Effect of Tapered Quarter Wavelength Phase-Shifted Grating on Reflective Properties of a Bistable DFB Semiconductor Laser Amplifier

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ABSTRACT

Using the steady-state model based on the coupled-mode and carrier rate equations, in this paper, we analyzed the effects of tapered quarter wavelength phase-shifted (QWS) grating on the reflective bistable characteristics of a distributed feedback semiconductor laser amplifier (DFB-SLA). We also compared the results with those of a uniform DFB-SLA. For laser amplifiers driven to yield the same unsaturated peak amplifier reflectivity, tapered quarter-wavelength phase shifting decreased the required modal gain. Therefore, we recommended applying this kind of non-uniformity to save required injected bias current in reflective bistable DFB-SLA based systems. Meanwhile, the transfer matrix method (TMM) was utilized for the numerical simulations.

KEYWORDS: reflective optical bistability, tapering, and phase shift

INTRODUCTION

When a semiconductor laser diode is biased below oscillation threshold, it acts as a semiconductor laser amplifier (SLA). Researchers have utilized optical bistability in SLA's for optical logic and optical signal processing [1-4]. In a distributed feedback (DFB) SLA, bistability is supported by feedback provided by a built-in diffraction grating. It has been concluded that a bistable DFB-SLA in comparison to a bistable Fabry-Perot SLA, offers the advantage of controlling the input/output characteristics by tailoring the DFB transmission through some non-uniformities of its grating [5]. Also it has been demonstrated that optical bistability was observed at input power levels of a few μw in DFB-SLA's [6]. On the other hand, reflection from DFB SLA's, unlike transmission, exhibits a variety of bistable hysteresis shapes, each with its own switching behavior. So that as presented in [7], due to the frequency detuning of the optical input signal, the reflective bistable characteristics might be in an S-shaped, inverted S-shaped, and loop-shaped hysteresis. This diversity increases the potential applications of bistable DFB SLA's. So far, the effects of quarter wavelength phase-shifting with tapering of a DFB-SLA's grating on its trans-missive bistable characteristics have been investigated and concluded that this non-uniformity widens the spectral range of low-threshold bistable switching and increases the on-off switching contrast [8]. However, the effects of this non-uniformity on its reflective bistable characteristics have not been discussed. Therefore, we decide to show how quarter wavelength phase-shifting with tapering can affect the variety of the reflective hysteresis in this paper. The layout of the paper is as follows: in Sec. 2, we present the physical and the theoretical models used in our numerical analysis. In Section 3, our numerical results are presented. We first show that how the reflectivity is affected by grating non-uniformities. Next, the steady-state reflective bistable characteristics of a trapezoidal tapered QWS-DFB-SLA are calculated and compared with that of the uniform DFB structure, in Sec. 4. Finally, we close the paper by conclusions, in Sec. 5.

MATERIALS AND METHODS

A. Grating

Schematics of the various DFB gratings with the cavity length, *L* are shown in Fig. 1. Figure 1(a) illustrates a uniform grating, while Fig. 1(b) shows a quarter wavelength phase-shifted grating, and Fig. 1(c) illustrates a trapezoidal tapered grating whose depth is a function of the axial variable, *z*. Since the coupling coefficient, κ, is associated with the perturbed relative permittivity, its numerical value depends on the shape, depth, and period of the corrugation, Λ. Hence, for a tapered DFB structure, instead of κ used for a non-tapered structure one should use κ_{eff} similar to that presented in [8].

