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Nonlinear dynamics and synchronization of an array of single mode laser diodes in external cavity subject to current modulation

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ABSTRACT

We study the dynamics of an array of single mode laser diodes subject to filtered feedback provided by an external reflection grating. Our numerical simulations show that by modulating the injection current the array can be phase synchronized leading to high power coherent emission. The output peak power density can be varied by tuning the modulation frequency and can be resonantly enhanced once the frequency matches the inverse of external cavity round trip time and mode-locking behavior is realized. Both non-resonant and resonant injection current modulation results in an excellent degree of phase synchronization and coherence at certain modulation amplitudes and frequencies that is manifested by coherent enhancement of far-field optical intensity.

1. Introduction

Laser diodes (LDs) are compact optical devices that impact large variety of applications including optical communications and optical storage. The dynamics of LDs and diode arrays have been extensively studied during the past three decades. However, and despite the impressive advance in laser diode production, the output power from single mode LD remains quite limited. Coherent beam combining provides a viable path to increase coherent emission power from many small lasers [1–12].

As a consequence of coherent beam combination, in-phase locking of LDs can be realized resulting in a constructive interference along the optical axis. The power density along the optical axis at far-field increases significantly and for perfect in-phase locking the power density along optical axis it scales with the number of LDs, N, as N^2. The N^2 scaling is a consequence of the far-field angle decrease by a factor of N. In order to achieve stable phase-locking, it is essential to optically couple individual LDs in the array. A practical way to realize optical coupling is by means of an external Talbot cavity with diffraction feedback coupling provided by a flat partially reflecting mirror (optical coupler) [1–5,7,8] or by a diffraction grating [6,9,10].

Achieving phase synchronization of LDs poses a very intriguing challenge. Synchronization of semiconductor laser diode array (LDA) comprised of single mode laser diodes has been investigated theoretically predominantly employing the nearest-neighbor and global coupling between the lasers [11,13–16]. Master-slave architectures, clustered architectures, and other unique configurations have also been investigated [11,17–20]. The dynamics of each array element is commonly described by the Lang and Kobayashi equations [21] in which the time delay plays a very important role [11]. In the case of global coupling the process of synchronization shows analogy to the process found in the Kuramoto model [22].

Weak periodic modulation has proven to be a very useful method to control the dynamics of a variety of systems [23–26], including single mode CO_2 lasers [27,28], multimode solid state lasers [29] and semiconductor lasers with external feedback operated close to threshold [30]. In fact, semiconductor lasers can be directly modulated to very high frequencies [31], a property on which communication systems with intensity modulation and direct detection rely on. However, in contrast to chaos control, communications applications typically use a stable LD with relatively high modulation amplitude to ensure detection reliability and fast modulation rate [32]. Besides, since the information to be transmitted has pseudo-random statistics, the modulation is not periodic and for fast modulation rates the dynamics of the system may depend on previous bits [33].

In this paper, we describe the dynamical behavior of a LDA with filtered time-delayed global coupling subject to a modulated injection current. We considered both non-resonant and resonant

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modulation. When the modulation frequency is much lower than the inverse of the external cavity round-trip time and operating current of a globally coupled laser diode is several times higher than the threshold current, high level of phase synchronization was realized. When the modulated frequency is close to the inverse of the external cavity round-trip time (resonant modulation) and injection current is close to the lasing threshold, collective "spikes" with the period around 20 ps emerge. This short pulse behavior is identified as "mode-locking" and the mode-locking was significantly amplified by the LDA. High peak power density emission is achievable provided coherence of LDs is well-maintained.

Our paper is structured in the following way. We will describe the theoretical model in details in Section 2. In Section 3, we will present results of our numerical simulations. Our conclusions are presented in Section 4.

2. Modeling

Fig. 1 shows the schematic design of a LDA with an external Talbot cavity, which provides diffraction feedback coupling. By properly choosing the parameters of the LDA (such as emitter size, array pitch and the number of LDs), global diffraction feedback coupling can be achieved.

In our simulations, the dynamics of an array of single mode LDs is described by the set of rate equations in the Lang–Kobayashi approximation [21]. The external grating feedback is modeled as a filtered feedback as described in Refs. [34,35]. The dynamics of laser diode array with grating feedback is described by the following set of equations ($j=1\ldots N$):

$$\frac{dE_j(t)}{dt}=\frac{1+i\alpha}{2}[G_j(N_j,E_j)-\gamma]E_j(t)-\omega_jE_j(t)+\sum_k C_{jk}F_k(t), \tag{1}$$

$$\frac{dN_j(t)}{dt}=I_j(t)-\gamma_nN_j(t)-G_j(N_j,E_j)|E_j(t)|^2, \tag{2}$$

$$\frac{dF_j(t)}{dt}=\Lambda E_j(t-\tau)+(i\Omega-\Lambda)F_j(N_j,E_j), \tag{3}$$

$$G_j(N_j,E_j)=g(N_j(t)-N_0)/(1+s|E_j(t)|^2), \tag{4}$$

where $E_j(t)$ is the slowly varying complex amplitude of the electric field of LD j, α is the line-width enhancement factor of the

