doi:10.3788/gzxb20144311.1114001

偏置调幅波调制下的单模激光光强关联函数随时间的演化

叶庆
(武汉纺织大学 电子与电气工程学院,武汉 430073)

摘 要:采用线性近似法计算了单模激光损失模型在输入偏置信号的调幅波时的光强关联函数 $C(t)$. 发现光强关联函数 $C(t)$ 随时间 t 的演化存在多种变化形式(不规则周期递增、递减等多种振荡形式). 结果表明:当 $a_0=0.1$ 时,出现平坦的不规则周期性振荡;低频调制信号频率 Ω 可调整不规则周期振荡的周期;量子噪音强度 Q 和高频载波信号频率 ω 能改变曲线 $C(t)$ 的初始值和周期.

关键词:单模激光;噪音;光强关联函数;调幅波
中图分类号:TN241 **文献标识码**:A **文章编号**:1004-4213(2014)11-1114001-4

Evolution of the Intensity Correlation Function in a Single-mode Laser with a Biased Amplitude Modulation

YE Qing
(*School of Electronic and Electrical Engineering, Wuhan Textile University, Wuhan* 430073, *China*)

Abstract: By using the linear approximation method, the intensity correlation function $C(t)$ of loss model laser system with a biased amplitude modulation was calculated. The different forms (irregularly periodic increasing, decreasing and so on) were obtained in the evolution of the intensity correlation function $C(t)$ with the time t. The results indicate that: in the case of $a_0=0.1$, the flat irregularly periodic oscillation is shown; the period of irregularly periodic oscillation is adjusted by the low frequency Ω of modulation signal; the initial value and the period of $C(t)$ can be changed by the intensity of quantum noise Q and the high frequency ω of carrier signal.

Key words: Single-mode laser; Noise; Intensity correlation function; Amplitude modulation wave
OCIS Codes: 140.3570; 030.6600

0 Introduction

The intensity correlation function of laser system has been the subject attracted a great deal of attention in theory and experiment over last decades. It is mainly limited by single-frequency signal[1-4] in these researches, but in face fact the broadband-amplitude modulation is adopted. For an instance, the carrier signal has been asked for wider range of frequency in communications. Adding signal to radiation source of laser as an information transfer will have broader application prospects. Moreover, Fulinski and Telejko put forward the conclusion which is existed between the noises[5], then Cao Li *et al.*[6] give a minute study on one-dimension stochastic system driven by the relationship between pump noise and quantum noise. As we know, the intensity correlation function which is a basic statistic quantity in describing the dynamic properties and the statistical properties of a laser system will play an important and a special role. Gui Di *et al.*[7] discuss the intensity correlation function of gain model with colored-pump noises. However, there are few previous works in which the effects of intensity correlation function in loss-noise model with a biased amplitude modulation are considered, as far as we know.

By adopting the linear approximation method, we

Foundation item: The National Natural Science Foundation of China(No. 10275025)
First author: YE Qing(1982—), female, lecturer, master, mainly focuses on laser physics and statistical physics. Email:yeq97@wtu.edu.cn
Received: Apr. 11, 2014; **Accepted**: Jul. 3, 2014

study the time evolution of intensity correlation function for a loss-noise model of a single-mode laser system driven by both colored pump noise and the quantum noise with the cross-correlation between its real and imaginary parts. From the intensity correlation function we also can get the intensity correlation time, statistical fluctuation, the Signal-to-Noise Ratio (SNR) of laser system, and so on. With the SNR of laser system, we can further reveal the phenomenon of stochastic resonance to optimize the output stability of laser system.