B. Theory

If $A(z)$ and $B(z)$ are the slowly varying amplitudes of the forward and backward propagating fields through a DFB structure, respectively, then the coupled-mode equations can be defined as [9]

$$\frac{dA}{dz} = i\Delta\beta A + i\kappa B \qquad (1a)$$

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$$\frac{dB}{dz} = -i\Delta\beta B - i\kappa A \qquad (1b)$$

where $\Delta\beta = \beta - \beta_0$ is the detuning of the wave number β from the Bragg wave number, $\beta_0 = \pi/\Lambda$. The boundary conditions neglecting facets reflectivity are given by
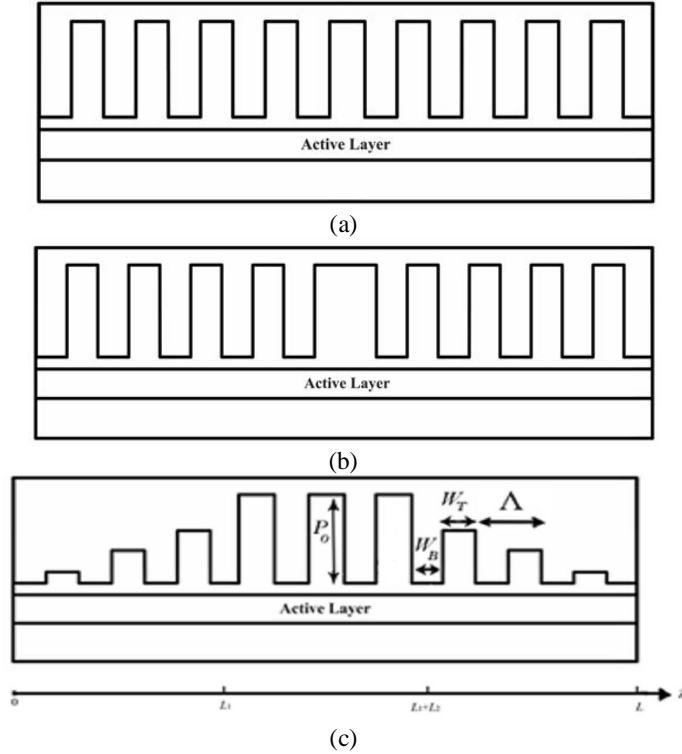

(a)

(b)

(c)

Fig. 1: Schematic diagram of a DFB-SLA with: (a) uniform, (b) QWS, and (c) trapezoidal tapered gratings.

$$A(z = 0) = A_i$$
$$B(z = 0) = A_r$$
$$B(z = L) = 0$$
$$A(z = L) = A_t \qquad (2)$$

where A_i, A_r, and A_t are the slowly varying amplitudes of the incident, reflected, and transmitted optical waves, respectively. For our analysis, we divide the laser into small sub-sections of equal lengths. Note that the length of each sub-section should be much longer than the period of the DFB structure (i.e. $l >> \Lambda$), otherwise the coupled-mode description is no longer valid [10]. For semiconductor laser amplifiers, an appropriate form of $\Delta\beta$ including the gain is given as

$$\Delta\beta = \delta - ig(1 - i\alpha)/2 + i\alpha_{int}/2 \qquad (3)$$

where α is the line width enhancement factor and governs the change in the refractive index through variations in the carrier density, α_{int} is the internal loss due to scattering and free carrier absorption, δ is due to the detuning of the free-space wavelength, from the Bragg wavelength, and g is the modal power gain given as

$$g = \Gamma a(N - N_0) \qquad (4)$$

where a is the differential gain parameter, N is the carrier density, N_0 is the carrier density at transparency, and Γ is the optical confinement factor. On the other hand, the rate equation for the carrier density in a semiconductor laser amplifier is given by

$$\frac{dN}{dt} = \frac{J}{ed} - \frac{N}{\tau_c} - \frac{g}{\hbar\omega_0} I \qquad (5)$$

where J is the current density in the active region of thickness d, e is the electron charge, τ_c is the carrier life time. $\hbar\omega_0$ is the photon energy, and $I = |A(z)|^2 + |B(z)|^2$ is the optical intensity. In solving (5), we neglect carrier

diffusion by assuming that its effect is to average any variations in carrier density which occur over distances smaller than the diffusion length (~2 µm). The carrier density for CW signals and pulses much wider than the carrier life time τc (~100 ps) reaches a steady state value resulting a new expression for the modal power gain as

$$g = \frac{g_0}{1 + \bar{I}}$$
(6)

where $g_0 = \Gamma a N_0 (J/J_0 - 1)$ is the unsaturated value of the modal power gain, J_0 is the current density at transparency, and $\bar{I} = I/I_{sat}$ is the optical intensity normalized to the saturation intensity, I_{sat}. Finally, assuming that coupling coefficient and gain are constant, in each sub-section, the forward and backward fields can be obtained numerically, using transfer matrix method (TMM) [11].

