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Modeling of optically controlled reflective bistability in a vertical cavity semiconductor saturable absorber

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ABSTRACT

Bistability switching between two optical signals has been studied theoretically utilizing the concept of cross absorption modulation in a vertical cavity semiconductor saturable absorber (VCSSA). The probe beam is fixed at a wavelength other than the low power cavity resonance wavelength, which exhibits bistable characteristic by controlling the power of a pump beam ($\lambda_{pump} \neq \lambda_{probe}$). The cavity nonlinear effects that arises simultaneously from the excitonic absorption bleaching, and the carrier induced nonlinear index change has been considered in the model. The high power absorption in the active region introduces thermal effects within the nonlinear cavity due to which the effective cavity length changes. This leads to a red-shift of the cavity resonance wavelength, which results a change in phase of the optical fields within the cavity. In the simulation, the phase-change due to this resonance shifting is considered to be constant over time, and it assumes the value corresponding to the maximum input power. Further, an initial phase detuning of the probe beam has been considered to investigate its effect on switching. It is observed from the simulated results that, the output of the probe beam exhibits either clockwise or counter-clockwise bistability, depending on its initial phase detuning.

1. Introduction

Optical bistability occurring in both active and passive devices have drawn considerable attention over the past decades because of their applications in optical switching [1], memory elements such as optical flip–flops [2,3], and all-optical logic operations [4–6]. Most of the devices show bistable characteristics utilizing the nonlinearity of carriers in the active region, in combination with an intrinsic feedback cavity. In some cases the carrier nonlinearities are controlled by the external current-biasing. However, some devices exhibit bistable characteristics by controlling the carriers through optical pumping. Bistable switching between two optical signals were studied first time using optical bistability occurring in a Fabry–Perot semiconductor laser amplifier working in transmission mode [7]. The study reported the output of the probe beam exhibit bistable characteristics by controlling the power of an input pump beam. Also, a transition from clockwise to counter-clockwise bistability of the probe beam has been demonstrated using the probe's initial phase detuning. Later on an extensive study of wavelength switching between two optical signals were carried out both experimentally and theoretically using some devices like semiconductor laser amplifier (SLA) [8], distributed feedback semiconductor optical amplifier [9], and Fabry–Perot SLA [10]. In this paper, we have studied numerically the bistable switching between two optical signals using a passive VCSSA device.

A vertical cavity semiconductor quantum wells (QWs) structure has numerous applications in all-optical logic operations [4,5], optical switching [11,12], and regeneration of optical signals [13,14]. A VCSSA is an asymmetric micro-resonator embedded with semiconductor multiple quantum well structure (MQWs). The MQWs act as a saturable absorber, and exhibit high nonlinearity due to the excitonic absorption within the well structure. This effect has been used to construct devices such as high speed modulators [15], optical bistable devices [16–18], and picosecond mode-locked lasers [19]. On the other hand, a VCSSA offers a number of advantages, including its easy fabrications, flexibility in coupling with optical fibers, high switching contrast, lowest noise figure, and polarization independent operation.

This paper is organized as follows. In Section 2, we have illustrated a theoretical model that describes precisely the nonlinear phenomenon of optical bistability occurring in the micro-resonator. Section 3, describes the study on optically controlled reflective bistability of a probe beam using the dynamic model of cross-absorption modulation (XAM). Also, the effects of both wavelength and the phase detuning of the probe beam on switching have been investigated in this section, and Section 4 concludes.

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2. All-optical bistable characterization of a VCSSA

Optical bistability occurring in some devices plays an important role in the field of optical communication and optical computing [8]. The mechanism behind the optical bistability occurring in a VCSSA could be explained by using both nonlinear absorption and dispersion in the QWs. The absorptive bistability arises from the power dependence of the absorption coefficient, which produces saturation of carriers in the quantum well region. On the other hand, the dispersive bistability arises from the power dependence of refractive index change [20]. Here, we have considered the combined effect of carrier dependence of absorption coefficients and refractive index change to study bistability in our model.

The structure of VCSSA is well described in some previous reports [5,12]. The structure comprises a bottom distributed Bragg reflector (DBR), an InP spacer layer, semiconductor multiple quantum wells (MQWs) as the saturable absorber (active region), an InP cap layer, and a top DBR [21]. The nonlinearity of a VCSSA is achieved by the modulation of absorption in the active region. This is possible by controlling the intracavity power, through properly selecting the top mirror reflectivity R_t and the input optical power [19]. Usually the device operates in the reflection mode. The total intensity reflectivity of the device at cavity normal incidence is given by

$$R = \frac{R_t + R_b\, e^{-2\alpha D} - 2\sqrt{R_t R_b}\, e^{-\alpha D} \cos(\phi_{rt})}{1 + R_t R_b\, e^{-2\alpha D} - 2\sqrt{R_t R_b}\, e^{-\alpha D} \cos(\phi_{rt})} \tag{1}$$

where R_t and R_b, are the intensity reflectivity of the top and bottom mirrors, respectively, α is the total absorption coefficient, and ϕ_{rt} is the single round-trip phase of the optical field within the cavity. The total absorption coefficient α includes two terms; the non-saturated absorption of the device (α_{NS}) and the excitonic absorption within the MQWs. The total absorption is thus defined as

