

Investigation the dynamic of nano quantum cascade lasers with optoelectronics feedback

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Article Information

Received: 21/02/2020

Accepted: 12/05/2020

Keywords:

Nano quantum cascade lasers, Optoelectronics FeedBack, Purcell Effect, Spontaneous Emission Factor, and Rate Equation Model.

Abstract

In this paper, a theoretical investigation of negative optoelectronic feedback study in Nano quantum cascade lasers is presented. The present rate equation model has been modified to include the nano laser factors such as the Purcell factor and the spontaneous emission factor. The results indicate that the present rate equation model can be using to study the effect of Purcell factor and the spontaneous emission factor on the negative optoelectronic feedback in Nano quantum cascade lasers. It is found that the increase in Purcell factor value leads to increase in photon number and decrease the carrier number in all quantum states. Also, the dynamic of photon number (S) tends to stable at constant value with the increase of Purcell effect i.e. there is small variation in photon number and carrier number (N_1, N_2, N_3). The decreases in enhanced spontaneous emission factor value leads to increases in carrier number and decreases the photon number and we note small variation in these values.

Introduction:

Semiconductor lasers are solid state lasers that depend on the transitions between conduction band and Valence band to produce a photon in active region in contrast, quantum cascade lasers (QCLs) are a semiconductor lasers produce a photon in active region via the inter sub band transitions in conduction band only. Also, since the active region in (QCLs) consists of several parts, each electron produces a photon in each region. The most important properties that resulting from the optimum design are low losses and high injection efficiency. Also, the carrier and photon number depend on gain stages number. The inter sub band transition between the energy levels in conduction band is the only process in conduction band that leads to emission of light. The photon lifetime and energy are a function of the QW width and not dependent on the material energy gap. QCLs are the main devices in several important applications in the optical communications system, medical purposes, imaging systems, remote sensing, biological sciences, astrophysics sciences and space communications [1,2]. Since 1994, QCLs have been improved to get optimum values for static and dynamic properties such increasing lasing wavelength and output power, decreasing the threshold current and operating temperature [3,4]. In nano-cavity, the high quality factor and small volume lead to enhance the mode density and spontaneous emission rate because of Purcell effect [2]. It is well-known that the level lifetime depends on the Purcell coefficient value

where the high value leads to a small carrier lifetime or small level lifetime. Also, high value Purcell coefficient leads to decrease the carrier number and increase the photon number, both the static and dynamic properties of nano-laser depend on Purcell coefficient F and spontaneous emission factor β where the high value of both factors leads to desirable properties of semiconductor laser and semiconductor amplifier such as two photon absorption (TPA), cross gain modulation (XGM) and four-wave mixing (FWM). In chaotic secure communications, the semiconductor lasers has considerably sensitive to instabilities that resulting from external input power and using as a chaotic source for information security. There are many configuration systems that using to produce the chaotic output such as the optical injection from an external laser and optical feedback from an external mirror and the optoelectronic feedback [5,6]. The rapid development of communication systems needs new energy sources with unique characteristics that differ from those found in previously known lasers such as the small integral size and optimum dynamic and static properties. This paper presents a theoretical study of the effect of both the Purcell factor and the spontaneous emission factor on the dynamic of nano quantum cascade laser in the presence of optoelectronic feedback. We organize this research as follows, the second section presents a form of average equations. The third section presents the results and discussion. Finally, the last section presents the conclusions.

Rate Equations Model:

Figure 1 shows a schematic diagram of optoelectronic feedback in a NQCL.

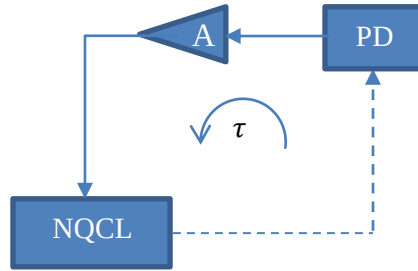


Fig. 1 Schematic diagram of optoelectronic feedback in NQCL .

