



The 25<sup>th</sup> Iranian Conference on  
Optics and Photonics (ICOP 2019),  
and the 11<sup>th</sup> Iranian Conference on  
Photonics Engineering and  
Technology (ICPET 2019).  
University of Shiraz,  
Shiraz, Iran,  
Jan. 29-31, 2019



## بررسی تاثیر پارامتر حبس شدگی نوری بر عملکرد لیزر فانوی بلور فوتونی

گلشن حمزه<sup>۱</sup>، محمد رزاقی<sup>۱</sup> و عارف رسولزاده زالی<sup>۲</sup>

<sup>۱</sup>گروه مهندسی برق، دانشکده مهندسی، دانشگاه کردستان، سنندج

<sup>۲</sup>دانشکده مهندسی برق و کامپیوتر، دانشگاه تربیت مدرس تهران

چکیده - در این مقاله عملکرد یک لیزر فانو بلور فوتونی بررسی و شبیه سازی شده است. در این شبیه سازی معادلات انتشار حاکم بر لیزر، با استفاده از روش تفاضل محدود حل شده است. براساس شبیه سازی انجام شده، رفتار دینامیکی لیزر در دو رژیم عملکرد موج پیوسته و خود-پالس بررسی شده است. جهت بهینه سازی عملکرد لیزر پارامتر حبس شدگی نور در نانوکاوک تغییر داده شده است. عملکرد لیزر براساس این تغییرات بررسی شده است. با توجه به شبیه سازی انجام شده، با تغییر پارامتر حبس شدگی از ۰/۱ تا ۰/۳۲، ماکزیمم تغییرات انرژی ۰/۲۷ پیکوژول، تغییرات کل عرض در نصف ماکزیمم (FWHM) ۰/۰۰۹ نانوثانیه و ماکزیمم تغییرات فرکانس ۰/۷۳۸ گیگاهرتز در سیگنال خروجی مشاهده شده است.

کلید واژه - خود-پالس، فاکتور حبس شدگی میدان نانوکاوک، فانو لیزر، نانوکاوک

## Investigation of optical confinement factor effect on photonic crystal Fano laser performance

Golshan Hamzeh<sup>1</sup>, Mohammad Razaghi<sup>1</sup>, and Aref Rasoulzadeh Zali<sup>2</sup>

<sup>1</sup>Dept. of Electrical Eng., School of Engineering, University of Kurdistan, Sanandaj, Iran

<sup>2</sup>Faculty of Electrical and Computer engineering, Tarbiat Modares university, Tehran, Iran

[g.hamzeh@eng.uok.ac.ir](mailto:g.hamzeh@eng.uok.ac.ir)

[m.razaghi@uok.ac.ir](mailto:m.razaghi@uok.ac.ir)

[aref.rasoulzadehzali@modares.ac.ir](mailto:aref.rasoulzadehzali@modares.ac.ir)

**Abstract-** In this paper the operation of a photonic crystal Fano laser is analyzed and simulated. In this simulation, the propagation equations are solved using the finite difference method. The dynamical behavior of the laser is demonstrated for two regimes of operation, continuous-wave and self-pulsing. In order to optimize laser operation, the nanocavity field confinement factor has been swept and its effects on the laser operation is investigated. Based on our simulations by changing this confinement factor from 0.1 to 0.32, the maximum energy, full width at half maximum and frequency variations of 0.27 pJ, 0.009 ns and 0.738 GHz in the output signals are respectively observed.

Keywords: Self-pulsing, nanocavity field confinement factor, Fano laser, nanocavity

## 1. Introduction

Photonic crystal lasers are the newest type of lasers used in photonic integrated circuits [1]. The use of cavities created by linear defect in the laser structure, increases the light-matter interaction. It also makes possible to control cavity modes, which can lead to a large bandwidth and low threshold laser. Linear and point defects lasers have many advantages, such as low-power consumption [2, 3] and very high speeds[3, 4].

A new type of photonic crystal lasers is so-called Fano lasers. It consists of a photonic crystal linear defect waveguide, a conventional mirror based on the termination of the waveguide, and a newly proposed Fano mirror. These lasers are able to generate very narrow pulses (self-pulse) For the first time in 2014, the Fano Laser structure was introduced [3]. Then, in 2016, it was demonstrated experimentally and theoretically, that by this laser light pulses at gigahertz frequencies can be produced [5]. In 2017, laser performance was investigated in two modes of continuous wave and self-pulse [1].

In this paper, we first describe the Fano laser structure. Then laser operating modes using the finite difference method is simulated. Finally, we will investigate the dynamical behavior of the laser accordingly.

## 2. Fano Laser Structure

The Fano laser structure is shown in Fig. 1. This structure was first introduced in [3] which is based on the creation of alternate pattern of air-holes in a InP membrane. The laser cavity is based on a photonic crystal waveguide due to a linear defect in the photonic crystal structure. The left mirror is a conventional broadband mirror that is created by a photonic crystal waveguide termination with air-holes. In contrast, the right mirror is based on the Fano resonance. As shown in Fig. 1, the reflection in this mirror is consequence of the interference between the continuum of waveguide modes and the discrete resonance of a side- coupled

nanocavity known as Fano resonance. One of the most important characteristics of this mirror is that it is a very narrow-band mirror.

