

Laser detection by electronic instead of optical heterodyne using a two-frequency laser

Lei LI (✉)¹, Changming ZHAO², Suhui YANG²

¹ Shanghai Institute of Optics and Fine Mechanics, Shanghai 201800, China

² School of Information Science and Technology, Beijing Institute of Technology, Beijing 100081, China

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Abstract A laser ranging system using a two-frequency laser is demonstrated, and the lidar-radar concept is introduced. A laser beam carrying 100 MHz radio frequency is obtained by a monolithic nonplanar ring single-frequency oscillator and an acousto-optical modulator, which is used as the light source of the two-frequency detecting experimental setup. With the optical transmitting and collecting system, the displacement information of a target mounted on a motorized translation stage is achieved. In signal processing, the displacement is obtained by calculating the phase difference between the reference and detection signals executed by a radio-frequency lock-in amplifier. The ranging system turns the optical heterodyne into an electronic demodulation, and the repetition error is less than 3%. The system takes advantage of the signal processing technologies of radar, and meanwhile maintains the advantages of laser detection.

Keywords lidar-radar, two-frequency laser, beat frequency, heterodyne

1 Introduction

In the application of target electromagnetic detection and identification techniques, the lidar system [1] and the radar system [2] have their individual unique advantages. The lidar system has been known to provide good transverse spatial resolution relative to the radar system, while the radar system has a wider ranging extension and is sensitive to the phase of the backscattered signal which leads to the achievement of Doppler velocity information. Therefore, people attempt to combine these two detection technologies and thus the lidar-radar concept has been proposed [3]. During earlier times, a similar technique was applied in underwater target detection [4,5].

Achieving a laser beam which carries radio frequency is the key technology of the lidar-radar system. Various methods for realizing a beat frequency laser have been proposed in recent years, such as seeding two very stable single-frequency lasers, having different frequencies in the same amplifier resonator [6], utilizing the beat frequency in a laser cavity with separate optical paths [7], and directly using two longitudinal mode lasers [8], etc. In this paper, the beat frequency realized by a nonplanar ring oscillator (NPRO) and an acousto-optical modulator (AOM) is presented. The subcarrier radio frequency (RF) 100 MHz laser beam is achieved through optics mixing to detect the displacement of the target.

2 Displacement measurement principle and experiment setup

The whole lidar-radar system for displacement measurement is illustrated in Fig. 1, where $R(t)$ is the optical path difference between the detecting laser beam and the reference laser beam. The system consists of three parts: the beat-frequency laser source, the optical transmitting and receiving segment and the signal processing unit.

2.1 Beat-frequency laser source

The single-frequency laser beam from a narrow linewidth (2 kHz/5 μ s) NPRO [9] is split by a polarizing beam splitter. One of the laser beams is diffracted by an AOM with 100 MHz frequency shift and is mixed with another unshifted single-frequency beam, then the laser beam carrying a 100 MHz radio beat-frequency is achieved at the left end of the beam splitter prism. Their equations are given by

$$\begin{aligned} E_1(v_1) &= A_1 \cos(2\pi v_1 t), \\ E_2(v_2) &= A_2 \cos(2\pi v_2 t), \end{aligned} \quad (1)$$

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E-mail: lilei@siom.ac.cn

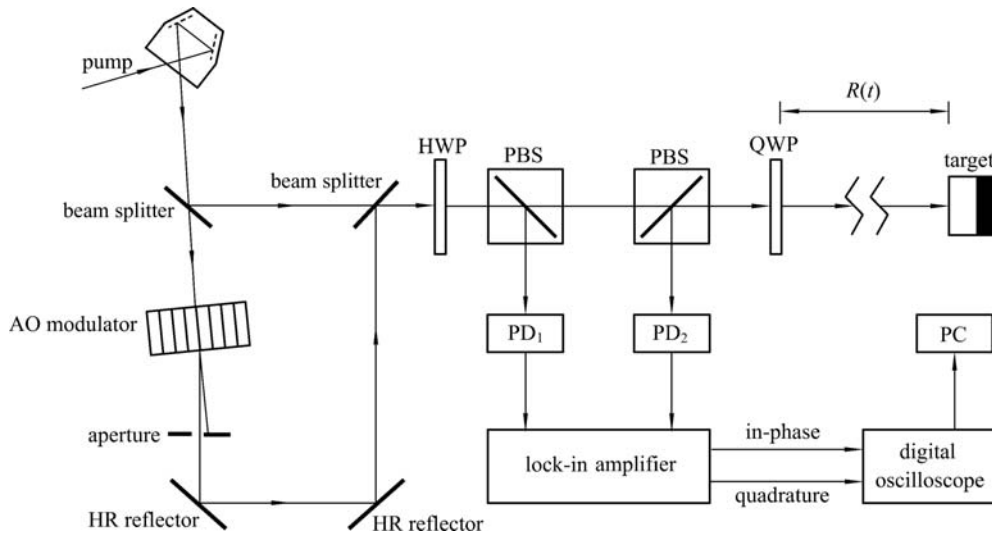


Fig. 1 Experimental setup of displacement detection (HWP – half-wave plate; PBS – polarized beam splitter; QWP – quarter-wave plate)

