Laser interferometry: current trends and future prospects

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ABSTRACT

The last few years have seen major advances in laser interferometry. The use of laser diodes whose output wavelength can be controlled by varying the injection current has led to the development of several new techniques in interferometry, as well as new methods for multiplexing fiber-interferometer sensors. New fields have also been opened up by phase-conjugate interferometers and the use of squeezed light. This paper will review some of the current trends in laser interferometry and discuss some future possibilities.

1. INTRODUCTION

The last few years have seen several new developments in the field of laser interferometry. Perhaps the most impressive of these has been the increasing use of laser diodes to replace gas lasers as light sources for interferometry. In addition, the fact that the output wavelength of a laser diode can be controlled by varying the injection current and can also be modulated over a wide frequency range has opened up many new and interesting interferometric techniques. Another major area of activity has been the development of fiber interferometers for measurements of temperature, pressure, and electrical and magnetic fields. Laser diodes have made it possible to multiplex such interferometric sensors so that measurements can be made of different quantities, at different points, with a single system. Yet another new area of work has been the use of lasers to generate a phase conjugate wave in a medium with a nonlinear susceptibility; this capability has led to new types of interferometers with unique properties. Finally, completely new possibilities have been opened up by the production of squeezed states of light with lower quantum noise than normal light.

2. WAVELENGTH MODULATION OF LASER DIODES

A change in the injection current of a laser diode produces, in addition to a change in the output power, a shift in the output wavelength. The latter effect is due to two causes. One is the change in the refractive index of the active region induced by the change in the density of the charge carriers, which is almost independent of the modulation frequency. The other is the thermally induced change in the refractive index and the length of the cavity, which can be neglected at high modulation frequencies (> 10 MHz), but becomes dominant at low modulation frequencies.[1,2] These characteristics have been utilized effectively in several types of interferometers.

3. FREQUENCY-MODULATION INTERFEROMETRY

Direct interferometric measurements of distances can be made with a laser diode by a technique analogous to FM radar.[3] Figure 1 shows a system that combines heterodyne techniques with fringe counting to measure both relative displacements and absolute distances with high accuracy.

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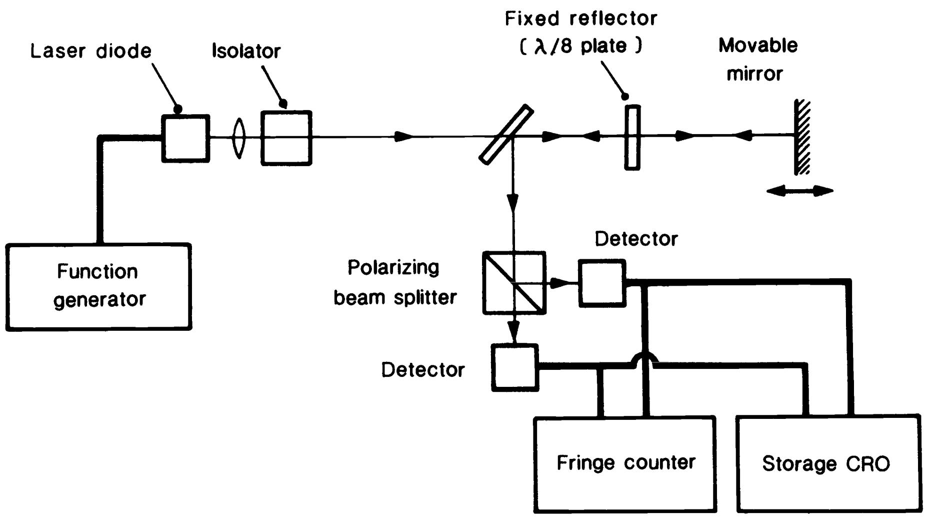

Fig. 1. Fringe-counting interferometer using a tunable laser diode (Kubota *et al*, 1987).

Interference takes place between a reference beam reflected from the front surface of a $\lambda/8$ plate and the signal beam reflected from a movable mirror. The signal beam returns as a circularly polarized beam, and its two orthogonally polarized components are divided at a polarizing beam splitter to produce two fringe patterns whose intensities vary in quadrature. The sign of a displacement of the mirror, as well as its magnitude, can be determined by a fringe counter.

Absolute measurements of distance can be made by sweeping the frequency of the laser linearly with time by varying the injection current. For an optical path difference L, the two beams reach the detector with a time delay L/c, where c is the speed of light, and they interfere to yield a beat signal with a frequency $\Delta\nu = (L/c)(d\nu/dt)$, where $d\nu/dt$ is the rate at which the laser frequency is varying with time. Distances of a few metres can be measured with an accuracy of 100 μm.

