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Achieving high resolution measurement using laser diode operating at period one

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Abstract

Copyright 2019 SPIE. When a part of light emitted by a laser is back-reflected or back-scattered from an external target and re-enters the laser cavity, both the laser intensity and its wavelength can be modulated. This is so-called self-mixing effect (SME), the optical feedback interferometry (OFI) utilizes such effect in an LD developed various applications. In this paper, we use a dualcavity OFI system that operating in period one state, the laser intensity from this system exhibits an oscillation with its amplitude modulated by a traditional single cavity OFI signal. The dual-cavity OFI system has the same measurement resolution as the single cavity which is half laser wavelength. This paper developed a method to improve the resolution by using fringe subdivision. Our simulation result shows that this method can achieve subnanometer resolution.

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Abstract

When a part of light emitted by a laser is back-reflected or back-scattered from an external target and re-enters the laser cavity, both the laser intensity and its wavelength can be modulated. This is so-called self-mixing effect (SME), the optical feedback interferometry (OFI) utilizes such effect in an LD developed various applications. In this paper, we use a dual-cavity OFI system that operating in period one state, the laser intensity from this system exhibits an oscillation with its amplitude modulated by a traditional single cavity OFI signal. The dual-cavity OFI system has the same measurement resolution as the single cavity which is half laser wavelength. This paper developed a method to improve the resolution by using fringe subdivision. Our simulation result shows that this method can achieve subnanometer resolution.

Keywords: laser diode, optical sensing, optical feedback interferometry, dual cavity, period one, fringe subdivision.

I Introduction

A laser diode (LD) with a single external cavity has been proposed for interferometric measurement. Over the years, a number of names are used to describe such sensing configuration, e.g. optical feedback interferometry (OFI), self-mixing interferometry (SMI), or external cavity interferometry. As a promising non-contact sensing technology, OFI has attracted much attention of researchers in recent decades due to its merits of minimum part-count scheme, low cost in implementation, ease in optical alignment and half wavelength measurement resolution. Several of OFI based sensing have been reported, such as displacement, laser related parameters, imaging, chaotic radar, acoustic detection, biomedical applications etc. [1-4]. Recently, an LD with dual-cavity has been studied to improve the performance of an OFI system. In [5], 2-D vibration measurement of multiple targets are achieved using dual-cavity OFI systems. The work in [6] explored that the displacement sensitivity can be enhanced by 5 times compared to the single cavity OFI with an accurate location control for one of the two cavities. All of the above methods require the LD to work at a steady state. With the increase of the optical feedback level, an LD will leave the steady state and enter other operation states such as period-one (P1), multi-periodic and chaos, and rich dynamics can then be observed . The work in [7] shows when the dual-cavity OFI systems operating in P1, the laser intensity exhibits an oscillation with its amplitude modulated by a traditional OFI signal (generated with a single cavity and LD operating at steady state). It is also observed that the modulation depth is remarkably larger than the magnitude of a traditional OFI signal. This leads to significant increase in the sensitivity of sensing and measurement. Based on work [7], this paper focus on achieving a high resolution measurement using fringe subdivision. Fringe subdivision is one of the essential method to improve the measurement resolution of optical instruments. With the aid of basic signal processing technique, we can achieve an accuracy of a nanometer or a subnanometer level for displacement measurement.

II System Design

A dual-cavity OFI system consists a lens, a LD and a photodiode (PD) that is commonly packed at the rare back of the LD. A beam splitter is used to direct the light into two

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different targets. The initial cavity length between the LD to the target is called the measurement cavity. This target generates the displacement. It has weak reflective surface and it is in a continuous movement. The distance between the LD to the second target is called the control cavity. The second target is in a static movement, it is used to control the optical feedback of the system that to ensures the system works at P1 state. With the control cavity, the system can have a high measurement resolution and a high application gain.

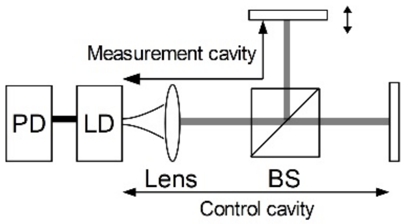

Fig. 1, The dual-cavity system

The behaviour of the single cavity OFI is described by the well-known L-K equations. The dual-cavity OFI can be modelled as below by modifying the L-K equations [7].

$$\frac{dE(t)}{dt}=\frac{1}{2}\left\{G\left[N(t),E(t)\right]-\frac{1}{\tau_p}\right\}E(t)+\frac{\kappa_1}{\tau_{in}}\cdot E(t-\tau_1)\cdot\cos\left[\omega_0\tau_1+\phi(t)-\phi(t-\tau_1)\right]+\frac{\kappa_2}{\tau_{in}}\cdot E(t-\tau_2)\cdot\cos\left[\omega_0\tau_2+\phi(t)-\phi(t-\tau_2)\right] \quad (1)$$

$$\frac{d\phi(t)}{dt}=\frac{1}{2}\alpha\left\{G\left[N(t),E(t)\right]-\frac{1}{\tau_p}\right\}-\frac{\kappa_1}{\tau_{in}}\cdot\frac{E(t-\tau_1)}{E(t)}\cdot\sin\left[\omega_0\tau_1+\phi(t)-\phi(t-\tau_1)\right]-\frac{\kappa_2}{\tau_{in}}\cdot\frac{E(t-\tau_2)}{E(t)}\cdot\sin\left[\omega_0\tau_2+\phi(t)-\phi(t-\tau_2)\right] \quad (2)$$

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

In Eq.(1)-Eq.(3), there are three variables, i.e., electric field amplitude $E(t)$, electric field phase $\phi(t)$ and carrier density $N(t)$. $\phi(t)$ is can be expressed as $\phi(t)=[\omega(t)-\omega_0]\,t$, where $\omega(t)$ is the instantaneous optical angular frequency for an LD with external feedback, and ω_0 is the unperturbed optical angular frequency for a solitary LD. $G\left[N(t),E(t)\right]=G_N\left[N(t)-N_0\right]\left[1-\varepsilon\Gamma E^2(t)\right]$ is the modal gain per unit time. The laser intensity waveform $E^2(t)$ also called OFI signal can be obtained through solving the LK equations. The detailed physical meanings of the symbols in the LK equations can be found in [7].

