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Influence of sinusoidal modulation on mode competition and signal distortion in multimode InGaAsP lasers

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ABSTRACT

This paper investigates influence of large-signal modulation on mode oscillation in InGaAsP/InP lasers. The mode competition dynamics under modulation are examined in terms of the temporal trajectories of the total output and the strongest modes as well as their Fourier spectra. The mode coupling induced by the strong spectral gain suppression is evaluated by both the correlation coefficients among the strongest modes and their signal distortion. We show that small and moderate modulations at the multimode hopping of the laser modulate the mode hopping along with modulation of each mode. The mode coupling is characterized by anti-correlation among the modes like as the non-modulated laser. Under modulation with the resonance frequency, the increase in the modulation depth changes mode coupling from anti-correlation to positive correlation and then to complete coupling that correspond to emission of periodic pulses. The mode coupling is characterized by mode competition distortion, which measures the amount of power carried by the mode signal at the frequency of multimode-hopping.

1. Introduction

The InGaAsP/InP semiconductor material system has received much attention in the design of light sources emitting in the wavelength range 1.0–1.65 μm [1]. This wavelength range includes the long wavelength region 1.3–1.6 μm important for optical fiber communication systems where both dispersion and loss of silica fibers are considerably reduced compared with the 0.85-μm region [2,3]. InGaAsP/InP-based light sources include laser diodes [4], superluminescent diodes [5], and recently the multimode interferometry (MMI) superluminescent emitting diodes (SLEDs) [6,7]. In addition, InGaAsP/InP quantum well structures are used for a variety of optoelectronic devices, such as electro-optic modulators for fiber optic communication [8], solar cells [9], and infrared detectors [10].

Cost-effective InGaAsP/InP lasers use Fabry–Perot (FP) resonators whose structure is rather simple. These lasers, however, were proved in both experiment and theory to oscillate mostly in several longitudinal modes, which hop in semi-periodic fashion [11,12]. This mode hopping is manifestation of mode coupling and competition due to strong modal gain suppression. The cross-modal gain suppression has two spectral types, symmetric and asymmetric [13]. The symmetric gain suppression (SGS) has a similar effect on modes on both wavelength-sides of the central mode. The asymmetric gain suppression (AGS) works to increase gain of modes on the longer wavelength side of the central modes while decreasing that of modes on the shorter side. This AGS is generated from pulsation of the injected carriers at the beating frequency of the oscillating modes of the laser cavity [14–17]. When the laser supports only the fundamental transverse mode, the gain suppression effects can be beneficial to control mode competition in such a way to increase the side mode suppression ratio (SMSR), achieving single mode oscillation [13]. A typical example is the AlGaAs/GaAs laser. However, in long-wavelength InGaAsP/InP lasers, the gain spectrum is rather wide and shallow around the lasing mode, and the linewidth enhancement factor is large [11]. These properties contribute to strengthen AGS and make shallow the gain of modes in the long-wavelength neighbor of the central mode. The closed values of gain of these modes result in strong coupling among them and an asymmetric multimode output spectrum [12,14].

In several applications of the semiconductor laser, such as analog fiber links [18], the laser is subjected to direct sinusoidal modulation. The laser is excited (modulated) by a sinusoidal electrical signal in addition to the dc bias component. The modulation bandwidth of the laser is limited by its relaxation frequency due to nonlinear coupling between the injected carriers and emitted photons in the laser cavity [19]. Depending on the modulation conditions, this nonlinear coupling may induce uniform/non-uniform continuous signals or pulses associated with sub- or higher-order harmonic distortions (HDs) [19], which are

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pronounced under modulation frequencies around the relaxation frequency [18]. Mode dynamics of semiconductor lasers under sinusoidal modulation and HD were the subject of several previous studies; however, the concerned laser was oscillating nearly in single-mode. Nakamura et al. [20] showed that the lasing spectrum of a nearly-single mode laser remains single-mode unless the modulation depth exceeds a certain critical level. Lau et al. [21] and Lau [22] supported this finding indicating that this critical modulation depth exceeds ~75–90%. He showed also that under high-frequency modulation, both the number of lasing modes and the linewidth of the individual modes increase with the increase of the modulation depth [22]. Yee and Walford [23] analyzed the direct modulation of individual longitudinal modes in nearly single-mode lasers, showing that the intensity modulation of a mode is different from that of the others, and gain suppression enlarges the ratio of the modulation responses of a side mode and the main mode [23]. Morton et al. [24] studied the harmonic and intermodulation distortion in InGaAsP lasers basing on a multimode rate equation model taking into account the spatial and spectral hole burning. They supported the theoretical results with experimental investigations. However, the study concerned with the total laser output while information on modulation response of the oscillating modes was not given [24]. Basing on a multimode rate equation model that takes into account SGS and AGS, Ahmed and Yamada [25,26] has recently investigated influence of sinusoidal modulation on mode competition and the associated HD and noise in the shorter-wavelength AlGaAs lasers. They showed that even when the non-modulated laser oscillates in two modes, it oscillates in single mode as long as the modulation depth is less than ~0.5 and the modulated waveform is continuous and uniform signals [25,26]. They indicated that small and moderate modulations work in such a way to increase the gain of one mode while suppressing the gain the other modes. HD and noise were found to be enhanced when the laser is modulated around the relaxation frequency and under low-frequency modulation with large values of the modulation depth [25]. Both HD and noise are higher when the laser oscillates in single mode than when it oscillates in two modes [26].

