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Effect of Nonlinear Gain on the Phase Noise of Y-branch Lasers: Numerical Study

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***Abstract*—Effect of nonlinear gain on the phase noise of Y-branch lasers is studied by numerical simulations, which are based on the developed transmission line model (TLM) and multimode rate equations superposed by Langevin noise sources and nonlinear gain terms. The nonlinear gain is found to have severe effects on the phase noise of the Y-branch lasers.**

Keywords—phase noise; MGY laser; nonlinear gain;

I. Introduction

Fast tunable lasers with wide tuning range have become the key element of transmitters for reconfigurable or wavelength-flexible networks and Dense Wavelength Division Multiplexing (DWDM) systems [1]. Among the available widely tunable laser sources, modulated grating Y-branch (MGY) lasers are fast multi-electrode tunable devices that offer accurate wavelength control and wide wavelength tuning range [2]. As reported in the detailed experimental phase noise characterization [3], however, the MGY lasers exhibit more serious phase noise characteristics, which will be a barrier for their applications in coherent optical communication systems.

The phase noise of a semiconductor laser originates from the spontaneous emission and it can be calculated by Henry's linewidth formula. However, for the MGY laser, the linewidth can be further broadened by 1/f noise or carrier shot noise in the passive sections [4]. Meanwhile, the passive sections in the MGY laser lead to longer cavity length and smaller longitudinal mode spacing, which increases chances of mode hopping and generates nonlinear gain. Impacts of nonlinear gain on the phase noise of normal semiconductor lasers have been reported [5]. For monolithic tunable lasers, the nonlinear gain is regarded as the origin for that the side mode suppression ratio (SMSR) appears not to occur at the center of mode-hop-free areas, but shifts towards a higher wavelength mode, which have been observed in the measurements of the MGY lasers [3]. Furthermore, operation conditions of a MGY laser vary with its emitting wavelength, making influence of the nonlinear gain more complicated. Whereas, effects of the nonlinear gain on the phase noise of the MGY laser have not yet been studied. In this paper, we report some progress of theoretical investigation of the phase noise of a MGY laser, where nonlinear gain terms included in.

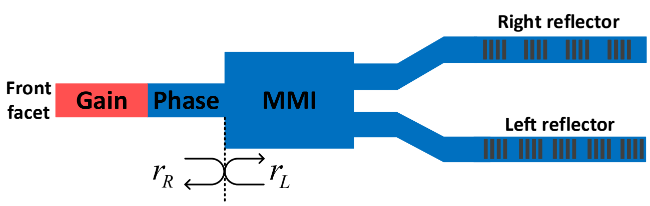

Fig. 1. Schematic layout of the MGY laser.

II. Simulation Model

A schematic layout of the MGY laser is shown in Fig.1. A gain and a phase section are followed by a 1×2 Multi-Mode interferometer (MMI) splitter. Each output waveguide of the splitter contains a sampled grating distributed Bragg reflector (DBR) mirror. By setting a reference plane at the interference between the phase section and the MMI, r_L and r_R are effective reflection coefficients for the left-going and right-going fields at the reference plane. The threshold condition can be expressed by: $r_L r_R = 1$, which is adopted to obtain the emitting wavelength and the carrier density in the active section. Afterwards, the nonlinear gain is introduced into multimode rate equations.

The nonlinear gain can be divided into a static and a dynamic part. So the modal gain can be redefined as:

$$G_m = A\left(1 - B_m S_m - \sum_{k\neq m}\left(C_{mk} + D_{mk}\right) S_k\right) \tag{1}$$

where A accounts for the linear gain, S_m is the photon density of mode m, B_m is self-saturation coefficient, C_{mk} is the static cross-saturation coefficient of mode k induced by mode m, and D_{mk} represents the dynamic nonlinear gain induced by the beating between different longitudinal modes. The ratio of static cross- to static self-saturation coefficient is related to the intraband relaxation time τ_{in}. And the relation between them can be written as:

$$C_{mk} = \frac{2\left(2+\tau_{in}^{\ 2}\left(\omega_m - \omega_k\right)^2\right)}{3\left(1+\tau_{in}^{\ 2}\left(\omega_m - \omega_k\right)^2\right)} B_m \tag{2}$$

where ω_m is the angular frequency of mode m. Contributions of dynamic nonlinear gain are more complicated, because not only the gain but also the refractive index are changed considerably. The dynamic nonlinear gain coefficient is described by:

$$D_{mk} + iE_{mk} = \sum_{i=1}^{3} \frac{\left(1 - i\alpha_i\right)/P_{si}}{1 + P_t/P_{si} - i\tau_i\left(\omega_m - \omega_k\right)} \tag{3}$$

where D_{mk} and E_{mk} represent the impacts on the gain and the refractive index, respectively. P_t is the total photon density, the linewidth enhancement factors are given by α_i, ($i = 1,2,3$) for carrier density pulsation (CDP), carrier heating (CH) and spectral-hole burning (SHB). It is necessary to take the changed refractive index into account in the phase rate equation, which can be expressed as:

