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Stochastic resonance for bias signal-modulated noise in a single-mode laser

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Abstract

By using the linear approximation method, the laser intensity power spectrum and signal-to-noise ratio (SNR) are calculated for a gain-noise model of a single-mode laser driven by colored cross-correlated pump noise and quantum noise, each of which is colored. We found that stochastic resonance(SR) appears in the behavior of the SNR versus not only the pump noise intensity and the self-correlation time, but also the bias current and the frequency of the signal. Moreover, a two-peaked SR occurs in the dependence of the SNR upon the self-correlation time when the cross-correlation coefficient between the both noises is positive, negative and zero, and the resonance peak is sharp. We also find both SR and suppression appear when the SNR varies with the frequency of the signal.

Keywords: Linear approximation method; Colored cross-correlation noises; Bias signal modulation; Stochastic resonance

1. Introduction

Since Benzi et al. [1] originally discovered the phenomenon of stochastic resonance (SR), it was observed in experiments in a variety of scientific fields and has attracted much attention [2–12]. Hence, there are a large number of theoretical and experimental reports about the hot subject. In recent years, there have been considerable developments in the process of exploring the essence of SR. First, Fulinski and Gora [13] and Rosario et al. [14] detected that SR can take place in linear systems or in the absence of a periodic force. It meant that all the three factors, nonlinearity systems, noises, and periodic signals, are not necessary to think of as three essential ingredients for the onset of SR. Next, Vilar and Rubi [15] and Zarkin et al. [16] found the multi-peaked SR, the so-called stochastic multiresonance. To date, it has been a focus investigation on SR. Finally, in traditional concept, the dependence of signal-to-noise ratio (SNR) upon noise intensity was generally used to quantify the characteristic quantity of SR, however, Barzykin and Seki [17] proposed that,

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for colored noise, SR can also be characterized by the dependence of SNR upon noise correlation time. Thus, it made the meaning of SR become wider.

In the process of optical communication, a signal inevitably modulates noises in laser output intensity, the so-called modulated noises, when the signal modulates the laser carrier wave. Moreover, for many other optical devices, for example, semiconductor laser amplifiers, the similar behavior exists. Therefore, it is very important to investigate this kind of modulated noise for practical applications. In 1992, Dykman et al. [18] studied the phenomenon of SR that appeared in an asymmetric bistable model driven by a bias signal-modulated noise. They found that the bias signal-modulated noises can better describe and reveal SR characters of this kind of stochastic systems, and their results were well in agreement with experiments. Further, in 2002, Cao and Wu [19] studied characteristics of SR in a linear system driven by bias signal-modulated noise, and found a single-peaked SR in the behavior of SNR versus the noise intensity and the noise correlation time, respectively, when the noises satisfy negative correlation.

In the technology of optical communication, there are two forms of modulation, the so-called direct signal modulation and bias signal modulation. In this letter, by means of the linear approximation method, we investigate SR which is induced by a bias modulation signal in a gain-noise model of a single-mode laser driven by colored cross-correlated pump noise and quantum noise, each of which is colored and calculate the intensity correlation function, power spectrum and SNR. In the model, the self-correlation time is different from the cross-correlation one. We found that not only the single-peaked SR appears in the dependence of the SNR upon the pump noise intensity Q, but also the two-peaked SR occurs in the behavior of the SNR versus the self-correlation time τ_1. The two-peaked SR can appear when the correlation coefficient between the both noises is positive, negative and zero, and the phenomenon is not reported to date. Moreover, there is a sharp peak in the SNR vs. the bias current i_0 curve, and both SR and suppression appear in the SNR vs. Ω curve, i.e., the SNR exhibits SR when it varies with the bias current i_0 and the frequency of the signal Ω.

2. The output power spectrum and SNR of a single-mode laser

Consider a gain-noise model of a single-mode laser driven by colored cross-correlated pump and quantum noise, each of which is colored. The intensity equation for the single-mode laser with an input bias signal is

$$\frac{\mathrm{d}I}{\mathrm{d}t} = -2KI + \frac{2\Gamma}{1+\beta I}I + D + \frac{2I}{1+\beta I}[i_0 + A\cos(\Omega t)]\xi(t) + 2\sqrt{I}\eta(t), \tag{1}$$

where the statistical property of the pump noise $\xi(t)$ and the quantum noise $\eta(t)$ is assumed as follows:

$$\begin{aligned}
&\langle \xi(t) \rangle = \langle \eta(t) \rangle = 0,\\
&\langle \xi(t)\xi(t') \rangle = \frac{Q}{2\tau_1}\exp\left(-\frac{|t-t'|}{\tau_1}\right),\\
&\langle \eta(t)\eta(t') \rangle = \frac{D}{2\tau_2}\exp\left(-\frac{|t-t'|}{\tau_2}\right),\\
&\langle \xi(t)\eta(t') \rangle = \langle \eta(t)\xi(t') \rangle = \frac{\lambda\sqrt{QD}}{2\tau_3}\exp\left(-\frac{|t-t'|}{\tau_3}\right) \quad (-1 \leqslant \lambda \leqslant 1).
\end{aligned} \tag{2}$$

In Eqs. (1) and (2), I is the laser intensity, K represents the loss coefficient, $\beta = A/\Gamma$, A and Γ represent the self-saturation and gain coefficients; Q and D are the intensities of the pump and quantum noise, respectively; λ is the cross-correlation coefficient between the noises and the self-correlation times of the noises and the cross-correlation time between the noises are τ_1, τ_2 and τ_3, respectively, i_0 is a bias current, $A_0\cos(\Omega t)$ is a periodic signal and Ω is the frequency of the signal. The term $i_0 + A\cos(\Omega t)$ multiplies the pump noise $\xi(t)$, i.e., $\xi(t)$ is modulated by the periodic signal and the bias current. Let

$$I = I_0 + \delta(t), \tag{3}$$