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Analysis on the transient of a self-mixing interferometry sensing system

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Abstract

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Keywords

interferometry, mixing, analysis, self, system, transient, sensing

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***Abstract*—The transient of a self-mixing interferometry (SMI) sensing system is investigated in this paper by solving the well known Lang and Kobayashi (LK) equations. Specifically, the influence of two important system parameters, i.e., the feedback level factor and the linewidth enhancement factor, on the transient is discussed, showing that the decay time and the oscillation period of the transient respectively increases and decreases with the increase of the feedback level factor, and both increase with the increase of linewidth enhancement factor. The results presented in this paper are useful for designing a stable SMI system.**

Keywords*—*semiconductor lasers; self-mixing interferometry; transient; stability; optical feedback

I. INTRODUCTION

Self-mixing interferometry (SMI) is an emerging and promising sensing system mainly composed by a semiconductor laser (SL) and a moving external target [1, 2]. In contrast to the traditional interferometric sensing techniques, the SMI has attracted intensive research due to its advantages of impact structure, low-cost and simple implementation [3-7]. The SMI system is based on the self-mixing effect which occurs when a portion of light emitted by the SL reflected by the external target re-enters the SL cavity, leading to the modulation in both the amplitude and frequency of the SL output power. The modulated power is known as the SMI signal which can be used for measuring the metrological quantities of the external target and the parameters associated with the SL itself [8-13].

The mechanism of generating an SMI signal has been studied extensively since its development [2, 14, 15]. However, only few work focus on the dynamical behaviour of the SMI, especially the transient of the SMI. Recently, [16] investigated the transient of an SMI, and showed that the transient contains the information of the target's distance and reflectivity. In this paper, based on the well known Lang and Kobayashi (LK) equations [17] which describe the dynamical behaviour of an SL with optical feedback, we numerically investigate how the two important system parameters, i.e., the feedback level factor and the linewidth enhancement factor, influence the transient of an SMI signal, from which useful information can be obtained for desinging an SMI system with fast response to achieve the equailibrium.

II. THEORY

A. Mathematical model

The SMI sensing system can be described by the well known Lang and Kobayashi (LK) equations [17] by considering a time varying feedback phase $\phi_f(t)$ related to the movement trace of the external target $L(t)$, i.e., $\phi_f(t)=4\pi L(t)/\lambda_0$ where t and λ_0 are respectively the time series and laser wavelength. The LK equations are a set of delayed differential equations (DDEs) and re-written as followings:

$$\frac{dE(t)}{dt}=\frac{1}{2}\left\{G\left[N(t),E(t)\right]-\frac{1}{\tau_p}\right\}E(t)+\frac{\kappa}{\tau_{in}}\cdot E(t-\tau)\cdot\cos\left[\phi_f(t)+\phi(t)-\phi(t-\tau)\right] \tag{1}$$

$$\frac{d\phi(t)}{dt}=\frac{1}{2}\alpha\left\{G\left[N(t),E(t)\right]-\frac{1}{\tau_p}\right\}-\frac{\kappa}{\tau_{in}}\cdot\frac{E(t-\tau)}{E(t)}\cdot\sin\left[\phi_f(t)+\phi(t)-\phi(t-\tau)\right] \tag{2}$$

$$\frac{dN(t)}{dt}=J-\frac{N(t)}{\tau_s}-G\left[N(t),E(t)\right]E^2(t) \tag{3}$$

where $G\left[N(t),E(t)\right]$ is the modal gain per unit time:

$$G\left[N(t),E(t)\right]=G_N\left[N(t)-N_0\right]\left[1-\varepsilon\Gamma E^2(t)\right] \tag{4}$$

In (1)-(4), the other three variables $E(t)$, $\phi(t)$ and $N(t)$ are respectively the electric field amplitude, electric field phase and carrier density. The controllable system external parameters are namely the feedback strength κ , external cavity roundtrip time τ and the injection current J . Note that for an SMI system, it usually prefers to use another parameter to represent the combined effect of κ and τ on the waveform of the SMI signal. This important parameter is called the feedback level factor which is denoted as C and expressed as [18]:

$$C=\frac{\kappa}{\tau_{in}}\tau\sqrt{1+\alpha^2} \tag{5}$$

When $C<1$, the SMI signal contains sinusoidal-like fringes. For $C>1$, the SMI signal shows asymmetric hysteresis and produces sawtooth-like fringes. The scenario behind the relationship between the SMI signal and C has been well-established and presented in [2, 15].

