Over 100 GHz 3-dB down Bandwidth by Direct Modulation of a Coupled Cavity DFB-LD due to Photon-Photon Resonance

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***Abstract-* This paper reports on 3-dB down bandwidth of 110.6 GHz by direct modulation of a coupled cavity DFB-LD with phase-shifted /uniform gratings due to photon-photon resonance when the injected current is 3.5 times the threshold current.**

I. INTRODUCTION

Direct modulations of laser diodes (LDs) attract attentions again in order to construct low-cost optical fiber communication networks. To date high speed direct modulations of LDs by push-pull modulations [1]-[4], external injection of laser light [5], photon-photon resonance [6]-[10] have been reported. In this paper, a coupled cavity DFB-LD with phase-shifted/uniform gratings is numerically studied. When the injected current is 3.5 times the threshold current, the 3-dB down bandwidth, which is an index of maximum speed for direct modulations of LDs, is 110.6 GHz. This value is higher than the reported highest value 95.9 GHz in Ref. 9.

II. OPERATING PRINCIPLE AND STRUCTURE

Rate equations are given by

$$\frac{\mathrm{d}}{\mathrm{d}t}S_1 = \Gamma_1\left[G_1 - \beta_1 S_1 - \theta_{12} S_2\right]S_1 - \frac{1}{\tau_{\mathrm{ph1}}}S_1,$$

$$\frac{\mathrm{d}}{\mathrm{d}t}S_2 = \Gamma_2\left[G_2 - \beta_2 S_2 - \theta_{21} S_1\right]S_2 - \frac{1}{\tau_{\mathrm{ph2}}}S_2,$$

$$\frac{\mathrm{d}}{\mathrm{d}t}n = \frac{J}{ed} - \left[G_1 - \beta_1 S_1 - \theta_{12} S_2\right]S_1 - \left[G_2 - \beta_2 S_2 - \theta_{21} S_1\right]S_2 - \frac{1}{\tau_n}n,$$

where S_1 is photon density of the main-mode, S_2 is photon density of the sub-mode, Γ_i is an optical confinement factor, G_i is an amplification rate, β_i is a self-saturation coefficient, θ_{ij} is a cross-saturation coefficient, $\tau_{\mathrm{ph}i}$ is photon lifetime where subscripts i and j are 1 or 2, n is carrier concentration, J is injected current density, e is the elementary charge, d is total thickness of active layers, τ_n is carrier lifetime. Stable condition for coexistence of the main-mode and the sub-mode is given by

$$\beta_1\beta_2 - \theta_{12}\theta_{21} > 0,$$

which is known as weak coupling in laser physics. Stable longitudinal mode operations need $S_1/S_2 \geq 10^4$, corresponding to the sub-mode suppression ratio (SMSR), which is equal to or larger than 40 dB. Small-signal analysis for $S_1 \gg S_2$ gives the resonance frequency f_{r}, which is written as

$$f_{\mathrm{r}} \simeq \frac{1}{2\pi}\left[\frac{\partial G_1}{\partial n}\frac{S_{10}}{\tau_{\mathrm{ph1}}} + \Gamma_1 S_{10}\Gamma_2 S_{20}(2\beta_1\beta_2 - \theta_{12}\theta_{21})\right]^{1/2},$$

Here S_{10} and S_{20} are steady state values of S_1 and S_2, respectively. The resonance frequency is enhanced due to the second term $\Gamma_1 S_{10}\Gamma_2 S_{20}(2\beta_1\beta_2 - \theta_{12}\theta_{21})$.

Figure 1 illustrates a schematic structure of a proposed coupled cavity DFB-LD. Region 1 has phase-shifted gratings with the grating coupling coefficient κ_1=40 cm^{-1}, the region length L_1=300 μm, the corrugation pitch Λ_1=238.45 nm, and the phase-shift $\Delta\Omega_1 = -\pi$ at the center of Region 1. Region 2 has uniform gratings with the grating coupling coefficient κ_2=38 cm^{-1}, the region length L_2 =310 μm, the corrugation pitch $\Lambda_2 = \Lambda_1 - \Delta\Lambda$. Both facets are anti-reflection coated and the power reflectivities R_1 and R_2 are assumed to be zero.

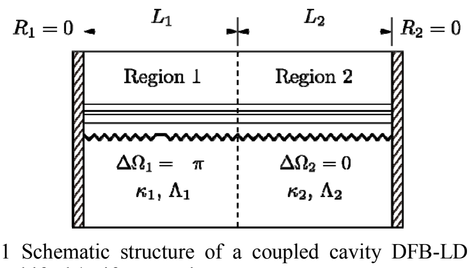

Fig. 1 Schematic structure of a coupled cavity DFB-LD with phase-shifted /uniform gratings.

