مدلسازی اثر ناخالصی نوع P بر نویز شدت نسبی درلیزرهای نقطه کوانتومی

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چکیده- در این مقاله به مدلسازی اثر ناخالصی نوع p بر مشخصه نویز شدت نسبی در لیزرهای نقطه کوانتومی در طول موج ۱/۳ میکرومتر پرداخته شده است. معادلات نرخ الکترونها و حفره ها در سه تراز گسسته در نقاط کوانتومی به همراه دو تراز پیوسته در چاه کوانتومی و ناحیه سد پتانسیل به همراه معادله نرخ فوتونها در رژیم سیگنال کوچک حول نقطه کار به فرم خطی درآورده شده و سپس منابع نویز لنجوین اضافه گردیده است. محاسبات نشان می دهد که ناخالصی نوع P باعث کاهش میزان نویز شدت نسبی در لیزرهای نقاط کوانتومی می گردد. با افزایش جریان پمپ، توان خروجی لیزر نقطه کوانتومی آلاییده شده افزایش یافته و از میزان نویز شدت نسبی کاسته می شود. این رفتار کاهشی نویز در اثر افزایش جریان و مقادیر شدت نویز محاسبه شده با نتایج تجربی گزارش شده همخوانی دارد.

کلید واژه- لیزر نقطه کوانتومی، ناخالصی نوع p، گین غیرخطی، منابع لنجوین، نویز شدت نسبی.

Theoretical Modeling of p-doping Effect on Relative Intensity Noise in 1.3μm InAs/GaAs Quantum Dot Lasers

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Abstract- In this paper we investigate theoretically the effect of p-doping on the relative intensity noise characteristics of 1.3μm InAs/GaAs quantum dot lasers. The rate equations for electrons and holes in three QDs' discrete levels, wetting and barrier states besides the rate of photons have been linearized in small signal regime around the operating point. Calculations demonstrate that p-doping would decrease the relative intensity noise of the quantum dot lasers. By increasing the injection current, the output power rises and the noise intensity reduces in p-doped QD laser which is in agreement with reported experimental results.

Keywords: Quantum dot lasers, P-doping, Nonlinear gain, Langevin sources, Relative intensity noise.

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1 Introduction

In recent decade, semiconductor quantum dot (QD) lasers have been widely attracted to realize enhanced performances demanded for high speed optical communication systems [1]. From theoretical point of view, three dimensional confinement of carriers in quantum dots would results in the formation of the population inversion under much lower current injection. Since the successful report on growth of self-assembled InAs/GaAs(InP) QDs in Stranski-Krastanow (SK) mode with considerable crystal quality and high areal density, intensive experimental efforts have been devoted to realize proposed superior performances of QD lasers in the range of 1.3(1.55)μm wavelength [1]. Although low threshold current at room temperature have been observed in some real 1.3 μm InAs/GaAs QD lasers, temperature stability of these lasers had degraded from theoretical predictions [2]. This is attributed to the closely energy spaced of the discrete hole states in QDs. One effective suggested method to overcome thermal broadening of holes is to provide excess hole concentrations via moderate p-doping in GaAs barrier. Higher modal gain and more temperature stability of threshold current have been observed in p-doped QD lasers experimentally [3]. However injection of more excess holes to the wetting layer, leads to higher non-radiative Auger recombination [4]. One of the essential characteristics of a laser to be investigated is its noise aspect. Actually the value of the relative intensity noise (RIN) plays a key role in estimating the transmission data rate and the maximum possible distance of fibre-optic links. How much lower be the RIN value of a laser, higher transmission rate through longer distance could be reliable [5]. The first measurements on intensity noise of p-doped QD lasers in 1.3μm wavelength have been reported in 2012 by G. Lin et. al.[6]. Their results have shown a level of -135 to -155 (dB/Hz) over a wide range of frequency up to 10(GHz), for a p-doped 1.3μm quantum dot laser in which the QD layers have been grown with uniform barrier thickness [6]. In this paper we seek to study the effects of p-doping on RIN value of InAs/GaAs QD lasers from a theoretical point of view. The rest of this paper is organized as follows. In Section 2, we present the governing equations and the theoretical modeling approach. In Section 3, the results on the intensity noise analysis of a QD laser are discussed. Finally, conclusions are presented in Section 4.

