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Influences of quantum noises on direct-modulated properties of 1.3-μm InGaAsP/InP laser diodes*

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Due to the zero dispersion point at 1.3μm in optical fibres, 1.3-μm InGaAsP/InP laser diodes have become main light sources in fibre communication systems recently. Influences of quantum noises on direct-modulated properties of single-mode 1.3-μm InGaAsP/InP laser diodes are investigated in this article. Considering the carrier and photon noises and the cross-correlation between the two noises, the power spectrum of the photon density and the signal-to-noise ratio (SNR) of the direct-modulated single-mode laser system are calculated using the linear approximation method. We find that the stochastic resonance (SR) always appears in the dependence of the SNR on the bias current density, and is strongly affected by the cross-correlation coefficient between the carrier and photon noises, the frequency of modulation signal, and the photon lifetime in the laser cavity. Hence, it is promising to use the SR mechanism to enhance the SNR of direct-modulated InGaAsP/InP laser diodes and improve the quality of optical fibre communication systems.

Keywords: InGaAsP/InP laser diodes, carrier noise, photon noise, linear approximation method
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1. Introduction

InGaAsP/InP double-heterostructure laser diode is an illuminant device that functions by means of electronic transitions between the conduction and valence bands, so the quantum noises are inevitable.[1] Especially, when a laser diode is direct-modulated, the high density carriers and photons strongly fluctuate with space and time in an active region of the laser diode. Moreover, when the quantum noises are cross-correlated, they will greatly affect the direct-modulated properties of the laser diode.

Since the phenomenon of stochastic resonance (SR) was originally discovered by Benzi *et al*[2] and Nicolis C and Nicolis G[3] in 1981, it has been intensively investigated in many scientific fields, in order to improve properties of those systems by using the positive effect of noises.[4,5] In optical systems, SR has attracted a wide interest. In 1988, McNamara *et al* first observed that the output signal-to-noise ratio (SNR) in a ring laser versus the input noise intensity exhibited a maximum, i.e. stochastic resonance.[6] Subsequently, Vemuri and Roy studied a bistable ring laser by using numerical simulation, and they also found a bell-shaped behaviour in the dependence of the SNR on the noise intensity.[7] Grohs *et al* observed the SR again based on the optically bistable behaviour in 1994, which was achieved by the thermally induced absorption nonlinear characteristic of CdS crystals.[8]

In 2003, we found that the SR could be used to enhance the SNR of modulated laser systems and improve optical fibre communication quality by investigating the SR in the gain–noise model of single-mode lasers.[9,10] The model we considered there is a gain–noise model, which corresponds only to class-A lasers.[11] However, it is the 1.3-μm InGaAsP/InP laser diode that is widely used in optical fibre communication systems now, since an electric signal can be directly modulated to the injection current of a semiconductor laser. There are two advantages for this kind of modulation. One is that the output optical intensity can be easily modulated by an electric signal, the other is that the electric signal can be di-

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rectly converted into an optical signal. Therefore it is more practical and important to investigate the SR of semiconductor lasers to enhance their modulation properties and improve optical fibre communication quality.

In this work, by introducing a carrier noise and photon noise into a single-mode 1.3-μm InGaAsP/InP laser diode system, we investigate the behaviour of the SR induced by the carrier noise and photon noise, and their influences on the direct-modulated properties of the laser diode. In order to prevent distortion of the modulated signal, laser diodes must operate in a linear region in the course of the signal modulation. Hence, the rate equations of InGaAsP/InP laser diode can be treated using the linear approximation method.[9−11] With the cross-correlation between the carrier noise and photon noise taken into account, we calculate the SNR of the directed-modulated single-mode InGaAsP/InP laser diode system and obtain an analytic expression of the SNR. By virtue of the expression of the SNR, we analyse the characteristics of the SNR as a function of the bias current density, the influences of the cross-correlation coefficient of the carrier noise and photon noise, the frequency of the modulation signal, and the life time of photons in the laser cavity.

