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ویژگی های مدولاسیون لیزر فوتونیک کریستال فانو

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چکیده-در این مقاله ما لیزر فوتونیک کریستالی را تحلیل خواهیم کرد که یکی از آینه های آن برپایه اثر فانو است. آینه ی فانو بر مبنای تداخل بین مدهای نوری موجبر و مد نوری تکی مربوط به نانوکاواک بوجود می آید. نشان داده خواهد شد که با افزایش ناکوکی بین نانوکاواک و فرکانس لیزر، توان خروجی از یکی از پورت ها که تحت عنوان cross-port شناخته میشود، کاسته خواهد شد و در حالی که توان خروجی از دیگر پورت مربوط به لیزر یعنی through-port افزایش خواهد داشت. بعلاوه، مدولاسیون جریان لیزر بررسی خواهد شد و نشان داده خواهد شد که با مدولاسیون جریان، لیزر فانو شبیه لیزر معمولی رفتار خواهد کرد. همچنین نتیجه گیری خواهد شد که با افزایش ناکوکی بین نانوکاواک و فرکانس لیزر، فرکانس تشدید لیزر افزایش خواهد یافت.

کلید واژه- لیزر فوتونیک کریستال، تشدید فانو، مدولاسیون جریان لیزر، ناکوکی فرکانسی

Modulation Properties of Photonic Crystal Fano Laser

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Abstract- We analyzed a laser with a mirror realized by Fano interference between the discrete resonance of the nanocavity and continuum of waveguide modes. The steady-state behavior of the photonic crystal Fano laser (PhC-FL) is investigated and shown that by increasing the detuning the output power from cross-port decreases however from through-port increases. In the case of current modulation of the FL, it behaves like a conventional laser and its bandwidth is limited by carrier dynamics limited by relaxation oscillation frequency. It is shown that by increasing the modulation amplitudes the accuracy of the small signal results decreases since it is assumed a very negligible dynamical change around the steady-state point. Furthermore, it is also shown that by increasing the detuning the relaxation oscillation frequency increases.

Keywords: Photonic Crystal Laser, Fano resonance, Current Modulation, Detuning

1. Introduction

To demonstrate ultra-compact lasers, introducing defects in photonic crystals (PhCs) make it possible for the realization of high quality optical cavities [1−3]. Due to the improved light-matter interaction and possibilities of controlling the cavity modes, these novel types of lasers enjoy from many advantages such as ultrahigh speed and ultralow threshold currents [1,2]. Different structures have been developed yet based on Fano resonance and its rich physics has been extensively explored in these devices [1]. In our recent work [3], we have demonstrated and analyzed a Fano laser (FL) with a narrow band mirror which realized by Fano interference between the continuum of waveguide modes and discrete resonance of the nanocavity [1]. Due to the destructive interference between the optical field transmitted through the nanocavity and through the waveguide, this structure indicates the ultra-narrow reflection spectrum centered about the nanocavity resonance. As a result, it leads to a laser with unique characteristics such as single mode laser, self-pulsing characteristics and the possibility of modulation of the laser via its Fano mirror [1,2]. It was recently demonstrated that by considering nonlinearities in the Fano mirror, self-sustained pulse trains at gigahertz frequencies can be generated [2]. Furthermore, FL can be frequency modulated (FM) via the nanocavity mirror at frequencies much larger than 1 THz because the laser bandwidth is not limited by carrier dynamics as for conventional lasers [1]. Also, the laser exhibits rich dynamics when changing the amplitude of the resonance modulation which leads to a new regime of operation with a train of pulses in the output [1,2].

Here, we report a detailed investigation of the dynamical behavior of the FLs considering current modulation of FL. Small signal model is developed to compare its results with the numerical results of the laser modulations. We show that by current modulation of the FL, it behaves like conventional laser which its intensity and frequency modulation bandwidth are limited by carrier dynamics.

2. Modeling

The temporal coupled mode theory (CMT) is used to model the dynamics of the field stored in the nanocavity and coupled to the straight waveguide. Fig. 1 shows the schematic view of the proposed PhC line-defect laser based on Fano interference between waveguide mode and side coupled nanocavity mode [1-3].

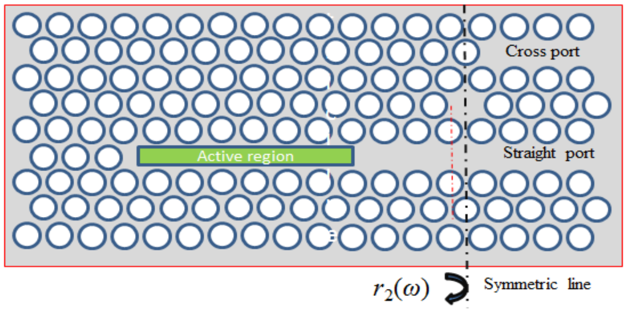

Fig. 1: Schematic of line-defect PhC-FL with right mirror formed by Fano interference and left mirror formed by simply terminating the waveguide. The upper waveguide is cross-port and is not essential for laser performance.