RESULTS AND DISCUSSION

A. THE SMALL-SIGNAL REFLECTIVITY

By reflectivity resonance, we mean a localized spectral region of either high or low reflectivity [12]. In order to determine the reflectivity resonance frequencies, for a DFB-SLA, we first studied its reflection characteristics for an input optical signal of $I<<I_{sat}$. In this situation, by neglecting $\bar{I}$ in the denominator of (6), one can approximate $g \approx g_0$. Furthermore, the propagation through the entire amplifier is characterized by the total transfer matrix resulting from the product of all transfer matrices. Meanwhile, for the QWS-DFB-SLAs, in general, the transfer matrix at the phase-shift location should be multiplied by the matrix [13]

$$\begin{bmatrix} e^{i\pi/2} & 0 \\ 0 & e^{-i\pi/2} \end{bmatrix}$$
(7)

Considering a trapezoidal tapered QWS-DFB structure with the parameters given in [8], the wavelength dependence of the reflectivity, $R = I_{ref}/I_{in} = |A_r|^2/|A_i|^2$ for this DFB-SLA could be shown in Fig. 2(a). To

(a)

(b)
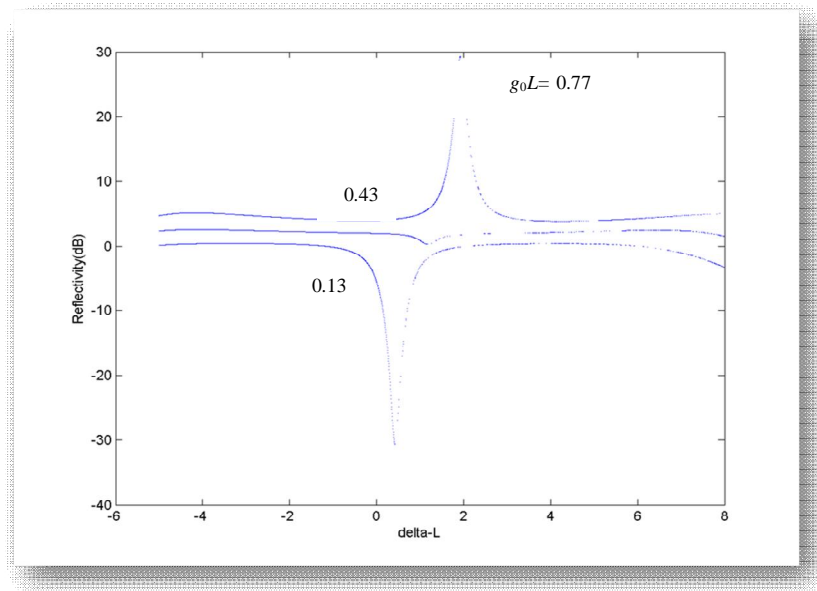
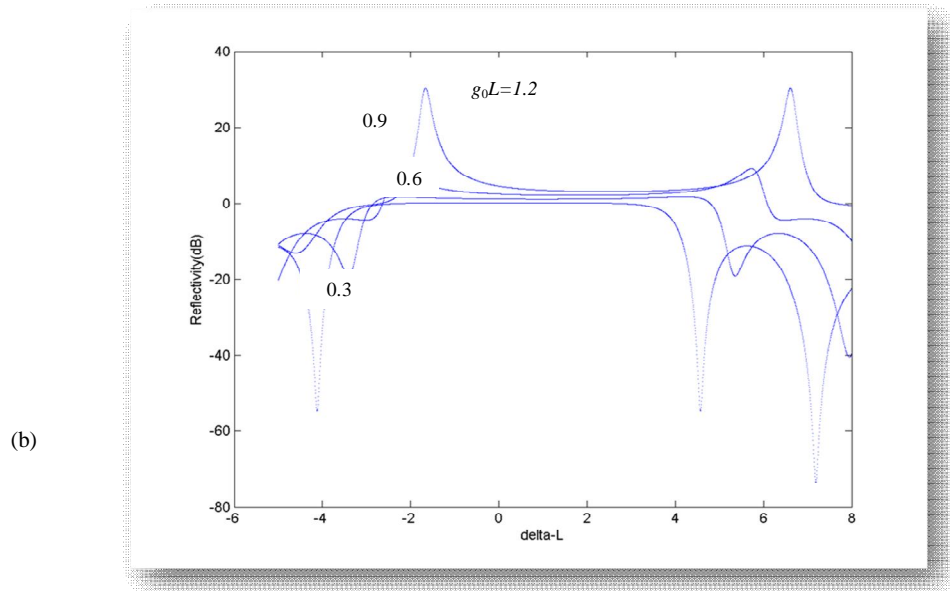Fig. 2: Wavelength dependence of the amplifier reflectivity, R, with α=5 and α_{int} =0 for:
(a) The tapered QWS-DFB SLA with $\kappa_{eff}L$= 3 and $g_0L = 0.77$corresponding to R=30 dB;(bThe uniform DFB SLA with κL=3 and $g_0L = 1.2$ corresponding to R=30 dB [12].