Fig. 1 shows the optical path (dashed line) and the electronic path (solid lines). The emitted light from a NQCL is detected by photodetector (PD) and the detected photocurrent is fed back through a bias Tee circuit. To study the dynamic of nano quantum cascade laser, the rate equations model must be modified to include Purcell factor F and spontaneous emission factor β . The equations for carrier number in states 1,2 and 3 and the equation of photon number are given by [10].

$$\frac{dN_3}{dt} = \eta \frac{I_{in}}{q} \left(1 + \frac{\zeta S(t - \tau) - S_{off}}{S_s} \right) - \frac{N_3}{\tau_{32}} - \frac{N_3}{\tau_{31}} - \frac{F\beta N_3 S}{\tau_{sp}} - G(N_3 - N_2)S \quad (1)$$

$$\frac{dN_2}{dt} = \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} + G(N_3 - N_2)S \quad (2)$$

$$\frac{dN_1}{dt} = \frac{N_3}{\tau_{31}} + \frac{N_2}{\tau_{21}} - \frac{N_1}{\tau_{out}} \quad (3)$$

$$\frac{dS}{dt} = ZG(N_3 - N_2)S_T - \frac{S}{\tau_p} + \frac{F\beta N_3}{\tau_{sp}}(S + 1) + ZGN_3S \quad (4)$$

Where q is the fundamental charge N_i where $i=3,2$ and 1 represents the carrier number in each state. η is the injection current efficiency, I_{in} is the bias current, $\zeta S(t - \tau)$ is the feedback signals, τ is the delay time, G is the gain factor, S_{off} is a constant, the transition times of carrier between levels are τ_{31} , τ_{32} and τ_{21} , τ_p is the lifetime of photon, τ_{out} is tunnelling time of carrier, Z is the active region parts number, ζ is the feedback coefficient laser circuit and S_s is the steady-state value for the photon number. Finally, τ_{sp} is the spontaneous emission lifetime in free space.

Results and Discussions:

The principal goal in the present study is to investigate the effect of the parameters of nano quantum cascade lasers, namely Purcell factor F and the spontaneous emission factor β on the dynamic of negative optoelectronic feedback. The present simulation is done by using the values of parameters listed in table I.

Table I: The parameters values in present simulation [7-10].

Symbol	Value	Unit
η	0.4	
β	1	
N	40	
F	17	
I	1	mA
G	1.2×10^5	s^{-1}
τ_{sp}	7	Ns
τ_p	0.36	Ps
τ_{32}	2.1	Ps
τ_{31}	2.6	Ps
τ_{21}	0.5	Ps
τ_{out}	0.5	Ps

Figure 2 shows the results of negative optoelectronic feedback in nano quantum cascade laser with delay time equal to 4.67 ns. In the figure, phase portrait and chaotic temporal waveforms of carrier number and photon number. Since the injection current value is small and also the photon lifetime, therefore one can find that the small values of both carrier and photon number are expected. As shown in same the dynamic of photon number has changed after the delay time and the chaotic behaviour is very clear in the present simulation. Figures 3 and 4 shows the phase portrait and chaotic temporal waveforms of carrier number and photon number of NQCL with $F=20$ and $F=25$ respectively.

