Interferometer for measuring displacement and distance

Toshihiro Kubota

Department of Photographic Technology, Kyoto Institute of Technology, Matsugasaki, Sakyo-ku, Kyoto 606, Japan

Makoto Nara

Nippon Kougaku K.K., 1-6-3, Nishioi, Shinagawa-ku, Tokyo 140, Japan

Toshihiko Yoshino

Institute of Industrial Science, University of Tokyo, 7-22-1, Roppongi, Minato-ku, Tokyo 106, Japan

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A simple interferometer for measuring both relative displacement and absolute distance is fabricated that uses a laser diode. The sign of the displacement is detected by means of a $\lambda/8$ plate, and the distance is measured by a FM radar technique of modulating the laser-diode frequency. Measurement accuracies of 0.02 μm for displacement and 100 μm for distance are obtained over a range of a few meters.

Many methods have been presented for measuring relative displacement or absolute distance by optical techniques, such as the use of an interferometer, the detection of the phase difference between the signal and reference beams created by modulating the laser light, and the detection of the time delay of a pulsed beam reflected from an object.

In the case of measurement of displacement accurately to within a few meters, interferometry is the most precise method. The heterodyne interferometer using Zeeman lasers is well known for this purpose but is complicated and expensive.

In this Letter a simple apparatus for measuring both displacement and distance is presented in which a laser diode and a $\lambda/8$ plate are used. Displacement is measured, along with its direction, by using the $\lambda/8$ plate. On the other hand, distance is measured by a FM radar technique using the dependence of the operating frequency of a laser diode on injection current.[1]

The basic arrangement of the proposed interferometer is shown in Fig. 1. A linearly polarized collimated beam from a laser diode travels to a moving mirror M, whose displacement is to be measured. A $\lambda/8$ plate C, whose axis of polarization is inclined at 45° to the direction of polarization of the incident beam, is inserted into the path. Interference occurs between the reference beam reflected from the front surface of C and the signal beam reflected from M. The unwanted reflection from the back surface of C can be eliminated by antireflection coating or wedge shaping of the plate.

The signal beam becomes circularly polarized after passing through C in both directions, generating a phase difference of $\pi/2$ between the orthogonally polarized components along the $\parallel$ and $\perp$ directions in Fig. 1. The two beams are recombined to produce interference fringes between components with the same polarization. These are divided by a polarization beam splitter PBS after being reflected by a beam splitter BS and are detected by photodetectors PD_1 and PD_2. The intensities of the interference fringes are proportional to $1 + \cos\theta$ and $1 + \sin\theta$ for the $\parallel$ and $\perp$ components, respectively, where θ is the phase difference between the reference and object beams. Therefore, one can determine the sign of the displacement of M as well as its magnitude by the fringe-counting method. IS is an optical isolator that prevents the reflected beams from C and M from returning to the laser diode.

It is well known that the frequency of a laser diode changes with the injection current. This feature of laser diodes has been used for distance measurements, such as contour fringe generation,[2] short-distance measurements using a heterodyne method,[3] and range finding using optical-feedback-induced mode hops.[4] In our method, a FM radar technique is used to measure distance. The frequency of the laser diode is modulated by the function generator, and the beat frequency generated by interfering the reference and object beams is measured.

The principle of measurement is shown in Fig. 2.

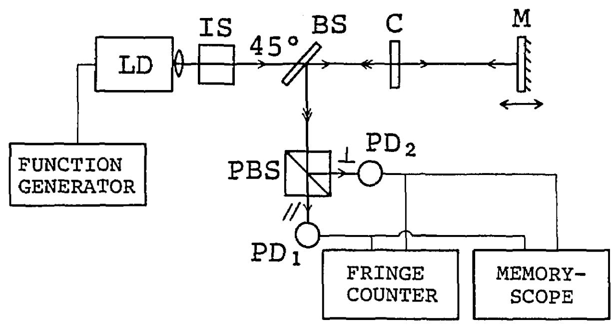

Fig. 1. Schematic diagram of the interferometer for measuring displacement and distance.