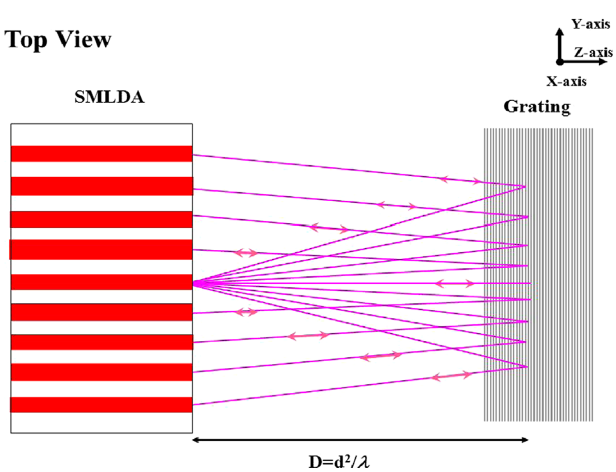

Fig. 1. Schematic design of external Talbot cavity for an array of single mode laser diodes. SMLDA: an array of single mode laser diodes. Reflection grating posted at the Talbot distance to provide the diffraction feedback coupling among the laser diodes. Littrow configuration mounted grating reflects the first-order diffraction and couples the zero-order diffraction out. The diffraction coupling among LDs is simply indicated by using optical rays.

Table 1
Some parameter values for laser diode used in numerical simulation.

Symbol	Parameter	Value
g	The differential gain coefficient	1.5×10^{-5} ns^{-1}
s	Gain saturation coefficient	2.0×10^{-7}
N_0	The number of carriers at transparency	1.5×10^{8}
λ	Laser wavelength	770 nm
α	Line width enhance factor	5.0
γ	The photon decay rate	500.0 ns^{-1}
γ_n	The carrier decay rate	0.5 ns^{-1}
τ_{in}	Internal cavity round trip time	11.67 ps
T	External cavity round trip time	3.0 ns
Ω	Center frequency of grating	20.0 GHz
Λ	Bandwidth of grating	16.0 GHz
R_3	Power reflection from grating	0.83%
κ_f	Feedback strength	10 ns^{-1}

semiconductor laser, γ is the LD photon decay rate, ω_j is the detuning of LD j with respect to a common reference frequency, and C_{jk} is the coupling between LD j and k, F_k is the kth LD feedback electric field filtered by grating with time-delay τ, N_j is the carrier number of LD j, J_j is the jth LD injection current, γ_n is the carrier decay rate, G_j is the jth LD gain coefficient, Ω is the central frequency of the grating and Λ is the band-with of grating, g is gain coefficient, N_0 is the carrier number at transparency, and s is the gain saturation coefficient. We integrate the delay equations with a fourth-order Adams–Bashforth–Moulton predictor–corrector method with integration time step of 0.2 ps.

We consider a 1D array in which the coupling contribution between LD j and k is given by $C_{jk}=\kappa_f e^{-i\Phi}K_{jk}(d_x^{|j-k|})$, where κ_f is feedback strength, Φ is the phase retardation generated by the feedback, and d_x accounts for the ratio of decay of the coupling strength as the separation between the laser diodes increases ($d_x\le1$). The physical nature of coupling between the lasers is due to radiation exchange between some diodes in the array. Without laser coupling, laser diode phase are independent therefore only partial coherence may be observed [36]. The function K_{jk} represents a normalization function on the coupling matrix, ensuring that $\Sigma_{j=1}^{M}C_{jk}=\kappa^f e^{-i\Phi}$. We use the function $K_{jk}=d^{|j-k|}/\Sigma_{j=1}^{N}d^{|j-k|}$. This ensures that there is no energy gain or loss from the coupling system other than that from the scaling κ^f. When $d_x=1.0$, the perfect global coupling is realized. For $d_x<1.0$, C_{jk} decays approximately exponentially with the distance between the lasers j and k. Based on the laser diode array geometry configuration (emitter size and pitch of laser diode array), we can estimate the value of d_x. Except otherwise noticed, in this paper, we let $\Phi=0$, implying that there is no phase lag.

In general, the value of time-delay τ depends on the distance between each LD and the grating. Since the distance between LDs on the chip is much smaller than the distance between the array and the grating, for simplicity, we assume that the time-delay τ the same value for all the lasers. For the same reason, we assume that the feedback phase factor is the same for all lasers and only depends on the distance between the array and the grating.

The individual LDs of the LDA should be considered to be slightly different due to irregularities in the fabrication process. The most important difference to be considered is the lasing frequency. This is accounted setting a different frequency detuning for each LD on the array. The characteristic values of the laser array parameters are presented in Table 1.

3. Results and discussion

In this section we describe our numerical results for synchronization of the LDA subject to modulation of the injection current.