III Measurement Algorithm

First, we developed an algorithm that to count the integer fringes over the displacement of the measured target. In the simulation we set the following parameters, the initial length for the measurement cavity is $L_{01}=0.10m$, the measrued target is in a continues linear displacement shown as Fig. 2(a). It has optical feedback level $C_1=0.1$. The initial length for the control caivty is $L_{02}=0.24m$, the control target is in static movement and to ensure the system operates at P1 state, we set the optical feedback level $C_2=4.0$. Through solving the Eq.(1)-Eq.(3), the OFI signal in P1 region (OFI-P1) is obtained and shown in Fig. 2(b). As reported in [7], the envelop of OFI-P1 signal is the traditional OFI signal. Therefore, the OFI-P1 has the same sensing resolution as the single cavity OFI signal which is half of the laser wavelength.

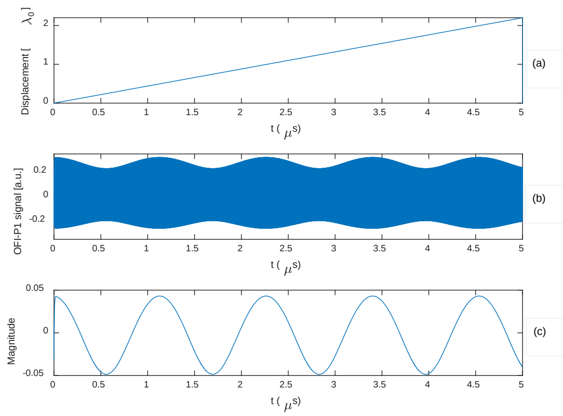

Fig. 2. (a) The displacement of the measured target. (b) The OFI-P1 signal. (c) The envelop of the OFI-P1 signal.

To count the number of the fringes, we applied the zero-crossing detection on the envelop of OFI-P1 then perform differentiation on the results. Fig. 3 shows the displacement of the target, it is corresponded to 5 integer fringes.

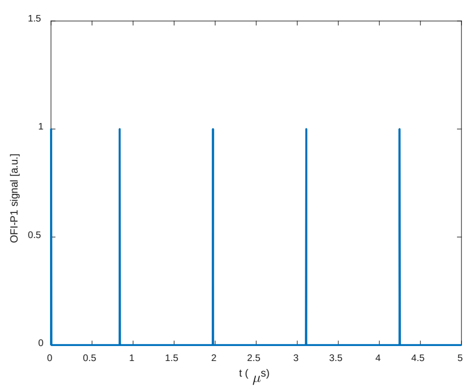

Fig. 3. The target displacement corresponded fringes.

The displacement measurement using fringe counting method will not be applicable if the target has a displacement that is less than half laser wavelength. To increase the resolution, each integer fringe is subdivided into serval fractional fringes. We apply the zero-crossing detection directly on the OFI-P1 signal then take the differentiation on the results. Fig. 4(a) shows both the integer fringes and fractional fringes.

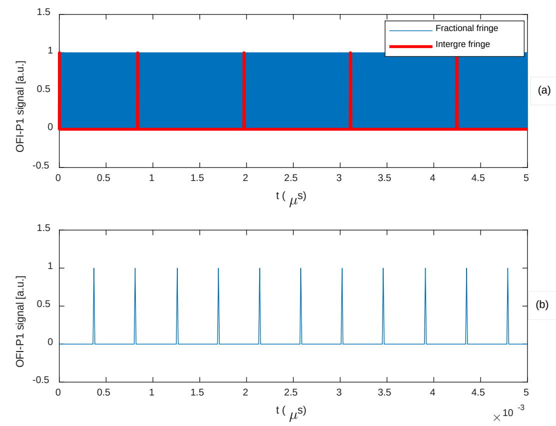

Fig. 4. (a) Integer fringes and fractional fringes. (b) The fractional fringes in the first 0.005 us.

Our simulation results show that within each integer fringe, it contains 2573 fractional fringes and there are 1707 fractional fringes after the last integer fringe. Therefore, the displacement d of the target can be expressed as

$$d = N * \frac{\lambda}{2} + N' * \frac{\lambda}{2M} \qquad (4)$$

Where N is the integer fringe number, N' is the fractional fringe number after the last integer fringe and M is the number of fractional fringe in each integer fringe.

IV Conclusion

In a dual-cavity OFI system operating in P1, the laser intensity exhibits an oscillation with its amplitude modulated by a traditional single cavity OFI signal. The dual-cavity OFI system has the same measurement resolution as the single cavity which is half laser wavelength. This paper developed a method to improve the resolution of the dual-cavity OFI system by using the fringe subdivision. Our simulation result shows that this method can achieve subnanometer resolution.

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