Another important parameter in (2) is the linewidth enhancement factor α which describes many aspects of laser behaviour, such as spectral effects, modulation response, injection locking and the response to external optical feedback. All the meanings and values of other SL parameters appeared in (1)-(4) are listed in Table I.

Table I. The meanings and values of SL parameters in L-K equations

Symbol	Physical Meaning	Value
G_N	modal gain coefficient	$8.4\times10^{-13}m^3s^{-1}$
N_0	carrier density at transparency	$1.4\times10^{24}m^{-3}$
ε	nonlinear gain compression coefficient	$2.5\times10^{-23}m^3$
Γ	confinement factor	0.6
τ_p	photon life time	$2.0\times10^{-12}s$
τ_{in}	internal cavity round-trip time	$8.0\times10^{-12}s$
τ_s	carrier life time	$2.0\times10^{-9}s$

B. *Transient of an SMI system*

Figure 1(b) shows an SMI signal generated using the LK equations by setting $C = 2.5$, $\alpha = 6.0$, $J = 1.7J_{th}$ and $L(t) = L_0 + \Delta L(t) = 0.1 + 1.5\lambda_0 \sin(2\pi ft)$, where L_0 and $f = 400kHz$ are respectively the initial external cavity length and vibration frequency of the external target, while all the other parameters values are used as shown in Table I. The vibration trace $\Delta L(t)$ is shown in Fig. 1(a). Note that in Fig. 1(b), the SMI signal is denoted as $I(t)$ which is the light intensity $E^2(t)$ after normalization. The calculation of $E^2(t)$ uses the fourth order Runge Kutta integration algorithm.

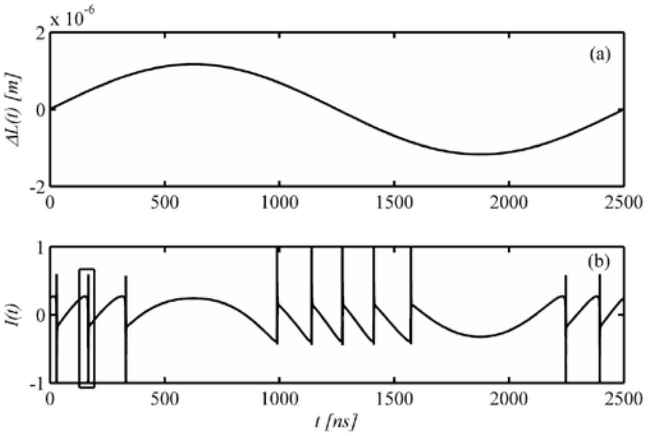

Fig. 1. An SMI signal generated using the LK equations. (a) vibration trace of the external target, (b) the SMI signal represented by the normalized light intensity $I(t)$.

From Fig. 1(b), we can see that the transient occurs at the discontinuities on the SMI signal. To see the details of the transient, we zoom one of discontinuity in Fig. 1(b), and show it in Fig. 2, where two properties, i.e., the decay time τ_D and oscillation period Ω , can be defined to describe the trasient of an SMI signal [16].

