Phase Correlation Between Longitudinal Modes in Semiconductor Self-Pulsating DBR Lasers

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***Abstract*—Phase correlation leading to self-pulsation (SP) in semiconductor distributed Bragg reflector (DBR) lasers is investigated experimentally and theoretically. Under proper biasing conditions, the laser oscillates with three main modes and we observe that each two-modes beating provides SP with identical spectral linewidth. Under the same operating conditions, the measured spectral linewidths of the beating modes are much larger than the linewidth of the self-pulsating signal. These results demonstrate the natural occurrence of passive mode-locking (PML) and phase correlation in semiconductor DBR lasers. A model based on multimode coupled-wave rate equations, including four-wave mixing (FWM), is developed to describe PML and SP in the gain region of the laser cavity. This model demonstrates that the existence of phase correlation between longitudinal modes is due to FWM.**

***Index Terms*—Distributed Bragg reflector (DBR) lasers, four-wave mixing (FWM), mode-locked lasers, phase synchronization, self-pulsating lasers.**

I. Introduction

ALL-OPTICAL clock recovery, a crucial element for all-optical regeneration at very high bit rates, attracts much attention as it would supercede hybrid optoelectronic schemes [1]. Among the different approaches investigated so far, self-pulsating semiconductor lasers operating in passive mode-locking (PML) are attractive structures. Two types of self-pulsation (SP) semiconductor lasers have been extensively studied for clock recovery at 40 Gb/s: index-coupled or gain-coupled distributed feedback lasers [2], [3], and distributed Bragg reflector (DBR) lasers [4]. The DBR-based approach offers operating advantages such as a broad range of biasing conditions and tunability of the emmitted wavelength.

The origin of SP in multimode semiconductor lasers without saturable absorber is usually attributed to nonlinear mechanisms of interaction between the modes in the gain region [5], [6]. Among these mechanisms, four-wave mixing (FWM) is a phase sensitive phenomenon that was first introduced by Bogatov [7] to semiconductor lasers, and has been extensively investigated further by Agrawal [8]–[10]. In fact, the beating between adjacent modes generates a modulation of the carrier density, leading to SP at the mode-spacing frequency. Recently, Nomura [11] *et al.* have reported the importance of relative phase difference between modes, starting from mode coupling analysis in semiconductor lasers previously developed in [12] and [13]. In this letter, we report experimental results on spectral linewidths of self-pulsating signal and longitudinal beating modes. These results clearly demonstrate the phase correlation between longitudinal modes in DBR semiconductor lasers. Such a correlation is explained theoretically by introducing FWM in multimode standard rate equations.

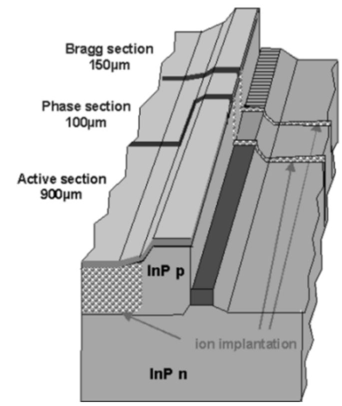

Fig. 1. Scheme of a semiconductor DBR laser.

II. Experimental Results

The studied DBR laser has three sections: active, phase, and Bragg, as shown in Fig. 1. The ridge waveguide, which is 1.3 μm wide over the three sections, is burried with p-doped InP. All sections are electrically isolated from each others by ion implantation of the interelectrode regions. The active section has a length of 900 μm and consists of six quantum wells. The Bragg section length of 150 μm was chosen to select only three modes. The passive sections (phase and Bragg) both contain a quaternary layer with a photoluminescence peak at 1.45 μm so that they are optically transparent at the lasing wavelength around 1.57 μm. Moreover, it is to be noted that there is no saturable absorber effect within these sections. The output light from the dc-biased laser, whose total length is about 1 mm, is coupled into a single-mode fiber and then led to a 50-GHz bandpass photodiode. The resulting photocurrent is observed through an electrical spectrum analyzer (ESA) with a span of 18 MHz and a resolution bandwidth of 300 kHz. Fig. 2(a) shows an example of a radio-frequency (RF) spectrum of the photocurrent for a fixed operating point. We observe on this figure that the photocurrent exhibits a Lorentzian shape at a frequency of 39 GHz. The measured spectral linewidth at half maximum of this RF signal is