where A_1 and A_2 are the two laser beam light amplitudes, respectively, and ν_1 and ν_2 are their corresponding light frequencies. When the incidences of the two parallel light waves impinge on the high speed photodiode surface, the photo current will be

$$\begin{aligned} i_p &\approx I = E^2(t) = [E_1(\nu_1) + E_2(\nu_2)]^2 \\ &= A_1^2 \cos^2(2\pi\nu_1 t) + A_2^2 \cos^2(2\pi\nu_2 t) \\ &\quad + A_1 A_2 \cos[2\pi(\nu_1 + \nu_2)t] \\ &\quad + A_1 A_2 \cos[2\pi(\nu_1 - \nu_2)t]. \end{aligned} \quad (2)$$

Because of the photodiode response frequency upper limit, only the beat frequency will be under the photodiode's cutoff frequency, then the beat signal expression is given by

$$\begin{aligned} i_p &= E_{\text{beat}}^2 = A_1 A_2 \cos[2\pi(\nu_1 - \nu_2)t] \\ &= A \cos(2\pi f_{\text{rf}} t). \end{aligned} \quad (3)$$

Here the beat frequency $f_{\text{rf}} = \nu_1 - \nu_2$ is the 100 MHz RF frequency. We can use such a beat-frequency laser beam as the light source of the lidar-radar system.

2.2 Optical transmitting and receiving system

The transmitting and receiving system consists of two polarized beam splitters, a half-wave plate and a quarter-wave plate. The beat-frequency laser beam is divided into two paths at the left polarized beam splitter: the first path is used to generate a reference signal on the high-speed photodiode PD₁, and the other path is formed by the detecting laser beam. In order to measure the displacement and velocity of a moving target, a mirror is mounted on a motorized stage used as the testing target. The detecting laser beam is transmitted and returned through a

quarter-wave plate. The detecting signal is achieved by the backscattered light impinging on the high-speed photodiode PD₂. Then the reference signal and detecting signal are fed into the RF lock-in amplifier.

2.3 Signal processing unit

The signal processing function is executed by a RF lock-in amplifier (SR844, Stanford Research System), and in this experiment it is operated in the “external” mode. The RF lock-in amplifier provides performance with a frequency range of 25 to 200 MHz and a drift-free dynamic reserve up to 80 dB; it can also communicate with a computer through a general purpose interface bus (GPIB) or through RS-232 interfaces. The core of the lock-in amplifier is a phase-sensitive detector, which can detect very weak signals with respect to a stabilized reference. The principle of the phase-sensitive detection (PSD) is quadrature demodulation, which can deduce the in-phase section and quadrature item. Then, amplitude and phase information can be obtained.

The voltage from the high-speed photodiode PD₂ acts as the detecting signal, which is given by

$$\begin{aligned} V_s &= V_{s1} + V_{s2} \\ &\quad + 2\sqrt{V_{s1} V_{s2}} \sin\left[2\pi f_{\text{rf}} t + 2\pi \frac{R(t)}{\Lambda}\right], \end{aligned} \quad (4)$$

where V_{s1} and V_{s2} are the output voltages of the photodiode produced, respectively, $\Lambda = cf_{\text{rf}}$ is the synthetic wavelength, and c is the velocity of light in vacuum. The voltage from the photodiode PD₁ acts as the reference signal, which is given by

$$V_r = V_{r1} + V_{r2} + 2\sqrt{V_{r1} V_{r2}} \sin(2\pi f_{\text{rf}} t), \quad (5)$$

and then Eq. (4) can be reduced to

$$V_s = V_{s1} + V_{s2} + 2\sqrt{V_{s1}V_{s2}} \sin[2\pi f_{rf}t + \varphi(t)]. \quad (6)$$

Here, the constant phase shifts have been discarded, $\varphi(t) = 4\pi R(t)/\Lambda$ is the phase difference between the detecting signal and the reference signal, and $R(t)$ is the optical path difference between the detecting laser beam and the reference laser beam, which includes the target's distance information. The $\Lambda = 3$ m due to beat frequency $f_{rf} = 100$ MHz, and when the $\varphi(t)$ changes from 0 to 2π , the corresponding displacement is from 0 to 1.5 m, so the measured nonambiguity range (NAR) is 1.5 m. Related to the distance exceeding 1.5 m, it can be extended by using two different synthetic wavelengths Λ_1 and Λ_2 to solve the problem.