2 Theoretical Modeling

Regarding the various system of rate equations for modelling characteristics of QD lasers, we develop a rigorous theory based on the theoretical model of Ref. [7]. For evaluating the relative intensity noise of 1.3μm QD lasers, the separate electron and hole states for GaAs-barrier and wetting layer have been included in addition to the nonlinearity of gain. The definition and value of all the parameters used in this model have been outlined in table I. Since the concentration of carriers in wetting layer state, strongly affects the Auger recombination process, the carrier relaxation rate have been calculated considering phonon-assisted and Auger relaxation [7].

Table I- Value of structural parameters

Symbol	Meaning	Value
n	Number of QD layers	8
ρ	Surface density of QDs(cm^{-2})	6×10^{10}

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b	Barrier thickness(nm)	324
N_a	Doping of barrier(cm^{-3})	5×10^{16}
L_a	Cavity Length(μm)	300
Sa	Area of active region(μm^2)	2×300
θ_c	Coverage of QDs	0.157
d	Distance from doped layer to cap layer(nm)	10
t_{bd}	Transition time from doped layer to cap layer(ps)	5.22

The rate equations have been written considering the lasing action from the QDs' ground state and first excited state as the first and the second lasing modes respectively under pumping current density of J (A/m^2). To investigate the RIN, we consider a time dependent small signal perturbations, $\delta n_B^{e(h)}(t), \delta f_i^{e(h)}(t)$ and $\delta s_j(t)$ for all the carrier concentration in barrier, densities of occupation probabilities of QD levels and wetting layer state and photon densities around the steady state work point as follows.

$$n_B^{e(h)}(t) = N_B^{e(h)} + \delta n_B^{e(h)}(t) \quad (1)$$

$$f_i^{e(h)}(t) = F_i^{e(h)} + \delta f_i^{e(h)}(t) \ , \ (i = w, 0, 1, 2) \quad (2)$$

$$s_j(t) = S_j + \delta s_j(t) \ , \ (j = 0, 1) \quad (3)$$

While $n_B^{e(h)}(t)$ and $f_i^{e(h)}(t)$ $(i = w, 0, 1, 2)$ stand for the whole time dependent value of the electrons (holes) concentration in GaAs barrier, density of occupation probabilities for electrons (holes) in wetting layer and three discrete energy levels in QDs respectively and $s_{0(1)}(t)$ represents the total number of photons of the first (second) lasing mode. The steady state values of the mentioned variables, $N_B^{e(h)}, F_i^{e(h)}$ and S_j under a fixed injection current, would be calculated by solving twelve coupled rate equations. As well the small signal parts of the rate equations might be linearized by neglecting the quadratic and higher powers of δ's. Langevin noise sources are added to the rate equations. In rate equation of the holes in wetting layer state, the term $\frac{N_a \theta_c d}{t_{bd}}$ is added to represent the excess hole concentration in the p-doped QD lasers. It has been allowed the gain to vary with photon numbers for nonlinear gain effects [7]. Under Markovian assumptions, the Langevin noise sources might satisfy the following general relations [8].

$$\langle F_k(t) \rangle = 0 \quad (4)$$

$$\langle F_k(t), F_{k'}(t') \rangle = 2D_{kk'}\delta(t - t') \quad (5)$$

Where angle brackets $\langle \cdot \rangle$, show the ensemble average and $D_{kk'}$ denotes the diffusion coefficients associated with the corresponding noise sources. The auto-correlation D_{kk} can be considered as the terms in the rate equations which have been added to or subtracted from the number of carriers and photons [8]. The cross-correlation coefficients $D_{kk'}$ can be interpreted as the terms which have been subtracted from the number of carriers and photons [8]. By taking Fourier transform from the linear small signal rate equations and representing them in a single matrix equation, we obtain a closed from. The intensity noise at a given frequency ω would be characterized by the relative intensity noise (RIN) per unit bandwidth defined as [8]:

$$\frac{RIN}{\Delta f} = \frac{S_p(\omega)}{{S_T}^2} \quad (6)$$

while $S_T = S_0 + S_1$ stands for the total number of photons at steady state work point. The total spectrum of photons might be evaluated by solving the matrix equation.

In the next section, the numerical calculated results of RIN in the 1.3μm InAs QD lasers based on the above model would be presented.