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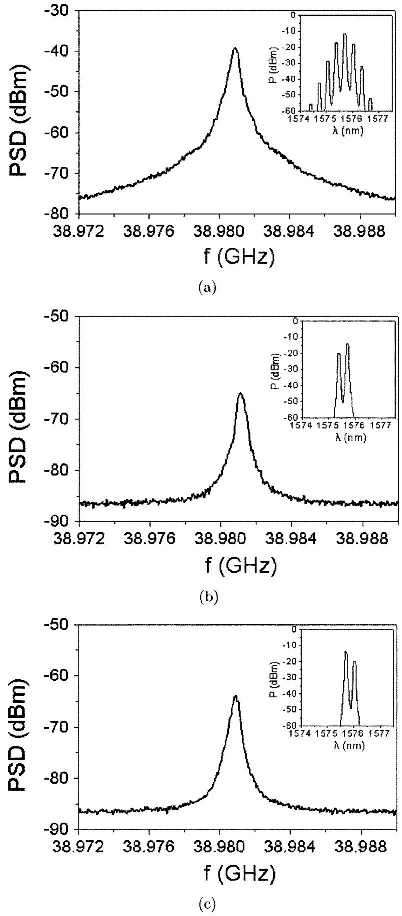

Fig. 2. RF spectrum of (a) the DBR laser at the operating point, (b) the beating component between Modes 1 and 2, and (c) the beating component between Modes 2 and 3. The inserts are the corresponding optical spectra.

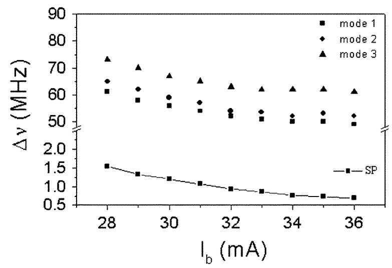

Fig. 3. Evolution of the spectral linewidths of longitudinal modes and SP in function of the Bragg injected current between two mode jumps.

about 700 kHz. The optical spectrum at this operating point is also shown in the insert of Fig. 2(a). It shows that the laser operates in a three-modes regime, because the fourth mode is at least 10 dB lower than the third one. The main mode is called Number 2, and the next modes, respectively, on the left and on the right are called Number 1 and Number 3.

To go further in our experiment, we want to isolate the two beating components at the mode-spacing frequency that constitute the SP signal. The coupled output light is now led to a monochromator, which acts as an optical tunable bandpass filter. Setting the filtering bandpass to 0.5 nm, the monochromator enables the selection of two optical modes and also the study of their beating component after photodetection. Then, the filtered optical signal is directly led to the photodiode followed by the ESA, still with a resolution bandwidth of 300 kHz. Fig. 2(b) displays the RF spectrum of the photocurrent representing the beating component of Modes 1 and 2 that are represented in the insert. We observe that this spectrum also appears as a Lorentzian shape signal, whose maximum power is largely reduced compared with the one of Fig. 2(a). This 25-dB reduction corresponds roughly to the power losses due to the optical filtering. The measured spectral linewidth at half maximum is about 730 kHz, which is close to the spectral linewidth of the entire SP signal. Similarly, the RF spectrum representing the beating component of Modes 2 and 3 is shown by Fig. 2(c) and the insert shows the corresponding filtered optical spectrum. The measured spectral linewidth at half maximum is about 710 kHz. This means that the Lorentzian shapes generated by the beatings between Modes 1 and 2 and between Modes 2 and 3 have the same spectral linewidth. Therefore, this experiment shows that SP is composed of two beating components with equal linewidths. Since phase noise is the origin of spectral linewidth, such a result proves that the relative phases of adjacent modes have the same phase noise characteristics, suggesting that the modes are partly correlated under PML operation.

To confirm phase correlation, the longitudinal modes are individually filtered by setting the bandpass of the monochromator to 0.1 nm in order to measure their spectral linewidths, using a self-homodyne technique based on an interferometer. The spectral linewidths of longitudinal modes are measured with the same resolution bandwidth as that in the measurement of SP signal. Fig. 3 shows the spectral linewidths of longitudinal modes and SP signal with an increasing injected current in the Bragg section of the DBR laser, until a mode jump occurs. We first observe in Fig. 3 that the spectral linewidths of the longitudinal modes decrease with increasing current. Such a decrease was attributed to the decrease of the effective phase-amplitude coupling factor [14]. We observe also that the linewidth of the RF signal is affected by the increase of Bragg current and follows the decrease of the linewidths of the longitudinal modes. Furthermore, we can easily see that the linewidth of SP signal is always largely narrower than that of the longitudinal modes as in FP semiconductor lasers [6]. Such a result demonstrates that the phase of each longitudinal mode fluctuates upon spontaneous emission, leading to the linewidth measured of the order of several tens of megahertz. However, the reduced linewidth of the SP signal, of the order of megahertz, shows that these fluctuations are largely synchronized.

