m}$ , the device length  $L = 3 \text{ mm}$ , the linear refractive index  $n_0 = 3.325$ , and the nonlinear refractive index  $n_2 = -5.3 \times 10^{-12} \text{ cm}^2/\text{W}$ .

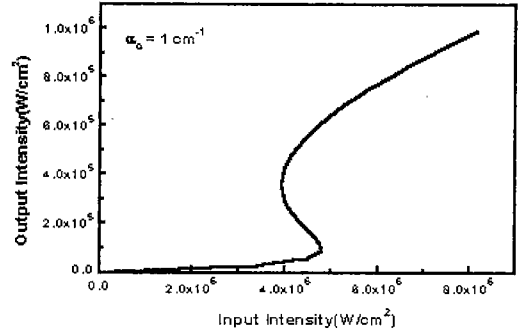
Fig. 3 shows that a chirped grating DFB waveguide exhibits bistable switching at a much smaller input power. In passive waveguide devices, however, numerical calculation shows that only a small portion of the input light can be transmitted through the device because of the light absorption by the device. Moreover,  $\lambda/4$ -shifted DFB devices may exhibit optical bistability at a higher input power than devices with a uniform grating due to the effect of absorption, as shown in Fig. 4. To overcome the effect of the absorption, we can introduce gain by injecting current to the device. A DFB waveguide with current injection (or, a DFB laser amplifier) may provide amplification as well as bistability at the same time.

The optical field distribution inside the DFB semiconductor laser amplifier (SLA) can be calculated by using the standard coupled mode equations,

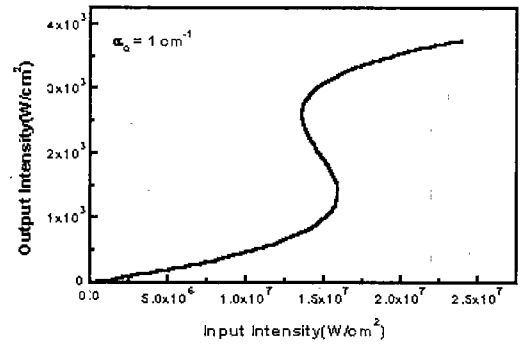
$$\begin{aligned} \frac{dA}{dz} &= \left[ i\delta + \frac{g}{2}(1 - i\alpha_H) - \frac{\alpha_{int}}{2} \right] A + i\kappa B, \\ -\frac{dB}{dz} &= \left[ i\delta + \frac{g}{2}(1 - i\alpha_H) - \frac{\alpha_{int}}{2} \right] B + i\kappa A, \end{aligned} \quad (2)$$

where  $A$  and  $B$  are the slowly varying envelopes of the forward- and backward-propagating fields, respectively.  $g$  is the gain coefficient,  $\kappa$  is the coupling coefficient, and  $\alpha_{int}$  is the internal loss. The linewidth enhancement factor  $\alpha_H$  represents the coupling between the optical gain and the refractive index in semiconductor gain media. The detuning parameter  $\delta$  is given by

$$\delta = \frac{2\pi n_0}{\lambda_0} - \frac{\pi}{\Lambda}, \quad (3)$$



(a)



(b)

FIG. 4. Optical bistability in a DFB waveguide with absorption ( $\alpha_0 = 1 \text{ cm}^{-1}$ ): (a) uniform DFB waveguide, (b)  $\lambda/4$ -shifted DFB waveguide.

where  $n_0$  is the spatially averaged modal index,  $\lambda_0$  the operating wavelength, and  $\Lambda$  the period of the built-in grating, respectively. The transmission characteristics of a DFB SLA device can be calculated by following the transfer-matrix method described in [6]. The parameters used in our numerical calculation are as follows: the operating wavelength  $\lambda_0 = 1.55 \text{ }\mu\text{m}$ , the device length  $L = 300 \text{ }\mu\text{m}$ , the unsaturated gain  $g_0 L = 0.6339$ , the coupling coefficient  $\kappa L = 3$ , the linewidth enhancement factor  $\alpha_H = 5$ , the internal loss  $\alpha_{int} = 0$ , the saturation intensity  $I_s = 1 \text{ MW/cm}^2$ , and the normalized detuning  $\delta L = 1.3$ .