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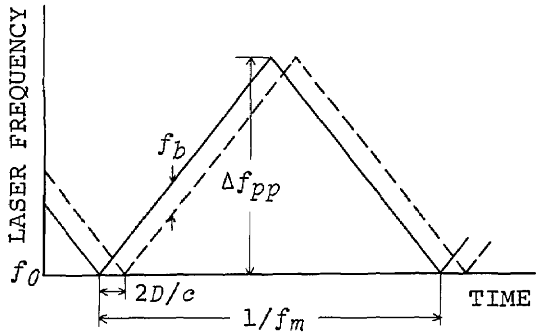

Fig. 2. Principle of measurement of FM radar system.

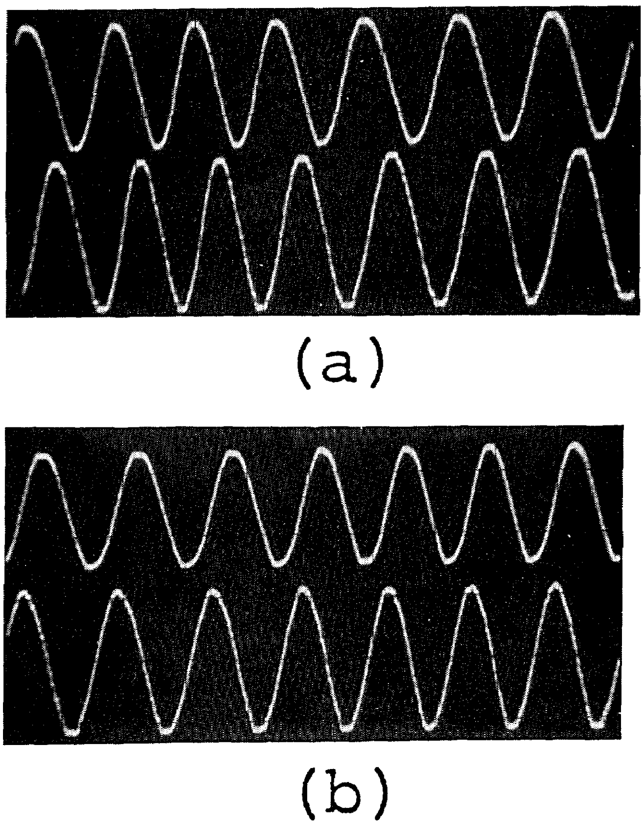

Fig. 3. Oscilloscope traces of the interference fringes. Mirror M is moved (a) to the right and (b) the left.

The injection current is modulated in a triangular wave (frequency f_m, modulated amplitude ΔI_{pp}) using the function generator. When the optical path difference between C and M is D, the two beams reflected from C and M arrive at the detector (PD_1, for example) with a time delay of $2D/c$ (c is the speed of light), and they interfere to yield the beat signal. The frequency of the beat signal f_b is proportional to D and is given as

$$D = [c/(4\chi \Delta I_{pp} f_m)] f_b, \tag{1}$$

where χ is a constant representing the laser-frequency dependence on injection current. The distance D is then calculated by measuring f_b. Thus the absolute distance as well as the relative displacement can be measured by this interferometer.

Some experiments were carried out using the laser diode (Hitachi HL 7802E) operating in a single longitudinal mode at wavelength $\lambda = 0.79$ μm. Typical examples of the relative displacement measurement are shown in Figs. 3 and 4. Figure 3 shows the traces of the interference fringes displayed on an oscilloscope when M is moved at a constant speed. (a) and (b) correspond to the curves observed when M is moved to the right- and left-hand sides, respectively. For both the cases, the upper and lower traces correspond to the $\parallel$ and $\perp$ components. It is clearly seen from Fig. 3 that the interference fringes are out of phase by $\pm\pi/2$ from each other depending on the direction of movement of M. One fringe corresponds to the change in D of $\lambda/2$. If we set the minimum detectable fringe number ΔN as 1/20 for a typical example, it is possible to

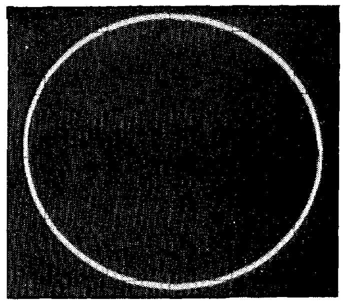

Fig. 4. Lissajous's figure of the interference fringes.