1 Calculation and description

The equation of the intensity for a loss-noise model of a signal-mode laser with a biased amplitude modulation is given by

$$\frac{\mathrm{d}I}{\mathrm{d}t'}=2a_0 I-2AI^2+Q(1-|\lambda_q|)+2Ip_R(t')+2\sqrt{I}\varepsilon_r(t')+B(1-D\cos(\Omega t'))\cos(\omega t') \tag{1}$$

where the quantum noise and the pump noise are correlated in the following forms

$$\langle p_R(t')\rangle=\langle\varepsilon_r(t')\rangle=0;\ \langle p_R(t)p_R(t')\rangle=\frac{P}{2\tau}e^{-|t-t'|/\tau}$$
$$\langle\varepsilon_r(t)\varepsilon_r(t')\rangle=Q(1+|\lambda_q|)\delta(t-t')$$
$$\langle p_R(t)\varepsilon_r(t')\rangle=\langle p_R(t')\varepsilon_r(t)\rangle=0 \tag{2}$$

In Eqs. (1) and (2), a_0 and A represent the net gain and the self-saturation, I is the laser intensity, B and D are the amplitudes of carrier signal and modulation signal, Ω is the frequency of modulation signal with low frequency, ω is the frequency of carrier signal with high frequency, $p_R(t)$ is the real part of the pump noise, $\varepsilon_r(t)$ is the quantum noise of phase lock, P and Q are the intensities of the pump noise and the quantum noise respectively, τ is the time of self-correlation, and λ_q is the cross-correlation coefficient between the real and imaginary part of the quantum, and $-1\leqslant\lambda_q\leqslant 1$.

Let $I=I_0+\delta(t')$, where $I_0=a_0/A$ is the deterministic steady-state intensity, and $\delta(t')$ is the perturbation term. We linearize Eq. (1) around the deterministic steady-state intensity I_0, thus get

$$\frac{\mathrm{d}\delta(t')}{\mathrm{d}t'}=-\gamma\delta(t')+Q(1-|\lambda_q|)+2I_0 p_R(t')+2\sqrt{I_0}\varepsilon_r(t')+B(1-D\cos(\Omega t'))\cos(\omega t') \tag{3}$$

where $\gamma=2a_0$, the result is

$$\delta(t')=e^{-\gamma t'}\left[\frac{Q(1-|\lambda_q|)}{\gamma}(e^{\gamma t'}-1)+2I_0\int_0^{t'}p_R(s)\cdot e^{\gamma s}\mathrm{d}s+2\sqrt{I_0}\int_0^{t'}\varepsilon_r(s)\cdot e^{\gamma s}\mathrm{d}s+B\int_0^{t'}[1-\cos(\Omega s)]\cdot\cos(\omega s)\cdot e^{\gamma s}\mathrm{d}s\right] \tag{4}$$

According to the Steady-State Mean Intensity Correlation Function (SSMICF) defined by

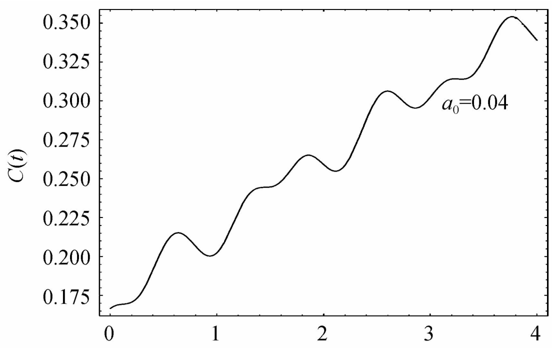
$$C(t)=\lim_{t'\to\infty}\overline{\langle I(t')I(t'+t)\rangle}=\lim_{t'\to\infty}\left(\frac{\Omega}{2\pi}\int_{t'}^{t'+2\pi/\Omega}\langle I(t')I(t'+t)\rangle\mathrm{d}t'\right)$$

