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Dispersive bi-stability in a vertical microcavity-based saturable absorber due to photo–thermal effect and initial phase-detuning

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ABSTRACT

Round-trip phase-shifts with intensity of an input signal due to saturable index change and optically induced thermal effects in a vertical cavity semiconductor (quantum wells) saturable absorber (VCSSA) are investigated analytically to observe counter-clockwise bi-stability in transmission mode and clockwise bi-stability in reflection mode. Simultaneous effects of Kerr nonlinearity and cavity heating on resonance wavelength-shift of the VCSSA micro-cavity are investigated. It is found that these bi-stable characteristics are possible to the absorption edge of nonlinear material for long wavelength side operations of low intensity resonance wavelength of the micro-cavity, where dispersion of absorption and refraction are neglected over a small range of optical wavelength tuning ($\delta\lambda \sim 10$ nm). Simulations are carried out to find out optimized parameters of the device for bi-stable characteristics. Operations are demonstrated for InGaAs/InP quantum wells based VCSSA with low intensity resonance wavelength of 1570 nm. For counter-clockwise bi-stable switching at working wavelength of 1581 nm, an input intensity variation of $0.79I_S$ is required with top (R_t) and back DBR reflectivity (R_b) of 91% and 93%, respectively, where I_S represents the absorption saturation intensity of nonlinear medium. Whereas, the clockwise bi-stability occurs at $0.22I_S$ for working wavelength of 1578 nm with R_t of 90% and R_b of 98%, respectively.

1. Introduction

Optical bi-stability (OB) is reported both in active [1–11] and passive [12–18] devices based on vertical cavity semiconductors. The active devices are also sometimes known as semiconductor laser amplifiers, Fabry–Perot semiconductor optical amplifiers (FPSOAs) and distributed feed-back semiconductor optical amplifiers (DFBSOAs) [9–11]. The vertical cavity semiconductor optical amplifier (VCSOA) is an active device where the OB occurs due to saturation of both refractive index and gain induced by external biasing. In the last few years, study has also been pursued on the passive vertical cavity devices like vertical cavity semiconductor saturable absorber (VCSSA) consisting of Fabry–Perot cavity embedded with quantum-wells (QWs) material. These devices show clockwise OB due to optical feedback through nonlinear absorption in reflection mode [15] and also counter clockwise OB in transmission mode due to saturation of nonlinear index [16]. However, no report is there where OB is considered for nonlinear phase-shift due to both optically induced thermal effects and saturable index change with wavelength detuning from low intensity resonance of Fabry–Perot micro-cavity. These passive and polarization independent operations may be useful for designing AND/OR and NAND/NOR logic operations, wavelength conversion, optical flip–flop etc. A typical schematic configuration of VCSSA as reported in [18] is considered. The saturation of absorption and nonlinear index change predominantly occurs in the QWs layer sandwiched between the distributed Bragg reflectors (DBR) of the Fabry–Perot cavity.

Hurtado et al. [19] predicted the occurrence of bi-stability due to negative initial phase detuning and non-linear phase change with intensity of an optically pumped VCSOA. Marki et al. [20] demonstrated counterclockwise, clockwise and butterfly bi-stability in VCSOA at 1550 nm working for transmission and reflection using the differential gain characteristics. This type of device may be useful for all-optical regeneration, two wavelength switching [21,22], logic operations [23], optical flip–flop [24] etc. The saturable absorbers (SAs) based passive devices are particularly attractive, owing to their simplicity, cost effectiveness and realizable in a simple scheme of all-optical 2R regeneration [25]. Signals with high-repetition-rate may be applicable to QWs based SA device due to ultrafast carrier recombination rate [26,27]. The 2R regeneration [28–33] is also reported using this type of SA device.

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In this work, we present theoretical study on counter-clockwise and clockwise optical bi-stability in transmission and reflection mode of a VCSSA due to its strong dependence on detuned wavelength of the applied signal. To the best of our knowledge, this is the first speculation on the occurrence of counterclockwise optical bi-stability in passive device, except the one by Garmire [16] where only saturation of refractive index is considered. Also, the dependency of top and back DBR reflectivity of the micro-cavity on the nonlinear phase-shift dependent OB is presented in this paper. In addition, we present non-linear characteristics of round-trip phase-shift, single-pass absorption and average absorbed intensity with input intensity of the micro-cavity by the nonlinear medium of the VCSSA. The results are compared with the ones reported in active devices [8,19,20] where biasing takes the role of introducing nonlinear phase as compared to the heating effects in the present case.

2. Device analysis

The transmitted and reflected intensity of an asymmetric vertical cavity semiconductor saturable absorber for normal incidence of an input signal is given by [15,16]

$$\left(\frac{I_{trans}}{I_S}\right)=\left(\frac{I_{in}}{I_S}\right)\frac{(1-R_t)(1-R_b)e^{-\alpha d}}{(1-\sqrt{R_tR_b}e^{-\alpha d})^2+4\sqrt{R_tR_b}\sin^2(\phi/2)e^{-\alpha d}} \tag{1}$$

and

$$\left(\frac{I_{ref}}{I_S}\right)=\left(\frac{I_{in}}{I_S}\right)\frac{(\sqrt{R_t}-\sqrt{R_b}e^{-\alpha d})^2+4\sqrt{R_tR_b}\sin^2(\phi/2)e^{-\alpha d}}{(1-\sqrt{R_tR_b}e^{-\alpha d})^2+4\sqrt{R_tR_b}\sin^2(\phi/2)e^{-\alpha d}} \tag{2}$$

where, I_{in}, I_{trans}, I_{ref} and I_S are incident, transmitted, reflected intensity and saturation intensity of the nonlinear medium; R_t and R_b are the top and back DBR intensity reflectivity of the Fabry–Perot cavity, respectively. Also, ϕ is the total round-trip phase covered by the signal inside the Fabry–Perot cavity, αd is the single-pass absorption of the QW material and d is length of the QW layers.

The single-pass absorption has both saturable part and non-saturable part. The intra-cavity intensity dependent total absorption is given by [34–38]

$$\alpha d=\alpha_{ns}d+\alpha_0 d/\{1+(I_C/I_S)\} \tag{3}$$

where, α_{ns} and α_0 are the non-saturable and small-signal absorption coefficients of the absorber medium, respectively. Here, the small-signal absorption coefficient is considered due to plasma-induced excitonic bleaching and the inter-band absorption is neglected. The I_C is intra-cavity intensity of the VCSSA.

The length-averaged intra-cavity intensity according to [39], is given by

$$\left(\frac{I_C}{I_S}\right)=\left(\frac{I_{in}}{I_S}\right)\frac{(1-R_t)(1-e^{-\alpha d})(1+R_be^{-\alpha d})}{\alpha d\left\{(1-\sqrt{R_tR_b}e^{-\alpha d})^2+4\sqrt{R_tR_b}e^{-\alpha d}\sin^2(\phi/2)\right\}} \tag{4}$$

Now a relationship between input, transmitted, reflected and average absorbed intensity due to energy conservation can be derived using Eqs. (1), (2) and (4)

$$\left(\frac{I_{ref}}{I_S}\right)=\left(\frac{I_{in}}{I_S}\right)-\alpha d\left(\frac{I_C}{I_S}\right)-\left(\frac{I_{trans}}{I_S}\right) \tag{5}$$

The total round-trip phase covered by the input signal inside the Fabry–Perot cavity is

$$\phi=\phi_0+\phi_1+\phi_2 \tag{6}$$

where, ϕ_0, ϕ_1 and ϕ_2 are the linear, Kerr nonlinear and thermal phase-shift experienced by the input signal. According to [17], the Kerr nonlinear saturable phase-shift is

$$\phi_1=\frac{4\pi n_{2S}d}{\lambda_W}\frac{(I_C/I_S)}{\{1+(I_C/I_S)\}} \tag{7}$$

where, n_{2S} is the saturated nonlinear index and λ_W is the working wavelength of input signal.

Now we want to derive the optically induced thermal effects to the resonance wavelength-shift of micro-cavity. A linear red shift occurs to the resonance with temperature caused by thermal effects of the intra-cavity intensity, as both refractive index and thickness depend on temperature. The rise of temperature of the micro-cavity affects to the direct band gap energy of the absorber medium. According to Varshni's empirical idea [40], the resonance wavelength at higher temperature is given by

$$\lambda_{reso}(T_{act})=\lambda_{reso}(300)+\frac{d\lambda_{reso}}{dT_{act}}(T_{act}-300) \tag{8}$$

The rise of temperature is proportional to the average power absorption by the absorber. Then average actual temperature of the nonlinear medium becomes

$$T_{act}=300+R_{th}P_{abs} \tag{9}$$

where, R_{th} is the overall effective thermal resistance of nonlinear medium which depends on the type of absorber medium.

According to [39], the average power absorbed by a QW absorber within a Fabry–Perot cavity is

$$P_{abs}=AI_S\left(\frac{I_C}{I_S}\right)\alpha d \tag{10}$$

where, A is cross-sectional area of the micro-cavity.

Then the increase of temperature in absorber layer from Eqs. (9) and (10) becomes

$$\Delta T=R_{th}AI_S\left(\frac{I_C}{I_S}\right)\alpha d \tag{11}$$

As well as, the nonlinear red-shift of resonance wavelength of the micro-cavity with intra-cavity intensity becomes (from Eq. (8))

$$\begin{aligned}(\Delta\lambda_{reso})_{red-shift}&=\left(\frac{d\lambda_{reso}}{dT_{act}}\right)\Delta T\\ \text{Using Eq. (9)}\quad&=\left(\frac{d\lambda_{reso}}{dT_{act}}\right)R_{th}P_{abs}\\ \text{With Eq. (10)}\quad&=\left(\frac{d\lambda_{reso}}{dT_{act}}\right)R_{th}AI_S\left(\frac{I_C}{I_S}\right)\alpha d\end{aligned} \tag{12}$$

where, $d\lambda_{reso}/dT_{act}$ is the rate of change of resonance wavelength with average actual temperature.

So, the nonlinear phase-shift due to thermal effect at any higher intensity becomes

$$\phi_2=4\pi nd\left(\frac{1}{\lambda_W}-\frac{1}{\lambda_{reso}+(\Delta\lambda_{reso})_{red-shift}}\right) \tag{13}$$

where, λ_{reso} is the low intensity resonance wavelength which corresponds to $\phi_0=2m\pi$.

3. Modeled VCSSA

Nonlinear phase-shift is negligible at zero light level. But with increase of input intensity, the cavity resonance is tuned from low intensity resonance to blue-shift and blue-shift to red-shift due to simultaneous effects of Kerr nonlinearity and optical induced thermal growth. Then, a nonlinear phase-shift occurs with input intensity due to mismatch of working wavelength and resonance wavelength. If working wavelength is considered longer wavelength side from low intensity resonance wavelength of the micro-cavity, then the VCSSA shows dispersive bi-stability in both transmission and reflection.