Realize $R = 30$ dB, the parameter g_0L was chosen 0.77 centered at the detuning δL=1.8, where as shown in Fig. 2(b) the reflectivity peak could be achieved with g_0L=1.2 centered at the detuning δL=6.8 for the uniform DFB laser amplifier[12]. In fact, when we apply a tapered quarter wavelength phase-shifting to the grating of the uniform DFB laser amplifier, it seems that (i) feedback for the wavelength corresponding to the Bragg wave number is increased; (ii) the effective distribution of injected electrical current into the cavity is also increased. These reductions require the SLA to be pumped at a lower modal gain to achieve the same small-signal peak amplifier reflectivity.

B. ANALYSIS OF REFLECTIVE OPTICAL BISTABILITY

Optical bistability occurs as the gain of a DFB-SLA is saturated by increasing its optical intensity within the device. On the other hand, one effect of non-uniform gratings is to alter the intensity distribution within the amplifier. The non-uniform intensity profile in an active semiconductor will create a non-uniform gain profile via saturation. The modal gain, however, is used in the calculation of the transfer-matrix elements, which are in turn used to compute the optical intensity distribution. To account for this nonlinear behavior, we solve for the gain and intensity distributions using an iterative approach similar to as illustrated in [8]. Setting the unsaturated modal gain in a value yielding the peak R=30 dB, if we selected short wavelengths with normalized detuning less than that corresponding to the reflectivity peak such as δL=1.45 and 6.785 for the tapered QWS-DFB-SLA and the uniform DFB-SLA, respectively, then an S-shaped reflective hysteresis, as shown in Fig. 3(a) and Fig. 3(b), appeared. When the normalized detuning was reduced from 1.45 to 1.3 and from 6.785 to 6.085, for the tapered QWS-DFB and uniform DFB laser amplifiers, respectively, then, as shown in Fig. 4(a) and Fig. 4(b), the optical signal exhibited a loop-shaped hysteresis. A third hysteresis shape was generated for even longer wavelengths. Figure 5(a) showed the appearance of an inverted S-shaped reflected-intensity hysteresis for the tapered QWS-DFB-SLA. In order to reach this shape we should have reduced the normalized detuning from 1.3 to 1.0. On the other hand, as Figure 5(b) illustrated, this occurred for the uniform DFB-SLA, when the normalized detuning was reduced from 6.085 to 4.685 [12]. The variety of bistable hysteresis shapes could be understood as follows [12]. We know that the optical bistability is based on a positive feedback loop occurring for the optical intensity within the DFB SLA. For signal wavelengths initially tuned close to a cavity resonance, a low internal power is required to seed optical bistability. The relatively low internal power during the positive feedback loop allows the gain to remain relatively high under saturation. Thus, the reflectivity resonance is a peak during the positive feedback loop. Moreover, we find that the reflectivity resonance spectrally overlaps the cavity resonance, which is also shaped like a high peak. Since the cavity and reflectivity resonances are similar, the reflected intensity switches in the same manner, as evident by the S-shaped hysteresis of Fig. 3. In contrast, signal wavelengths initially tuned far from the region that the cavity resonance is a peak, require higher optical intensities to seed the positive feedback loop. The correspondingly large internal powers saturate the gain

