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Study of dynamic chirp in direct modulated DFB laser for C-OFDR application

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ABSTRACT

A description of the chirp induced by direct modulated DFB laser is presented. Two approaches are considered: the first one is based on a resolution of laser rate equations; the second, on a simulation with a commercial software. We compare results of the two approaches, we demonstrate that the optical frequency can be controlled via the injected current. We also characterize the linear variation of the optical frequency in time (for triangular and sawtooth modulation), in order to choose the appropriate values of laser and modulation parameters for a perfect linearity of the chirp in time. This study will be very helpful to validate the use of direct linear modulated DFB laser as a tunable source in Coherent Optical Frequency Domain Reflectometry technique C-OFDR. We present a simulation result of Mach–Zehnder delay time measurement based on C-OFDR system using a direct modulated semiconductor laser source. The obtained results are very important because it depicts the beat frequencies relating to each delay time, with respect to the modulation format used. This is very encouraging for the implementation of an experimental C-OFDR.

1. Introduction

Coherent Optical Frequency Domain Reflectometry technique (C-OFDR) [1–3] is the most suitable technique for the optical network components characterization [4–8]. Ideal reflectometry should have enough (high) spatial resolution to locate closely-separated reflection sites within the network under test, at interfaces in connectors, for example [9,10]. In addition, the sensitivity and range should be (high) enough to measure Rayleigh backscattering throughout an optical fiber network [5,6]. Although this technique is well known for several years, it has not seen broad commercial implementation so far. The main reason is that the constraints on the source are heavy, and a simple, non-expensive yet reliable source giving the desired performance (spatial resolution, sensitivity and range) was lacking. Indeed high spatial resolution in the measurement depends on the sources having a large, phase-continuous, linear tuning range [3,11]. According to previous work [3,11–14] there are several method to tune laser source frequency.

Although some initial experimental work has been reported [2,3], there remains a need for more complete theoretical foundation of the direct modulated semiconductor DFB laser use in C-OFDR. In [2,3], linear (span) sweep (chirp) of the DFB laser optical frequency can be obtained via triangular and sawtooth modulation of the source injected current.

In our previous work [15,16], we have studied the DFB laser chirp for different type of laser direct modulation and demonstrated that the linear sweep of laser optical frequency can be obtained by triangular and sawtooth modulations.

In this paper, using a commercial Optiwave software (Optisystem 5) and rate equations [17,18], which describe the interaction between photons and carrier populations inside the active region of the laser diode, we evaluate the dynamic variation of the optical frequency, in the case of direct triangular and sawtooth modulation. We also discuss the laser parameters impact on the linearity of the frequency in time. By using commercial software Optisystem, we simulate C-OFDR fiber optic implementation, to measure the delay time of a Mach–Zehnder,with a periodic linear tuned DFB laser source. This tuning is performed using a direct sawtooth or triangular modulation of the laser source. Simulated results will be useful for the implementation of an experimental C-OFDR setup using DFB laser source.

2. Theory

Rate equations [17,18] describe the variation of the injected carrier and photon population number N and P, respectively, inside the active region of semiconductor laser. For a single-mode semiconductor laser, these equations can be written as following:

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$$\frac{dP}{dt} = \Gamma A(N - N_{tr})(1 - \hat{\epsilon}P)P - \frac{P}{\tau_p} + \beta\Gamma\frac{N}{\tau_n}, \quad (1a)$$

$$\frac{dN}{dt} = \frac{I}{q} - \frac{N}{\tau_n} - \Gamma A(N - N_{tr})(1 - \hat{\epsilon}P), \quad (1b)$$

where I is the total injected current, q is the electric charge, N_{tr} is the carrier population at transparency, τ_p is the photon lifetime, τ_n the carrier recombination lifetime and Γ is the confinement factor. β is the spontaneous emission fraction, $\hat{\epsilon} = \epsilon/V$ is the normalized gain compression factor, V is the active region volume. A is the gain coefficient.

Let us consider $I = I_0 + i(t), P = P_0 + p(t), N = N_0 + n(t)$, where I_0 is the dc component and P_0, N_0 are the steady state solutions obtained by setting the left side of Eqs. (1a) and (1b) equal to zero, $p(t)$ and $n(t)$ are the deviations from the steady state as response to $i(t)$. Development in Taylor series to the second order of these equations take the following form:

$$\dot{p} = \alpha_1^1 p + \alpha_2^1 n + \alpha_{11}^1 pn + \alpha_{20}^1 p^2, \quad (2a)$$

$$\dot{n} = \alpha_2^1 p + \alpha_2^2 n + \alpha_{11}^2 pn + \alpha_{20}^2 p^2 + \xi e(t), \quad (2b)$$

where α_j^i are coefficients depending on the physical parameters of semiconductor laser, developed in [20]. We solve this nonlinear equations system by using the Volterra series theory [19–21], for the case of strained Multi Quantum Well DFB laser, str-MQW (1550 nm). We give its physical parameters in Table 1.

Let us consider, first, the case of triangular modulation of the injected current $i(t)$, which is given by:

$$i(t) = \frac{8I_m}{\pi^2}\sum_{l=0}^{k}\frac{1}{(2l+1)^2}\cos((2l+1)\omega_m t) \quad \text{with } k > 3. \quad (3)$$

Second, the sawtooth modulation of the injected current $i(t)$, given as following:

$$i(t) = \frac{I_m}{\pi}\sum_{l=0}^{k}(-1)^{l+1}\frac{\sin(l\omega_m t)}{l}, \quad (4)$$

where I_m is the modulation amplitude of the current, which is defined by $I_m = m(I_0 - I_{th}), m$ is the modulation coefficient and I_{th} is the threshold current of the laser diode, $\omega_m = 2\pi f_m$ is the modulation frequency.