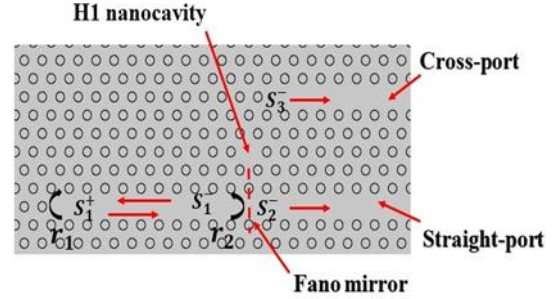


Fig. 1: The Fano laser structure with radius  $r = 100$  nm and the lattice constant  $a = 425$  nm

## 3. Governing Equations

The equations governing the Fano laser are as follows [1]:

$$\frac{da(t)}{dt} = (-i\delta_c - \gamma_T)a(t) + (\gamma_c^{1/2})s_1^+(t) + (1/2)(1 - i\alpha)\Gamma_c \nu_g g_N (N_c(t) - N_0)a(t) \quad (1)$$

$$s_1^-(t) = -P(\gamma_c^{1/2})a(t) \quad (2)$$

$$s_2^-(t) = s_1^-(t) - (\gamma_c^{1/2})a(t) \quad (3)$$

$$s_3^-(t) = i(\gamma_p^{1/2})a(t) \quad (4)$$

$$\frac{dN_c(t)}{dt} = -N_c/\tau_c - \Gamma_c \nu_g g_N (N_c(t) - N_0) \quad (5)$$

$$Q_x = \omega_r / \gamma_x \quad (6)$$

$$Q_x = \omega_r / \gamma_x \quad (7)$$

Here,  $a(t)$  is the nanocavity field and  $s(t)$  is the propagation field in the waveguide. The signs  $+$  ( $-$ ) refer to traveling toward (far from) the Fano mirror in Fig 1. In addition,  $\delta_c = \omega_c - \omega$ , where  $\omega$  is the laser frequency and  $\omega_c$  is the nanocavity resonance frequency. Also  $\gamma_T$  is the total nanocavity passive decay rate,  $\gamma_c$  is the nanocavity waveguide coupling decay rate,  $\gamma_i$  is the out-of-plane and scattering losses decay rate and  $\gamma_p$  is the coupling to the cross-port decay rate. The corresponding Q-factors are defined as Eq. (7). Where  $\omega_r$  is the reference frequency. In addition,  $\tau_c$  is an effective carrier lifetime within the nanocavity,  $\gamma_c$  is the nanocavity

field confinement factor,  $v_g = c/n_g$  is the group velocity,  $g_N$  is the differential gain,  $N_0$  is the transparency carrier density of the active material, and  $V_{NC}$  is the volume of the nanocavity. Finally,  $P = I(-I)$  is the parity of the cavity mode with respect to the Fano mirror.

## 4. Investigation of Laser Performance

The Fano laser has two working dynamical regions, the continuous wave (CW) and the pulsed train region, which is called self-pulsing (SP). Generally, the lasers start lasing at currents above the threshold current. The laser operation area depends on many factors such as the pump current,  $J_{pump}$ , the nanocavity frequency  $\omega_c$ , and the nanocavity field confinement factor,  $\Gamma_c$ .

### 4.1. Continuous Wave Operation

Generally, if the biased current of the Fano laser is far more than threshold current, its output will be in CW mode. Fig. 2 shows a numerical simulation of the output power of the Fano laser and also its carrier density. The biased current and detuning are assumed  $J = 2J_{th}$  and  $\Delta\omega_c = \omega_c - \omega_r = 0.52\gamma_T$ , respectively.

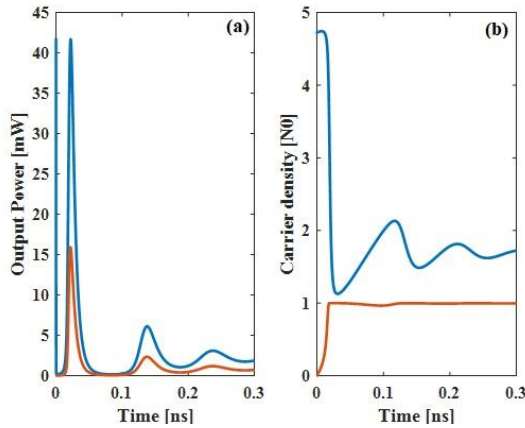


Fig. 2: (a) laser output power (b) normalized carrier density of the nanocavity and waveguide versus time in continuous wave operation regime

The results are in good agreement with results shown in [1]. As depicted in Fig. 2, since the nanocavity is pumped through the laser field, so the nanocavity carrier density cannot be increased from  $N_0$ . Therefore, by increasing the nanocavity carrier density, the absorption rate in nanocavity

decreases and, as a result, the reflection coefficient increases [1].

