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Bistability characteristics of different types of optical modes amplified by quantum dot vertical cavity semiconductor optical amplifiers

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ABSTRACT

We have studied the characteristics of optical bistability of different types of optical modes amplified by small-size quantum dot vertical cavity semiconductor optical amplifiers operated in reflection. Our analysis reveals that TE_{01} mode exhibits stronger intensity-dependent non-linearity in small radius devices, which results in stronger optical phase modulation and therefore larger hysteresis width compared with the other modes. The effect of the wavelength detuning of the input signal on the shape of the hysteresis loop is studied. We find that butterfly hysteresis loop exhibits the largest hysteresis width compared with clockwise and counterclockwise loops. Our analysis reveals that doping the quantum dots with p-type doping slightly reduces the hysteresis width while doping the dots with n-type doping clearly increases the hysteresis width for any wavelength detuning. We estimate that the hysteresis width of quantum dot active layer will exhibit higher hysteresis width compared with quantum well active layer having the same threshold gain.

1. Introduction

Vertical-cavity semiconductor optical amplifiers (VCSOAs) are attractive devices because of their small size, low power consumption, high coupling efficiency to optical fiber, low cost of manufacturing and packaging, and polarization independent gain [1–5]. Moreover VCSOAs can be fabricated in two-dimensional arrays, which facilitate on-wafer testing. Because of their small gain per pass, VCSOAs require mirrors with high reflectivity. Actually light penetrates significantly inside the DBRs which enlarges the effective length of the cavity. In addition, a standing optical wave is created inside the cavity, which requires careful positioning of the active layers to benefit from the gain enhancement mechanism.

Quantum dot (QD) nanostructures have attracted much attention in recent years since they have the potential to enhance the performance of lasers and optical amplifiers due to the discrete structure of their energy levels [6]. QD semiconductor optical amplifiers (SOAs) have shown enhanced characteristics when compared with quantum well-based devices [7]. The incorporation of QD in the active layer of SOAs results in a suppression of pattern effects and enhances the high-speed operation of the device. Vertical-cavity semiconductor optical amplifiers (VCSOA) have demonstrated optical bistability and hysteresis in the input-output characteristics of the device [1]. The optical bistability is due to the dispersive optical nonlinearity of the active layer whose refractive index is dependent on the incident optical power. When external optical power is injected to a VCSOA the refractive index is changed which moves the resonant frequency toward longer wavelengths depending on the amount of the injected power and therefore result in optical bistability. The nonlinear characteristics of VCSOA can be utilized in many applications such as optically controlled wavelength filters, wavelength based logic gates, analog to digital optical conversion, waveform reshaping and polarization modulation and switching [8–13].

Microcavity effects in VCSELs lead to enhanced values of the spontaneous emission rate. The enhancement of the spontaneous emission rate is determined by many factors such as the wavelength detuning between the emitter and the cavity mode, the position of the emitter in the cavity, the quality factor of the cavity, the quantum emitter linewidth and polarization [14,15]. The high-finesse of the cavity in VCSOAs results in a narrow gain bandwidth, which eliminates out-of-band noise and provides channel selection in multi-wavelength systems. The narrow gain spectrum also eliminates the need for adding an optical filter at the output of the amplifier and reduces the cost. 20 dB gain with ~1 Å 3 dB bandwidth was experimentally measured in InGaAs quantum well active layer [16]. The resonant wavelength in [16] was tuned by varying the driving current (device temperature) to match exactly the wavelength of the input light. Wen et al. [1] have reported experimental observation of optical bistability in a VCSOA operated in reflection mode. The counterclockwise hysteresis loops are observed over a range of bias currents and initial phase detuning.

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The initial phase detuning (i.e., initial wavelength detuning) of the input was done in [1] by changing the source wavelength through the rotation of a grating in the laser source. Hurtado et al. [4] have presented a theoretical study of the reflective optical bistability occurring in a VCSOA, they have shown that bistability is strongly dependent on the applied bias current and the initial phase detuning. They also predicted the appearance of the X-bistable and the clockwise bistable loop. Zhang et al. [17] have reported the possibilities to realize optical flip-flop in VCSOA using anti-resonant reflecting optical waveguide. To our knowledge there is no work in the literature that studies the effect of the type of the input optical signal and the size/radius of the cavity on the input–output characteristics of quantum dot VCSOA operated in the reflection mode. In this paper, we will study the characteristics of optical bistability of different types of optical modes amplified by small-radius quantum dot vertical cavity semiconductor optical amplifiers operated in reflection mode. This work is motivated by the fact that reducing the size of the cavity alters many features of the device, For example, the threshold conditions and the power loss of the fundamental mode are different than that of the next higher mode [14,18].

2. Theory

2.1. QD model

The investigated device is a cylindrical vertical cavity device with top and bottom DBRs. The VCSOA is made of a separate confinement heterostructure that contains inner and outer cladding layers and layers of QDs that are placed in the center of the cavity. The energy band diagram of the active layer exhibits multiple energy states in both the conduction and the valence bands. Experimental data have shown that 1.3 μm InAs/GaAs QD exhibits three energy states in the conduction band and eight energy states in the valence band plus a wetting layer state [7]. The energy separations are 60 meV for electron states and 10 meV for the hole states. The rate equation for electrons in the i-th energy state is given by [6,7]

$$\frac{\partial f_i^n}{\partial t} = \left(R_{i+1,i}^{nc} - R_{i,i+1}^{ne}\right) - \left(R_{i,i-1}^{nc} - R_{i-1,i}^{ne}\right) - \frac{f_i^n f_i^p}{\tau_{iR}} - R_i^{st} \tag{1}$$