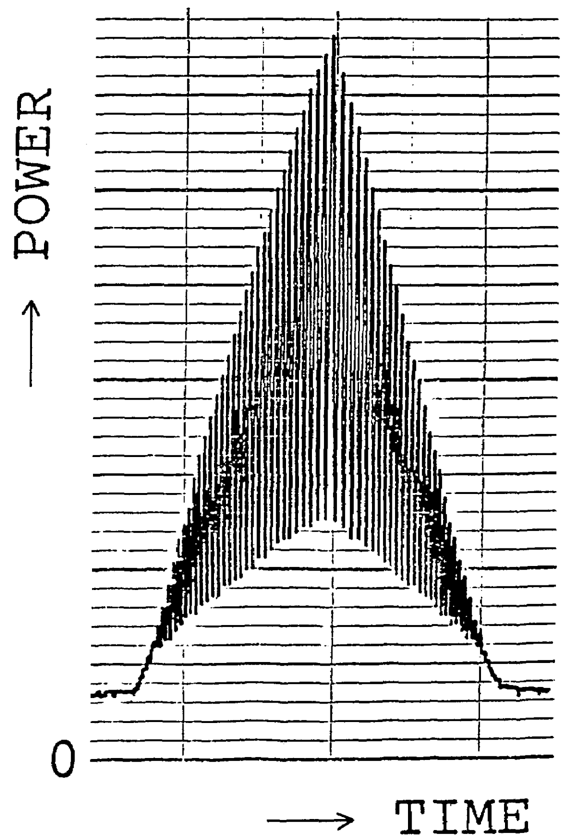

Fig. 5. Typical sample of the beat signal. $f_m = 90$ Hz, $\Delta I_{pp} = 15$ mA, and $D = 6$ cm.

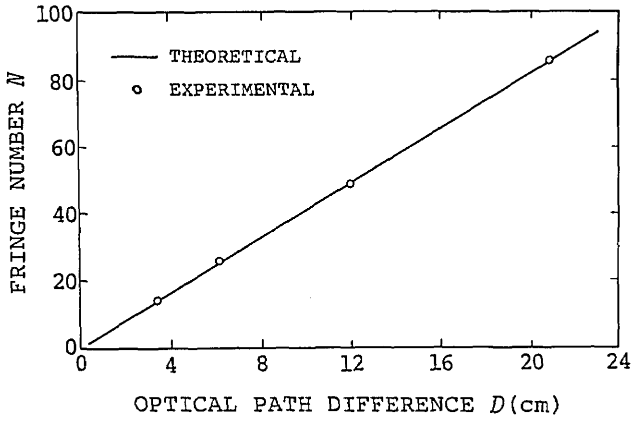

Fig. 6. Fringe number N versus optical path difference D.

detect a change in displacement with an accuracy of $\lambda/40$, that is, 0.02 μm. Figure 4 shows the Lissajous figure of the interference fringes when M moves. The bright circular curve traces clockwise or counterclockwise, depending on the direction of movement of M. One turn corresponds to a displacement by $\lambda/2$. Therefore a large change in displacement can be measured by counting the net number of turns by using the fringe counter.

Next we show the experimental results for the measurement of absolute distance. Figure 5 shows a typical example of the beat signal between the two beams reflected from C and M. This trace was obtained by storing the beat signal, using a memory scope, and plotting the output on a recorder. The modulation frequency f_m and the amplitude ΔI_{pp} were 90 Hz and 15 mA, respectively. The frequency of the laser diode changed linearly with injection current, and the rate of change χ was measured as 4.1 GHz/mA. The relation between the number of fringes of the beat signal N ($=f_b/2f_m$) and the optical path difference D is shown in Fig. 6. A good linear relation is obtained between N and D. D is also obtained by measuring the time required for the change in one fringe of the beat signal. The minimum detectable distance ΔD is given as

$$\Delta D = c\Delta N/2\Delta f_{pp}, \tag{2}$$

where $\Delta f_{pp} = \chi \Delta I_{pp}$. If we set $\Delta N = 1/20$ again, ΔD is approximately 100 μm. The dynamic range of distance measurement depends on the coherence length of the laser diode. In the present case, the measurable absolute distance is a few meters.

When a polarization-maintaining fiber is inserted between the beam splitter BS and the $\lambda/8$ plate C shown in Fig. 1, remote measurements of relative displacement and absolute distance are possible with the improved method of operation of the remote interferometer using an optical fiber.[5]

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