Undoped active layers consist of five 7.5 nm-thick $In_{0.557}Ga_{0.443}As_{0.982}P_{0.018}$ strained quantum wells, which are sandwiched by 23 nm-thick undoped $In_{0.738}Ga_{0.262}As_{0.568}P_{0.432}$ barriers. The substrate is n-InP with impurity concentration of 10^{18}cm^{-3}. The upper cladding layer is p-InP with impurity concentration of 5×10^{17}cm^{-3}. The waveguide is 1.5 μm wide. Region 1 and Region 2 form a coupled cavity. When the corrugation pitch difference $\Delta\Lambda$ is large enough, a wavelength of the

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main-mode is Bragg wavelength in Region 1, and wavelengths of sub-modes are wavelengths of other resonance modes of the coupled cavity. Region 1 and Region 2 have a common anode and a common cathode. As a result, Region 1 and Region 2 are modulated in phase, in contrast to the push-pull modulations [1]-[4] where two regions are modulated with anti-phase. Therefore, modulation scheme for this work will be simpler than that for the push-pull modulation of DFB-LDs.

Lasing characteristics are simulated by a commercial simulator, PICS3D (Crosslight), in which Poisson's equations and two-dimensional Helmholtz equations are solved self-consistently with a finite element method.

III. SIMULATED RESULTS AND DISCUSSIONS

In Fig. 2 the resonance frequency f_r is shown as a function of the grating pitch difference $\Delta\Lambda$ for the injected current I =20 mA. The resonance frequency f_r is highest at $\Delta\Lambda$=1.7 nm where the resonance frequency f_r is 77.5 GHz, which is 10.8 times of f_r =7.16 GHz when $\Delta\Lambda$ is 0.1 nm.

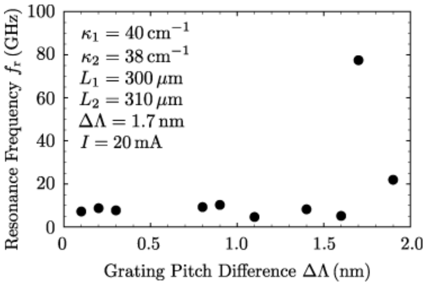

Fig. 2 Resonance frequency f_r as a function of the grating pitch difference $\Delta\Lambda$.

In Fig. 3 the resonance frequency f_r is plotted against the relative bias current $I/I_{th}-1$ where I_{th} is the threshold current and $\Delta\Lambda$ is 1.7 nm. The resonance frequency f_r increases gradually with an increase in $I/I_{th}-1$.

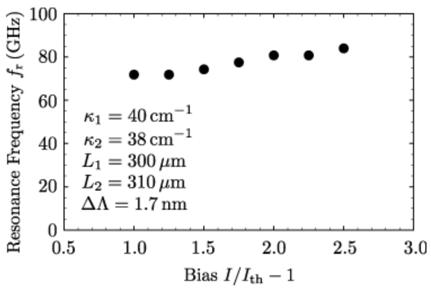

Fig.3 Resonance frequency f_r as a function of $I/I_{th}-1$.

In. Fig. 4 frequency response is revealed when $\Delta\Lambda$=1.7 nm and $I/I_{th}-1$=2.5. The resonance frequency f_r is 83.9 GHz, which is higher than the previous highest value 71.3 GHz in Ref. 9. The 3-dB down bandwidth is 110.6 GHz, which is the record high value which exceeds 95.9 GHz in Ref. 9. .

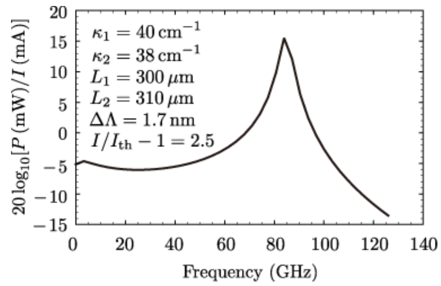

Fig.4 Frequency response.

In Fig. 5 oscillation spectrum is drawn when $\Delta\Lambda$=1.7 nm and $I/I_{th}-1$=2.5. The wavelength of the main-mode is 1.52446 µm which is Bragg wavelength in Region 1. The sub-modes generated by the coupled cavity are not clearly observed, but several slight peaks exist in the side lobes of the main-mode.

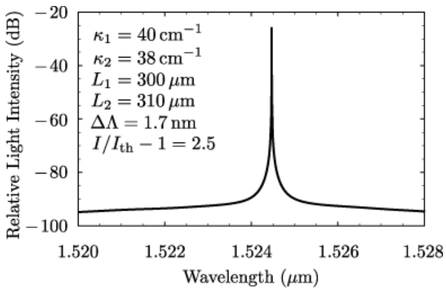

Fig.5 Oscillation spectrum.

IV. CONCLUSIONS

Lasing characteristics of the coupled cavity DFB-LD with phase-shifted /uniform gratings were simulated. When the grating pitch difference $\Delta\Lambda$ between Region 1 and Region 2 was 1.7 nm and $I/I_{th}-1$=2.5, the 3-dB down bandwidth was enhanced to the record high value 110.6 GHz.

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