In  $\lambda/4$ -shifted DFB semiconductor laser amplifiers, strong light intensity localized near the grating phase-shift brings about the increase of refractive index because of the carrier depletion. In order to compensate for this, we introduced structural chirping to a  $\lambda/4$ -shifted DFB laser amplifier by making the grating period longer as we move away from the grating phase-shift. The grating period distribution of a chirped grating is shown in Figs. 5 and 6 shows that

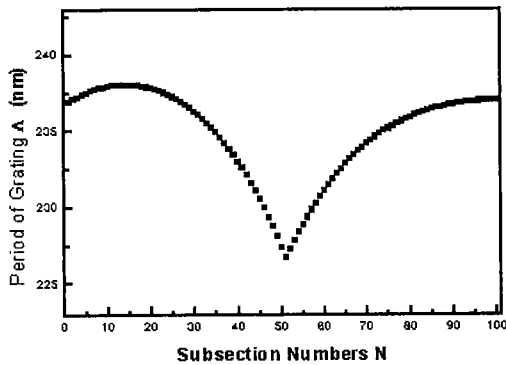


FIG. 5. The grating period distribution in a  $\lambda/4$ -shifted DFB SLA with chirped grating.

a chirped DFB laser amplifier exhibits bistable switching at a much smaller input power. It may be noted that low threshold operation can be achieved by compensating the intensity-dependent chirp in SLAs, while we enhanced the chirping in passive DFB devices. Effect of chirping in a DFB laser amplifier was studied in an earlier work where the grating period is increased linearly along the amplifier length [6]. Our results are different from theirs in that ours are achieved without any increase of the amplifier gain by the pump current.

In conclusion, we found that chirped-grating DFB devices exhibit bistable switching at a lower input power by studying the effect of chirping on optical bistability in  $\lambda/4$ -shifted nonlinear DFB devices.

#### ACKNOWLEDGMENTS

This work was supported by the Advanced Photonics Technology Project of the Ministry of Science and

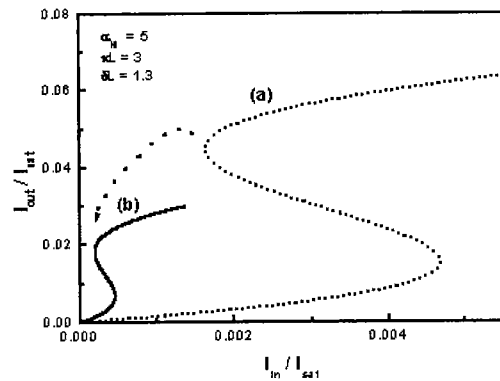


FIG. 6. Optical bistability in  $\lambda/4$ -shifted DFB semiconductor laser amplifiers with the normalized value of external injection current  $g_0L = 0.6339$ : (a) not chirped, (b) chirped.

Technology.

\*Corresponding author : thyoan@hyowon.pusan.ac.kr.

#### REFERENCES

- [1] F. Jeannes, E. Lugagne-Delpon, C. Tanguy, and J. L. Oudar, *Opt. Commun.* **134**, 607 (1997).
- [2] T.-H. Yoon, D.-S. Shin, D.-B. Kim, J.-C. Kim, and S.-H. Kim, *Jpn. J. Appl. Phys.* **37**, 4397 (1988).
- [3] K. Nakatsuhara, T. Mizumoto, R. Munakata, Y. Kigure, and Y. Naito, *IEEE Photon. Technol. Lett.* **10**, 78 (1998).
- [4] S. Radic, N. George, and G. P. Agrawal, *Opt. Lett.* **19**, 1789 (1994).
- [5] M. J. Adams and R. J. Wyatt, *Proc. Inst. Elect. Eng. pt. J* **134**, 35 (1987).
- [6] D. N. Maywar and G. P. Agrawal, *IEEE J. Quantum Electron.* **33**, 2029 (1997).
- [7] K. Nakatsuhara, T. Mizumoto, R. Munakata, and Y. Naito, *Appl. Opt.* **35**, 1507 (1996).