In order to extend the distance without ambiguity, two driving frequencies of AOM have been introduced, and the optical distance L is presented by

$$L = N\Lambda_1 + n_1\Lambda_1 = N\Lambda_1 + \frac{\varphi_1}{2\pi}\Lambda_1, \quad (7)$$

$$L = N\Lambda_2 + n_2\Lambda_2 = N\Lambda_2 + \frac{\varphi_2}{2\pi}\Lambda_2. \quad (8)$$

Here, N is an integer, and Λ_1 and Λ_2 are the wavelengths of the two laser beams' synthetic wavelengths, respectively. Then integer N and the distance L can be calculated by

$$N = (n_1\Lambda_1 - n_2\Lambda_2)/(\Lambda_2 - \Lambda_1), \quad (9)$$

$$L = \frac{\Lambda_1\Lambda_2(n_1 - n_2)}{\Lambda_2 - \Lambda_1}. \quad (10)$$

To avoid the distance ambiguity, the following condition has to be met

$$L < \frac{\Lambda_1\Lambda_2}{\Lambda_2 - \Lambda_1}. \quad (11)$$

For example, choose the beat frequency $f_{rf} = 100$ MHz, the corresponding $\Lambda_1 = 3$ m, then change the beat frequency a little to $f_{rf} = 99.9$ MHz, and $\Lambda_2 = 3.003$ m, so we can measure the targets in the range $\Lambda = 3003$ m ≈ 3 km. This kind of method requires a critical operating stability of the two-frequency laser.

3 Measurement results

In order to measure the displacement and velocity of a moving object, a mirror is mounted on a motorized stage as target. The stage moves back and forth along an optical bench, which is controlled by a stepping motor. The target reciprocates in the 20 cm range, and the phase difference $\varphi(t) = 4\pi R(t)/\Lambda$ is achieved by the lock-in amplifier signal

processing unit; then the displacement can be calculated via a programmed computer software, and the velocity also can be achieved by the displacement time differential. We developed an application interface using Visual Basic language, where the trace of the target's displacement and velocity can be displayed in the application windows. Figure 2 shows the records of the displacement and velocity when the target moves back and forth, the trace in Fig. 2(a) is the curve of displacement, and Fig. 2(b) shows the corresponding velocity curve. After data processing, the system repetition error is less than 3%.

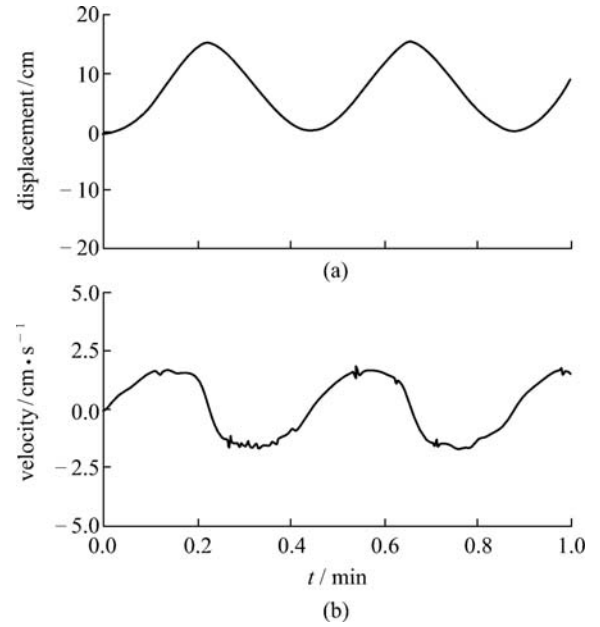


Fig. 2 Displacement and velocity measurements

In the experiment, the stability of the lidar-radar system is very important, and the measurement accuracy is sensitive to the alignment of the two laser beams. Since the two polarized beam splitter PBS separates the beat frequency into two orthogonally linearly polarized components to realize the measurement, the adjustment of the optical path is vital to the performance of the system. In order to improve the laser beam combined alignment characteristics, it is better to use the two-frequency laser described in reference paper [10], providing the tunable beat notes at RF frequencies with 100% modulation depth and good frequency stabilization. Furthermore, for applications such as fast signal tracking [11], a two-frequency laser as the voltage-controlled oscillator (VCO) [12] is demonstrated. The frequency stabilization is then realized by means of analogue phase-locked loops (PLL) based either on frequency-mixing with an independent microwave synthesizer [10] or suppressed carrier technique [13]. In particular, higher frequencies in the microwave range will be achieved with monolithic lasers [14].

4 Conclusion

The displacement measurement has been studied as a lidar-radar system, involving a single frequency monolithic NPRO and an acousto-optical modulator to produce a beat frequency laser beam. The less than 3% repetition error provides validity for such an optical-carried RF laser detection system. Because of the similarity of the two components of the two-frequency laser, disturbance factors will always have the same impact on them, and the phase of the synthetic RF signal of the lidar-radar system will always have remarkable anti-jamming abilities. However, as a developing combination technology of electronics and optics [15–20], the study of the lidar-radar system still has a long way to go in military and other applications.

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