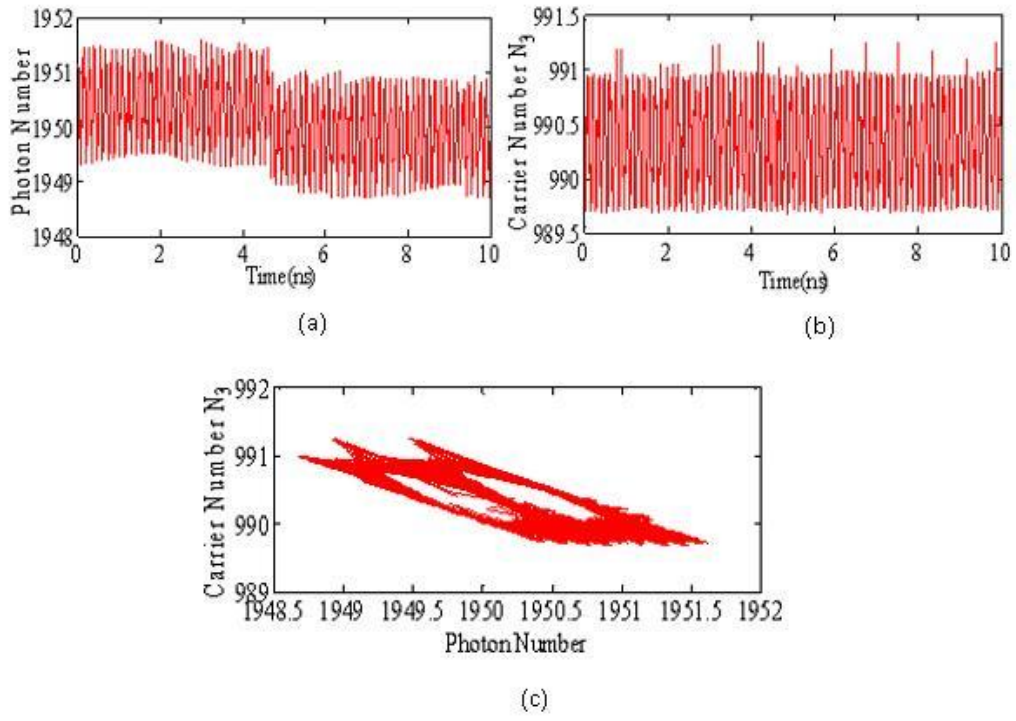


Fig.2 chaotic temporal waveforms of photon number and carrier number and Phase portrait of NQCL with $F=15$ and $\tau = 4.67$ ns.

- a Show the relationship between photon number and time at $F=15$.
- b Show the relationship between carrier number in level three and time at $F=15$.
- c Show the relationship between carrier number in level three and photon number at $F=15$.

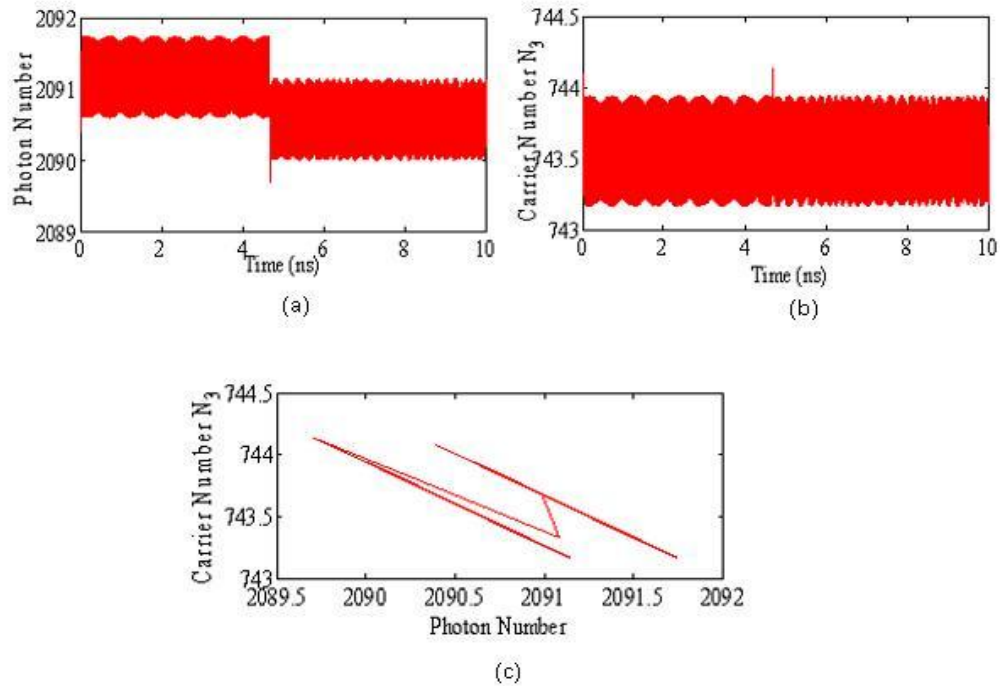


Fig.3. chaotic temporal waveforms of photon number and carrier number and Phase portrait of NQCL with $F=20$ and $\tau = 4.67$ ns.

- a Show the relationship between photon number and time at $F=20$.
- b Show the relationship between carrier number in level three and time at $F=20$.
- c Show the relationship between carrier number in level three and photon number at $F=20$.

As we shown in figures, the increase in purcell effect leads to increase in photon number and decrease the carrier number i.e. increase of the output power. Also, the dynamic of photon number tends to periodic behavior with the increase of purcell effect. This results coming in good agreement with other references.

