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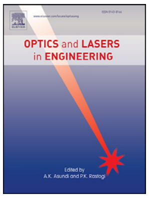

Improvement on vibration measurement performance of laser self-mixing interference by using a pre-feedback mirror

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ABSTRACT

In the laser self-mixing interference vibration measurement system, the self mixing interference signal is usually weak so that it can be hardly distinguished from the environmental noise. In order to solve this problem, we present a self-mixing interference optical path with a pre-feedback mirror, a pre-feedback mirror is added between the object and the collimator lens, corresponding feedback light enters into the inner cavity of the laser and the interference by the pre-feedback mirror occurs. The pre-feedback system is established after that. The self-mixing interference theoretical model with a pre-feedback based on the F–P model is derived. The theoretical analysis shows that the amplitude of the intensity of the interference signal can be improved by 2–4 times. The influence factors of system are also discussed. The experiment results show that the amplitude of the signal is greatly improved, which agrees with the theoretical analysis.

1. Introduction

Laser self-mixing interference refers to the effect that when the output light of the semiconductor laser has been reflected or scattered by external objects, part of the reflected or scattered light will return back to the laser cavity, and interference with the light in the cavity, then modulate the characteristics of laser output [1–3].Because the feedback light contains the information of external objects, it is widely used in the measurement of displacement [4,5], vibration [6,7], velocity [8,9] and so on. Compared with the traditional optical measurement method, the laser self-mixing interference method has a simple and compact structure, low cost and high precision, so it gets more and more attention [10].

In the self-mixing interference vibration measurement, when the measured target reflectivity is low, the amount of light reflected into the laser cavity is very small, the measurement system is in weak optical feedback, the measurement signal is weak and the amplitude of the signal is small at this time [11], the tilt direction of the waveform is also not obvious enough to detect the direction of the vibration, and it will bring great difficulties in the subsequent signal processing. In order to improve this situation, researchers have done a lot of work, e.g. (a) Designing a filter circuit to reduce the noise to increase the SN ratio and amplify the amplitude [12]. This method can filter out the noise, but it needs a complex circuit design, and the stability of the system may not be good. (b) Studying new signal reconstruction algorithm to improve the ability of resisting noise [13]. Although this method does not require additional circuit, it is not widely applicable and the accuracy is not very high. (c) Using phase modulation technique to improve the measurement accuracy [14]. This method can extract the interference signal very well and has a very high precision, but it is very complex and the cost is high. In this paper, the laser self-mixing interference vibration measurement optical path with a pre-feedback mirror is presented, a high reflectivity (comparing with that of the object's surface to be measured) optical mirror is added in the optic path as a pre-feedback mirror, it consists another resonance cavity, and the pre-feedback mirror and the laser's two cavity surfaces consist a structure which is similar to external cavity semiconductor laser. So the spectral line of the laser becomes narrow according to the principle of energy distribution, it can be seen that the frequency selectivity becomes better, and the probability of resonance with the feedback light of the surface of the object to be measured is greatly increased. So it can be known that when the mirror is in a right position, it can greatly enhance the signal amplitude and the degree of the tilt, and make the subsequent processing easier.

2. Principle

The theoretical study of the self-mixing interference effect provides a theoretical guide for the application of self-mixing interference technology. During this process, the researchers have established the L–K model of rate equations [15], the three mirror cavity model theory [16], the five mirror cavity model [17], and self-injection locking theory model

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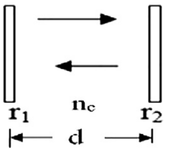

Fig. 1. The laser cavity.

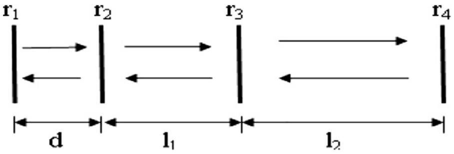

Fig. 2. The self-mixing interference model with a pre-feedback mirror.

[18]. The mathematical model of laser self-mixing interference is obtained, and the expressions are as followed [19]:

$$\phi_F = \phi_0 - C\sin(\phi_F + \arctan \alpha) \tag{1}$$

$$P = P_0[1 + mG(\phi_F)] \tag{2}$$

$$G(\phi_F) = \cos(\phi_F) \tag{3}$$

In the above formulas, C is the feedback strength factor, α is linewidth enhancement factor, ϕ_0 and ϕ_F are the phase without optical feedback and with optical feedback respectively. P_0 is laser power without optical feedback, and P is the modulated laser power. m is the modulation coefficient, $G(\phi_F)$ is the interference function.

It is laser cavity in the Fig. 1, d is the cavity length, the complex refractive index of the laser is $n_c = n - ig$, n is about the propagation velocity of light in the medium, g contains the gain coefficient and the attenuation of the light in the medium, r_1, r_2 is the reflection coefficient of amplitude of the laser's front face and back-end respectively [20].

The laser oscillation condition can be expressed as Eq. (4).

$$r_2 r_1 e^{2gk_0d} e^{i2nk_0d} = 1 \tag{4}$$

$$k_0 = \frac{2\pi}{\lambda_0} \tag{5}$$

Where k_0 is the number of the vacuum wave of the light in the center frequency. λ_0 is the wavelength of the oscillation laser.

From the Eq. (4), the Eq. (6) is achived:

$$\begin{cases} g_0k_0 = -\frac{1}{2d}ln(r_1r_2) \\ 2n_0k_0d = 2\pi M, M = 0, 1, 2\cdots \end{cases} \tag{6}$$

n_0 and g_0 are the real and imaginary parts of the complex refractive index of the laser respectively, which is formed by the stable oscillation.

The self-mixing interference model with a pre-feedback mirror is shown in Fig. 2.

In the Fig. 2, r_2 r_3 and r_4 are the reflection coefficient of the laser's back-end, the pre-feedback mirror and the surface of the external object respectively. The distance from the laser facet to the pre-feedback mirror is l_1, and the distance between the pre-feedback mirror and the external object is l_2.the external cavity of the target and the pre-feedback mirror will be been equivalent in turn, and finally, the optical feedback effect of the external cavity is equivalent to the output end of the laser [21]. The expressions of equivalent reflectivity are the Eqs. (7) and (8).

$$r_{34} = r_3 + (1 - r_3^2) r_4 e^{-i\varphi_2} \tag{7}$$

$$r_{234} = r_2 + (1 - r_2^2) r_{34} e^{-i\varphi_1} \tag{8}$$

As found in Eqs. (7) and (8), $\varphi_2 = \omega\tau_2$, $\varphi_1 = \omega\tau_1$, $\tau_2 = 2l_2/c$, $\tau_1 = 2l_1/c$. c is the vacuum speed of the light, ω is the angular frequency of laser. From the Eqs. (6) and (7), it can be obtained:

$$r_{234} = r_2\left[1 + \xi_1 e^{i(\omega\tau_1)} + \xi_2 e^{i(\omega\tau_1 + \omega\tau_2)}\right] \tag{9}$$

Where $\xi_1 = (1 - r_2^2)r_3/r_2$, $\xi_2 = (1 - r_2^2)(1 - r_3^2)r_4/r_2.\xi_1$ is the feedback coupling coefficient of the pre-feedback mirror, and ξ_2 is the feedback coupling coefficient of the target.

According to the Eqs. (4)–(6), (9), after the simplified processing, the expressions of the laser self-mixing interference measurement with a pre-feedback mirror can be expressed as:

$$\omega = \omega_0 - \frac{\sqrt{1+\alpha^2}}{\tau_d} \sin\left[\xi_1\left(\omega\tau_1 + \arctan\alpha\right) + \xi_2 \sin\left(\omega\tau_1 + \omega\tau_2 + \arctan\alpha\right)\right] \tag{10}$$

$$\Delta p = \left|\xi_1 \cos\left(\omega_{max}\tau_1\right) - \xi_1 \cos\left(\omega_{min}\tau_1\right) - 2\xi_2\right| \tag{11}$$

Eqs. (10) and (11) can be further expanded.

$$\omega = \omega_0 - \frac{c\sqrt{1+\alpha^2}}{2d} \times \sin\left[\xi_1\left(\frac{2\omega l_1}{c} + \arctan\alpha\right) + \xi_2 \sin\left(\frac{2\omega l_0}{c} + \frac{2\omega\Delta l}{c} + \arctan\alpha\right)\right] \tag{12}$$

$$\Delta p = \left|\xi_1 \cos\left(\frac{2\omega_{max} l_0}{c} + \frac{2\omega_{max}\Delta l}{c}\right) - \xi_1 \cos\left(\frac{2\omega_{min} l_0}{c} + \frac{2\omega_{min}\Delta l}{c}\right) - 2\xi_2\right| \tag{13}$$

Where c is the velocity of the light, l_1 is the position of the pre-feedback mirror, l_0 is the length of the external cavity, the value is equal to $l_1 + l_2$, Δl stands for external vibration, ω_{max} and ω_{min} are the maximum and minimum values of the laser angular frequency respectively .From the Eq. (13), it can be seen that when there is no external optical feedback, Δp is a constant value(i.e. Fig. 1), but Δp will change with the position of the pre-feedback mirror when the feedback light enters into the cavity(i.e. Fig. 2), if the pre-feedback mirror is in an appropriate position, the value of Δp can be great, so it can be known that the amplitude of the measured signal can be effectively improved by using a pre-feedback mirror. It can improve the accuracy of the AD sampling and bring great convenience for the subsequent signal processing.

According to the Eq. (13), using MATLAB to simulate the model, The simulation conditions are as follows: the laser wavelength is 635 nm, the initial external cavity length is 0.3 m, and the target feedback coupling coefficient is 0.00061, the feedback coupling coefficient of the pre-feedback mirror is 0.002, and the positions of the pre-feedback mirror are 0.068 m, 0.078 m, 0.098 m and 0.106 m respectively. The simulation results are shown in Fig. 3.

It can be seen from the Fig. 3 that the existence of the pre-feedback mirror makes the amplitude of the interference signal and the inclination of the interference fringe increase slightly. When the mirror is in a proper position, the amplitude can be increased.

According to the Eq. (13), the theoretical analysis of the pre-feedback waveform is as follows. Other parameters remain the same, the position of the pre-feedback mirror and its feedback coupling coefficient are the variables, and the results are shown in Fig. 4.

In order to determine the influence of the factors on the change law of the pre-feedback interference waveform, the specific analyses are as follows.

Firstly, other parameters remain the same, the initial external cavity lengths are 0.3 m, 0.4 m and 0.5 m respectively, and the simulations are shown in Fig. 5.

The amplitudes of the Fig. 5(a)–(c) were taken, as shown in Table 1.

From the Eqs. (12) and (13), it can be seen that ω will reduce when l_0 increase, the two factors work together to make the Δp almost unchanged. So it can be known that the length of the external cavity has almost no influence on the amplitude of the signal. The simulation results in Fig. 5 and Table 1 can also be used to prove this conclusion.