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Nanometer-resolution displacement measurement system based on weak feedback effect of dual-frequency laser

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Abstract

A novel nanometer-resolution displacement measurement system based on weak feedback effect of Zeeman-birefringence dual-frequency laser has been demonstrated. An experimental setup based on an optical feedback dual-frequency laser is developed to realize displacement division and direction discrimination utilizing phase delay between the optical feedback fringes of the two orthogonally polarized lights. The sub-division circuits of fringes are mainly composed of Field Programmable Gate Array (FPGA) and Micro Controller Unit (MCU), can realize 400 subdivisions for each fringe. The FPGA is used to realize the division of integral number fringes, and the MCU is used to realize the “division” of the fractional number fringes through program of look-up table. The total measured displacement is the value sum of both the integral part and the fractional part. A comparison experiment with the HP5529A interferometer was carried out resulting in a linearity of about $5 \times 10^{-6}$, and a concise theoretical model is given to explain the experimental results. The proposed system has a theoretical resolution as high as 0.791 nm, as well as a function of direction discrimination. Thereby, it can meet some demands of high-precision displacement measurements.

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Keywords: dual-frequency laser, displacement measurement, optical feedback, sub-division circuit

1. Introduction

Laser intensity can be modulated when its output lights are reflected back into its original laser cavity by an external reflector such as a mirror. This phenomenon is called self-mixing interference or optical feedback. The conventional self-mixing system is simply consisted of a laser and a feedback mirror. When the feedback mirror moves a displacement of half laser wavelength, a fringe of laser output intensity is produced and the intensity modulation depth is comparable to a conventional interferometer [1]. Optical feedback phenomenon was first reported by King [2] and it has been widely studied for imaging [3, 4], displacement [5-8] or velocimeter [9-11]. Some theoretical models have been created to explain self-mixing interference phenomena [12-14].

Recently, some attention has been paid to the optical feedback in dual-frequency lasers. The majority of research about optical feedback system has focused on semiconductor laser, which can only output singly polarized light. In a

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traditional semiconductor laser optical feedback system, the total light intensity changes can be observed, but it’s difficult to distinguish the direction of the displacement. However, He-Ne dual-frequency laser optical feedback system [15-17] is different: we can separate the optical feedback signals into two orthogonally polarized lights and study their optical feedback characteristics respectively, and the two way signals can be used to identify the direction of displacement.

At present, displacement measurement systems based on dual-frequency laser feedback effect usually achieve a resolution of 79.1 nm, but higher displacement resolution is required in more and more fields of precision measurements. How to further raise the resolution of the nanometer level displacement measurements becomes a problem that must be solved.

In this study, both dual-frequency laser feedback technology and intelligent digital sub-division technology have been used and combined, and a sub-nanometer level high-resolution optical feedback displacement measurement system is produced.

2. Dual-frequency laser optical feedback experimental setup and phenomenon

2.1. Experimental setup

![Fig. 1. Dual-frequency laser optical feedback experimental setup.](image)

The experiment setup is shown in Fig. 1. The 632.8 nm He-Ne laser used is a Zeeman-birefringence dual-frequency laser whose cavity is composed of mirror M2 and mirror M1. H is a magnet which is used to produce Zeeman effect. The laser output power is 0.45 mW and the laser cavity length is 155 mm. F is the force added to the transmission window plate of the laser tube so as to produce birefringence. The dual-frequency laser outputs two orthogonally polarized frequencies o-light and e-light. O-light is parallel to the magnetic field while e-light is perpendicular to the magnetic field. The frequency difference of the dual-frequency laser is 6.7 MHz. Mirror M3 is the external feedback mirror with a reflectivity of 10%, the purpose is to ensure that optical feedback in a weak feedback status, so that the sinusoidal signal can be acquired. Mirror M1 and mirror M2 form the external cavity whose length l is about 360 mm. PBS is a polarizing beam splitter (e.g. Walloston prism). The PBS is used to separate the tail lights into two parts corresponding to two orthogonally polarized frequencies –o-light and e-light, and their intensities are detected by photo detectors D1 and D2, respectively. The signals received by the two photo detectors are digitalized by an A/D card and stored into a computer.

The experimental system can generate 90° phase difference in order to achieve different polarization direction of light feedback.