where t is time, f_i^n and f_i^p are respectively the occupation probability for the electrons and holes in the i-th state where $i=0$ represents the ground state. $R_{i+1,i}^{nc}$ is the electron capture rate from the $(i+1)$th state to the i-th state and $R_{i,i+1}^{ne}$ is the electron emission rate from the i-th state to the $(i+1)$th state. τ_{iR} is the spontaneous radiative lifetime in i-th state and R_i^{st} is stimulation emission rate. The capture and emission rates are respectively given as [7]

$$R_{i+1,i}^{nc} = \frac{(1-f_i^n) f_{i+1}^n}{\tau_{i+1,i}^n}\left(b_{i+1,i}^n + c_{i+1,i}^{np} f_w^p + c_{i+1,i}^{nn} f_w^n\right) \tag{2}$$

$$R_{i,i+1}^{ne} = \frac{f_i^n (1-f_{i+1}^n)}{\tau_{i,i+1}^n}\left(b_{i+1,i}^n + c_{i+1,i}^{np} f_w^p + c_{i+1,i}^{nn} f_w^n\right) \tag{3}$$

where f_w^p and f_w^n are respectively the occupation probability for the holes and electrons in the wetting layer, $\tau_{i+1,i}^n$ is the electron capture time from the $i+1$ state to the i-th state and $\tau_{i,i+1}^n$ is the electron escape time from the i-th state to the $i+1$ state. $b_{i+1,i}^n$ is the phonon-assisted coefficient, $c_{i+1,i}^{nn}$ is the electron–electron Auger-assisted coefficient and $c_{i+1,i}^{np}$ is the electron–hole Auger-assisted coefficient.

The last term in Eq. (1) represents the stimulation emission rate which is given by

$$R_i^{st} = \sum_k \frac{v_g a_{ik} (f_i^n + f_k^p - 1) S_{av}}{N_Q}$$

where S_{av} is the average photon density inside the cavity, N_Q is the dot volume density and a_{ik} is the material gain coefficient of the active layer which is given by

$$a_{ik} = a_{ik}^{\max} \frac{\hbar\omega_{ik}^{\max}}{\hbar\omega} \mathrm{Exp}\left(\frac{-(\hbar\omega - \hbar\omega_{ik}^{\max})^2}{2\sigma_{ik}^2}\right) \tag{4}$$

where σ_{ik} is the inhomogeneous line broadening, $a_{ik}^{\max}$ is the maximum gain coefficient for the i–k transition, $\hbar\omega$ is the photon energy of the amplifier and $\hbar\omega_{ik}^{\max}$ is the energy corresponding to the gain peak of the i–k transition. The modal gain of the active layer (i.e., the l-th layer) is

$$g_l = \sum_{i=0}^{M_n} \sum_{k=0}^{M_p} a_{ik} (f_i^n + f_k^p - 1) \tag{5}$$

The rate equation for the wetting layer state is

$$\frac{\partial f_w^n}{\partial t} = \frac{J}{\tau_{wR}} - \left(\frac{(1-f_{M_n}^n) f_w^n}{\tau_{w,M_n}^n} - \frac{f_{M_n}^n (1-f_w^n)}{\tau_{M_n,w}^n}\right) - \frac{f_w^n}{\tau_{wR}} \tag{6}$$

where f_w^n is the occupation probability for the electrons in the wetting layer, J is the normalized applied current, τ_{w,M_n}^n is the electron capture time from the wetting layer to the M_n state and $\tau_{M_n,w}^n$ is the electron escape time from the M_n state to the wetting layer, and τ_{wR} is the spontaneous radiative lifetime in wetting layer. Similar rate equations are modeled for the hole states.

Under quasi-Fermi equilibrium condition, the capture and escape lifetime are related to each other via $\tau_{i,i+1}^{n,p}/\tau_{i+1,i}^{n,p} = \mathrm{Exp}(\Delta_{i+1,i}^{n,p}/KT)$ where K is Boltzmann constant, T is the absolute temperature and $\Delta_{i+1,i}^{n,p}$ is the energy separation between the i and the $i+1$ states.

The relation between the electron and the hole concentration is governed by the charge neutrality equation which is given by

$$N_A + \sum_{i=0}^{M_n} N_i f_i^n + N_w = N_D + \sum_{k=0}^{M_p} N_k f_k^p + P_w \tag{7}$$

where N_k is the volume density of the k-th state, N_A and N_D are the acceptor and donor concentrations respectively, and N_w and P_w are the electron and the hole concentration of the wetting layer. M_n and M_p are the number of electron and hole states respectively

2.2. VCSOA model

The structure under consideration is a standard 3λ cavity. The VCSOA consists of a top mirror with pairs of quarter wave layer of indices n_1^t and n_2^t, 3λ cavity of index n_a which consists of quantum dot nanostructures and bottom mirror with pairs of quarter wave layer of indices n_1^b and n_2^b. The VCSOA is a cylindrical cavity with radius equal to R. We assume that the cavity is surrounded by air with refractive index $n_0=1$ for $r > R$. The VCSOA is grown on a substrate with refractive index of n_s. The solution of Maxwell's equations indicates that hybrid modes as well as TE and TM modes can propagate inside cylindrical vertical cavities. In hybrid modes both polarizations must be taken into account to satisfy the boundary conditions [18]. Hybrid modes have both $E_z \neq 0$ and $H_z \neq 0$ are labeled EH_{mn} and HE_{mn}, depending on the whether E_z or H_z is dominant. The first subscript (m) refers to the azimuthal number and the second subscript (n) refers to the radial mode number, i.e., showing how many times E_z and H_z change sign in the radial direction. The fundamental mode in vertical cavities is HE_{11} (which has a radial intensity distribution with a maximum at the center), and the first higher order mode consists of $\boldsymbol{TE}_{01}$, TM_{01}