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Quantum effect on characteristics of semiconductor ring laser

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ABSTRACT

A bistable semiconductor ring laser (SRL) with two counter propagation modes has been triggered by optical pulse injection which added to the initial nonlasing mode. As the optical pulse injection (OPI) has an important role in switching and lasing of SRL, we have to find a reliable area to achieve its amplitude and frequency. Numerical results show an increase in amplitude of OPI leading to switching time decreasing as well as an increase to amplitude oscillation. It is shown that in order to prevent the oscillation in laser output characteristic, the OPI power must be less than 2 mW. We have also investigated the effect of quantum wells on active region structure of SRL. It is obvious by increasing the quantum well numbers the output optical power has been increased and the switching time has been decreased. The main advantage of this research work is to apply separate confinement heterostructure (SCH) to multi quantum well (MQW) structure to extract numerical model for amplitude and phase of SCH-SRL. Using SCH in MQW-SRL active region will increase the output power to 0.8 mW and decrease threshold current to 12 mA.

1. Introduction

Semiconductor ring lasers (SRL) are one of the important candidates for optoelectronic integrated circuits (OEICs) and optical gates because of their many advantages such as high efficiency, minimum loss, and no requirement grating or cleaved facet. Mirror losses reduction due to elimination of mirror in ring laser leading to a reduction in optical losses. Since optical interaction occurs in the active region, it has strong effect on the lasers output characteristics. Therefore, quantum well, quantum dot and Y-Junction-Coupled S-Section are the major structure which used in SRLs active region [1–4].

SRLs are obtained by two operations including unidirectional and bi-directional applications [5–8] mostly focusing on bistability operation of this laser. SRLs have circular cavity as shown in Fig. 1 where optic can do circulation in two directions; clockwise (CW) and counter-clockwise (CCW). In bi-directional operation of SRL before applying external optical injection, SRL lases in initial CCW direction when optical pulse has been injected into nonlasing CW direction, laser has been triggered so that optical switching occurs and laser began to lase in new CW direction. A ring laser consists of a ring laser having two independent counter-propagating resonant modes over the same path; the difference in the frequencies is used to detect rotation. It operates on the principle of the Sagnac effect which shifts the nulls of the internal standing wave pattern in response to angular rotation. Interference between the counter-propagating beams, observed externally, results in motion of the standing wave pattern, and thus indicates rotation.

SRL studied in this paper is the branch of the quantum well laser. Quantum well laser become popular because of its good performance compared to conventional bulk lasers. Using quantum wells in laser active region structure is extremely appealed due to its high efficiency, low threshold current density, excellent temperature feature, high modulation rate, narrow line width, large photon gain and wavelength adjustability. In single quantum well laser, due to carrier scattering into cavity, the annihilation of injected carrier in QW has been increased and makes difficulties to inject all electron carriers into QW region. Therefore, threshold current has been increased and optical pulse power has been decreased. To solve the carrier scattering problem, a SCH model will be used in laser active region where the QW region separated from cladding region by assimilating undoped structure having highest energy gap. In order to increase the laser optical power it is better to use MQW structure in active region.

Due to importance of OPI in switching and triggering of bistable SRL, the effect of OPI SRL output characteristic has been

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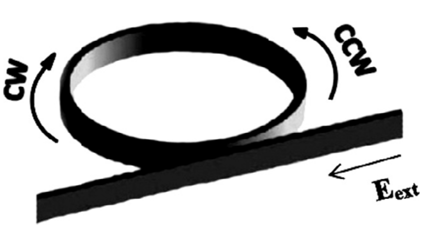

Fig. 1. Circular SRL with an external optical injection. CCW direction is initial lasing direction before the optical injection (Eext). It is switched to the CW direction after the injection.

investigated. Consequently, the number of QW equals to 1, 5 and 10 are applied into active region structure to investigate the effect of QWs on laser output characteristics. To improve the laser output powers and threshold current in MQW, we propose to add SCH to SRL.

2. Rate equation with two mode model

The model is based on two-mode model with counterclockwise and clockwise propagation mode excited by an external optical pulse injection. A structure property of model is same as the properties in Ref. [9,10,11]. In single longitudinal mode operation, the electric field inside the ring cavity can be expressed as [9]:

$$E(x,t) = E_1(t)\exp[-i(\omega_{o1}t - kx)] + E_2(t)\exp[-i(\omega_{o2}t + kx)] \tag{1}$$

where E1, E2 are electric field of mode 1 (CCW) and mode 2 (CW), $\omega_{01,2}$ is the optical frequency of the this modes; x " the longitudinal spatial along the ring trajectories" is positive for CCW direction and negative for CW direction. External optical injection will be added to the ring laser as shown by equation below [9]:

$$E_{ext}(x,t) = E_{ext}(t)\exp[-i((\omega_{02}t + \Delta\omega_{ext}t + \Delta\varphi_{ext}) + kx)] \tag{2}$$

where $\Delta\omega_{ext}$ is the angular frequency detuning between the external injection and the free-running ring laser mode and $\Delta\varphi_{ext}$ is the phase difference between them.

External optical injection switches the initial lasing direction into nonlasing direction.