2.1. Steady-state Characteristics

It is helpful to find the light-current (*L-I*) characteristics of an FL and compare the order of the power from two ports. So to demonstrate this aim, the cross-port and through-port powers upon current change are illustrated in Fig. 2 (a) and 2(b). As shown in this figure for a given injected current, the power value from the cross-port is higher than that of through-port. It is because, at resonance frequency where the waveguide (laser) field frequency and nanocavity resonance frequency coincide, the destructive interference between the nanocavity field and waveguide field limits the through-port power. On the other hand, since the cross-port power is related to the power stored in the nanocavity, its level is higher than through power. The parameters those are used in our simulations are mentioned in ref [3].

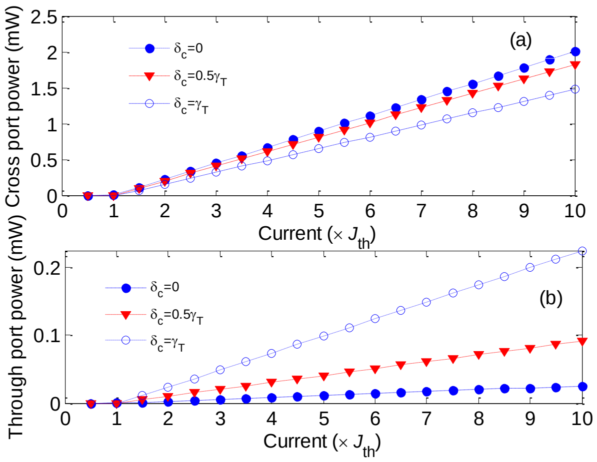

Fig. 2: Output power versus current for (a) cross-port and (b) through-port with three different detuning of δ_c=0 (filled circle), 0.5γ_T (triangular), and γ_T (open circle).

By introducing detuning to the nanocavity resonance frequency, the output power corresponding to cross-port decreases since the effective reflection coefficient decreases and field stored in the nanocavity decreases. Conversely, by introducing detuning the through-port power increases. It is because by increasing the detuning, the interference between two fields in the waveguide and the nanocavity mirror is less destructive. Accordingly, the through-port power increases more than one order of magnitude as detuning increases from 0 to γ_T.

2.2. Small signal model

The laser dynamics is first analyzed by numerically solving the equations governing FL rate equation. Then the results are compared with small signal approach results. We assume that the dynamical change because of the modulation perturbation in fields and carrier density values around their steady-state values are negligible. For all dynamical variables by performing an expansion around the steady-state solutions, a set of approximate rate equations for can be achieved. Meanwhile, the production terms of two or more small signal variables should be neglected. The details of the equations that are used for our simulations are given in Ref. [1].

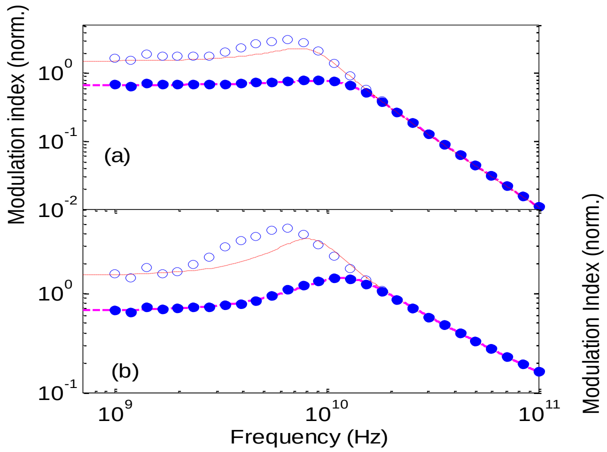

Fig. 3: Numerical (circles) and small signal approach (dashed or dotted lines) simulation for power modulation index versus modulation frequency with current modulation amplitude of 0.9 mA for two different biased currents of J/J_{th}=5 (open circles) and 10 (filled circles) for (a) cross-port and (b) through-port. The quality factor of the nanocavity is assumed Q_{NC}=500.

