A NEW LASER MEASUREMENT SYSTEM
FOR
PRECISION METROLOGY

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Abstract

Laser measurement systems, based on optical heterodyne interferometry, have been a valuable tool for precision metrology for almost two decades. During this period measurement requirements have steadily increased without an accompanying improvement in system capabilities. This paper describes a new laser head, electronics, and interferometers that satisfy present needs and have the attributes to meet future requirements.

I. INTRODUCTION

Over the past 17 years laser measurement systems, based on optical heterodyne interferometry[1], have become an attractive tool for dimensional metrology. This is due primarily to the inherent accuracy provided by interferometry, which measures optical path change in units of the wavelength of light. Coupled with heterodyne detection, this unit of measure can be further sub-divided while retaining a high signal-to-noise level. Using interferometers with specific designs, the measured optical path change can be related to physical quantities such as linear displacement, rotation, straightness, flatness, squareness, and parallelism as well as changes in the refractive index of air.

The combination of the laser source, interferometers, receivers, electronics, computational algorithms and display make up a laser measurement system, shown schematically in Figure 1. Currently, available systems have undergone little change over the years to keep up with constantly increasing measurement needs. Higher resolution and, simultaneously, higher rates of change are required, as are interferometers that are less sensitive to thermal and mechanical disturbances. This paper gives an overview of a new laser measurement system which incorporates these enhancements with the proven methods of optical heterodyne interferometry.

II. THE LASER HEAD

For the laser measurement system to operate in the optical heterodyne mode, the beam from the laser head must have two components that are orthogonally linearly polarized and differ in frequency by a fixed amount. Each frequency must be known absolutely and they must remain stable for the life of the laser.

To accomplish this, the laser head is comprised of three main components: an actively thermally stabilized He:Ne laser tube; an acousto-optic frequency shifter; and a birefringent combining prism. Figure 2 shows a schematic of the laser head. The laser tube emits two axial modes which are orthogonally linearly polarized and differ in frequency by approximately 640 MHz. A small fraction of the beam is sampled by two detectors after the linear polarizations have been separated by a birefringent separating prism. A controller is used to adjust the temperature of the laser tube, and thus its length, to keep the intensity ratio between the two detectors at a constant value. This fixes the frequencies of the two axial modes to the gain curve of the laser. This is confirmed by mixing the beam from the laser tube with the beam from an iodine stabilized He:Ne laser, as shown in Figure 3, and monitoring the beat frequency. Experimental results are shown over a twenty-four hour period. Frequency stability over the lifetime of the laser tube is expected to be better than one part in 10^7.

It would be convenient to use the beam directly from the laser tube in the laser measurement system; however, the frequency difference is too high to be used easily. Therefore, another means is needed to generate a beam with the required characteristics. This is achieved by first placing a polarizer in the beam so that only one polarization (and frequency) is transmitted. This single frequency beam then passes through an acousto-optic frequency shifter. One half of the beam intensity is transmitted unaltered while the other half is diffracted at a small angle and upshifted in frequency by 20 MHz. The polarization of each beam is at an angle of 45° to the plane defined by the undiffracted and diffracted beams, and therefore, may be thought of as having equal vertical and horizontal components. After the beams leave the acousto-optic frequency shifter they immediately enter the birefringent combining prism before they spatially separate by an appreciable amount. The prism is designed to satisfy two conditions: to refract one polarization component of the undiffracted beam and the orthogonal polarization component of the diffracted beam so that they exit the prism collinearly; and to operate at the nominal condition for minimum deviation so that alignment is not critical. Two unused beams, also generated, are blocked by an aperture. The operation of the acousto-optic frequency shifter in combination with the birefringent combining prism is shown schematically in Figure 4 where the diffraction and combining angles have been greatly exaggerated to show the individual beams. The beam now has two orthgonally linearly polarized components which differ in frequency by 20 MHz. Before leaving the laser head the beam is expanded and collimated.