3 Results and Discussion

In order to investigate the RIN properties of 1.3μm QD lasers, twelve rate equations have been solved under constant injection current J within Runge-Kutta method. The Light-Current (L-I) characteristics of un-doped and p-doped QD lasers have been calculated at temperature T=300K and have shown in Figure 1. As depicted in p-doped QD laser, the output power is higher than un-doped one because of excess holes which provide higher modal gain. The values of RIN in p-doped and un-doped QD lasers have been evaluated in Figure 2, for injection current density of J=12 (kA/cm^2). It is demonstrated that noise intensity has lower level in p-doped QD lasers comparing with un-doped one.It can be deduced that p-doping introduces two new terms added to cross and auto-correlation coefficients of hole density at wetting layer state. Among these two terms, the term added to cross correlation coefficient has negative value with larger amplitude comparing with positive value of the new term in auto correlation coefficient. Hence RIN in p-doped QD laser gets smaller value than in un-doped one. It is also depicted that although p-doping improves noise intensity characteristics but it

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reduces modulation bandwidth by decreasing resonance frequency.

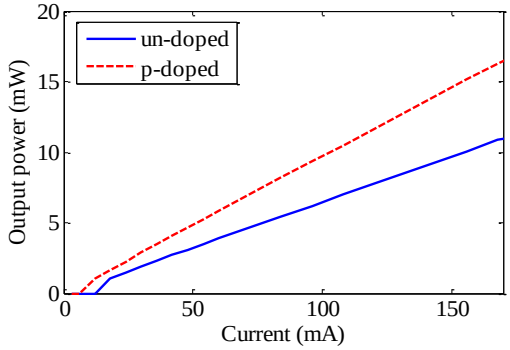


Figure 1- L-I characteristics of un-doped and p-doped QD lasers at temperature T=300K.

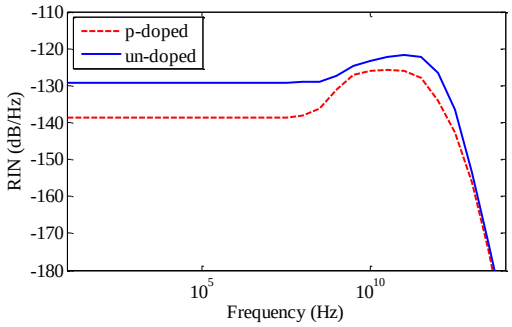


Figure 2- RIN in p-doped with doping concentration of $N_a=5\times10^{16}(cm^{-3})$ and un-doped QD lasers at I=12 (mA)

To investigate the effect of injection current on noise intensity of p-doped QD lasers, we have evaluated RIN value of p-doped QD laser with 8 QD layers and QD areal density of $\rho=6\times10^{10}(cm^{-2})$ similar to structural parameters considered at [6]. Figure 3, shows RIN value of p-doped QD laser with doping concentration of $Na=5\times10^{16}(cm^{-3})$ at three current density of $J_1=6$, $J_2=12$ and $J_3=18$ (kA/cm^2). As it is shown by increase of current and output power, the RIN value reduces from -130 to -140 (dB/Hz). It is evident that increase of output power results in decrease of relative intensity noise. This reduction behaviour due to increase of current and calculated amplitudes of RINs are in agreement with experimental results of G. Lin et. al. for uniform p-doped QD laser[7].

4 Conclusions

The evaluated values of RIN in p-doped and un-doped QD lasers demonstrate that noise intensity has lower level in p-doped QD lasers comparing with un-doped one. It is also depicted that although p-doping improves noise intensity characteristics of QD lasers but it reduces their modulation bandwidth by decreasing the resonance frequency. From calculations it is also evident that increase of output power results in decrease of relative intensity noise. This reduction behaviour due to increase of output power and calculated amplitudes of RINs are in agreement with experimental results reported recently.

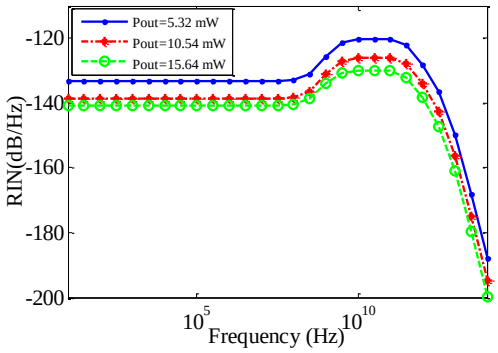


Figure 3- RIN value of p-doped QD laser with doping concentration of $Na=5\times10^{16}(cm^{-3})$ at three current density of $J_1=6$, $J_2=12$ and $J_3=18$ (kA/cm^2)

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