The time evolution of the fields in the cavity can be described as:

$$\frac{dE_1}{dt} = \frac{1}{2}(1-i\alpha)\left(\Gamma G_n(N-N_{tr})(1-\varepsilon_s|E_1|^2-\varepsilon_c|E_2|^2)-\frac{1}{\tau_{p1}}\right) E_1 + i(\omega_{O1}-\omega_{th})E_1 \tag{3}$$

$$\frac{dE_2}{dt} = \frac{1}{2}(1-i\alpha)\left(\Gamma G_n(N-N_{tr})(1-\varepsilon_s|E_2|^2-\varepsilon_c|E_1|^2)-\frac{1}{\tau_{p2}}\right) E_2 + i(\omega_{O2}-\omega_{th})E_2 + K_{ext}E_{ext}\exp[-i(\Delta\omega_{ext}t+\Delta\phi_{ext})] \tag{4}$$

$$\frac{dN}{dt} = \frac{\eta_i I}{eV} - \frac{N}{\tau_e} - G_n(N-N_{tr})\cdot((1-\varepsilon_s|E_1|^2-\varepsilon_c|E_2|^2)|E_1|^2 + (1-\varepsilon_s|E_2|^2-\varepsilon_c|E_1|^2)|E_2|^2) \tag{5}$$

where E1, E2 are electric field of mode 1 (CCW) and mode 2 (CW), α is the line width enhancement factor, Γ expresses the optical confinement factor, *and* and ω_{02} are optical frequencies of these modes, ω_{th} represents the longitudinal resonant frequency at threshold. N is the carrier density in the active region, N_{th} is the carrier density at transparency. K_{ext} is the coupling parameter of the external injection; $K_{ext} = \sqrt{(T \times \tau_l)/f_b}$; where T is the external coupling parameter. E_{ext} is the field amplitude of injection and $\Delta\phi_{ext}$ is always set to be 0 because the external field injected into the nonlasing direction which initially has little power. ε_s and ε_c are self and cross-gain saturation coefficients, respectively. τ_{p1} and τ_{p2} are photon lifetime in the ring cavity for modes 1 and 2, respectively. I, η_i, e, V and τ_e are bias current, injection efficiency, electronic charge, volume for the quantum wells active region and carrier lifetime, respectively.$G_n = \upsilon_g \times g_n$ where υ_g and g_n are group velocity and differential gain at transparency, respectively [12]. Since the bending loss is lower than the mirror loss, it is neglected in our laser rate equation. The bending value is less due to the cavity circularity and less bending [17,18,19].

Internal backscattering causes linear coupling between the counter-propagating modes which can dominate SRL's operation at low bias current. However, it is neglected due to biasing of laser current above threshold so that nonlinear coupling plays a much more important role based on equation (3) [16].

By assuming initial zero condition, normalized variables and parameters are defined as below [20]:

$$E_{1,2} = \sqrt{G_n\tau_s}\cdot E_{1,2}; \tag{6}$$

$$n = G_n(N-N_0)\cdot\tau_p; \tag{7}$$

$$s=\frac{\varepsilon_s}{G_n\tau_s};\ c=\frac{\varepsilon_c}{G_n\tau_s};\ k_d=2\tau_p\cdot K_d;\ k_c=2\tau_p\cdot K_c;\ \gamma=\frac{\tau_p}{\tau_s};\ \mu=\frac{J-J_0}{J_{TH}-J_0};$$

k_d and k_c are dissipative and conservative scattering coefficients, μ is the pump parameter, defined as a function of the actual injected current density J. The threshold current J_{TH} and transparency current J_0 densities, which are respectively given by:

$$J_{TH} = \frac{e_d}{\tau_s}\left(N_0 + \frac{1}{G_n\tau_p}\right);\quad J_0 = \frac{ed}{\tau_s}.N_0$$

Reflection is the major problem that decreases extinction rate between lasing and nonlasing modes which can be eliminated by antireflection methods such as coating.

By assuming CCW as initial lasing mode, optical pulse injected to nonlasing CW direction and $E(t) = A(t)\exp(-j\varphi)$, the phase and amplitude of two fields inside the ring will be expressed as [9,12]:

$$\frac{dA_1}{dt} = \frac{1}{2}\left(\Gamma G_n(N-N_{tr})(1-\varepsilon_s A_1^2-\varepsilon_c A_2^2)-\frac{1}{\tau_{p1}}\right)A_1 \tag{8}$$

$$\frac{d\phi_1}{dt} = \frac{\alpha}{2}\left(\Gamma G_n(N-N_{tr})(1-\varepsilon_s A_1^2-\varepsilon_c A_2^2)-\frac{1}{\tau_{p1}}\right) - (\omega_{o1}-\omega_{th}) \tag{9}$$

$$\frac{dA_2}{dt} = \frac{1}{2}\left(\Gamma G_n(N-N_{tr})(1-\varepsilon_s A_2^2-\varepsilon_c A_1^2)-\frac{1}{\tau_{p2}}\right)A2 + (K_{ext}A_{ext}\cos\phi_2) \tag{10}$$

$$\frac{d\phi_2}{dt} = \frac{\alpha}{2}\left(\Gamma G_n(N-N_{tr})(1-\varepsilon_s A_2^2-\varepsilon_c A_1^2)-\frac{1}{\tau_{p2}}\right) - (\omega_{ext}-\omega_{th}) - \frac{K_{ext}A_{ext}}{A_2}\sin\phi_2 \tag{11}$$

$$\frac{dN}{dt} = \frac{\eta_i I}{eV} - \frac{N}{\tau_e} - G_n(N-N_{tr})\cdot((1-\varepsilon_s A_1^2-\varepsilon_c A_2^2)A_1^2 + (1-\varepsilon_s A_2^2-\varepsilon_c A_1^2)A_2^2) \tag{12}$$

where $A_{1,2}$ and $\varphi_{1,2}$ are amplitude and phase of mode 1 and 2, respectively.

3. Quantum well effect

Using of quantum well in laser active region is extremely attractive due to its numerous advantages that expressed in introduction section. In QW structure the motion of carrier is quantified in two