Impact of Cavity Size on Optical Injection Locking in Semiconductor Ring Lasers

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***Abstract*— Effects of the size of semiconductor ring laser on the strength of optical injection locking are discussed. Theoretical model has been developed to study the influence of for frequency response of locked semiconductor ring laser in the master slave configuration using phase modulation of master laser is discussed. In the unidirectional regime the locking range of semiconductor ring laser becomes wider when semiconductor ring laser with smaller size is used.**

***Keywords*— Semiconductor ring lasers, optical injection locking, bandwidth enhancement, bistability**

I. INTRODUCTION

Over last two decades a lot of research work has been proposed to develop high speed optical modulators and laser diodes to fulfil the requirements of future demands of high data rate communication systems. Modulation bandwidth of the laser source is an important question for the future broadband applications such internet tv, video transmission and voice over IP. It has become a key issue for emerging complex modulation based communication that involves both amplitude and phase in (quadrature amplitude modulation) with coherent detection. The highest direct modulation bandwidth of free-running laser reported so far is about 30GHz [1].

Optical injection locking (OIL) in semiconductor lasers (SLs) [2] appears to be very significant in accomplishing frequency chirp reduction, single-mode operation, noise reduction and in achieving huge modulation bandwidth enhancement [3]. Earlier the enhancement in the 3dB bandwidth of OIL lasers has been discussed both experimentally and theoretically. It has been shown that the modulation bandwidth of OIL slave laser in the master-slave configuration can be significantly increased [4] in the master-slave configuration. Though, these systems are not suitable for coplanar integration as the reflected light from the slave laser has to be stopped from entering back into the master laser using an isolator [5].

Semiconductor ring laser (SRL) can be a promising slave laser device for integrated OIL master-slave configuration while modulating the master laser. SRL works only in the direction receiving injected light, so there is no feedback into the master laser. In [5], we have already demonstrated enhancement in the bandwidth. SRL is a prospective candidate for all-optical processing due to fast switching time in terms of pico-seconds [6]-[7]. Directional bistability is a key characteristic of SRL [8] and a variety of applications are based on it including all-optical logic [9], all-optical label swapping[10], all-optical memory[11], all-optical regeneration [12]. The phenomena of optical injection locking and four-wave mixing [13] have also been reported in the SRL at particular conditions. A variety of applications has been reported using these two phenomena such as bandwidth enhancement [5], all-optical multicast [14], all-optical logic gates[15] and millimetre wave (mm-wave) generation and modulation [16].

In this paper, effects of cavity size on the optical injection locking are discussed. Enhancement in the bandwidth of SRL due decrease in its size is predicted. Smaller the size stronger will be injection locking. Stable locking region becomes wider with the decrease in the cavity length of slave OIL-SRL. Theoretical analysis of rate equation of OIL-SRL using phase modulation of the master laser is discussed in detail. Simulation analysis using different sizes of SRL predicts modulation bandwidth of >500GHz. It can be very vital for future 400Gbps optical transmission systems.

Fig. 1 illustrates the master slave bandwidth enhancement system using SRL as slave laser. The RF signal from the network analyser is modulated with the (continuous wave) light entering from the master laser (ML) using an optical modulator. When the SRL is with this modulated signal, the output from the SRL is passed back to the vector network analyser (VNA) after converting back to electrical signal using photodiode. VNA measures the frequency response of the OIL SRL.

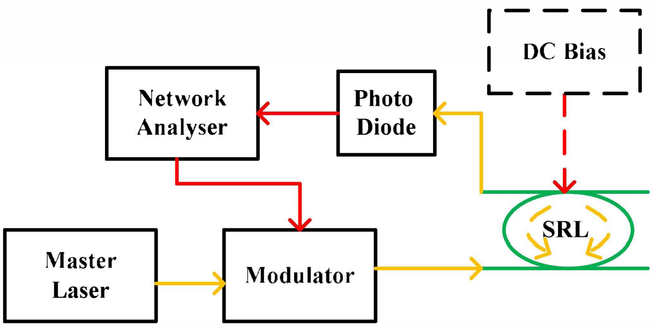

Fig. 1 Illustration of Bandwidth enhancement in slave SRL while modulating master laser

II. THEORETICAL MODEL

The modulated light is injected into the SRL in the in the counter clockwise (CCW) direction. When SRL is locked it works in the direction of injection. Without loss of generality, the rate equation of OIL SRL is only considered in CCW direction and can be described as:

$$\frac{dS(t)}{dt}=\Gamma v_g g_n\left(N(t)-N_{tr}\right)\left(1-\varepsilon_s S(t)\right)S(t)-\frac{S(t)}{\tau_p} \qquad (1)$$
$$+2\kappa_{inj}\sqrt{S(t)S_{inj}(t)}\cos\left(\phi(t)-\phi_{inj}(t)\right)$$

$$\frac{d\phi(t)}{dt}=\frac{\alpha}{2}\Gamma v_g g_n\left(N(t)-N_{tr}\right)\left(1-\varepsilon_s S(t)\right)-\frac{\alpha}{2\tau_p} \qquad (2)$$
$$-\kappa_{inj}\sqrt{\frac{S_{inj}(t)}{S(t)}}\sin\left(\phi(t)-\phi_{inj}(t)\right)-\Delta\omega_{inj}$$

$$\frac{dN(t)}{dt}=\frac{\eta_i I(t)}{qV}-\frac{N(t)}{\tau_N} \qquad (3)$$
$$-v_g g_n\left(N(t)-N_{tr}\right)\left(1-\varepsilon_s S(t)\right)S(t)$$