For constant zero detuning δ_{c0}=0, first, we investigate modulation of the laser injection current. Naturally, up to the relaxation oscillation frequency, the power modulation can follow the current modulation. Around relaxation oscillation, an enhancement of the response can be observable. The response drops dramatically, beyond the relaxation oscillation resonance. The relaxation oscillation frequency (ω_R) generally depends on the photon density. As a result by increasing the steady-state biased current i.e., increasing output power, ω_R increases until it saturates at very high biased currents. The damping of the response also increases by enhancing ω_R, i.e, the response flattens out as biased current increases

Fig. 3 shows the results of the numerical simulations and compares with those the small signal analysis for the power modulation index of the cross-port power (Fig. 3(a)) and through-port power (Fig. 3(b)) vs. modulation frequency. As shown in this figure by increasing the laser injection current from J=5J_{th} to 10J_{th} the modulation index decreases due to the fact that the maximum power fluctuation relative to the mean power decreases. Also, the relaxation oscillation frequency

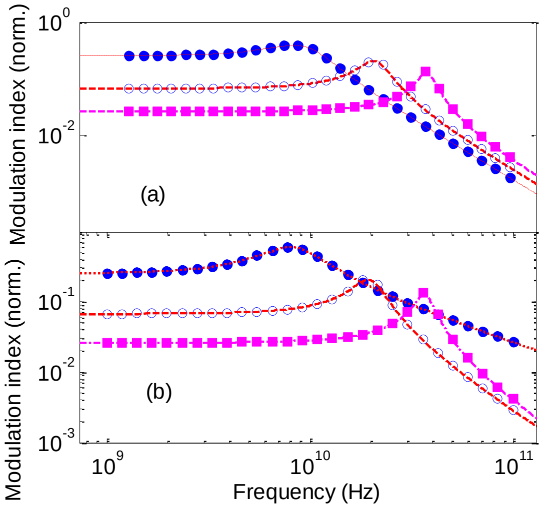

Fig. 4: Numerical (circles) and Small signal approach (dashed and dotted lines) simulation for modulation index vs. frequency for (a) Cross port power and (b) through port power when the current of the PhC FL is modulated by assuming same photon number of 1.65×10^4 and three different detunings of the nanocavity, $\delta_{c0}=0$ (filled circles), $\delta_{c0}=0.5\gamma_t$ (open circles), and $\delta_{c0}=\gamma_t$ (filled squares). The sinusoidal modulation of the laser is assumed to be as $2.26\times10^{-4}\sin(\omega t)$.

shifts from ~9 GHz to ~10 GHz. Furthermore, by increasing the bias current, the resonance peak flattens and broadens out like conventional laser [2]. It is clear that by increasing the biased current the modulation index decreases due to the increase of the maximum power fluctuation relative to the mean power. As a result for the lower biased current (i.e., J=5J_{th}) strong deviations between numerical and small-signal simulations is discernable.

The modulation index of the laser for -cross and through-ports as a function of modulation frequency for three different nanocavity detunings $\delta_{c0}=0$, $\delta_{c0}=0.5\gamma_t$, and $\delta_{c0}=\gamma_t$ while with same photon number of $I=1.65\times10^4$ is investigated in Fig. 4 (a)-(b). To compare the effect of the detuning on the relaxation oscillation frequency of the FL structure, the photon number is assumed to be the same ($I=1.65\times10^4$), which can be done by changing the biased current of the laser which we set the biased current 5J_{th}, 10J_{th}, and 13.5J_{th} for the case when the FL works with detuning of $\delta_{c0}=0$, $\delta_{c0}=0.5\gamma_T$, and $\delta_{c0}=\gamma_T$, respectively. The first point that can be concluded from the curves is that for the same photon number, the relaxation oscillation frequency for the laser with different detunings is not the same. For example for PhC-FL with detuning of $\delta_{c0}=0$, 0.5γ_T, and γ_T the corresponding relaxation oscillation frequencies are ω_R= 9 GHz, 20 GHz, and 36 GHz, respectively. This values of relaxation oscillation frequencies are approximately the same relaxation oscillation frequencies which depicted previously in nanocavity modulation part, c.f. Fig. 3. We can conclude that for an above-threshold condition when the photon number is constant, the relaxation oscillation frequency for PhC-FL strongly depends on the nanocavity detuning. So by adjusting the detuning, one can increase the relaxation oscillation frequency which can increase the 3-dB bandwidth of the laser. On the other hand, one should note that by increasing the detuning, the threshold current increases.

2.3. Conclusion

All in all, we have discussed steady state and small signal behavior of the PhC-Fl. It is shown that by increasing the biased current of laser its relaxation oscillation frequency increases. Also increasing the detuning of the nanocavity makes another possibility to increases the laser relaxation oscillation frequency.

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