When the laser current is modulated, the carrier population N is also modulated, and its peak-to-peak value increases when the modulation frequency f_m becomes close to the resonance frequency [20]. Moreover, as a consequence of this modulation, a deviation ν_{stat} of the laser principal mode frequency ν_0 is induced.

We demonstrate, by solving rate equations (2a) and (2b) in the two cases of modulation type, that the variation of the optical frequency $\delta\nu(t)$ of the laser source has the same shape and the same frequency of the electrical input variation $i(t)$. The optical frequency $\nu(t)$ in time can be deduced from the following expression:

$$\nu(t) = \nu_0 + \frac{1}{2\pi}\frac{d\Phi}{dt}. \quad (5)$$

$\Phi(t)$ is the electric field phase. By replacing the laser electric field phase variation $\frac{d\Phi}{dt}$ by its expression:

$$\frac{d\Phi}{dt} = \frac{\alpha}{2}\left[\Gamma A(N - N_{tr}) - \frac{1}{\tau_p}\right]. \quad (6)$$

A, Γ, N_{tr} and τ_p are laser parameters shown in Table 1. α is the amplitude-phase coupling parameter, commonly called the linewidth enhancement factor [18], optical frequency of the laser becomes:

$$\nu(t) = \nu_0 + \nu_{stat} + \delta\nu(t), \quad (7)$$

where ν_{stat} design the static frequency deviation of the laser principal mode frequency ν_0, depending on the bias level I_0/I_{th}:

$$\nu_{stat} = \frac{1}{4\pi}\alpha\left(\Gamma A(N_0 - N_{tr}) - \frac{1}{\tau_p}\right). \quad (8)$$

We plot in Fig. 1, the variation of ν_{stat} according to bias current level I_0/I_{th}. Simulation, and theoretical approach show a linear variation of ν_{stat} according to the ratio I_0/I_{th}, with almost the same slope. We note the perfect agreement between the simulated (dashed line) and theoretical (continued line) curves. The variation of ν_{stat} is independent from the modulation format and the modulation frequency f_m. $\delta\nu(t)$ the frequency chirping, corresponding to the optical frequency variation in time, can be written as following:

$$\delta\nu(t) = \frac{d\phi}{dt} = \frac{1}{4\pi}A\alpha\Gamma n(t). \quad (9)$$

The frequency chirp $\delta\nu(t)$ is calculated by solving rate equations in the two cases of modulation triangular and sawtooth:

For the triangular modulation

$$\begin{aligned}\delta\nu(t) = {} & B_2\sum_{l'=1}^{k}\frac{(\lambda_2\mathrm{Cos}[l'\omega_m t] - l'\omega_m\mathrm{Sin}[l'\omega_m t])}{l'^2(\lambda_2^2 + l'^2\omega_m^2)} \\ & + B_1\sum_{l'=1}^{k}\frac{(\lambda_1\mathrm{Cos}[l'\omega_m t] - l'\omega_m\mathrm{Sin}[l'\omega_m t])}{l'^2(\lambda_1^2 + l'^2\omega_m^2)} \\ & \times \text{with } l' = (2l+1) \text{ is an odd number}. \end{aligned} \quad (10)$$

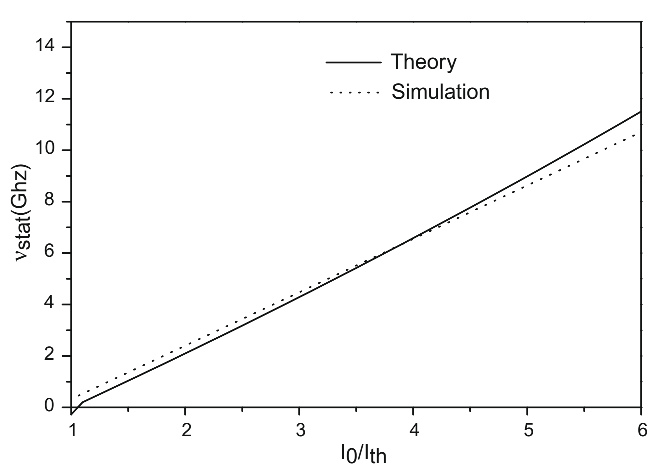

Fig. 1. Deviation ν_{stat} versus bias current level I_0/I_{th}.

Table 1
Typical parameters values for a 1.55 μm DFB str-MQW laser.

Parameters	Symbols	DFB str-MQW 1.55 μm
Cavity length	L	600 μm
Active region width	w	1.8 μm
Active-layer thickness	d	0.05 μm
Confinement factor	Γ	0.06
Line-width enhancement factor	α	5
Carrier density at transparency	n_{tr}	5.8×10^{17} cm^{-3}
Carrier lifetime	τ_n	1 ns
Photons lifetime	τ_p	4.3 ps
Gain coefficient	A	6.17×10^4 s^{-1}
Spontaneous-emissions fraction	β	10^{-4}
Threshold current	I_{th}	15.08 mA
Gain compression factor	ϵ	5×10^{-17} cm^3