4. PHASE-LOCKED INTERFEROMETRY

The output intensity from an interferometer depends on the phase difference between the two interfering beams which, in turn, is determined by the optical path difference and the illuminating wavelength. With a laser diode, it becomes possible to compensate for a change in the optical path difference by a change in the illuminating wavelength.[4]

A high degree of stabilization can be achieved, and dc drifts eliminated, with a system in which the injection current of the laser diode is modulated sinusoidally with a small amplitude.[5] As shown in Fig. 2, the injection current of the laser diode consists of a dc bias current i_0, a control current $i_c(x)$, and a sinusoidal modulation current $i_m(t) = i_m \cos \omega t$, so that the phase difference between the beams in the interferometer exhibits a sinusoidal modulation $\Delta\varphi(t) = \Delta\varphi \cos \omega t$, with an amplitude $\Delta\varphi \ll \pi$. The intensity in the interference pattern can be written as

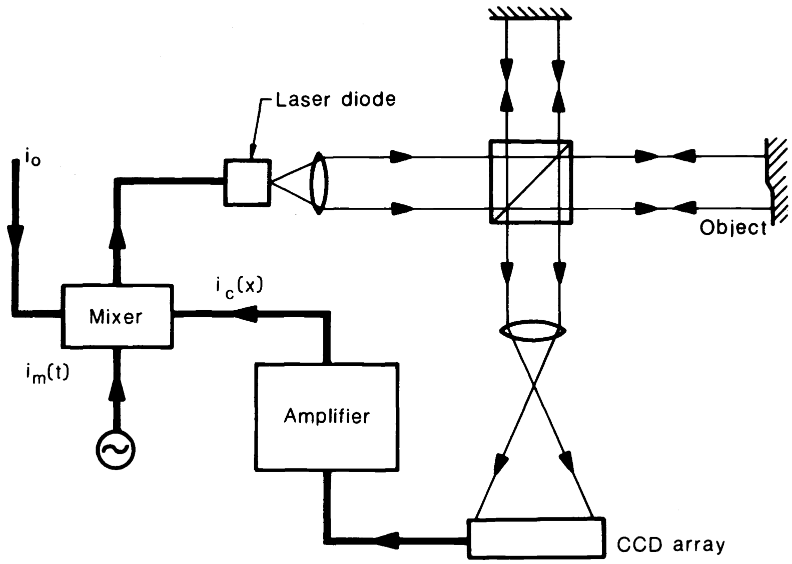

Fig.2. Phase locked laser diode interferometer for surface profile measurements (Suzuki *et al*, 1989).

$$I(t) = I_1 + I_2 + 2(I_1 I_2)^{\frac{1}{2}} \cos [\varphi + \Delta\varphi(t)] \quad (1)$$

where I_1 and I_2 are the irradiances due to the two beams taken separately, and φ is the mean phase difference between them. We can expand the last term on the right hand side of Eq. (1) to give the result

$$I(t) = I_1 + I_2 + 2(I_1 I_2)^{\frac{1}{2}} [J_0(\Delta\varphi) + 2J_2(\Delta\varphi)\cos 2\omega t + \ldots] \cos \varphi$$

$$-2(I_1 I_2)^{\frac{1}{2}} [2J_1(\Delta\varphi) \sin \omega t + 2J_3(\Delta\varphi) \sin 3\omega t + \ldots] \sin \varphi \quad (2)$$

The output at the modulation frequency has an amplitude $4(I_1 I_2)^{\frac{1}{2}} J_1(\Delta\varphi) \sin \varphi$, and becomes equal to zero when $\varphi = m\pi$, where m is an integer. Since both the magnitude and the sign of this signal change as it passes through zero, it can be used as the input to a servo system that varies the control current so as to lock the phase at this point. Changes in the optical path can be derived from measurements of the control current.

Measurements can be made across an object with a linear charge-coupled detector (CCD) array.[6] A sample-and-hold circuit is used to pick up the signal at any specified measurement point from the output of the CCD array. If the period of charge storage in the CCD array is much smaller than the period of the phase modulation, a continuous signal is obtained for each measurement point.