2.2. The experimental phenomena of dual-frequency laser optical feedback

As shown in Fig. 2, when the Zeeman-birefringence dual-frequency laser outputs simultaneously two orthogonally polarized lights with optical feedback, we can attain two orthogonal signals whose phase difference is about 90°. The upper curves of Fig. 2 shows the light intensities of the two orthogonal polarized lights: the hollow dot curve is the parallel optical feedback curve, and the solid dot curve is the vertical optical feedback curve. The lower curve shows the piezoelectric ceramic triangular wave drive signal. When the piezoelectric ceramic driving voltage rises, the vertical light is ahead of parallel light π/2, and when the PZT voltage drops, the vertical light lag the parallel light π/2 (that means, the vertical light is ahead of parallel light 3π/2). Therefore, when PZT voltage is decreasing, the laser cavity is shortened.
If the external cavity mirror moves every half-wavelength displacement, correspondingly the two light intensities changes a cosine fringe respectively, and the phase difference between the two fringes is $\pi/2$ or $3\pi/2$. When the external cavity stretches, the optical feedback curve of the parallel light exceeds that of the vertical light $\pi/2$ in phase. On the contrary, the optical feedback curve of the vertical light exceeds that of the parallel light $\pi/2$ in phase. These properties can be used to achieve the direction discrimination of the displacement.

3. **The theoretical basis of dual-frequency laser optical feedback**

The laser intensity with optical feedback can be expressed as follows [18]:

$$I = I_0 [1 + m \cos(\varphi)],$$  

(1)

where $I_0$ is the laser intensity without optical feedback, $m$ is the modulation coefficient of the optical feedback system, $\varphi = 4\pi l / \lambda$ denotes the external cavity phase delay when the light undergoes a round trip in the external cavity, $l$ is the external cavity length, and $\lambda$ is the laser wavelength.

A dual-frequency laser can output two orthogonally polarized lights and the intensity of these two lights can be expressed as:

$$I// = I_{0//} [1 + m \cos(\varphi)],$$  

(2)

$$I\perp = I_{0\perp} [1 + m \cos(\varphi + \Delta \varphi)],$$  

(3)

where $I_{0//}$ and $I_{0\perp}$ are the intensities of the //–light and the \perp–light without optical feedback respectively. $\Delta \varphi$ is the phase delay between the two lights’ intensity curves caused by mode competition. When only one kind of the orthogonally polarized lights is fed back into the laser cavity, this kind of the polarized light’s intensity varies actively with the movement of the feedback mirror. But the other kind of polarized light’s intensity will vary passively due to the mode competition between these two orthogonally polarized lights in the laser cavity. Mode competition makes the two lights’ intensities inverted to each other with $\Delta \varphi = \pi$. However, in the condition that both lights are fed back into the laser cavity, the intensity of either light varies actively with the movement of the feedback mirror because either of the polarized lights in the laser cavity can interfere with the light of the same polarization from the external cavity. Under this condition, because the mode competition is quite complex, the two lights’ intensity curves are no longer inverted to each other with $\Delta \varphi = \pi$, but a phase delay $\Delta \varphi = \pi/2$ is experimentally observed.

4. **Displacement measurement circuit design and the test results**

4.1. The overall design scheme
4.2. Subdivision Principle

The two light signals are converted into electric signals by the photo detectors. The two electric signals are then processed (I/V conversion and amplification successively) and converted into two square-wave signals respectively. The two square-wave signals enter the subdivision circuit in the FPGA and accomplish the displacement four-division implementation, and then the positive and the negative count pulse are extracted and transmitted into the 24-bit reversible counter, finally the FPGA fulfills the displacement’s counting of integral fringe numbers. This is in fact the main part of the displacement signal, namely large numbers counting.

In the four sub-division area, the two sine voltage signals with a 90° phase difference are strictly corresponding to the information of the displacement. The sine signal and cosine signal are collected, then the ratio of the two signals are calculated, at last the result of a tangent function or cotangent function has been acquired:

\[
A = \frac{V \sin \omega t}{V \cos \omega t} = \tan \omega t. \tag{4}
\]

The voltage \(V\) is the feedback signal amplitude which has regular fluctuations, but in fact the tangent function does not contain \(V\), so the influence of voltage amplitude fluctuations, which may reduce the measurement precision, can be eliminated basically.

The real-time sampling of the two signals has been converted into data by the A/D and read by the MCU. The MCU control program can recognize both polarity and absolute value of the signals, and it can automatically divide a signal period into eight regions.