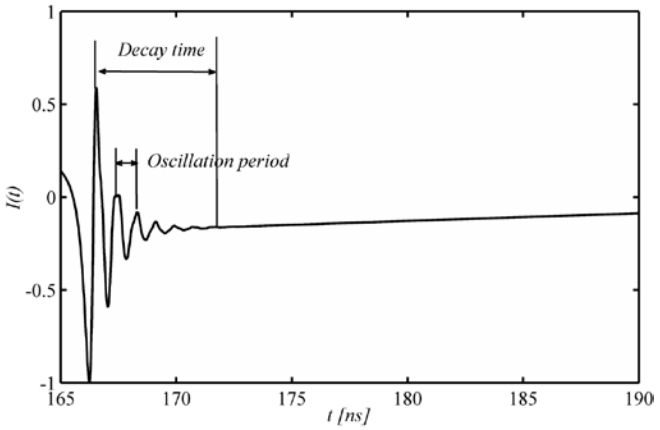

Fig. 2. One of the discontinuities of the SMI signal presented in Fig. 1(b) which shows the transient of the SMI signal.

III. SIMULATIONS

In this section, the influence of C on the transient of an SMI signal is firstly investigated based on the following procedures:

Step1: Set C in a range of [1.0 2.5] with 100 equally sapced values while all the other parameters values are the same with used for generating Fig. 1(b).

Step2: Choose a value of C and solve (1)-(4) to obtain $I(t)$.

Step3: Measure the decay time τ_D and oscillation period Ω of the transient.

Step4: Record the values of τ_D and Ω and repeat Step2 untill all the values of C have been chosen.

Based on the above steps, we can obtain the relationship between τ_D and C , as well as the relationship between Ω and C , which are respectively shown in Fig. 3(a) and (b). From Fig. 3, we can see that τ_D and Ω respectively increase and decrease with the increase of C .

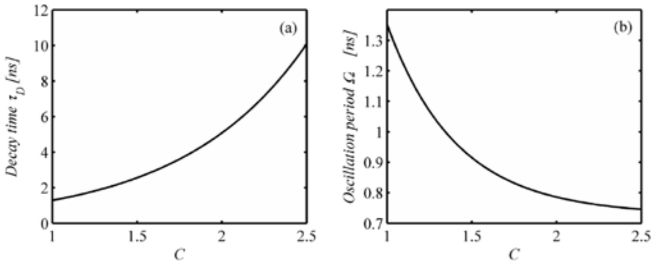

Fig. 3. (a) Relationship between the decay time τ_D and C , (b) relationship between the oscillation period Ω and C .

Similar to the first group of simulations, instead of setting C in a range in Step1, we set α in the range of [1.0 5.5], also with 100 equally spaced values while C is fixed to 2.5. This time, by choosing α value in Step2, we are able to see how α influences the decay time and oscillation period. The influence α is plotted in Fig. 4. It is interesting to notice that both τ_D and Ω increases with the increase of α , and tend to be stable after a certain value of α , e.g., after $\alpha = 4.5$, τ_D always equals to 10.15*ns*.

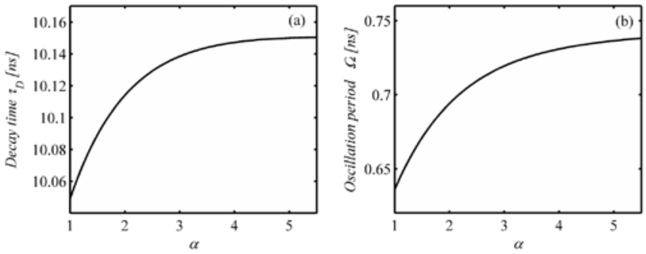

Fig. 4. (a) Relationship between the decay time τ_D and α , (b) relationship between the oscillation period Ω and α .

IV. CONCLUSION

This paper analyse the transient effect of the SMI sensing system. By considering a time varying feedback phase, the LK equations are numerically calculated and the influences of the feedback level factor C and the linewidth enhancement factor α on the transient are revealed. The results show that the decay time τ_D of the transient can be reduced by decreasing C or choose a SL with lower values of α . The results also show that the oscillation period Ω has different trent with respect to the increase of C and α , that is Ω decreases and increased respectively with the increase of C and α . The method and results presented in this paper are helpful for designing a stable SMI based sensing and instrunmentation.

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