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بررسی تاثیر پارامتر حبس‌شدگی نوری بر عملکرد لیزر فانوی بلور فوتونی

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چکیده- در این مقاله عملکرد یک لیزر فانو بلور فوتونی بررسی و شبیه‌سازی شده است. در این شبیه‌سازی معادلات انتشار حاکم بر لیزر، با استفاده از روش تفاضل محدود حل شده است. براساس شبیه‌سازی انجام شده، رفتار دینامیکی لیزر در دو رژیم عملکرد موج پیوسته و خود-پالس بررسی شده است. جهت بهینه‌سازی عملکرد لیزر پارامترحبس‌شدگی نور در نانوکاواک تغییر داده شده است. عملکرد لیزر براساس این تغییرات بررسی شده است. باتوجه به شبیه‌سازی انجام شده، با تغییر پارامتر حبس‌شدگی 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 حبس‌شدگی میدان نانوکاواک، فانو لیزر، نانوکاواک

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

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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.

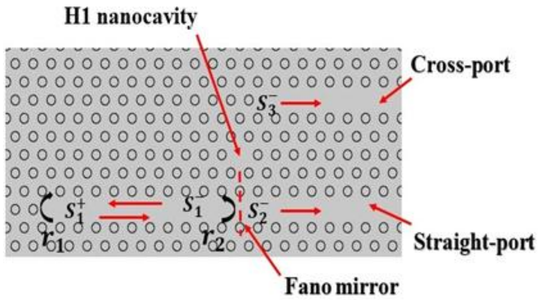

Fig. 1: The Fano laser structure with radius r = 100 nm and the lattice constant a = 425 nm

3. Governing Equations

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

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

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

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

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

$$dN_c(t)/dt = -N_c/\tau_c - \Gamma_c v_g g_N (N_c(t) - N_0)(|a(t)| \wedge 2)/\hbar\omega_r V_{NC} \quad (5)$$

$$\gamma_T = \gamma_c + \gamma_i + \gamma_p \quad (6)$$

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

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, δ_c = ω_c -ω, where ω is the laser frequency and ω_c is the nanocavity resonance frequency. Also γ_T is the total nanocavity passive decay rate, γ_c is the nanocavity waveguide coupling decay rate, γ_i is the out-of-plane and scattering losses decay rate and γ_p is the coupling to the cross-port decay rate. The corresponding Q-factors are defined as Eq. (7). Where ω_r is the reference frequency. In addition, τ_c is an effective carrier lifetime within the nanocavity, Γ_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, $P=1(-1)$ 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 ω_c, and the nanocavity field confinement factor, Γ_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.

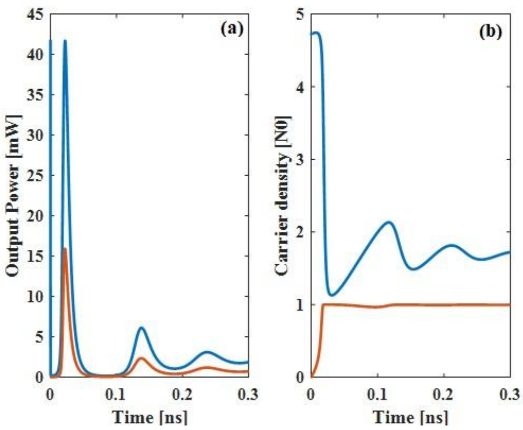

Fig. 2: (a) laser output power (b) normalized carrier density of the nanocavity and waveguide versus time in continuous wave operation regime

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).

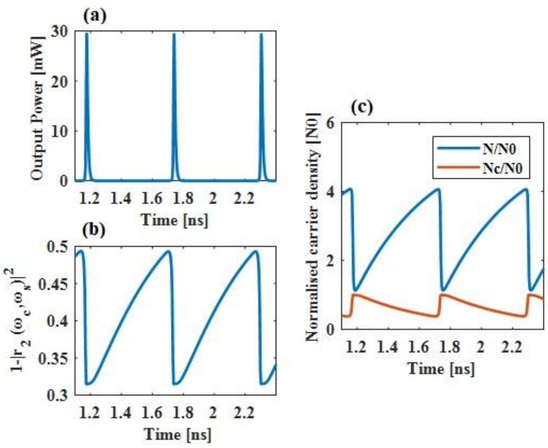

Fig. 3: (a) the laser output power, (b) $1-|r_2(\omega_c,\omega_s)|^2$; and (c) the normalized carrier density of the waveguide and nanocavacs versus time in the self-pulse operation regime

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 Γ_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 Γ_c >0.32. As shown in Fig. 4-a, the maximum energy variation of the output signal is 0.27 pJ. With increasing Γ_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.

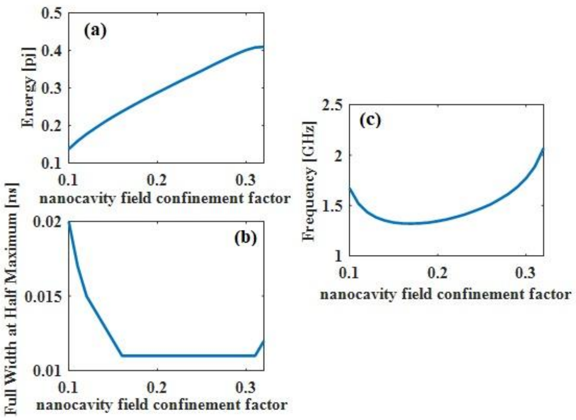

Fig. 4: (a) the energy, (b) FWHM; and (c) the frequency of the output signal versus Γ_c variations

As shown in Fig. 4-b, the maximum FWHM variation of the output signal is 0.009 ns. As the Γ_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 Γ_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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