III. THE MEASUREMENT OF OPTICAL PATH CHANGE

The measurement of a physical quantity, such as displacement or rotation, is accomplished by designing a specific interferometer which produces an optical path change as the physical quantity changes. Optical path changes can then be measured and related mathematically to the physical quantity. The beam returning from an interferometer contains information about the optical path change in the form of a phase change between the reference signal (from the acousto-optic frequency shifter driver) and the measurement signal (from the receiver). The phase difference between the two signals is measured every cycle and any phase changes are digitally accumulated. Figure 5 shows how the phase difference is measured. The stable 20 MHz sinusoidal reference signal and the sinusoidal measurement signal are each converted into square waves. The reference square wave is further integrated to produce a triangular wave. The triangular wave is sampled and digitized by an anologue-to-digital converter at each positive transition of the measurement square wave. Its value is then compared to the previous reading and any difference is added to an accumulator. Additional logic monitors the polarity of the reference square wave and the number of transitions of the triangular wave between samples and corrects the phase measurement accordingly. An optical path change of one vacuum wavelength, λ_V, or a physical path change of one wavelength in air, λ, in the interferometer causes the measurement signal to shift by one cycle with respect to the reference signal, which is equivalent to a change of 2^m-1 levels of digitization where m is the numbers of bits in the anologue-to-digital converter. Therefore, the optical path change is resolved in increments of $\lambda_v/(2^m-1)$. This measurement of optical path change is then mathematically converted to the measurement of the physical quantity being monitored. This is illustrated in the following section.

It should be noted that this measurement technique can simultaneously achieve high resolution and high rate of optical path change whereas other methods must sacrifice one for the other.

IV. NEW INTERFEROMETERS

To meet the needs for more accurate measurements, a new class of interferometers is required that minimizes the shortcomings of the typical interferometers presently used in laser measurement systems. Normally an interferometric consists of a number of optical elements, such as beamsplitters, mirrors, retroreflectors and waveplates, that are arranged so that the reference and measurement beams travel different optical paths. These interferometers are susceptible to path length errors due to thermal and mechanical effects. These effects can be reduced to a minimum by designing the interferometers so that the reference and measurement beams travel equal optical path lengths through each optical element in the main interferometer body.[2] The optical path only differs between a single reference and measurement surface. This design has the additional benefit that the main interferometer body can be physically separated from the reference and measurement surfaces so that space can be optimally used, particularly when the measurement is being made in a vacuum chamber. Only the reference and measurement surface need be mounted with care.

The following subsections describe a displacement and angle interferometer, and an interferometer for wavelength compensation based on these design concepts.

A. Displacement Interferometer

An interferometer has been developed that measures the displacement between a remotely mounted reference mirror and a movable mirror. This interferometer, shown in a simplified plane view and an isometric view in Figure 6 consists of the main interferometer body and the remote reference mirror mounted as close to the movable mirror as practical to minimize dead path. The incident beam has two orthogonally polarized components, the frequencies of which are depicted by solid and dotted beams. They are spatially separated by the polarization shear plate. The half wave plate rotates the polarization of one beam so that both beams are identically linearly polarized. The polarization beamsplitter, quarter-wave plate and retroreflector permit one beam to be reflected twice by the reference mirror and the other beam to be reflected twice by the movable mirror. The beams return traveling parallel to each other, the polarization of one beam being rotated by the half wave plate so that it is orthogonal to the other beam. The beams are then recombined by the polarization shear plate. Displacement of the movable mirror causes the optical path of the measurement beam to change relative to that of the reference beam. The optical path change, OPC, is related to displacement, d, by

$$\mathrm{OPC} = 4nd \tag{1}$$

where n is the refractive index of air. The system electronics measure the optical path change in terms of accumulated counts, N, as

$$\mathrm{OPC} = \frac{N\,\lambda_v}{2^m-1} = \frac{Nn\lambda}{2^m-1}\,. \tag{2}$$

Substituting Eq. (1) into Eq. (2) gives the displacement as,

$$d = \frac{N\lambda_v}{4n(2^m-1)} . \tag{3}$$

The resolution of this displacement interferometer is $\lambda/4(2^m-1)$ or $\lambda/508$ for $m=7$ (a seven bit analogue-to-digital converter).