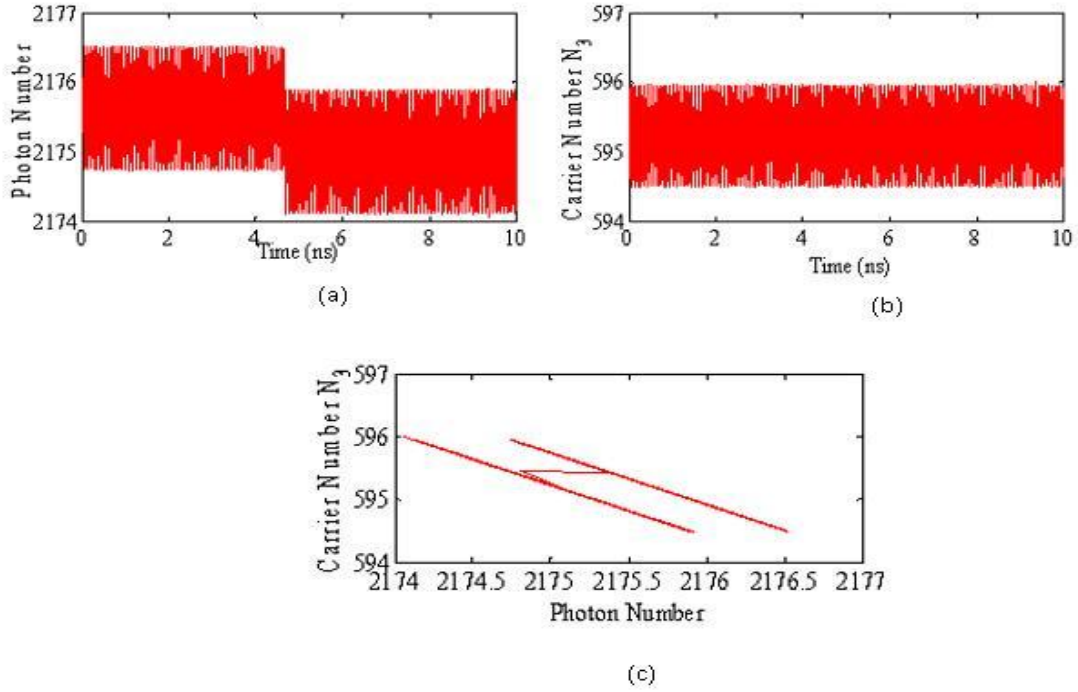


Fig.4 chaotic temporal waveforms of photon number and carrier number and Phase portrait of NQCL with $F=25$ and $\tau = 4.67$ ns

a Show the relationship between photon number and time at $F=25$.

b Show the relationship between carrier number in level three and time at $F=25$.

c Show the relationship between carrier number in level three and photon number at $F=25$.

Figures 5 and 6 shows the phase portrait and chaotic temporal waveforms of carrier number and photon number of NQCL with $\beta=0.5$ and $\beta =0.1$ respectively. As we shown in Figures, the increase in the spontaneous emission factor leads to increase in carrier number and decrease the photon number i.e. decrease of the output power. As we shown in Figures, the decrease in the spontaneous emission factor leads to decrease the photon number and increase the carrier number i.e. decrease of the output power. Also, the dynamic of photon value tends to stable at constant value with the increase of Purcell effect i.e. there is small variation in photon number and carrier number. As we know, the effects of decrease both the Purcell effect and the spontaneous emission factor in the same time cause the increase the threshold current where the small values of F and β means the increase carrier number in the upper states i.e. decreased the radiative transition.