inserting $I_0=a_0/A$ and $\gamma=2a_0$, we have

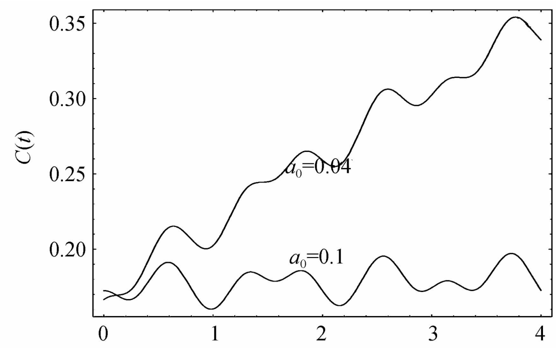
$$C(t)=I_0^2+\frac{2I_0^2P}{\tau}\left(\frac{\tau^2}{\gamma^2\tau^2-1}e^{-\|t\|/\tau}-\frac{\tau}{\gamma(\gamma^2\tau^2-1)}e^{-\gamma|t|}\right)+\frac{\pi B^2D^2}{4[\gamma^2+(\Omega+\omega)^2]^2}\left[\frac{\gamma^2}{\Omega+\omega}+(\Omega+\omega)\right]\cos((\Omega+\omega)t)+\frac{\pi B^2D^2}{4[\gamma^2+(\Omega-\omega)^2]^2}\left[\frac{\gamma^2}{\Omega-\omega}+(\Omega-\omega)\right]\cos((\Omega-\omega)t)+2I_0\frac{Q(1-|\lambda_q|)}{\gamma}+\frac{Q^2(1-|\lambda_q|)^2}{\gamma^2}(1-e^{-\gamma t})+2I_0\frac{Q(1+|\lambda_q|)}{\gamma}e^{-\gamma\|t\|}+\frac{\pi B^2}{\Omega(\gamma^2+\omega^2)}\cos(\omega t) \tag{5}$$

By virtue of the Eq. (5), the curves of $C(t)$ versus the time t with different coefficients are plotted from Fig. 1 to Fig. 4. In the following, we will discuss the evolution of the intensity correlation function of single-mode laser.

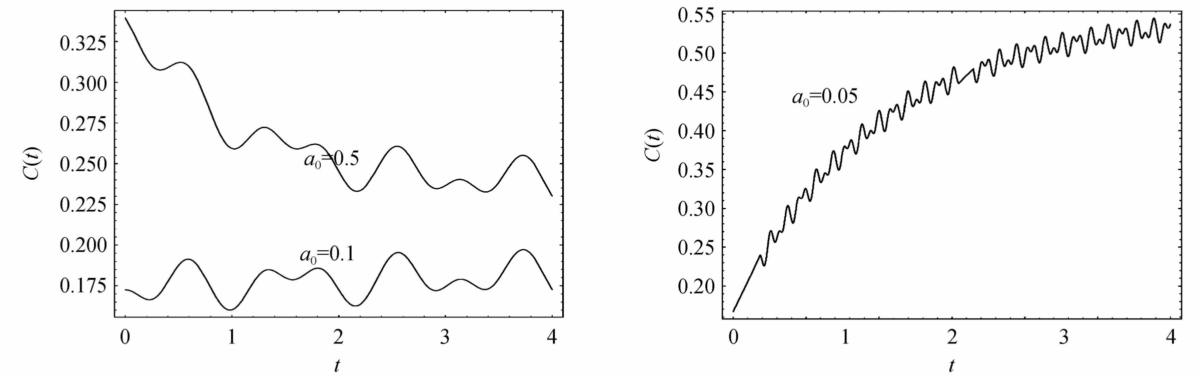
Choosing the net gain a_0 as a parameter, the curves are plotted in Fig. 1. As $a_0=0.04$, the curve of $C(t)-t$ appears increasing irregularly periodic oscillation in Fig. 1(a). In Fig. 1(b) this curve just changes to the flat oscillatory tendency with the net gain increasing to $a_0=0.1$. In the case for $0.1\leqslant a_0\leqslant 0.5$ in Fig. 1(c) this curve abruptly changes flat to decreasing oscillation. It exhibits long time evolution of



(a) a_0=0.04



(b) a_0=0.04,0.1



(c) a_0=0.1,0.5 (d) a_0=0.05

Fig. 1 $C(t)$ for the different values of a_0 where $A=1.2, P=0.001, \tau=0.1, \lambda_q=0.3, B=1, D=1.5$

$C(t)$ on $a_0=0.05$ in Fig. 1(d). The summary is that the oscillatory tendency is suddenly changed when the curve of $C(t)-t$ on $a_0=0.1$.

