Large Signal Simulation of Photonic Crystal Fano Laser

Aref Rasoulzadeh Zali[1], Yi Yu[2], Mohammad Kazem Moravvej-Farshi[1], and Jesper Mork[2]

[1]Faculty of Electrical and Computer Engineering, Advanced Devices Simulation Lab (ADSL), Tarbiat Modares University, P O Box 14115-194, Tehran 1411713116, Iran, aref.rasuolzadehzali@modares.ac.ir, farshi_k@modares.ac.ir.
[2]Department of Photonics Engineering, Technical University of Denmark, Ørsteds Plads, 2800 Kgs. Lyngby, Denmark, yiyu@fotonik.dtu.dk, jesm@fotonik.dtu.dk.

***Abstract*— We numerically investigate small and large signal modulation of a photonic crystal laser with a mirror based on Fano interference between continuum modes of a waveguide and a discrete mode of a nanocvaity. Our simulation shows that the instantaneous optical frequency of the laser signal can be modulated at frequencies exceeding 1 THz which is much higher than its corresponding relaxation oscillation frequency. Large signal simulation of the Fano laser is also investigated based on pseudo-random bit sequence at 0.5 Tbit/s. It shows eye patterns are open at such high modulation frequency, verifying the large bandwidth of the laser.**

I. INTRODUCTION

Introducing defects in photonic crystals makes it possible to realize high quality cavities. Employing these types of cavities in a laser structure, enhances light-matter interaction and gives the possibilities to control the cavity modes [1-3] which can lead to high bandwidth and low threshold lasers [2,3]. In this work, we analyze large and small signal modulation response of a photonic crystal Fano laser (PhC FL) which is depicted in Fig. 1. The Fano resonance is due to the interference between the continuum modes of a waveguide and the discrete mode of a nanocvaity [4]. PhC FL has two mirrors; the left mirror (r_L) is a broadband mirror realized by terminating the waveguide, while the right mirror realized by Fano interference, acting as very narrowband mirror. The PhC FL was experimentally demonstrated recently, showing exceptional properties such as single mode lasing and self-pulsing [5].

II. MODELING AND RESULTS

The reflection coefficient of the right Fano mirror is

$$r_2(\omega) = -P\gamma_c / \left[(\omega_c - \omega_r) + \gamma_T\right] \qquad (1)$$

where P is the parity of the nanocavity mode with P= 1 (−1) corresponding to an eigen mode which has even (odd) symmetry with respect to the symmetry line. $\gamma_T = \gamma_i + \gamma_c + \gamma_p/2$ is the total decay rate with γ_c, γ_i, and γ_p being the cavity-waveguide coupling rate, the intrinsic decay rate of the nanocavity including vertical scattering loss, and the coupling rate with the upper third port (cross port). The corresponding quality factors are given as $Q_x = \omega_r/2\gamma_x$ with ω_r being the angular frequency of the reference lasing mode at 1.55µm. Using Taylor expansion around the stationary solution, a dynamical model which governs the right ($A^+(t)$) and left propagating ($A^-(t)$) fields in the waveguide can be derived as [3]

$$\begin{aligned} dA^+/dt &= 0.5(1-i\alpha)\Gamma v_g g_N \left(N(t) - N_s\right) A^+(t) \\ &+ \gamma_L \left[A^-(t)/r_2(\omega_r) - A^+(t)\right], \end{aligned} \qquad (2)$$

where N_s, α, and $\gamma_L = c/(2n_g L)$, are respectively, the steady state carrier density, the absorption coefficient, and the inverse of the cavity round-trip time with c, n_g, and L being the light velocity in free space, the group refractive index, and the cavity length. Using temporal coupled mode theory, the dynamics of the field stored in the nanocavity can be incorporated as [3]

$$dA^-/dt = \left(-i\delta_c - \gamma_T\right) A^-(t) - P\gamma_C A^+(t). \qquad (3)$$

Here $\delta_c = \omega_c - \omega_r$ is the detuning of the mirror cavity resonance frequency (ω_c) from the reference frequency, ω_r. The