enough that the reflectivity resonance is a dip during the switching process. As the reflectivity resonance shifts to longer wavelength, the reflected signal intensity drops accordingly. Thus, the reflected intensity switches downward even though the average internal intensity switches upward. This behavior gives rise to a loop-shaped or even more to an inverted-S-shaped hysteresis. However, the detuning range for which the shape of hysteresis remains constant is narrower for the tapered QWS-DFB amplifier, e.g., to have an S-shaped hysteresis, the normalized detuning can be from 1.45 to near 1.3 for the tapered QWS-DFB amplifier, while to have this shape of hysteresis for the uniform DFB one, δL can be from 6.785 to near 6.085 which is a wider range. In fact, in the tapered structure, a lower range of wavelengths exhibit similar hysteresis shape because the decreased modal gain weakens the intensities at these wavelengths.
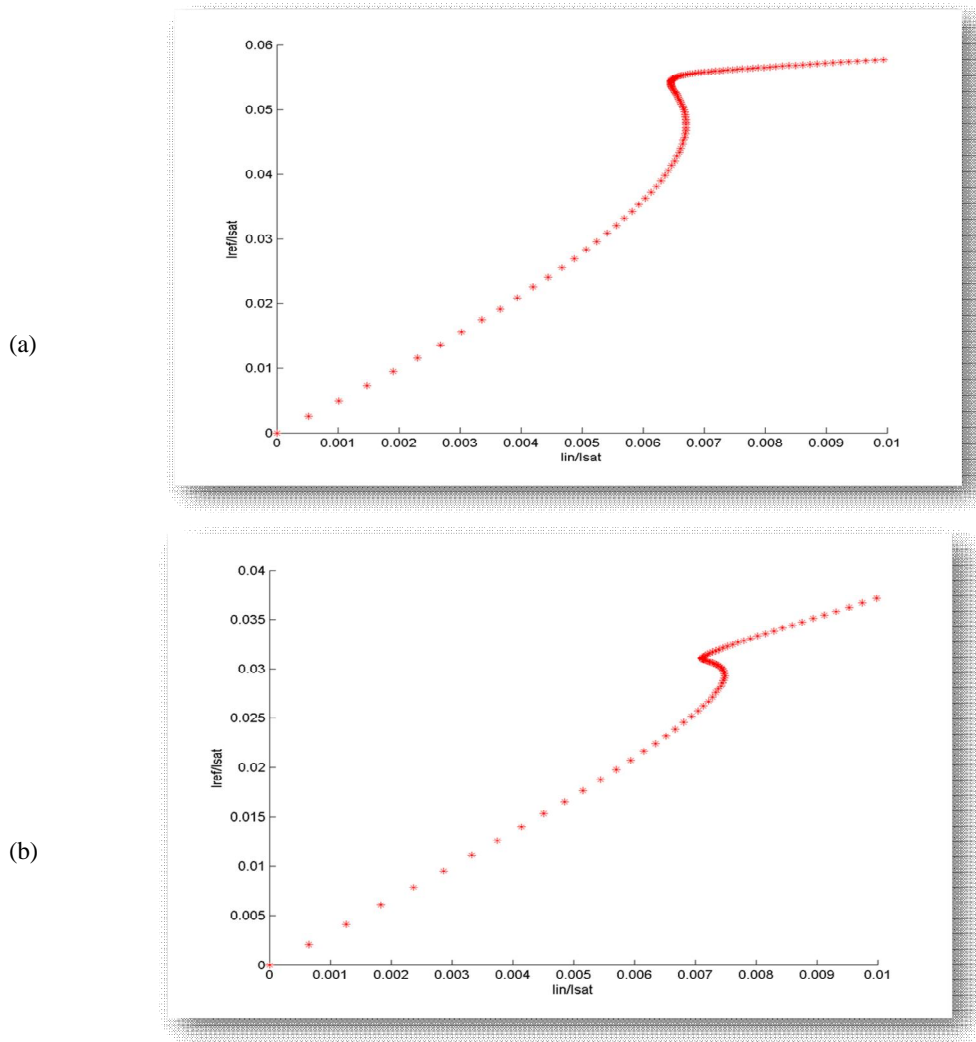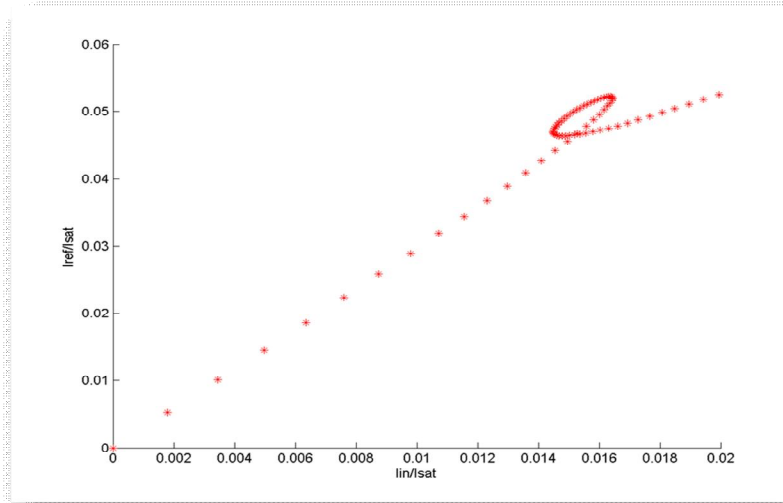
(a)