2. Model

Considering the carrier and photon noises, the single-mode rate equations of an InGaAsP/InP laser diode with Langevin noise sources can be written as[12]

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{j}{qd} - \frac{N}{\tau_{\mathrm{sp}}} - \frac{c}{n}g(N)S + F_{\mathrm{N}}, \tag{1}$$

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \left[\frac{c}{n}\Gamma g(N) - \frac{1}{\tau_{ph}}\right]S + \Gamma\beta\frac{N}{\tau_{\mathrm{sp}}} + F_{\mathrm{S}}, \tag{2}$$

where j is the injection current density, and N and S are respectively the carrier and photon densities in an active region of the laser, q and d are the electron charge and the active layer thickness, respectively. The spontaneous-emission lifetime τ_{sp} of carriers in the active region is mainly determined by the properties of the active layer material. The lifetime of photons in the laser cavity, τ_{ph}, is mainly determined by the total optical loss including the internal loss and the mirror facet loss. Generally, it is related to the crystalline quality in the active region, the laser cavity length and the mirror facet reflectivity. And Γ and $g(N)$ are the optical confinement factor and the optical gain as a function of the carrier density respectively. The spontaneous-emission factor β denotes a fraction of the spontaneous emission coupled into the lasing mode, and $\frac{c}{n}$ is the mode velocity. The Langevin noise terms F_{N} and F_{S} are the carrier noise and photon noise and represent fluctuations of the carrier and photon densities in the laser cavity respectively. It is assumed that the two noises are white ones and auto-correlated in the following form:

$$\begin{aligned} &< F_{\mathrm{N}}(t)F_{\mathrm{N}}(t+\tau) >= D_{\mathrm{NN}}\delta(\tau), \\ &< F_{\mathrm{S}}(t)F_{\mathrm{S}}(t+\tau) >= D_{\mathrm{SS}}\delta(\tau), \end{aligned} \tag{3}$$

where D_{NN} and D_{SS} denote the noise strengths of the carrier and photon densities. Considering the statistical property of the quantum noise and applying the steady-state rate equation, we find that the noise strengths of the carrier and photon densities are, respectively,[13]

$$\begin{aligned} D_{\mathrm{NN}} &= 2\beta N_0 S_0/\tau_{\mathrm{sp}} + 2N_0/\tau_{\mathrm{sp}}V_{\mathrm{a}}, \\ D_{\mathrm{SS}} &= 2\beta N_0 S_0/\tau_{\mathrm{sp}}, \end{aligned} \tag{4}$$

where N_0 and S_0 are, respectively, the steady-state carrier and photon densities and determined by the bias current density, and V_{a} is the volume of the active region of the laser diode. The stochastic spontaneous emission of electrons results in the fluctuation of the carrier density; meanwhile, part of photons generated by spontaneous emission couple into the lasing mode and result in the fluctuation of the photon density. Therefore the noises of carrier density and photon density are cross-correlated with each other. In order to simplify calculation, the two noises are cross-correlated in the form of delta-function[14]

$$\begin{aligned} < F_{\mathrm{N}}(t)F_{\mathrm{S}}(t+\tau) >&= < F_{\mathrm{S}}(t)F_{\mathrm{N}}(t+\tau) > \\ &= \lambda\sqrt{D_{\mathrm{NN}}D_{\mathrm{SS}}}\delta(\tau), \end{aligned} \tag{5}$$

where λ is the cross-correlation coefficient, and $-1 \leq \lambda \leq 1$.

For an InGaAsP/InP double-heterostructure laser diode, the dependence of the optical gain on the carrier density can be approximated as[15]

$$g(N) = a(N - N_{\mathrm{T}}), \tag{6}$$

where a is the gain coefficient, and N_{T} is the carrier density at transparency.

3. Power spectrum and SNR of photon density

The rate equations (1) and (2) are non-linear, and we cannot obtain their exact solutions analytically. However, because a laser diode is required to operate in a linear region in the course of signal modulation, the rate equations (1) and (2) can be solved by using the linear approximation method, i.e. small-signal analysis. Under direct-current modulation, the injection current density j, the photon density S and the carrier density N are all time-dependent, and each consists of two parts as shown below,

$$\begin{aligned} j &= j_0 + j_m \cos \Omega t, \\ S &= S_0 + \Delta S, \\ N &= N_0 + \Delta N, \end{aligned} \tag{7}$$

where j_0 is the bias current density, and j_m and Ω are the amplitude and frequency of the modulation signal, respectively. And ΔS and ΔN are the perturbing terms of the steady-state carrier density N_0 and photon density S_0 respectively. The rate equations (1) and (2) can be linearized by using Eqs.(7) and the truncated Taylor series of the optical gain

$$g(N_0 + \Delta N) = g(N_0) + G_0 \Delta N, \quad G_0 \equiv \frac{\mathrm{d}g}{\mathrm{d}n}\,|_{\mathrm{N_0}} .$$