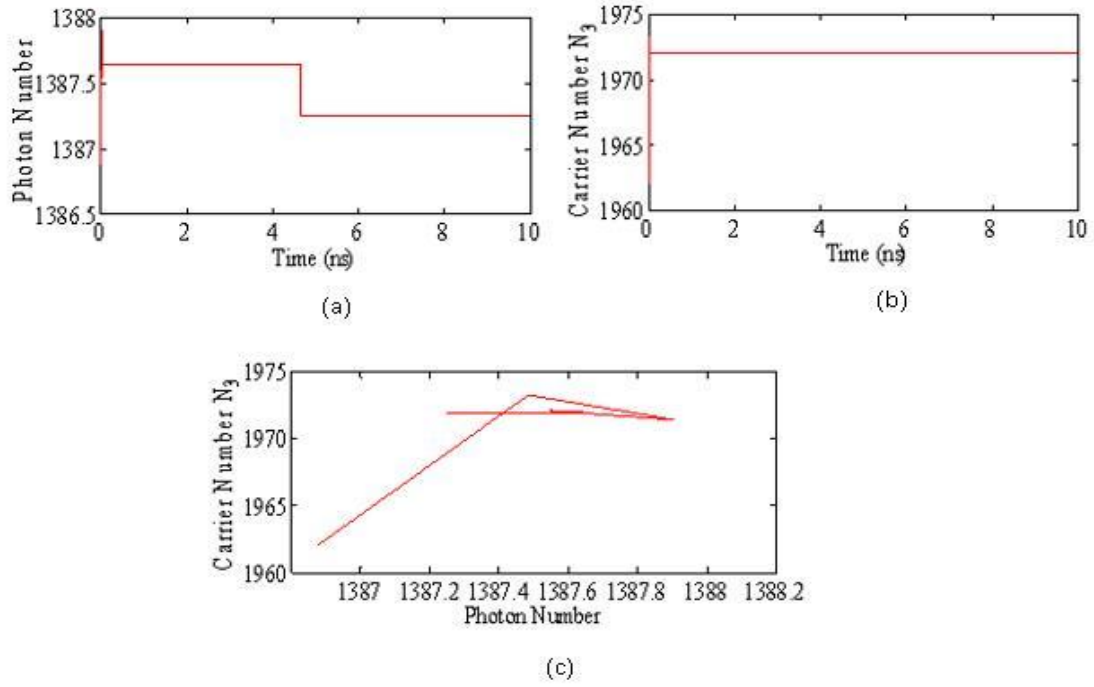


Fig.5 chaotic temporal waveforms of photon number and carrier number and Phase portrait of NQCL with $\beta=0.5$ and $\tau = 4.67$ ns.

a Show the relationship between photon number and time at $\beta = 0.5$.

b Show the relationship between carrier number in level three and time at $\beta = 0.5$

c Show the relationship between carrier number in level three and photon number at $\beta = 0.5$.

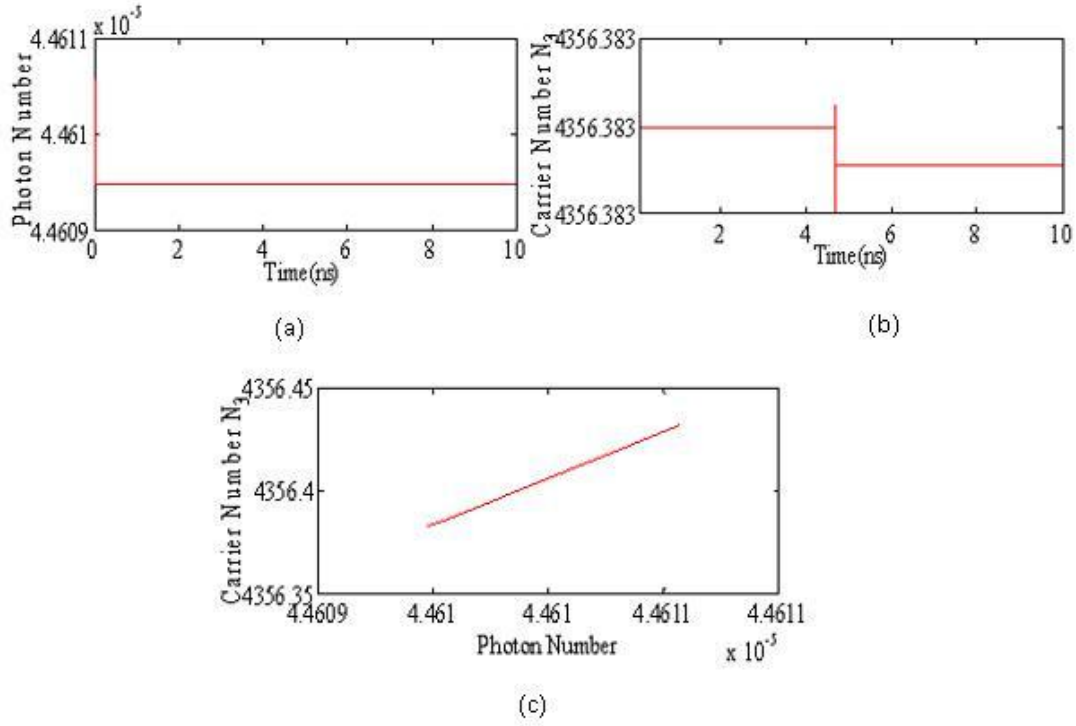


Fig.6 chaotic temporal waveforms of photon number and carrier number and Phase portrait of NQCL with $\beta=0.1$ and $\tau = 4.67$ ns.

a Show the relationship between photon number and time at $\beta=0.1$.

b Show the relationship between carrier number in level three and time at $\beta=0.1$.

c Show the relationship between carrier number in level three and photon number at $\beta=0.1$.