Choosing the low frequency Ω of modulation signal as a parameter, the curve of $C(t)-t$ is plotted in Fig. 2. The curves obviously change with the low frequency ($4\leqslant\Omega\leqslant5$). From the Fig. 2 we get that the low frequency Ω of modulation signal can wonderfully modulate the irregular oscillation in the time evolution of the intensity correlation function, and also it makes the curve to go to the periodic oscillation.

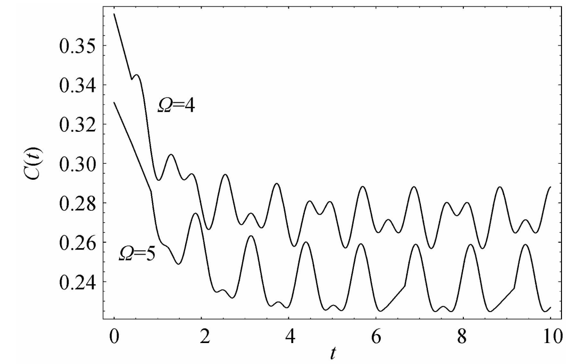


Fig. 2 $C(t)$ for the different values of Ω where $A=1.2$, $P=0.001, \tau=0.1, \lambda_q=0.3, B=1, D=1.5$

Than the curve of $C(t)-t$ is plotted in Fig. 3 by choosing the intensity of quantum noise Q as a parameter. When Q decreases, we get as follows that the curve integrally moves down and the shape of the curve nearly doesn't change.

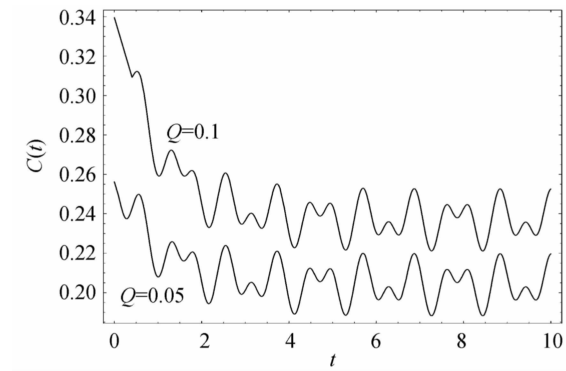


Fig. 3 $C(t)$ for the different values of Q where $A=1.2$, $P=0.001, \tau=0.1, \lambda_q=0.3, B=1, D=1.5$

Similarly, the curve of $C(t)-t$ by choosing the high frequency ω of carrier signal as a parameter is plotted in Fig. 4. With ω increasing, the curve of $C(t)-t$ oscillates faster as well as the initial value of $C(t)$ decreases.

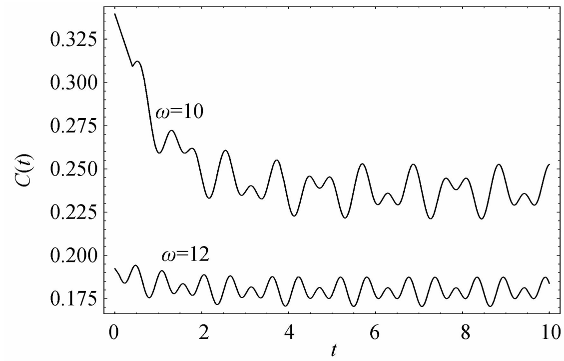


Fig. 4 $C(t)$ for the different values of ω where $A=1.2$, $P=0.001, \tau=0.1, \lambda_q=0.3, B=1, D=1.5$