We then obtain

$$\frac{\mathrm{d}\Delta N}{\mathrm{d}t} = A_1 \Delta N + A_2 \Delta S + \frac{j_m \cos \Omega t}{qd} + F_{\mathrm{N}}, \tag{8}$$

$$\frac{\mathrm{d}\Delta S}{\mathrm{d}t} = A_3 \Delta N + A_4 \Delta S + F_{\mathrm{S}}, \tag{9}$$

where

$$\begin{aligned} A_1 &= -(1/\tau_{\mathrm{sp}} + G_0 S_0 c/n), \\ A_2 &= -g(N_0)c/n, \\ A_3 &= \Gamma\beta/\tau_{\mathrm{sp}} + \Gamma G_0 S_0 c/n, \\ A_4 &= \Gamma g(N_0)c/n - 1/\tau_{\mathrm{ph}}. \end{aligned}$$

The linear set of Eqs.(8) and (9) can be readily solved in the frequency domain using Fourier analysis. We can obtain the solutions of ΔS and ΔN in the frequency domain by Fourier transform, and then the expression of ΔS in the time domain can be obtained by inverse Fourier transform. Finally, we calculate the power spectrum of the photon density, and the result is

$$\begin{aligned} S_{\mathrm{S}}(\omega) =& \frac{A_3^2(D_{\mathrm{NN}} + j_{\mathrm{m}}^2 \delta(\omega - \Omega)/q^2 d^2) + (\omega^2 + A_1^2) D_{\mathrm{SS}} - 2A_1 A_3 D_{\mathrm{NS}}}{(A_1 A_4 - A_2 A_3 - \omega^2)^2 + \omega^2 (A_1 + A_4)^2} \\ \equiv& S_1(\omega) + S_2(\omega), \end{aligned} \tag{10}$$

where $S_1(\omega)$ and $S_2(\omega)$ are the power spectra of the signal and noise, respectively. The SNR is given by[16]

$$\mathrm{SNR} = \frac{P_{\mathrm{S}}}{S_2(\omega = \Omega)} = \frac{(A_3 j_{\mathrm{m}}/qd)^2}{A_3^2 D_{\mathrm{NN}} + (\Omega^2 + A_1^2) D_{\mathrm{SS}} - 2A_1 A_3 D_{\mathrm{NS}}}, \tag{11}$$

where $P_{\mathrm{S}} = \int_0^\infty S_1(\omega) d\omega$.

4. Numerical results and discussions

For an InGaAsP/InP double-heterostructure laser diode, the spontaneous-emission lifetime of carriers and the volume of the active region are constants. From Eq.(4) we can see that the noise strengths of the carrier and photon densities are determined by the steady-state carrier and photon densities. Moreover, the steady-state carrier and photon densities are determined by the bias current density, so the two noise strengths are determined by the bias current density. When the bias current density varies, the two noise strengths vary correspondingly. Because the bias current density not only represents the steady-state operating point, but also determines the noise strengths, we mainly analyse the SR behaviour of the SNR dependence on the bias current density and the influences of the bias current density on directed-modulated properties.

In order to analyse properties of the SNR dependence on the bias current density j_0 in a semiconductor direct-modulation laser system, we plot the SNR-vs-j_0 curves according to the expression (11). Each curve corresponds to different parameters of the cross-correlation coefficient between the two noises, the fre-

quency of modulation signal, and the photon lifetime in the laser cavity.

Typical values of the parameters for a 1.3-μm InGaAsP/InP double-heterostructure laser diode, used in our calculation, are listed in Table 1.

Table 1. Typical values of the parameters for a 1.3-μm InGaAsP/InP double-heterostructure laser diode.