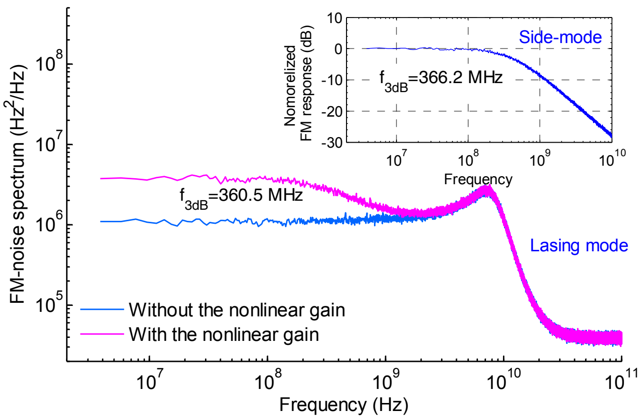

Fig. 2. Simulations of the FM-noise spectrum of the MGY laser with and without the nonlinear gain (SMSR=30 dB).

$$\frac{d\varphi_m}{dt}=\frac{1}{2}\alpha_1\Gamma v_g\left(A-A_s\right)+\frac{1}{2}\Gamma v_g A\sum_{k\neq m}E_{mk}S_k+F_{\varphi m}\left(t\right) \qquad (4)$$

where Γ is the optical confinement factor, v_g is the group velocity, A_s is the steady linear gain, $F_{\varphi m}(t)$ accounts for the Langevin noise source for the instantaneous phase.

III. Results and Analysis

The parameters for the laser structure and each nonlinear gain process are selected from [2, 6]. Simulations for the phase noise of the MGY laser with and without the nonlinear gain are first carried out, the calculated frequency modulation (FM) noise spectrums are presented in Fig. 2. Only the lasing mode and the largest side-mode are considered. It suggests that the FM-noise spectrum is enhanced at the low frequency range due to the nonlinear gain. The inset in Fig.2 shows the FM dynamic of the side-mode, we find that the spectral profile of enhanced FM-noise spectrum correlates well with the FM dynamic of the side-mode, which has a low-pass characteristic and the cutoff-frequency is essentially determined by the characteristic lifetime for the side-mode. Therefore, the noise source of the side-mode results in excess noise for the carrier in the active section in a presence of the nonlinear gain, which introduces the above excess phase noise.

Furthermore, the nonlinear gain can lead to the bi-stable state, and the instantaneously mode distribution can be modulated by the Langevin noise sources [7]. In order to investigate influence of this phenomenon on the phase noise, simulations are performed with a particular attention to the mode boundaries, where the lasing mode hopping can be observed easily. Fig. 3 (a) and (b) illustrate mode distribution for the mode hopping between case A and case B. Corresponding photonic dynamics are shown in Fig. 3 (c). Calculated FM-noise spectrums for these two cases are presented in Fig. 3 (d). For case A, the low frequency enhancement is remarkable, while for case B, there is no significant excess phase noise. According to (3-4), impacts of the dynamic nonlinear gain are asymmetrical, which make the phase noise related to the mode distribution. Therefore, mode hopping leads to phase noise hopping in Fig. 4(d). It indicates that the phase noise may hop without changing the tuning currents in the FM-noise measurements.

IV. Conclusions

In this paper, we have analyzed effect of the nonlinear gain on the phase noise of the MGY lasers by numerical simulations.

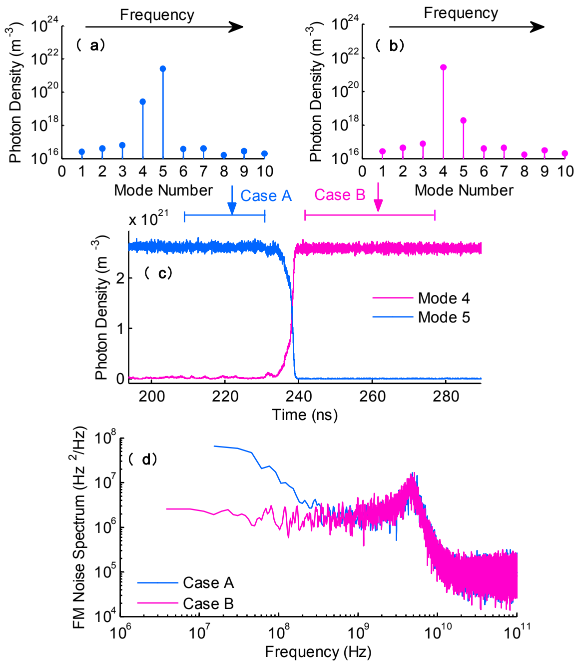

Fig. 3 Simulated results for the phase noise hopping phenomenon, (a) mode distribution for case A, (b) mode distribution for case B, (c) Photon density evolution during mode hopping, (d) FM-noise spectrum for case A and case B.

The results show that excess phase can be introduced by the nonlinear gain. Furthermore, the nonlinear gain can lead to the bi-stable state, and result in the phase noise hopping. The investigation is meaningful for the explanation of the complicated phase noise characterization of the MGY lasers.

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