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# Phase-locked laser diode array with two emitters facing an external cavity

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ABSTRACT

The rate equations have been used to study the laser diode array (LDA) positioned in an external cavity. The steady state of phase-locked LDA with two emitters has been analyzed. Analytical solutions to the steady state and the range of the frequency detuning have been deduced. The relations of the photon density, carrier density and frequency detuning have been studied. Finally, the affection of the reflectivity of the external mirror on the photon density has been investigated.

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## 1. Introduction

The commercially available high-power LDAs have been widely used in many fields. Following the increase of inter-emitter distances and stripe widths of individual emitters, the output power of the LDAs has been increased enormously. Unfortunately, this increase is achieved, to certain extent, at the expense of the beam qualities. External cavities have been accepted as an effective method to improve the performance of the LDAs [1–6]. At present, two most widely used theories have been proposed to study the external cavity locked LDAs. They are: Talbot cavity theory and coupling mode theory. The former is developed from the Talbot phenomenon based on the assumption that the LDA can be regarded as a periodically repeated coherent light source and the latter is based on the couplings between coherent fields of different emitters. These theories, which can be called as the post-locking theory in the sense that they are applicable to the coherently locked system, have been successfully used to describe the phase-locked LDA.

In recent years, the researches on the semiconductor lasers by using nonlinear rate equations have been advanced considerably [7–18]. These researches include self-injection of a single diode laser positioned inside an external cavity, master-slave injection and mutual-injection between two solitary diode lasers. Two physical processes can be extracted from an external cavity locked LDA. One is the self-injection, and the other is the mutual-injection between individual emitters, both injections are executed by the external cavity mirror. By using nonlinear rate equations, many nonlinear dynamical phenomena such as periodical oscillation, period-doubling bifurcation, chaos, and steady state all can be depicted clearly.

In this work, analytical solutions to the steady state of the LDA with 2 emitters have been deduced by using nonlinear rate equations. The main characteristics of the steady state have been studied from different point of view to the previous research work. The paper is organized as follows. In Section 2, the rate equations depicting the external optical feedback of an LDA with M emitters are given. In Section 3, analytical solutions to the steady state and the range of the frequency detuning have been deduced. Characteristics of the system running in the steady state have been analyzed and discussed. Finally, the conclusion is given in Section 4.

## 2. Rate equations

In order to facilitate the following discussions, here, we give a brief description to the external cavity phase locked LDA system, similar to that given by [4]. The system comprises an LDA containing M emitters positioned inside an external cavity. The reflectivities of the front facet (facing the external cavity) of the LDA and the external mirror are $R_1$ and $R_{ex}$, respectively. The length of the active region of each emitter is $l$. The distance from the external mirror to the front facet of the LDA is equal to $L/2$, The center-to-center distance of two adjacent emitters is $d$. It can be realized that part of the optical field emitted from one emitter can be turned back into itself after traveling inside the external cavity and being reflected by the external mirror. This process is usually categorized as the self-injection process. Meanwhile, part of the optical field emitted from one emitter, say, the $m$th emitter, departs from the $z$-direction when traveling inside the external cavity due to the diffraction and is finally injected into the $(m \pm 1)$th, $(m \pm 2)$th emitters, ... after being reflected by the external mirror. Of course, certain amount of light emitted from the $(m \pm 1)$th, $(m \pm 2)$th emitters, ... may be