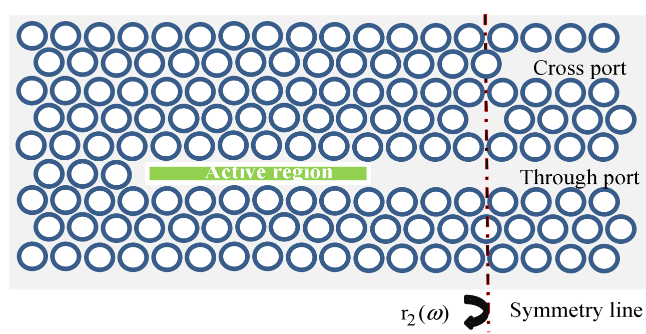

Fig. 1: Schematic of PhC FL with its right mirror, $r_2(\omega)$ formed by Fano interference. CP and TP correspond to the cross and through ports, respectively. The intrinsic quality factor of the nanocavity is 14300 and the total quality factor is 500.

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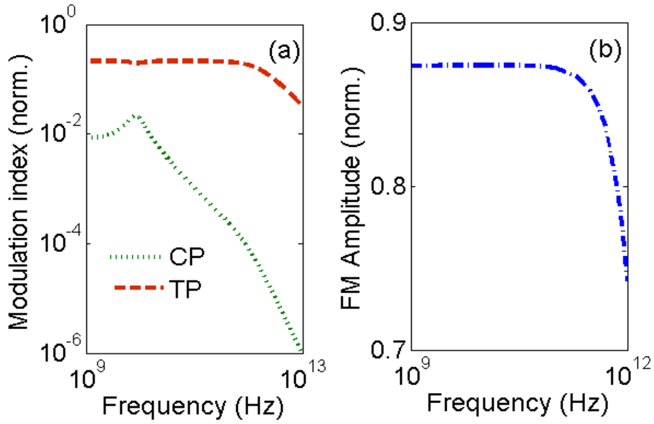

Fig. 2: (a) Modulation index for the CP and TP versus frequency; (b) FM amplitude of the CP filed (normalized to the amplitude of the modulation) versus frequency. The injected current and detuning are assumed $J = 5J_{th}$ and $\delta_c = 0.1\gamma_T + 0.05\gamma_T \sin(\omega t)$, respectively.

carrier density rate equation in the active region is [3]:

$$dN/dt = J/eV_c - N/\tau_s - v_g g(N) I(t)/V_P , \qquad (4)$$

where V_C is the active region volume, $V_P = V_C/\Gamma$ is the modal volume, J is the injected current, τ_s is the carrier lifetime, and $I(t) = \sigma_s|A^+(t)|^2$ is the photon number in the cavity with σ_s being a constant depending on the steady state solutions [3,5]. The output powers from to the CP and TP are given by $P_{CP} = 2\varepsilon_0 nc(\gamma_p/\gamma_c)|A^-(t)|^2$ and $P_{TP} = 2\varepsilon_0 nc|A^+(t) - A^-(t)|^2$, respectively. The parameters used in the simulations are: L=5μm, r_L=1, Q_p=10^4, g_N =5×10^{-20}, τ_s=0.5 ns, Γ=0.5, α=1, and n_g=3.5.

Modulation of the nanocvaity resonance frequency can be accomplished electrically or optically will be considered in this work. First, we consider that the nanocavity resonance is modulated as $\delta_c = 0.1\gamma_T + 0.05\gamma_T \sin(\omega t)$. Fig. 2(a) shows the modulation index for CP and TP versus the modulation frequency. The relaxation oscillation frequency (ω_{RO}) occurs at around 8GHz. The modulation index which is defined as maximum power fluctuation to the mean power, is higher for TP power than for the CP power due to the fact that the mean power of TP is lower than CP. In addition, for CP the modulation bandwidth (BW) is limited by the relaxation oscillation frequency (ω_{RO}), while for TP the modulation 3-dB BW extends to 1.5 THz. Fig. 2(b) shows the FM amplitude modulation of the cross port signal versus modulation frequency. FM amplitude is defined as maximum excursion of the cross port instantaneous optical frequency. It can be inferred that the 3-dB BW of the FM amplitude modulation of the cross port signal exceeds 1 THz not limited by ω_{RO}. These results are in accordance with [3].