2 Conclusions

In summary, we discuss the influences on the curve of $C(t)-t$ with the different parameters. Such as the net gain a_0, it can change tendency that the curve moves up or down. Changing the low frequency Ω of modulation signal can make the irregular oscillation close to the regularly periodic quantity. In addition, the intensity of high frequency ω of carrier signal can change the oscillating period of $C(t)$. Also the intensity of quantum noise Q can control the initial value of $C(t)$. According to the formula of the steady-state mean intensity correlation function $C(t)$, its change is decided by the exponential of the function "e" and the periodic signal. With increasing of the frequency ω, the curve of $C(t)$ presents down as a whole. And the curve $C(t)$ presents the attenuation process by the exponential $\gamma=2a_0$ increasing. Moreover, let Ω increase, the tendency of the curve will be changed more regularly. We adopt the linear approximation method, all the values for formula of normalized intensity fluctuation $C(0) \leqslant 1$ is established. The evolution will keep on irregular oscillating periodically for the time extension. It is easy to say that the Eq. (5) only retains the periodical oscillation part when the time lasts forever.

References

[1] LUO Xiao-qin, ZHU Shi-qun. Stochastic resonance in a bistable system with colored correlation between additive and multiplicati-ve noise[J]. *Chinese Physics B*, 2004, **13**(8): 1201-1209.

[2] ZHANG Liang-ying, CAO Li, WU Da-jin. Stochastic resonances in the linear model of Single-mode lasers driven by color noises with color cross correlation[J]. *Acta Physica Sinica*, 2003, **52**(5): 1174-1178.

[3] JIN Yan-fei, XU Wei, LI Wei. *et al*. Stochastic resonance for periodically modulated noise in a linear system[J]. *Acta Physica Sinica*, 2005, **54**(6): 2562-2567.

[4] CHENG Qing-hua, XU Da-hai, CAO Li, *et al*. Influence of noise with signal modulation on intensity correlation function of the single-mode laser[J]. *Journal of Optoelectronics Laser*, 2004, **15**(8): 998-1002.

[5] FULINSKI A. On the effect of interference of additive and multiplicative noise[J]. *Physics Letterts A*, 1991, **152**(1-2): 11-14.

[6] CAO Li, WU Da-jin. Stochastic dynamics for systems driven by correlated noise[J]. *Physics Letters A*, 1994, **185**(1): 59-64.

[7] GUI Di, XU Da-Hai CHENG Qing-Hua. Time evolution properties of intensity correlation function of single mode laser driven by periodic signal modulating colored-pump noises[J]. *Acta Photonica Sinica*, 2012, **41**(5): 541-546.

[8] YE Qing, LI Jing-Xing, YANG Ming, *et al*. Phenomenon of resonance in a two-mode laser with an input additive signal[J]. *Communications in Theoretical Physics*, 2010, **54**(5): 875-878.

[9] JIN Guo-xiang, ZHANG Liang-ying, CAO Li. Stochastic resonance of amplitude modulation wave noise in a single-mode laser[J]. *Journal of Huazhong University of Science and Technology (Natural Science Edition)*, 2008, **36**(2): 115-117.

[10] JIN Guo-xiang, ZHANG Liang-ying, CAO Li. Stochastic resonance in a single-mode laser driven by frequency modulated signal and colored noises[J]. *Chinese Physics B*, 2009, **18**(3): 952-957.

[11] CHEN De-yi, WANG Zhong-long, Intensity correlation function of the single-mode laser with the noise cross-correlation intensity being time period modulated[J]. *Acta Photonica Sinica*, 2009, **38**(4): 801-804.

[12] CHENG Li-mei, CAO Li, WU Da-jin. Intensity correlation time cross-correlation with an additive signal modulation[J]. *Acta Photonica Sinica*, 2005, **34**(6): 885-888.

[13] XU Da-hai, WU Zi-xia, CAO Li, *et al*. Influence of the input signal and noise on characteristic of stochastic resonance in a single-mode laser system[J]. *Acta Photonica Sinica*, 2005, **34**(9): 1311-1315.