5. SINUSOIDAL PHASE-MODULATING INTERFEROMETRY

In this case the amplitude of the phase modulation is larger than that used for phase locking (typically around π radians).[7] The modulation amplitude can be determined from the amplitudes of the components in the detector output at the modulation frequency and at its third harmonic. Once the modulation amplitude is known, the average phase difference between the interfering beams can be determined from the amplitudes of the components in the detector output at the modulation frequency and at its second harmonic. The need for frequency analysis of the signal can be eliminated by integrating the time-varying intensity in the interference pattern over four successive intervals, each corresponding to a quarter period of the phase modulation.[8]

The required modulation of the phase can be produced in this case also with a frequency-modulated laser diode.[9,10] The resulting intensity modulation can be eliminated by dividing the output from the interferometer by the signal from a reference detector.

6. PHASE-SHIFTING INTERFEROMETRY

Phase-shifting interferometry is now a well established technique. In this method, the optical path difference between the interfering wavefronts is changed in a number of equal steps, and the corresponding values of the intensity at each data point in the interference pattern are measured and stored. These intensity values can be used to obtain the original phase difference between the interfering wavefronts at this point.[11] With a laser diode, the phase steps can be introduced conveniently by modulating the injection current so as to shift the output wavelength appropriately.[12,13] Wavelength shifting is particularly attractive with large interferometers because of the difficulties involved in using piezoelectric translators for phase stepping with heavy mirrors.

For accurate measurements, the laser wavelength must be stabilized during each measurement. Fluctuations in the laser wavelength can be held to less than 1 part in 10^8 over a period of a few seconds by locking the laser wavelength to a resonance of a reference cavity (a Fabry-Perot etalon)[14,15] If the length of the reference cavity is four times the separation of the mirrors in the interferometer, phase steps of 90^0 can be introduced by locking the laser wavelength to successive resonances of the reference cavity.[16]

Errors due to the variation of the output power of the laser as its output wavelength is shifted can be eliminated by taking the average of two sets of measurements made with an additional phase shift of 180^0 between them.[17] This procedure also eliminates errors due to stray light.[18]

7. MULTIPLEXED FIBER-INTERFEROMETER SENSORS

Advances in fiber optics have made it possible to build analogs of conventional interferometers using single-mode optical fibers. Since the optical path in a fiber changes when the fiber is stretched and is also affected by the ambient temperature and pressure, fiber interferometers can be used as sensors for a number of physical quantities.[19]

Measurements can now be made with a single system, either of different quantities or at different locations, by multiplexing several optical fiber sensors. Laser diodes have been used in two techniques for this purpose: frequency-division multiplexing and time-division multiplexing.

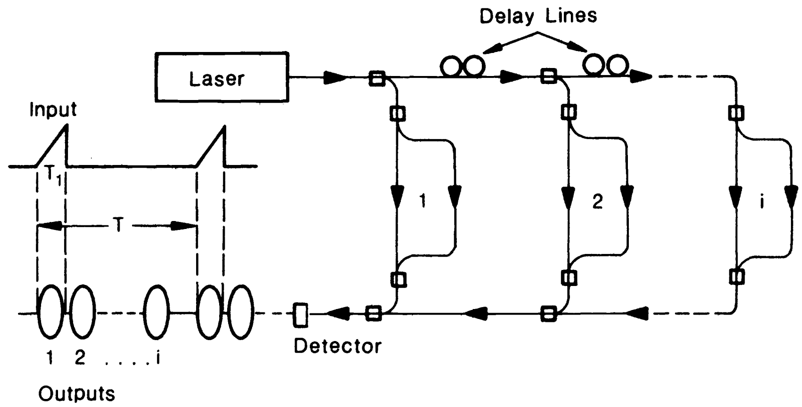

Fig. 3. Schematic of a time-division multiplexed system in which the laser injection current is modulated with a gated ramp (Farahi *et al*, 1988).

In frequency-division multiplexing, the system is set up so that the optical path difference for each sensor is different, and the angular frequency $\omega(t)$ of the laser source is ramped linearly with time. Over any sweep, we can assume that the variation of the laser frequency is given by the relation

$$\omega(t) = \omega_0 + a(t - nT) \tag{3}$$

where ω_0 is the initial angular frequency, a is the sweep rate, n is an integer and T is the period of the sweep. If Δt is the differential delay between the two paths in the interferometer, a pseudo-heterodyne output is obtained from the detector at a frequency $a\Delta t$ with a phase $\omega_0\Delta t$. Each interferometer therefore produces a different heterodyne frequency. Any small change in the optical path difference in a sensor results in a negligible change in the frequency of this beat signal, but a measurable change in its phase.[20-22]