(b)

Fig. 3: The appearance of S-shaped reflected-intensity hysteresis with α=5 and α_{int} =0 for:
(a) The tapered QWS-DFB SLA with $\kappa_{eff}L$= 3 and $g_0L = 0.77$ corresponding to R=30 dB;
(bThe uniform DFB SLA with κL=3 and $g_0L = 1.2$ corresponding to R=30 dB [12].
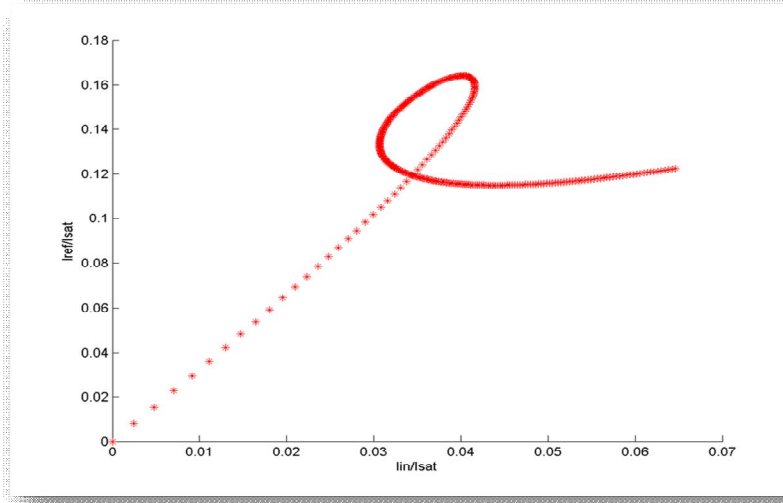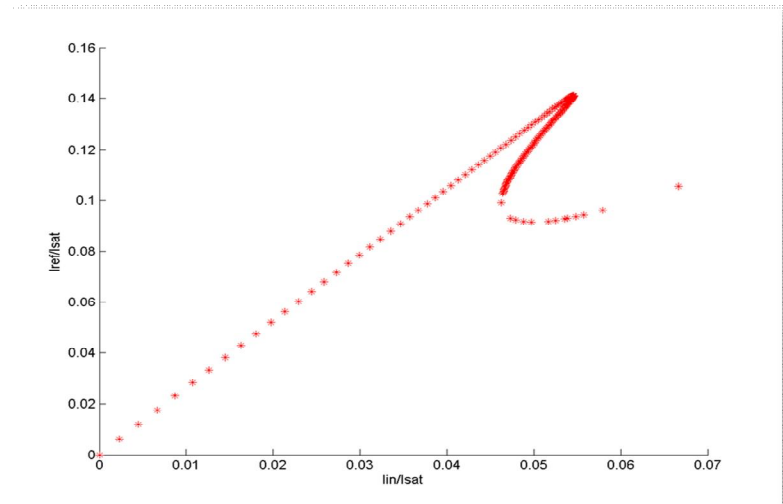
Fig. 4: The appearance of loop-shaped reflected-intensity hysteresis with $\alpha=5$ and $\alpha_{int}=0$ for:
(a) The tapered QWS-DFB SLA with $\kappa_{eff}L=3$ and $g_0L=0.77$ corresponding to $R=30$ dB;
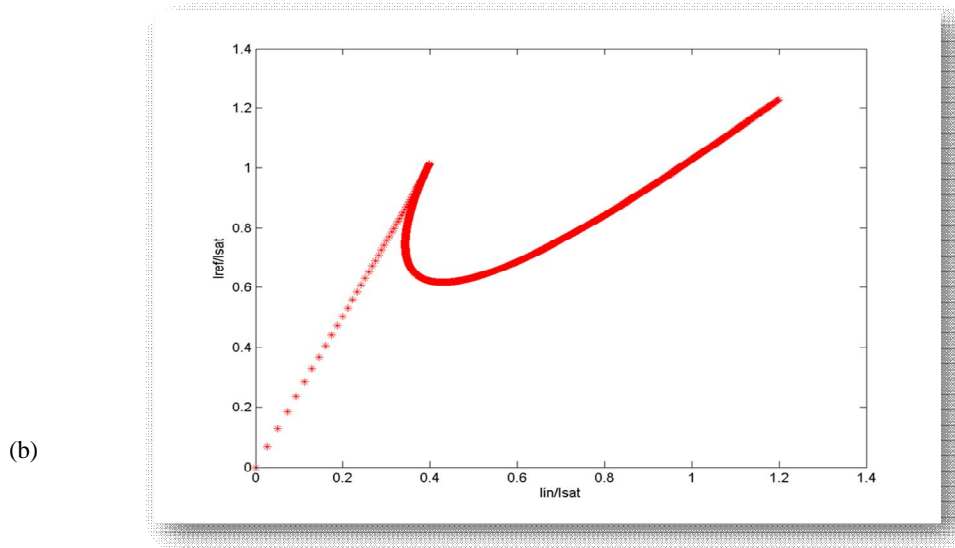(bThe uniform DFB SLA with $\kappa L=3$ and $g_0L=1.2$ corresponding to $R=30$ dB [12].

(b)

Fig. 5: The appearance of inverted S-shaped reflected-intensity hysteresis with α=5 and α_{int} =0 for:
(a) The tapered QWS-DFB SLA with $\kappa_{eff}L$= 3 and g_0L = 0.77corresponding to R=30 dB;
(bThe uniform DFB SLA with κL=3 and g_0L = 1.2 corresponding to R=30 dB [12].

CONCLUSIONS

In this paper, we derived a tapered QWS-DFB laser amplifier and a uniform DFB laser amplifier to yield the same unsaturated peak amplifier reflectivity. Then by calculating the steady-state reflective bistable response of a tapered QWS-DFB laser amplifier, we showed that for laser amplifiers driven to yield the same unsaturated peak amplifier reflectivity, tapered quarter-wavelength phase shifting decreased the required modal gain. Therefore, we recommended applying this kind of non-uniformity to save required injected bias current in reflective bistable DFB-SLA based systems, although this non-uniformity made the required detuning range to have a fixed hysteresis shape narrower.

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