Parameter	value
Cavity length/μm	250
Active-region width/μm	2
Active-layer thickness d/μm	0.2
Confinement factor Γ	0.3
Mode velocity (c/n)/(cm·s^{-1})	7.49×10^{9}
Spontaneous-emission factor β	1×10^{-4}
Spontaneous-emission lifetime τ_{sp}/ns	2.2
Gain coefficient a/cm^2	2.5×10^{-16}
Transparent carrier density N_T/cm^{-3}	1.0×10^{18}

1) Effect of the cross-correlation coefficient on the SNR-vs-j_0 curve

Figure 1 shows the SNRs as a function of the bias current density j_0 for different cross-correlation coefficients. For all values of the cross-correlation coefficient λ in the range $-1 \le \lambda \le 1$, there is a peak of the SR in each of the SNR-versus-j_0 curves. This is different from the case of class-A lasers, whose SR only occurs when $-1 \le \lambda < 0$.[11] As shown in Fig.1, when λ increases from -1 to 1, the SNR decreases, the resonance peak becomes lower, and its position moves toward the left side where the bias current density j_0 corresponding to the resonance peak decreases.

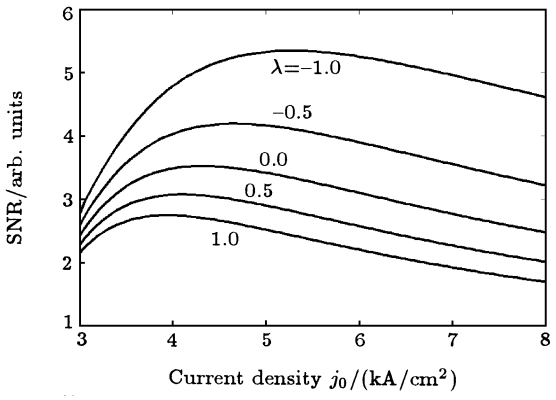


Fig.1. Signal-to-noise ratio (SNR) versus the bias current density with different cross-correlation coefficients.

2) Effect of the signal frequency on the SNR-vs-j_0 curve

Figure 2 shows the curves of the SNR as a function of the bias current density j_0 for different frequencies of modulation signals. In the whole range of the signal frequency Ω permitted by the modulation property of the laser diode, a peak of the SR also occurs in the SNR-vs-j_0 curve. When Ω increases from 1×10^8 Hz to 1×10^9 Hz, the SNR decreases, the resonance peak becomes lower, and its position moves toward the right side where the bias current density j_0 corresponding to the resonance peak increases as shown in Fig.2.

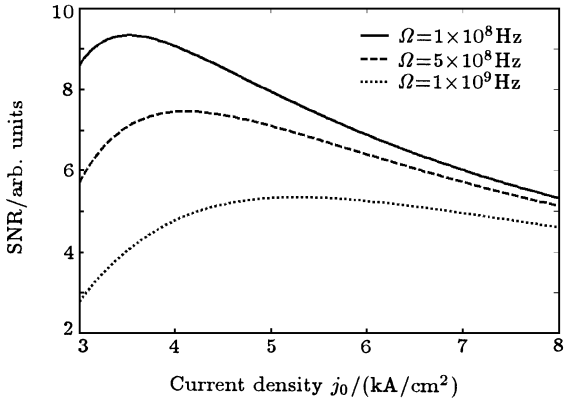


Fig.2. SNR versus the bias current density with different frequencies of modulation signals.

3) Effect of the photon lifetime on the SNR-vs-j_0 curve

Figure 3 shows the curves of the SNR as a function of the bias current density j_0 with different photon lifetimes in the laser cavity. For different photon lifetimes τ_{ph} in the laser cavity that correspond to different lengths and crystalline qualities of the laser cavity, a peak of the SR always occurs in the SNR-vs-j_0 curve. When τ_{ph} increases from 1.6×10^{-12} s to 3×10^{-12} s, the resonance peak of the SNR becomes higher and its position moves toward the left side as shown in Fig.3.