In this paper, we introduce a detailed study on the large-sinusoidal modulation of the multimode InGaAsP/InP lasers. The study is based on the multimode rate equation model given in [25]. We present new analyses of the modulation of the individual oscillating modes as well as their competition in both the time and frequency domains. The time domain characteristics include the temporal trajectories of both the modulated signals of the individual modes and the total laser output, correlation coefficients among the strongest oscillating modes, and SMSR. The frequency properties of these signals are determined by means of the fast Fourier transform (FFT) of the modulated signals and the signal harmonic distortion induced by mode competition. We focus on modulation with two characteristic frequencies of this laser; namely, the resonance frequency and the mode competition (hopping) frequency. The mode coupling is measured by both the coefficients of correlation among the oscillating modes and the associated signal distortion. We show that small and moderate modulations at the mode-competition frequency modulate both the modes and the mode hopping itself. The mode coupling is characterized by anti-correlation among the modes, which is softened with the increase of the modulation depth. The strong modulation is characterized by non-uniform periodic pulses with enhanced harmonic distortion. When the laser is modulated at the resonance frequency, the increase in the modulation depth changes mode coupling from anti-correlation to positive correlation and then to complete coupling where the laser emits periodic pulses. We characterize the mode competition under small-signal modulation by a new type of distortion called "mode competition distortion" (MCD) which decreases with the increase in the modulation depth.

In the following section, we introduce the simulation model of mode competition under modulation and the associated signal distortion. Section 3 gives the calculation procedures of modulation dynamics of the laser. Section 4 presents the simulation results of mode competition dynamics and distortion. Conclusions of the present work appear in Section 5.

2. Theoretical model of analysis

Under direct sinusoidal modulation, the modulation signal is applied directly to the semiconductor laser. The injection current to the laser is then composed of the bias current I_b and a modulation term as

$$I(t) = I_b + I_m \cos(2\pi f_m t) \tag{1}$$

where the modulation signal is characterized by the amplitude I_m and frequency f_m. Both I_m and I_m define the modulation depth as $m = I_m/I_b$. The mode dynamics of the semiconductor laser under sinusoidal modulation are then described by including this sinusoidal current into the multimode rate equation model of the laser. These multimode rate equations describe the time evolutions of the injected carrier number $N(t)$ and modal photon number $S_p(t)$, where $p = 0, \pm 1, \pm 2$ is the mode index [25]

$$\frac{dN}{dt} = \frac{1}{e} I(t) - \sum_p A_P S_p - \frac{N}{\tau_s} \tag{2}$$

$$\frac{dS_p}{dt} = (G - G_p) S_p + \frac{a\xi N}{V} \bigg/ \left\{ 1 + \left(2\frac{\lambda_p - \lambda_{peak}}{\delta\lambda} \right)^2 \right\} \tag{3}$$

where G_p is the gain of mode p whose wavelength is λ_p. The spectral distribution of G_p is defined as

$$G_p = A_p - S_p - \sum_{q \neq p} \left[D_{p(q)} + H_{p(q)} \right] S_q \tag{4}$$

where A_p and B are the coefficients of linear gain and gain suppression gain of mode p. The other coefficients $D_{p(q)}$ and $H_{p(q)}$ are coefficients of SGS and AGS by other oscillating modes $q \neq p$, respectively. These coefficients are given by [11]

$$A_p = \frac{a\xi}{V} \left[N - N_g - bV(\lambda_p - \lambda_{peak})^2 \right] \tag{5}$$

$$B = \frac{9}{2} \frac{\pi c}{\varepsilon_0 n_D^2 \hbar \lambda_0} \left(\frac{\xi \tau_{in}}{V} \right)^2 a |R_{cv}|^2 (N - N_s) \tag{6}$$

$$D_{p(q)} = \frac{4}{3} \frac{B}{(2\pi c \tau_{in}/\lambda_p^2)(\lambda_p - \lambda_q)^2 + 1} \tag{7}$$

$$H_{p(q)} = \frac{3}{8\pi} \left(\frac{a\xi}{V} \right)^2 (N - \overline{N}) \frac{\alpha \lambda_p^2}{\lambda_q - \lambda_p} \tag{8}$$

The last term in Eq. (3) represents inclusion of the spontaneous emission into the lasing mode. The central mode $p = 0$ with wavelength λ_0 is assumed to lie at the peak of the gain spectrum. The wavelength of the other modes is $\lambda_p = \lambda_0 + p\Delta\lambda$ where $\Delta\lambda$ is the mode wavelength separation. The mode index p is positive for modes with $\lambda_p > \lambda_0$, and is negative for modes with $\lambda_p < \lambda_0$. Definitions and the laser parameters in the above equations are given in Table 1. Long-wavelength lasers are characterized by large values of the AGS coefficient $H_{p(q)}$ because of the large values of the linewidth enhancement α-factor [14]. The strong asymmetric gain suppression manifests as mode p works to suppress gain of modes $q \neq p$ with shorter wavelength but enhance gain of the modes with longer wavelengths.