In time-division multiplexing, the optical input is pulsed and each sensor produces an output pulse which is separated in time from the other sensor signals.[23] Such a system can be implemented, as shown in Fig. 3, with a laser diode source which is driven by a gated saw-tooth current to produce pulses during which the laser frequency is ramped linearly. If the time between successive pulses is greater than the sum of all the delays, the outputs from the individual interferometers are separated in the time domain, and information on the phase can be recovered from each of the individual heterodyne signals.[24] Both these techniques can be combined to increase the number of interferometric sensors in a multiplexed system.[25]

8. LASER-FEEDBACK INTERFEROMETERS

Even a very small fraction of the output from a laser fed back into the laser cavity has a strong influence on the intensity of the beam. This feedback can be provided by an external mirror which constitutes the movable element in an interferometer. The operation of such an interferometer can be understood very simply by regarding the combination of the external mirror and the output mirror of

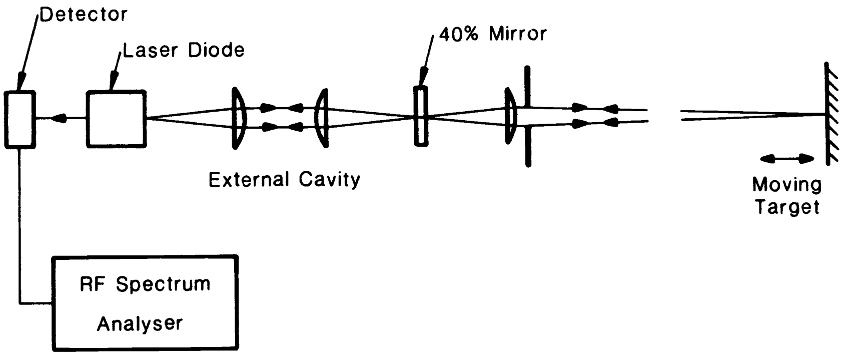

Fig. 4. Feedback interferometer using a laser diode for Doppler velocimetry (de Groot and Gallatin, 1989).

the laser as a Fabry-Perot interferometer with variable spacing (and, therefore, variable reflectivity at the laser wavelength).

A very compact laser-feedback interferometer can be set up with a mirror and a single-mode laser diode.[26] Small displacements can be detected by holding the laser current constant and monitoring the light output. An increased measurement range can be obtained by mounting the mirror on a piezoelectric transducer and using an active feedback loop to hold the optical path from the laser to the mirror constant.[27]

A similar setup can also be used for velocimetry. If the Doppler-shifted light reflected from the moving object is mixed with the original oscillating wave inside the laser cavity, the output from the rear end of the laser contains the beat signal.[28,29] The sense of the movement can be determined from the shape of the output waveform.[30]

Much greater sensitivity can be obtained if the laser diode is operated near threshold. The sharp reduction in the coherence length that normally results can be avoided by using, as shown in Fig. 4, an external cavity to ensure single-mode operation of the laser diode.[31] Measurements can be made with such a system at ranges up to 50 m.

9. PHASE-CONJUGATE INTERFEROMETERS

In a phase-conjugate interferometer, the wavefront under study is made to interfere with its conjugate. As a result, no reference wavefront is necessary, and the sensitivity is doubled.[32,33] A compact phase-conjugate interferometer that is an analog of the Fizeau interferometer uses a conventional partially reflecting mirror placed in front of a crystal of barium titanate which operates as an internally self-pumped phase conjugator.[34]

Interferometers in which both mirrors have been replaced by phase conjugating mirrors are unaffected by misalignment of the mirrors. The delay in the response of a phase conjugator, such as barium titanate, can be used to display dynamic changes

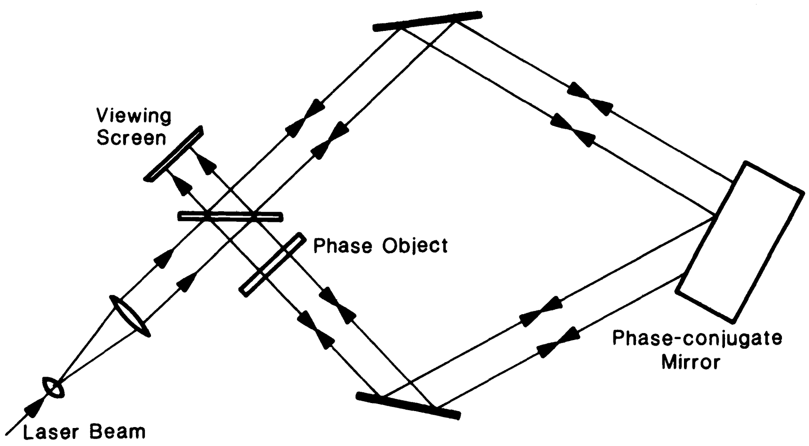

Fig. 5. Phase-conjugate interferometer used to display dynamic changes in the optical path difference (Anderson *et al*, 1987).