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injected into the $m$th emitter as well. This process is usually referred to as the mutual-injection. In other words, all the M emitters of the LDA phase-locked by the external cavity are affected by the self-injection and mutual-injection described above. The coupling coefficient $C_{nm}$ describing the injected optical field emitted from the $n$th emitter to the $m$th emitter is a complex quantity and can be expressed as [15]:

$$C_{nm} = Q_{nm}\ \exp(-iq_{nm}) \tag{1}$$

$$Q_{nm} = \eta_{nm}(1-R_1)\sqrt{\frac{R_{ex}}{R_1}} \tag{2}$$

$$q_{nm} = k_n L + k_x\,|m-n|\,d \tag{3}$$

When $n = m$, $C_{mm}$ denotes self-injection coupling coefficient. Considering the symmetry of the system, it can be concluded that $Q_{m,m+1} = Q_{m,m-1}$ (or $Q_{m+1,m} = Q_{m-1,m}$), $Q_{m,m+2} = Q_{m,m-2}$ (or $Q_{m+2,m} = Q_{m-2,m}$), etc. The parameter $\eta_{nm}$ accounts for the coupling efficiency between the $n$th and $m$th emitters. $q_{nm}$ indicates the phase-shift of the optical field emitted from the $n$th emitter and reflected back into the $m$th emitter. For the light wave with the wavelength of $\lambda_n$ emitted from the $n$th emitter and being reflected back into itself by the external mirror, its spatial frequencies are $k_z = k_n$ ($k_n = 2\pi/\lambda_n$), $k_x = 0$ (the spatial frequency in the $y$ direction is not considered in this paper). But for the light wave reflected back into the $m$th emitter, its two spatial frequencies are $k_z = k_n$, $k_x = k_n|m-n|d/L$. So $q_{nm}$ can be written as:

$$q_{nm} = k_n L + \frac{k_n(m-n)^2 d^2}{L} \tag{4}$$

In this work, it is assumed that the parameters of all emitters of the LDA are the same. The rate equations describing the mechanisms of the self-injection and mutual injection of the emitters can be expressed as [8]:

$$\begin{aligned}\frac{dP_m(t)}{dt} &= P_m(t)g[N_m(t)-N_t] \\ &+ \frac{2Q_{mm}}{\tau}\sqrt{P_m(t)P_m(t-\tau_{ex})}\ \cos[(\alpha_m(t)] \\ &+ \sum_n \frac{2Q_{nm}}{\tau}\sqrt{P_m(t)P_n(t-\tau_{nm})}\ \cos[\theta_{nm}(t)]\end{aligned} \tag{5}$$

$$\begin{aligned}\frac{d\phi_m(t)}{dt} &= \frac{1}{2}\beta g[N_m(t)-N_t) - \frac{Q_{mm}}{\tau}\sqrt{\frac{P_m(t-\tau_{ex})}{P_m(t)}}\ \sin[\alpha_m(t)] \\ &- \sum_n \frac{Q_{nm}}{\tau}\sqrt{\frac{P_n(t-\tau_{nm})}{P_m(t)}}\ \sin\left[\theta_{nm}(t)\right]\end{aligned} \tag{6}$$

$$\frac{dN_m(t)}{dt} = \frac{N_p}{T_e} - \frac{N_m(t)}{T_e} - \left\{T_{ph}^{-1} + g[N_m(t)-N_t]\right\}P_m(t) \tag{7}$$

where,

$$\alpha_m(t) = \phi_m(t) - \phi_m(t-\tau_{ex}) - q_{mm} \tag{8}$$

$$\theta_{nm}(t) = \phi_m(t) - \phi_n(t-\tau_{nm}) - (\omega_n-\omega_m)t - q_{nm} \tag{9}$$