$$\alpha D = \alpha_{NS} d + \frac{\alpha_0 d_1}{1 + P_C/P_{SAT}} \tag{2}$$

where α_0 is the low power material absorption coefficient of the saturable absorber, d is the physical length of the Fabry–Perot cavity which includes the cap layer, the MQWs (active regions), and the spacer layers, and d_1 is the length of the active region. It is observed that the excitonic absorption (second term of Eq. (2)) depends on the value of the intracavity power P_C, and the saturation power P_{SAT}. Further, the total phase ϕ_{rt} comprises of two terms; the linear phase of the optical field (ϕ_{LIN}), and the phase due to the Kerr-nonlinearity (ϕ_{Kerr}) [22]. Thus the total round-trip phase now becomes

$$\phi_{rt} = \phi_{LIN} + \phi_{Kerr} \tag{3}$$

The second term in the right hand side (RHS) of Eq. (3) is phase detuning due to the Kerr-nonlinearity, which comes up from the carrier induced nonlinear index change in the active region. The intensity dependent total refractive index of the QWs is defined as $n = n_0 + \Delta n$, where $\Delta n = n_{2S}\left[\frac{P_C/P_{SAT}}{(1+P_C/P_{SAT})}\right]$, with $n_{2S} = n_2 I_{SAT}$. n_2 represents the nonlinear index of the saturable region, and I_{SAT} is the saturation intensity. Thus, the phase due to the Kerr-nonlinearity becomes

$$\phi_{Kerr} = \frac{4\pi(\Delta n) d_1}{\lambda_W} = \frac{4\pi n_{2S} d_1}{\lambda_W}\left[\frac{P_C/P_{SAT}}{(1 + P_C/P_{SAT})}\right] \tag{4}$$

where λ_W is the working wavelength. The sign of nonlinear index (n_2) is negative, due to which the resonance shift towards the short wavelength side of the low-power cavity resonance wavelength (λ_{RES}). Further, the first term in the RHS of Eq. (3) represents the linear phase and is defined as

$$\phi_{LIN} = 4\pi n d\left(\frac{1}{\lambda_W} - \frac{1}{\lambda_{RES}}\right) \tag{5}$$

However, the total power absorption within the cavity introduces some thermal effects, because of which the resonance shifts towards higher wavelength side due to the increase in effective cavity length. This results in some additional phase to the optical field. Thus, the total corrected phase now becomes

$$\phi_{rt} = 4\pi n d\left(\frac{1}{\lambda_W} - \frac{1}{\lambda_{RES} + \Delta\lambda}\right) + \frac{4\pi n_{2s} d_1}{\lambda_W}\left[\frac{P_{CS}}{(1 + P_{CS})}\right] \tag{6}$$

where $P_{CS} = P_C/P_{SAT}$, $\Delta\lambda = (d\lambda_{res}/dT_{act}) R_{th} P_c \alpha D$ is the shift of the resonance wavelength due to thermal effects [23]. R_{th} is the effective thermal resistance of the semiconducting material and $d\lambda_{res}/dT_{act}$ is the rate at which the cavity resonant wavelength changes with actual temperature of the device and its value varies from 0.01 to 0.1 nm/K for InGaAs/InP QWs [24]. The thermal effect in the device persists for a time scale of few micro-seconds. In some previous studies the device characterization has been done considering the CW approximation [4], where the shifting $\Delta\lambda$ due to thermal effects is calculated for each values of the input power. But, this approximation is not acceptable when the device is treated with a high bit-rate optical signal having pulse width in the nano-seconds/pico-seconds order. For such a case $\Delta\lambda$ is considered to be constant, and it assumes the value corresponding to the pulse peak power i.e. $\Delta\lambda = \Delta\lambda(P_{IN}{}^{MAX})$. However, this thermal effect will not affect to the temporal characteristics of the signal. All simulated results that have been presented in this paper are calculated assuming $\Delta\lambda = \Delta\lambda(P_{IN}{}^{MAX})$. Also, the thermal shifting is depends on the input power (P_{IN}) through intracavity power (P_C). The length-averaged power inside the cavity can be expressed as

$$P_C = \frac{(1 - R_t)(1 - e^{-\alpha D})\left(1 + R_b e^{-\alpha D}\right) P_{IN}}{\alpha D\left(\left(1 - \sqrt{R_t R_b}\, e^{-\alpha D}\right)^2 + 4\sqrt{R_t R_b}\, e^{-\alpha D} \sin^2\left(\phi_{rt}/2\right)\right)} \tag{7}$$

Now, the power reflected from a VCSSA, follows the expression

$$P_{REF} = R(\phi_{rt}, \alpha) P_{IN} \tag{8}$$

where P_{IN} and P_{REF} are the incident and reflected powers of the optical signal, respectively. The input–output characteristic of the device at 1550 nm is shown in Fig. 1(a). The plot shows that the device exhibits a clockwise bistability, which can be explained as follows. It is observed from Eq. (2) and Eq. (7) that the absorption in the QWs decreases with increasing input power, this resulted an increase in intracavity power, which causes further decrease of absorption. This phenomenon continues until an abrupt change in excitonic absorption occurs at a specific input power (P_{down}), where the reflected power changes suddenly from a high to a low output state (as shown in Fig. 1b). With increasing the input power beyond P_{down}, thermal effect plays a significant role which further increases the reflectivity, and hence the reflected power increases (not shown in Fig. 1). Now, if the input power is decreased, the reflected power stays low even below P_{down}, because of the storage property of the Fabry–Perot cavity. On further decreasing the power, the absorption adjusts itself and the reflectivity increases suddenly at a given input power, called the switch-up power (P_{up}), and we observed a clockwise bistability in the reflection mode of operation. Again, from Eqs. (8) and (1), we observed that the reflected power, which depends on the reflectivity of the device, is a function of both phase and total absorption coefficients. The above two parameters strongly depend on the power inside the cavity, which is controlled by the feedback cavity