Where S(t) and $\phi(t)$ are the photon density and the phase of MRL in the CCW direction. $\Delta\omega_{inj}$ is the detuning frequency and it can be defined as $\Delta\omega_{inj}=\omega_M-\omega_f$, where ω_M and ω_f are lasing frequency of the master laser and MRL respectively. κ_{inj} accounts for the field coupling coefficient of the optical injection into the SRL cavity and it can be defined as $\kappa_{inj}=\sqrt{T/(1-T)}/\tau_l$, where T and τ_l are the output coupling ratio and round-trip time in the laser cavity respectively. The parameters α, Γ, v_g , g_n , N, N_{tr}, ε_s , τ_p , η_i , I, q, and τ_N are line-width enhancement factor, optical confinement factor, group velocity, differential gain at transparency, carrier density, carrier density at transparency, self-gain saturation coefficient, photon life-time, the quantum efficiency of the bias current I, the electron charge in the volume of active region V and carrier lifetime respectively. Note that V, N, τ_p depend on the length of the laser cavity.

By linearizing equations (1)-(3) the differential equation system may be placed in the matrix form as:

$$\begin{bmatrix}\delta S\\ \delta\phi\\ \delta N\end{bmatrix}=\mathrm{M}^{-1}\mathrm{X}$$

where
$$\mathrm{M}=\begin{bmatrix}a_{11}+j\omega & a_{12} & a_{13}\\ a_{21} & a_{22}+j\omega & a_{23}\\ a_{31} & a_{32} & a_{33}+j\omega\end{bmatrix}$$

The elements of state transition matrix **M** can be given as:

$$a_{11}=z\cos\phi_0, a_{12}=2zS_0\sin\phi_0,$$
$$a_{13}=-\Gamma v_g g_n S_0, a_{21}=-z\sin\phi_0/2S_0,$$
$$a_{22}=z\cos\phi_0, a_{23}=-\alpha\Gamma v_g g_n/2,$$
$$a_{31}=\left(1/\tau_p-2z\cos\phi_0\right)/\Gamma, a_{32}=0,$$
$$a_{33}=1/\tau_{Nd}+v_g g_n S_0$$

Where S_0, ϕ_0, ΔN are photon density, phase and carrier density difference respectively at steady state of injection locked SRL.

Where $z=\kappa_{inj}\sqrt{S_{inj}/S_0}$, and τ_{Nd} is differential carrier life time and it can be given as $\tau_{Nd}=1/A_g+2B_gN_0+3C_gN_0^2$. A_g, B_g and C_g represent Non-radiative coefficient, radiative coefficient and Auger recombination coefficient respectively. X is the input vector and driven separately in accordance with the modulation scheme. For phase modulated injection locking system, the input is phase modulated light signal injected from the phase modulator and the output is the phase modulation of the slave laser and it can be given as:

$$H_{PM}(j\omega)=\frac{\delta\phi}{\delta\phi_{inj}}=\frac{-a\omega^2+b\omega+C}{\det(\mathbf{M})} \qquad (4)$$

Where $a=z\cos\phi_0$, $b=z^2\left(1+a_{33}\cos^2\phi_0\right)$ and det(M) is the determinant of state-transition matrix M.

III. Discussion and Simulation Results

IV. Table I
Injection Locked SRL parameters

Qty.	Val.	Qty.	Val.
N	3.41	N_{qw}	5
α	2.52	Γ	0.62
W_{wg}	2 μm	η_i	0.5
T_{qw}	6 nm	N_{tr}	$1.25\text{x}10^{24}\ \text{m}^{-3}$
T	0.5	A_g	$2.1\text{x}10^{8}\ \text{sec}^{-1}$
B_g	$4.5\text{x}10^{-10}\text{cm}^3/\text{sec}$	C_g	$5.83\text{x}10^{-29}\text{cm}^6/\text{s}$

Simulation is based on the SRL device very similar to which used in [5], however different cavity sizes of SRL are assumed. It is assumed that the device is biased at 200mA. Table 1 presents the basic parameter values used in the simulations of the frequency response of Slave SRL. Fig. 2 illustrates stable locking range for different cavity lengths of SRL.

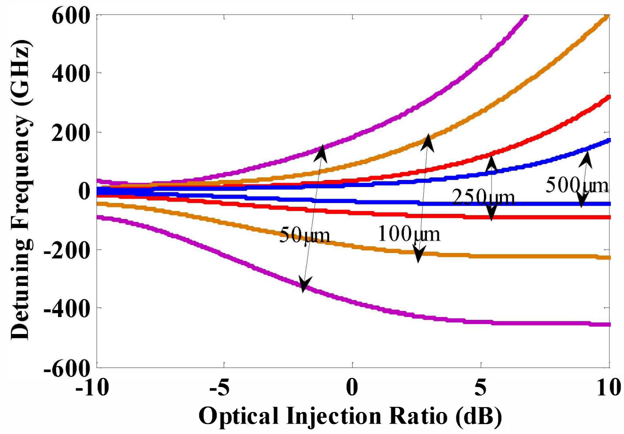

Fig. 2 Stable locking range of SRL with different cavity sizes

In the stable locking range bandwidth is enhanced and the resonance is broadened when the injection ratio is increased while the detuning frequency is kept constant. It is because