Large signal simulations are also carried out to predict the capabilities of the PhC FL for digital data transmission. By applying the pseudo-random bit sequence (PRBS) signal which its bit rate equaling to the 3-dB BW of the laser, open eye diagrams can be achieved, verifying that the laser can be

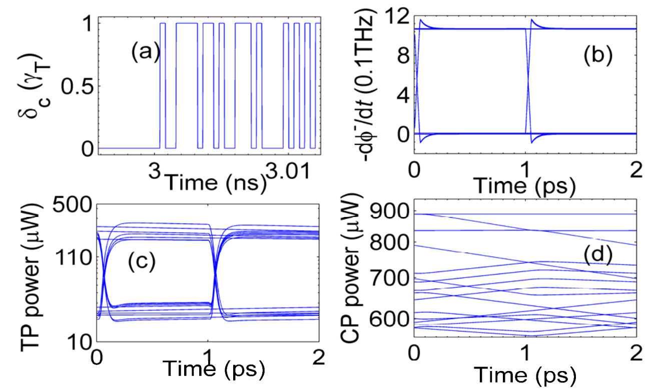

Fig. 3: (a) Amplitude of the nanocavity detuning resonance frequency, in terms of γ_T as a function of time; (b) Eye diagram of the cross port instantaneous optical frequency ; (c) Eye diagram of the TP power; (d) Eye diagram for CP power.

modulated at very high frequencies. Fig. 3(a) shows the time evolved nanocavity detuning (as input bit sequence) with the amplitude in the range of 0 and γ_T at 0.5 Tbit/s. Also, PRBS 5 (2^5−1 bit) is used to simulate the PhC FL eye diagram. The eye diagram of the FM amplitude of the CP filed is shown in Fig. 3(b). As expected, the eyes are open at 0.5 Tbit/s, which is anticipated from the small signal analysis in Fig. 2(b). This is the same case as for the TP power, as shown in Fig. 3(c). Finally, as shown in Fig. 2(a) the CP power bandwidth is limited by ω_{RO}, so with bit sequence of 0.5 Tbit/s, which is much higher than its 3-dB bandwidth, the eye pattern is closed, cf. Fig. 3(d), as anticipated from the small signal analysis.

III. Conclusion

In this work we investigated the small and large signal modulation of the photonic crystal Fano laser. Furthermore, the 3-dB bandwidth of the output parameters for FL are discussed. Finally, the eye diagrams for each case is investigated. We observe that such Fano lasers have intrinsic large signal modulation bandwidth much larger than the relaxation oscillation frequency. In a particular example we demonstrated large signal modulation at 500 Gbit/s.

IV. REFRENCES

[1] T. Baba, D. Sano, K. Nozaki, K. Inoshita, Y. Kuroki, and F. Koyama, “Observation of fast spontaneous emission decay in GaInAsP photonic crystal point defect nanocavity at room temperature,” Appl. Phys. Lett., vol. 85, pp. 3989-3991, 2004.

[2] S. Matsuo, *et al.*, “High-speed ultracompact buried heterostructure photonic-crystal laser with 13 fJ of energy consumed per bit transmitted,” Nat. Photonics, vol. 4, pp. 648-654, 2010.

[3] J. Mork, Y. Chen, and M. Heuck, "Photonic crystal Fano laser: Terahertz modulation and ultrashort pulse generation," Phys. Rev. Lett., vol. 113, no. 16, pp.163901-1:4, 2014.

[4] S. Fan, W. Suh, and J. D. Joannopoulos, “Temporal coupled-mode theory for the Fano resonance in optical resonators,” J. Opt. Soc. Am. A, vol. 20, pp. 569-572, 2003.

[5] Y. Yu, W. Xue, E. Semenova, K. Yvind, and J. Mork, “Demonstration of a self-pulsing photonic crystal Fano laser,” Nat. Photonics, vol. 11, pp. 81-84, 2017.