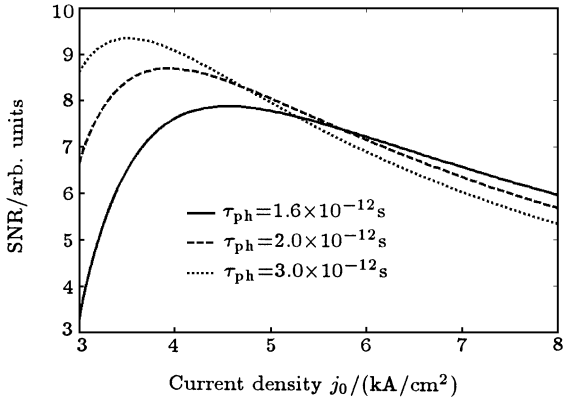


Fig.3. SNR versus the bias current density with different photon lifetimes in the laser cavity.

We emphasize that the results obtained by us-

ing the linear approximation method are reliable only when the conditions $j_{\rm m} << j_0$, $|\Delta N| << N_0$, $|\Delta S| << S_0$ are satisfied.[17] We ensure that the conditions $j_{\rm m} < j_0/100$, $|\Delta N| < N_0/100$ and $|\Delta S| < S_0/100$ are satisfied throughout this work by choosing appropriate parameter values. Furthermore, we also consider the frequency limit of modulation signal because the range of the direct-modulated frequency is determined by the frequency of the relaxation oscillations of InGaAsP/InP laser diodes.

5. Summary

We have investigated the behaviour of the SR in a 1.3-μm InGaAsP/InP laser diode system. According to the results, we know that the SR always appears in the dependence of the SNR on the bias current density and is strongly affected by the cross-correlation coefficient of the carrier and photon noises, the frequency of modulation signal, and the photon lifetime in the laser cavity. The properties of the SR of InGaAsP/InP laser diodes are much different from those observed in our previous work with class-A lasers involved.[9−11] Consequently, SR can take place more easily in InGaAsP/InP laser diode systems, and becomes more convenient in its application.

In recent years, optical fibre communication has developed rapidly. Due to the fact that InGaAsP/InP laser diodes can be easily modulated, they have become the mainstay of optical fibre communication systems. Hence it is useful to investigate the SR for practical applications in optical fibre communication systems. Consequently, our investigation shows the promise in restraining the noise, enhancing the SNR, and improving optical fibre communication quality. We believe that our results may be useful to optical fibre communication systems and optical fibre amplifier technology.

References

[1] Petermann K and Arnold G 1982 *IEEE J. Quantum Electron.* **QE-18** 543

[2] Benzi R, Sutera A and Vulpiani A 1981 *J. Phys.* A **14** L453

[3] Nicolis C and Nicolis G 1981 *Tellus* **33** 225

[4] Gammaltoni L, Hanggi P, Jung P and Marchesoni F 1998 *Rev. Mod. Phys.* **70** 223

[5] Hu G, Ditzinger T, Ning C Z and Hanken H 1993 *Phys. Rev. Lett.* **71** 807

[6] McNamara B, Wiesenfeld K and Roy R 1988 *Phys. Rev. Lett.* **60** 2626

[7] Vemuri G and Roy R 1989 *Phys. Rev.* A **39** 4668

[8] Grohs J, Apanasevich S, Jung P, Issler H, Burak D and Klingshirn C 1994 *Phys. Rev.* A **49** 2199

[9] Wang J, Cao L and Wu D J 2004 *Chin. Phys. Lett.* **21** 246

[10] Wang J, Cao L and Wu D J 2004 *Chin. Phys.* **13** 1811

[11] Wang J, Ma X Y, Cao L and Wu D J 2006 *Physica* A **359** 98

[12] Agrawal G P and Dutta N K 1986 *Long-Wavelength Semiconductor Lasers* (New York: Van Nostrand-Reinhold) p248

[13] Henry C H 1983 *IEEE J. Quantum Electron.* **QE-19** 1391

[14] Mei D C, Chen L E, Xie G Z, Cao L and Wu D J 1999 *Chin. Phys.* **8** 808

[15] Agrawal G P and Dutta N K 1986 *Long-Wavelength Semiconductor Lasers* (New York: Van Nostrand-Reinhold) p34

[16] Hu G 1994 *Stochastic Forces and Nonlinear Systems* (Shanghai: Shanghai Scientific and Technological Education Publishing House) (in Chinese) p227

[17] Agrawal G P and Dutta N K 1986 *Long-Wavelength Semiconductor Lasers* (New York: Van Nostrand-Reinhold) p258