III. Theoretical Analysis of Three-Modes DBR Lasers

To study phase correlation, we start from standard multimode rate equations and we include self-induced carrier density modulation [9]. These equations are similar to those already developed by Sargent [12] and Shore [13] to describe mode-locking and coupling in multimode lasers. However, in our model, we concentrate on the effect of carrier density modulation resulting from the beating of longitudinal modes selected by the DBR mirror to determine the origin of SP. As in our experiment, we consider three longitudinal modes propagating inside the cavity with mode-spacing $\Omega_{\rm sp}$. Then the resulting total photon density of the laser with three modes beating together contains terms

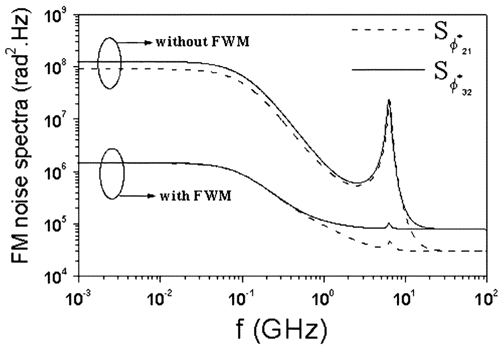

Fig. 4. Numerical calculations of FM noise spectra for the relative phases ϕ_{21} and ϕ_{32}, with or without FWM.

at $\Omega_{\rm sp}$ and a term at $2\Omega_{\rm sp}$, which are dependent on the relative phases ϕ_{ij} defined as $\phi_i - \phi_j$ between modes i and j.

The beating process among longitudinal modes modulates the carrier density at multiples of the mode-spacing frequencies. The latters vary from one couple of modes to the other in the DBR laser because of the dispersion of the effective length in the Bragg grating. The self-induced carrier density pulsation leads to cross-saturation and FWM through the creation of dynamic index and gain gratings, and generates modulation sidebands that act as optical injection signals for modes. Although modulation sidebands are both generated through amplitude modulation and frequency modulation (FM) mode-locking, the dominant effect here is FM mode-locking because of the quite large phase-amplitude coupling factor ($\alpha 2 \leq \alpha \leq 6$). Such a mutual injection-locking phenomenon reaches equilibrium when all mode-spacing frequencies are locked to the same value $\Omega_{\rm sp}$, leading to PML. Indeed, the output power observed in the time domain with an SHG autocorrelator have shown periodic variation in the PML region.

The rate equations derived from our model are linearized around the steady state solutions under continuous-wave operation and written explicitly in the Fourier domain to obtain the Fourier transform of the relative phase fluctuations $\widetilde{\delta\phi_{ij}}$. The FM noise spectra of relative phases are then derived from the Fourier transform of the relative phase fluctuations according to the following expression: $S_{\dot{\phi}_{ij}}(\Omega) = \langle \Omega^2 \cdot |\widetilde{\delta\phi_{ij}}|^2 \rangle$ [15]. Fig. 4 shows an example of calculations of FM noise spectra of the relative phases, with and without the introduction of FWM in our model. The solid curves describe the FM noise spectrum of the relative phase ϕ_{32} and the dashed ones describe the FM noise spectrum of the relative phase ϕ_{21}. We first observe that the introduction of FWM makes the FM noise spectra converge to the same value in the vicinity of zero analysis frequency. Since the linewidth of a Lorentzian shape RF spectrum is directly proportionnal to the limit at zero frequency of its FM noise spectrum, this result suggests that the Lorentzian shapes generated by the beatings between Modes 1 and 2 and between Modes 2 and 3 must have the same spectral linewidth, as observed experimentally in Fig. 2(b) and (c). We may also see in Fig. 4 that the FM noise is reduced by more than 15 dB at low analysis frequency with the introduction of FWM. The reduction ratio is lower than the 20-dB observed experimentally. The difference is attributed to the contribution of current source noise to the spectral linewidths of the modes. Such an observation suggests that the spectral linewidth reduction measured experimentally is related to FWM. Consequently, the theoretical analysis explains that the phase correlation demonstrated experimentally is due to FWM.

IV. Conclusion

In this letter, we have experimentally demonstrated that the phases of longitudinal modes are correlated in semiconductor SP DBR lasers. The main consequence is the enhanced spectral linewidth reduction of the SP signal compared with the linewidths of longitudinal beating modes. We have also introduced FWM in the standard coupled-mode rate equations to study the evolution of spectral linewidths. The predicted order of linewidth reduction ratio, larger than 10 dB, is in good agreement with experimental results and demonstrates theoretically that FWM is responsible for phase correlation between longitudinal modes. The importance of FWM in the SP mechanism is an essential feature to design future DBR lasers with higher performance for applications such as all-optical clock recovery.

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