in the optical path difference.[35] In the steady state, the interferometer shown in Fig. 5 is insensitive to spatial variations in the optical path difference, and the field of view is completely dark. However, any sudden local change in the optical path difference results in the appearance of a bright spot in the field, which fades away as the phase conjugator responds to the change.

10. SQUEEZED LIGHT

The electric field vector of a light wave can be represented as the sum of two quadrature components in the form

$$E = E_0 \, [X_1 \cos \omega t + X_2 \sin \omega t] \tag{4}$$

where X_1 and X_2 are complementary operators whose variances obey the uncertainty relationship. For normal coherent light the variances are equal. For a squeezed state the variances are unequal, though their product remains unchanged. It is possible, therefore, with squeezed light to reduce phase fluctuations, as shown in Fig. 6, at the expense of a corresponding increase in the amplitude fluctuations.[36]

While a number of nonlinear optical effects can be used to generate squeezed light, the most widely used method has been degenerate four-wave mixing in a nonlinear medium.[37] When energy is transferred from the two strong pump beams to the two weaker signal beams, correlations are established between the photons in the two weaker beams, and the resulting light exhibits the characteristics of squeezed states.

The production of squeezed states can be demonstrated with a balanced homodyne detector. The squeezed light is combined at a beam splitter with another strong beam from the same laser which acts as a local oscillator. The beams leaving the beam splitter are incident on two photodetectors, and the difference of the two

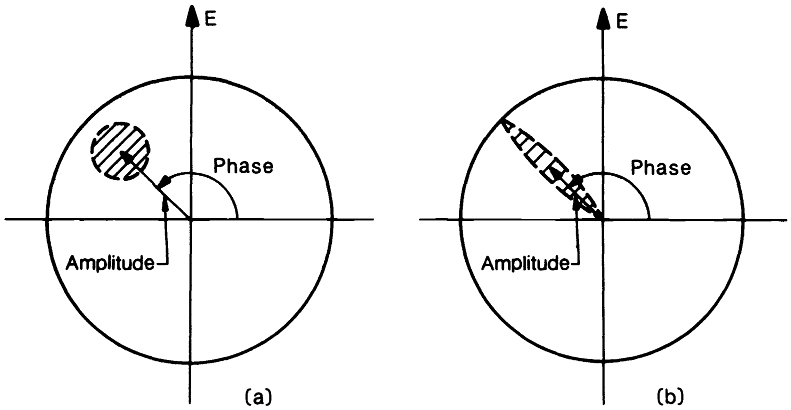

Fig. 6. Variances of phase and amplitude in (a) normal, and (b) squeezed light.

photocurrents is displayed. Intensity fluctuations due to the local oscillator are eliminated by this technique, so that the fluctuations in the output are essentially due to the signal. As the phase difference between the squeezed light signal and the local oscillator is varied, the detector becomes sensitive first to one quadrature amplitude and then to the other, and the output noise level changes accordingly.

The fractional error of interferometric measurements due to photon noise is $1/\sqrt{N}$, where N is the number of photons detected.[38] With squeezed light, the measurement uncertainty could be reduced, in principle, to $1/N$.[39] Accordingly, the use of squeezed light could lead to major improvements in the performance of interferometers and make it possible to measure extremely small displacements.

11. CONCLUSIONS

The past few years have seen major advances in laser interferometry. A survey of recent work reveals some clearly identifiable trends. One such trend is the increasing use of laser diodes as light sources for interferometry. Among their advantages over gas lasers are their compact size, low cost and low power consumption, and the ease with which a stable, single-mode output can be obtained. In addition, the fact that the output wavelength can be controlled by varying the injection current has been utilized very effectively in several new types of interferometers. Another significant trend is the increasing use of multiplexed fiber interferometers for simultaneous measurements of a number of physical variables at several points.

However, the most interesting future developments are likely to come from improved nonlinear optical materials, which should make systems using phase-conjugation practical and open the way to completely new techniques of interferometry involving the use of squeezed light.

All these possibilities point to an exciting future for laser interferometry.

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