### 4.2. Self-Pulsing Operation

As previously discussed, the working region changes with the change of pump current. As shown in Fig. 3 by assuming the bias current of the Fano laser to be  $J = 1.2J_{th}$ , the laser operates in the self-pulse region. In this region, by increasing the laser power, a stimulated emission occurs in the waveguide, as a result, the carrier density decreases in the waveguide. Therefore, the nanocavity carrier density increases (Fig. 3-c). The laser is constantly optically pumped, which results in the waveguide carrier density reaches the threshold value, which is equivalent to the carrier density of the un-pumped nanocavity where the lasing occurs (Fig. 3-c).

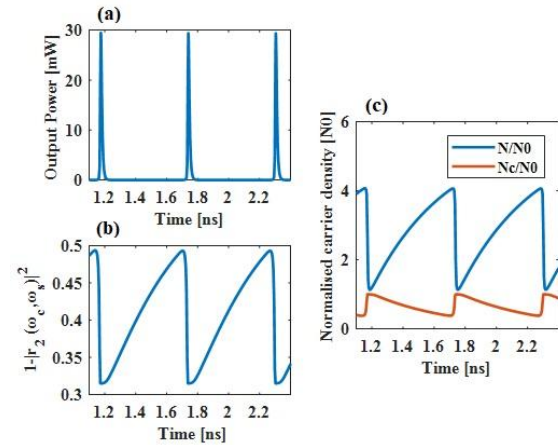


Fig. 3: (a) the laser output power, (b)  $1 - |r_2(\omega_c, \omega_s)|^2$ ; and (c) the normalized carrier density of the waveguide and nanocavacs versus time in the self-pulse operation regime

As the waveguide field increases, carrier density increases in nanocavity as well (Fig. 3-c), consequently, the absorption in nanocavity is decreased, which results in a reduction in mirror losses. As the stimulated emission increases in the laser waveguide, the waveguide carrier density drops below the threshold and the lasing is interrupted. Then again the density of the carrier in the waveguide begin to increase in contrast to the carrier density in the nanocavity which decreases due to the recombination. Accordingly the carrier density in the laser waveguide reaches the

threshold carrier density and this cycle repeats (Fig. 3-a) [1].

## 5. Laser Operation Dependency to Nanocavity Field Confinement Factor

As shown in Fig. 4, the more the nanocavity field confinement factor, lead to the more the field confinement in the nanocavity. In other words, by increasing  $\Gamma_c$  from 0.1 to 0.32, the energy stored in the nanocavity increases. Variation in nanocavity optical confinement factor leads to the variations in energy, frequency, and FWHM. The laser operates in continuous wave regime for nanocavity field confinement factors beyond  $\Gamma_c > 0.32$ . As shown in Fig. 4-a, the maximum energy variation of the output signal is 0.27 pJ. With increasing  $\Gamma_c$  from 0.1 to 0.32, the Fano mirror reflection increases. Due to the direct relationship between the output intensity of the laser and the reflection coefficient, the energy of the output signal increases.

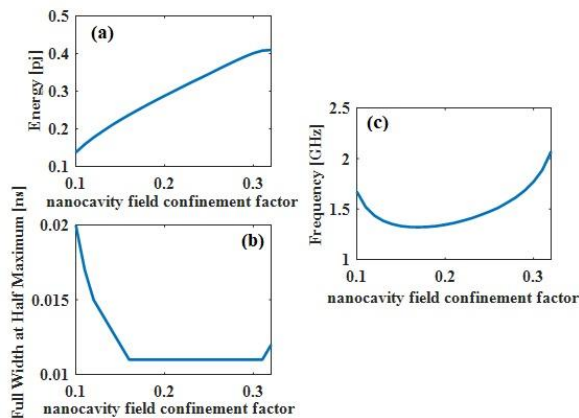


Fig. 4: (a) the energy, (b) FWHM; and (c) the frequency of the output signal versus  $\Gamma_c$  variations

As shown in Fig. 4-b, the maximum FWHM variation of the output signal is 0.009 ns. As the  $\Gamma_c$  increases, the output pulse becomes narrower and the carrier density in nanocavity reaches transparency  $N_0$  faster. As a result, the waveguide carrier density is depleted faster and the lasing is interrupted. Therefore, the maximum FWHM variation of the output signal is reduced. Finally, Figure 4-c shows that the maximum frequency variation of the output light is 0.738 GHz. With increasing  $\Gamma_c$ , the carrier density in the nanocavity

grows faster. Furthermore, the carrier density in the waveguide also grows faster and consequently it reaches to the threshold value sooner. So, the output field instantaneous frequency increases.

## 6. Conclusion

In this paper, the Fano laser structure was numerically investigated and its dynamical operation regimes was explained. The propagation equations were solved using the finite difference method. It was observed that by changing the nanocavity field confinement factor from 0.1 to 0.32, the maximum variation of the energy in the output port of the laser was 0.27 pJ, the maximum FWHM variation was 0.009 ns and the maximum frequency variation was 0.738 GHz in the output signal.

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