Conclusions :

Negative optoelectronic feedback is investigated using Nano intersubband lasers. This paper introduces a simple model to investigate the Negative optoelectronic feedback and the impacts of F and β on the dynamic of negative optoelectronic feedback. It is found that the increase in Purcell factor value leads to increase in photon number and decrease the carrier number in all quantum states. Also, the dynamic of photon number tends to periodic behaviour with the increase of Purcell effect. The decreases in enhanced spontaneous emission factor value leads to increases in carrier number and decreases the photon number in all quantum states. The increase in threshold current value is coming from the small values of both F and β .

References

1. Ohtsubo, J. (2013). Dynamics in semiconductor lasers with optical injection In *Semiconductor Lasers* (pp. 169-204). Springer, Berlin, Heidelberg.
2. Kane, D. M., & Shore, K. A. (Eds.). (2005). *Unlocking dynamical diversity: optical feedback effects on semiconductor lasers*. John Wiley & Sons.
3. Wójcik, A. K., Yu, N., Diehl, L., Capasso, F., & Belyanin, A. (2011). Self-synchronization of laser modes and multistability in quantum cascade lasers. *Physical review letters*, 106(13), 133902.
4. Tang, S., Chen, H. F., & Liu, J. M. (2001). Stable route-tracking synchronization between two chaotically pulsing semiconductor lasers. *Optics letters*, 26(19), 1489-1491.

5. ADAMSON, B. J., & Westbrook, M. T. (1988). Crafty birds and fitness fiends: Relationships of professional and leisure activities. *The Australian journal of physiotherapy*, 34(2), 67.
6. Waried, H. (2018). Synchronization of quantum cascade lasers with negative optoelectronic feedback. *Recent Advances in Electrical & Electronic Engineering (Formerly Recent Patents on Electrical & Electronic Engineering)*, 11(2), 167-175.
7. Waried, H. H. (2018). Synchronization of quantum cascade lasers with mutual optoelectronic coupling. *Chinese journal of physics*, 56(3), 1113-1120.
8. Waried, H. (2019). Chaos synchronization of coupled nano-quantum cascade lasers with negative optoelectronic feedback. *The European Physical Journal D*, 73(2), 39.
9. Waried, H. H. (2019). Controlling the Synchronization of Quantum Cascade Lasers with Negative Optoelectronic Feedback by Direct Current Modulation. *Iranian Journal of Science and Technology, Transactions A: Science*, 43(4), 2001-2011.
10. Waried, H. (2017). Modulation response and relative intensity noise spectra in quantum cascade lasers. *Physical Chemistry Research*, 5(2), 377-394.

التحقيق في ديناميكية الليزر الكمية المتعاقبة النانوية مع التغذية العكسية البصرية

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البحث مسجل من اطروحة دكتوراه الباحث الاول

الخلاصة:

في هذه الدراسة، تم تقديم دراسة نظرية التغذية العكسية البصرية السلبية في أشعة الليزر المتتالية النانوية. نظراً لأن تأثير الانبعاثات التلقائية عامل مهم في التجويف الدقيق، فقد تم إعادة النظر في نموذج معادلات المعدل ليشمل عامل تعزيز الانبعاثات التلقائية لبورسيل وعامل الانبعاثات التلقائية. تشير النتائج إلى أن نموذج معادلة المعدل الحالي يمكن استخدامه لدراسة تأثير عامل تعزيز الانبعاثات التلقائية لبورسيل وعامل الانبعاثات التلقائية على التغذية العكسية البصرية السلبية في الليزر الكمية المتعاقبة النانوية. لقد وجد أن الزيادة في قيمة عامل بورسيل تؤدي إلى زيادة عدد الفوتون وتقليل عدد الحامل في جميع حالات الكم. أيضاً، تميل ديناميكية عدد الفوتون إلى الاستقرار عند قيمة ثابتة مع زيادة تأثير بورسيل، أي أن هناك اختلافاً بسيطاً في رقم الفوتون وعدد الحامل. يؤدي الانخفاض في قيمة عامل الانبعاثات التلقائية المعزز إلى زيادة عدد الحامل ويقلل عدد الفوتون ونلاحظ تبايناً طفيفاً في هذه القيم.

معلومات البحث:

تاريخ الاستلام: 2020/02/21

تاريخ القبول: 2020/05/12

الكلمات المفتاحية:

الليزر الكمية المتعاقبة النانوية،
التغذية البصرية، عامل بورسيل، عامل
الانبعاثات التلقائية، نموذج معادلات
المعدل