The MCU can judge which region the instantaneous signal belongs to. In each region, the tangent function, namely the ratio of the two signals, are computed rapidly. If the absolute value of the tangent function is no larger than 1, the tangent function is output directly; Otherwise, if the absolute value of the tangent function is larger than 1, its reciprocal, namely the cotangent function is output. In this way, the absolute values of the output function always change in the range between 0 and 1, so they can be expressed by \(\tan \omega t\) or \(\cot \omega t\) with \(\omega t\) interval of \(0–\pi/4\). The \(\tan \omega t\) or \(\cot \omega t\) function values are stored in the ROM of the MCU. The total 50 tangent and arctangent function...
values as a table can be accessed in order to determine their phase in each region. The 50 tangent values are corresponding to 50 equal segments in each region. Thus the total subdivision number of the eight-quadrant is 8*50, namely 400 subdivisions. And each $\omega$ in a region is corresponding to a displacement $\Delta L$. The MCU looks up the data table and acquires the corresponding $c$ value, and then the “small number” $\Delta L$, are merged into four subdivision “large number” $N*\lambda/8$. Therefore, the total displacement expression is given as follows:

$$L = N \cdot \lambda / 8 \cdot c - \Delta L \cdot c,$$

(5)

where $\Delta L_0$ and $\Delta L$ are the corresponding fractional displacement values at the beginning and at the end of every displacement measurement respectively. This method raises the system response speed and simultaneously improves the displacement measurement resolution. The displacement measurement resolution of the system is theoretically $\lambda/800$, namely 0.791nm.

4.3. The FPGA Design

Fig. 4. Diagram of FPGA top level design.

The diagram of FPGA top level design is shown in Fig. 4. The top-level FPGA design mainly includes filter modules, four subdivision and discrimination modules, reversible counter, and data selector component. Fig. 5 is the simulation diagram of the FPGA working principle. The overall simulation waveforms are shown in Fig. 5. Among them, signal $a$ and signal $b$ are two signals with $90^\circ$ phase difference, when signal $a$ is $90^\circ$ ahead of signal $b$ in phase, the counters add counting, and the corresponding displacement is a positive value; when signal $a$ is $90^\circ$ behind signal $b$ in phase, the counters subtract counting, and the corresponding displacement is a negative value.

<table>
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</thead>
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<tr>
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<td>D 0</td>
</tr>
<tr>
<td>data[7...0]</td>
<td>D 13</td>
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</table>

Fig.5. Simulation diagram of FPGA working principle.

4.4. The MCU design

As shown in Fig. 6, a flow chart of the MCU control programs is given. The MCU mainly includes initialization procedure, a small number of acquisition subprogram, quadrant discrimination subprogram, look-up table subprogram, merging program of the big number and small number, displacement calculating subroutine, the LCD
control subroutine and so on. One of the programs mentioned above is the quadrant discrimination subprogram that can be used to determine the eight quadrants.

![Flow chart of MCU control programs.](image)

**4.5. The Experimental results**

![Graph showing HP5529A interferometer results.](image)

Fig.7 Results of comparison experiment with HP5529A interferometer.
To verify the characteristics of our proposed displacement measurement system, a comparison experiment with the HP5529A interferometer was carried out. The comparison experiment was under the ordinary room temperature (no thermostat), and the temperature drift is about 1-2°C. The two sets of measured displacement data of the two interferometers are shown in Fig. 7. The results show that the linearity is about $5 \times 10^{-6}$. The measurement results of our displacement measurement system are in accord with those of the HP5529A interferometer. The theoretical measurement resolution of our system is 0.791nm, and in a small area (less than 1mm) the actual measurement accuracy is about 40nm.

If our system is actually applied to high-precision nanometer measurement, good experimental conditions such as constant temperature, constant humidity, constant pressure, and high precision displacement guide rail, are required.

5. Conclusions

Optical feedback measurement technology is a promising new interferometric technology. Optical feedback interferometers have the same sensitivity as that of the conventional interferometers, and optical feedback displacement measurement systems are usually simple, compact, easily-collimated, therefore they can replace the conventional interferometers in a lot of applications.

In this paper, a novel nanometer-resolution displacement measurement system based on weak feedback effect of Zeeman-birefringence dual-frequency laser has been demonstrated. An experimental setup based on an optical feedback dual-frequency laser is developed to realize displacement division and direction discrimination utilizing phase delay between the optical feedback fringes of the two orthogonally polarized lights. The sub-division circuits of fringes are mainly composed of the FPGA and the MCU. The FPGA is used to realize the division of integral number fringes, and the MCU is used to realize the “division” of the fractional number fringes through program of look-up table. The total measured displacement is the value sum of both the integral part and the fractional part. A comparison experiment with HP5529A interferometer was carried out resulting in a linearity of about $5 \times 10^{-6}$, and a concise theoretical model is given to explain the experimental results. The proposed system has a theoretical resolution as high as 0.791 nm, as well as a function of direction discrimination. Thereby, it can meet some demands of high-precision displacement measurements as a substitution of traditional interferometers.

When our system is actually applied to high-precision nanometer measurements, it is necessary to limit experimental measurement conditions strictly so as to achieve high measurement precision. This is only our first exploring toward sub-nanometer displacement measurements, and further improvement work will be carried out later.

Acknowledgments

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References: