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Modeling of two wavelength switching using a reflective vertical cavity semiconductor saturable absorber

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ABSTRACT

Wavelength switching between two optical signals has been studied numerically utilizing the concept of cross-absorption modulation and partial cross-phase modulation in a reflective vertical cavity semiconductor saturable absorber (R-VCSSA). The switching performance of an R-VCSSA designed with high power impedance-matched top mirror reflectivity is studied by fixing a control beam (CB) at low power cavity resonance wavelength (λ_{res}) and a signal beam on the short wavelength side of λ_{res}, with a fixed low input power. On gradually increasing the CB input power, the carrier concentration within the cavity increases which modifies the absorption and the refractive index of the saturable absorber. This results in a change in the output power of both the beams. In the analysis we have considered a 40 Gb/s input signal. The high intra-cavity power introduces thermal effects within the VCSSA cavity due to which the effective cavity length of the device changes. The change in cavity length leads to a red-shift of the cavity resonance wavelength. This effect has also been incorporated in the model. The advantage of a VCSSA, used for switching is owing to its comparatively small carrier recombination time ($\sim$5 ps or less), which could be utilized for the high speed optical system.

1. Introduction

Vertical cavity semiconductor quantum-wells (QWs) structure has drawn considerable attention over the past decade because of their applications in optical switching [1], optical regeneration [2–4] and all-optical logic operations [5–7]. Wavelength switching between two optical signals has been studied in many nonlinear active devices. But, to our knowledge, no work on two wavelength switching (TWS) has yet been reported using a passive device like VCSSA. The wavelength switching between two optical signals of different wavelengths were studied first time using optical bi-stability occurring in a Fabry–Perot (F–P) semiconductor laser amplifier (FPSLA) working in transmission mode [8]. The work reports that the output of the signal beam exhibits both clockwise and counter-clockwise bi-stability depending on its initial phase detuning. Later on an extensive study of TWS were carried out both experimentally and theoretically using some devices like vertical cavity semiconductor optical amplifier (VCSOA) [9,10], distributed feedback semiconductor optical amplifier (DFBSOA) [11], semiconductor lasers [12] and quantum-dot vertical cavity surface emitting laser (QD-VCSEL)[13]. The TWS operation using a FPSLA [14] and a DFBSOA has been demonstrated at a bit rate of 800 MHz and 3 GHz, respectively with the switching power ranging from few to hundreds of microwatts. The switching in QD-VCSEL has been observed at 1300 nm with switching speed up to 2.5 GHz without using bi-stability of the device. In this paper, we have studied numerically the wavelength switching between two optical signals in a VCSSA, with a signal repetition rate of 40 GHz. However, the operation could be extended up to 160 GHz, depending on the carrier recombination time of the absorber.

A VCSSA is an asymmetric F–P resonator embedded with semiconductor multiple quantum-wells (MQWs) structure as the saturable absorber. The excitons in MQWs exhibit high nonlinearity. This effect has been used to construct devices such as high speed modulators [15], optical bi-stable devices [16–18], and picosecond mode-locked lasers [19]. In addition, the VCSSA have numerous advantages including its easy fabrications, polarization independent operation, lowest noise figure and flexibility in coupling with optical fibers.

In this paper, we have illustrated a theoretical model that describes precisely the spectral reflectivity of a VCSSA at different input powers. Then the wavelength switching between two optical signals is analyzed using cross-absorption modulation and partial cross-phase modulation. For the TWS operation, the most important parameters are the input power and wavelength of the signal and control beam, respectively. The total phase-shift that arises

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simultaneously from the optically induced thermal effect and the Kerr-nonlinearity is used to model the TWS operation. Also, the effect of top mirror reflectivity on switching performance has been studied. Then the switching of a 40 GHz RZ optical signal is discussed using the dynamic model of cross-absorption modulation (XAM) within the quantum-wells structure.

2. Characterization of a VCSSA

The structure of a VCSSA is well described in the previous reports [5,6]. It is considered as an asymmetric F–P cavity embedded with semiconductor multiple quantum-wells structure as the saturable absorber. An asymmetric F–P cavity is usually formed by the semiconductor/dielectric distributed Bragg reflector (DBR) with less reflective top mirror (R_t) and a highly reflective back mirror (R_b). The DBR is typically a periodic structure of semiconducting materials with alternating high and low refractive indices and each of thickness equals to the one-quarter of the desired wavelength. The reflectivity of the DBR depends on the number of paired layers as well as on the refractive index difference between the adjacent layers. Usually, the devices are grown by solid-source molecular beam epitaxy on an n-type InP substrate. It comprises a bottom DBR, an InP spacer layer, the absorber region (MQWs), an InP cap layer and a top DBR layer [20]. Both the cap and spacer layers allow multiple resonances of the device within the communication wavelength range, and their lengths are varied for different samples to achieve specific applications. The DBR layers and the QW layers are chosen to be same semiconductor materials for the requirement of lattice matching. In our model, an InGaAs/InP based MQWs is considered to operate the device near 1550 nm wavelength. Ultrafast optoelectronic device application using QWs based VCSSA can be achieved by reducing the recombination time using processes like low-temperature (*LT*) epitaxial growth [21–23] and ion implantation [24–26]. Due to the presence of non-radiative recombination centers, the excitonic lifetime gets determined by the intra-band relaxation times which are much shorter than the optical transition time. The excitonic lifetime is of the order of few picoseconds. This is desirable for the high speed switching. The saturation power increases as it is inversely proportional to the carrier lifetime [27]. The active region is coated with the few layers of SiO_2/TiO_2 providing the specified top mirror reflectivity at the operating wavelength. The top mirror reflectivity determines the amount of light entering the saturable absorber and therefore, controls the nonlinear reflectivity of the device [19]. The maximum nonlinearity of the VCSSA is achieved by the combined effects of asymmetric F–P cavity and the MQWs [1]. For such a device the expression for reflectivity at cavity normal incidence is given by [5]

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

where d is the length of the nonlinear cavity, α is the total absorption coefficient of the nonlinear medium and ϕ is the total round-trip phase of the optical signal within the F–P cavity. The total absorption coefficient α includes the two terms; the non-saturated part of absorption (α_{ns}) and the saturable absorption (α_{sat}). The non-saturated part is the background absorption of the nonlinear medium and is independent of the incident light power, whereas the saturated part is due to the excitonic absorption within the MQWs and it depends on the intra-cavity power according to [28]

$$\alpha=\alpha_{ns}+\alpha_{sat}=\alpha_{ns}+\frac{\alpha_0}{(1+P_c/P_{sat})} \tag{2}$$

where α_0 is the low-power material absorption coefficient of the saturable absorber. P_c and P_{sat} are the length-averaged intra-cavity power and the saturation power of the nonlinear medium, respectively. The total phase ϕ comprises of three terms; the actual/linear phase of the optical field (ϕ_0), the phase-shift due to the carrier induced nonlinear index change in the active region (ϕ_{Kerr}) [29], and the phase-shifting term that arises when the device is operated at a wavelength other than the cavity resonant wavelength (ϕ_{shift}). Thus, the total phase now becomes

$$\phi=\phi_0+\phi_{Kerr}+\phi_{shift} \tag{3}$$

Considering the cavity resonance at low input power, we have $\phi_0=2m\pi$, where 'm' is a positive integer. The second term in Eq. (3), is the phase detuning due to the Kerr-nonlinearity and is defined as

$$\phi_{Kerr}=\frac{4\pi n_{2s}d}{\lambda_w}\left[\frac{P_{cs}}{(1+P_{cs})}\right] \tag{4}$$

where, $P_{cs}=P_c/P_{sat}$ and n_{2s} is the nonlinear index change of the saturable region and the sign of index change is negative. Further we have

$$\phi_{shift}=4\pi(nd)\left(\frac{1}{\lambda_w}-\frac{1}{\lambda_{res}}\right) \tag{5}$$

where λ_w is the working wavelength of the input signal which is different from the low power cavity resonant wavelength (λ_{res}). But the total power absorption in the nonlinear medium introduces some thermal effects because of which the resonance shifts towards the higher wavelength side due to increase in effective cavity length (nd). This results in some additional phase to the optical field. Thus, the total corrected phase now becomes

$$\phi=\frac{4\pi n_{2s}d}{\lambda_w}\left[\frac{P_{cs}}{(1+P_{cs})}\right]+4\pi(nd)\left(\frac{1}{\lambda_w}-\frac{1}{\lambda_{res}+\Delta\lambda}\right) \tag{6}$$

where $\Delta\lambda=(d\lambda_{res}/dT_{act})R_{th}P_c\alpha d$, is the shift of the resonance wavelength due to the thermal effects [30]. Also, $d\lambda_{res}/dT_{act}$ is the rate at which resonant wavelength changes with the actual temperature and its value varies from 0.01 to 0.1 nm/K for InGaAs/InP QWs [31]. R_{th} is the overall effective thermal resistance of the nonlinear medium and it depends only on the type of the nonlinear medium. It is assumed that the optical power is uniform along the length of the nonlinear cavity. The length-averaged power inside the cavity can be expressed as [5]

$$P_c=\frac{(1-R_t)(1-e^{-\alpha d})(1+R_be^{-\alpha d})P_{in}}{\alpha d\left(\left(1-\sqrt{R_tR_b}e^{-\alpha d}\right)^2+4\sqrt{R_tR_b}e^{-\alpha d}\sin^2(\phi/2)\right)} \tag{7}$$

From Eqs. (2), (6) and (7), it is observed that the intra-cavity power that depends on the phase-shift and the total absorption are themselves modulated by the cavity power (P_c), where P_c depends nonlinearly to the input power (P_{in}).

The spectral reflectivities of the device with the top mirror satisfying the high power IM condition ($R_t=R_be^{-2\alpha_{ns}d}$) have been calculated at different input powers using the above equations and the results are plotted as shown in Fig. 1. For a VCSSA designed to satisfy the high power IM condition, shows maximum reflectivity at the low input power and it decreases with increasing the input power, which is observed from the plot. The parameters used in our simulations are given in Table 1. As the power increases, the absorption and the total phase-shift of the optical signal get changed according to the Es. (2) and (6), respectively. The cavity resonance shifts towards the shorter wavelength region (blue-shift) due to the Kerr-nonlinearity, whereas a red-shift of cavity