The subscripts $m$ (=1, 2, ...) and $n$ (=1, 2, ... here, $n \neq m$) correspond to the $m$th emitter and $n$th emitter. $P_m$ is the photon density. $\phi_m$ denotes the phase of the optical field. $N_m$ is the carrier density. $N_t$ is the threshold carrier density. $\omega_m$ is the free-oscillating angular frequency of the $m$th emitter. In this paper, $\omega_m$ of each emitter can be regarded as the same. $\beta$ is the linewidth enhancement factor. $g$ is the differential gain coefficient. $\tau$ is the round-trip time in the internal cavity, and can be expressed as $\tau = 2\mu l/c$. $c$ is the light velocity in the vacuum. $\mu$ is the refractive index of the medium in the active layer. $\tau_{ex}$ is the delay time induced by the optical feedback in the self-injection, and can be written as $\tau_{ex} = L/c$. $\tau_{nm}$ is the delay time for the light propagating from the nth emitter to the $m$th emitter, and can be expressed as $\tau_{nm} = [(m-n)^2 d^2 + L^2]^{1/2}/c$. $N_p$ is the carrier density injected by the pump current. $T_e$ is the carrier lifetime. $T_{ph}$ is the photon lifetime. In this work, we take the LDA containing 2 emitters as an example to carry out the analytical solution and calculation. The similar analysis and calculation are appropriate for an LDA including 3 or even more emitters only that the research work will be more complex. Of the 2 emitters, named emitter 1, emitter 2, respectively. The experimental setup of 2 emitters has been shown in Fig. 1. The parameters used in the calculation are listed in Table 1.

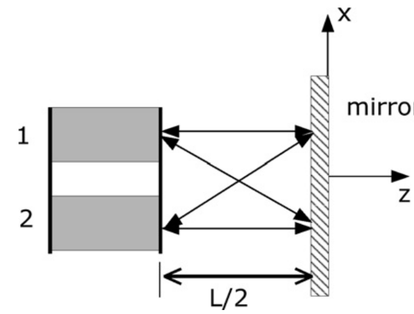


**Fig. 1.** Illustration of the self-injection and mutual-injection between emitter 1 and emitter 2.

**Table 1**
Parameters used in calculations.

| Parameters | Value |
|---|---|
| $d$ | 500 μm |
| $l$ | 350 μm |
| $\lambda_m$ ($m$ = 1, 2) | 803 nm |
| $T_e$ | 2.2 ns |
| $T_{ph}$ | 1 ps |
| $\beta$ | 4 |
| $g$ | $1.1 \times 10^{-12}$ m$^3$ s$^{-1}$ |
| $N_t$ | $1.8 \times 10^{24}$ m$^{-3}$ |
| $N_p$ | $2.7 \times 10^{24}$ m$^{-3}$ |
| $\mu$ | 3.6 |

## 3. Solutions to the steady state and discussion

Given that the 2 emitters are in symmetry, i.e., they have the same oscillating frequencies and threshold carrier densities in the free running state, and other intrinsic parameters are all same. For emitter 1, when the LDA is running in the steady state, one has

$$P_1(t) = P_1(t-\tau_{ex}) = P_1(t-\tau_{21}) = P_{1s} \tag{10}$$

$$\phi_1(t) = (\omega_0-\omega_1)t + \varphi_1 \tag{11}$$

$$N_1(t) = N_{1s} \tag{12}$$

Here, $P_{1s}$, $\phi_1$, and $N_{1s}$ denote the photon density, optical phase and carrier density of emitter 1 in the steady state, respectively. Inserting (10)–(12) into (5)–(7), one has

$$0 = \frac{1}{2}g[N_{1s}-N_t] + \frac{Q_{11}}{\tau}\cos(\delta_1) + \frac{Q_{21}}{\tau}\gamma_{21}\ \cos(\theta_{21}) \tag{13}$$

$$\Omega_1 = \frac{1}{2}g\beta[N_{1s}-N_t] - \frac{Q_{11}}{\tau}\sin(\delta_1) - \frac{Q_{21}}{\tau}\gamma_{21}\ \sin(\theta_{21}) \tag{14}$$

$$0 = \frac{N_p}{T_e} - \frac{N_{1s}}{T_e} - \left\{T_{ph}^{-1} + g[N_{1s}-N_t]\right\}P_{1s} \tag{15}$$

where,

$$\Omega_1 = \omega_0 - \omega_1, \qquad \gamma_{21} = \sqrt{\frac{P_{2s}}{P_{1s}}} \tag{16}$$

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