B. Angle Interferometer

An angle interferometer has been developed that measures small angular changes of a movable mirror. Unlike other angle interferometers, translation of the mirror has no effect on the measurement. The angle interferometer is very similar to the displacement interferometer except for the hole pattern in the reference mirror. The interferometer is shown schematically in Figure 7. In this configuration each beam is reflected once from the reference mirror and once from the movable mirror. The beams return traveling parallel to each other. Any rotation of the movable mirror causes the angle of incidence of the two beams on the polarization shear plate to change. This in turn introduces an optical path change between the two beams when they are recombined by the polarization shear plate. Depending about which axis the rotation occurs, the optical path change is given by,

$$OPC_x = 2hn_g \left[\sqrt{1-\left(\frac{\sin(\alpha-2\theta_x)}{n_g/n}\right)^2} - \sqrt{1-\left(\frac{\sin\alpha}{n_g/n}\right)^2} \right] , \tag{4a}$$

$$OPC_y = 2hn_g \left[\sqrt{1-\left(\frac{\sin\ (\cos^{-1}(\cos\alpha\cos2\theta_y))}{n_g/n}\right)^2} - \sqrt{1-\left(\frac{\sin\alpha}{n_g/n}\right)^2} \right] , \tag{4b}$$

and

$$OPC_z = 0 , \tag{4c}$$

where h is the thickness of the polarization shear plate, n_g is its refractive index relative to a vacuum, α is the angle of incidence of the beam from the laser on the polarization shear plate, and θ_x and θ_y are the angles of rotation about the x- and y-axes, respectively. The angle interferometer is intended to measure rotations about the x-axis which is perpendicular to the plane defined by the surface normal of the polarization shear plate and the beam from the laser.

The system electronics measure the optical path change as given by Eq. (2). Substituting this into Eq. (4a), and assuming small angular changes, the approximate expression for angular rotation about the x-axis is,

$$\theta_x = \frac{\sqrt{1-\left(\frac{\sin\alpha}{n_g/n}\right)^2}}{\sin 2\alpha} \; \frac{n_g \lambda_v}{2nh(2^m-1)} N \tag{5}$$

where θ_x is in radians. For the nominal values of α, n_g, and h, and m=7, this reduces to $\theta_x = 0.057$ N where θ_x is now in seconds. Since Eq. (5) is an approximation, there is an error associated with it which is shown in Figure 8 along with the system resolution (0.057 sec). For angular changes up to ±8 minutes the approximation is good to within one resolution element. For angular changes of ±30 minutes, the error is about one second. When greater accuracy is required, Eq. (5) can be replaced with a look-up table generated by using Eqs. (2) and (4a).

Rotation about the y-axis will cause unwanted counts to be accumulated, causing a measurement error. The error is less than one resolution element for angular changes of up to ±2 minutes. Rotation about the z-axis introduces no error.

Other errors can be introduced due to uncertainties in the values of the parameters appearing in Eq. (4). Only one of these cannot be controlled by manufacturing procedures. This is the angle of incidence, α, which depends on the alignment of the interferometer to the incident laser beam. For an alignment error of ±1°, the measurement error is less than one part in five hundred.

The angle interferometer has a limited range over which the movable mirror can rotate. This range is dependent on the separation between the interferometer and the movable mirror. The closer together they are, the greater the range. In practice the maximum range is about ±30 minutes and falls off to about ±5 minutes when the separation is one meter.

C. Optical Wavelength Compensator

Since the unit of measure for a laser measurement system is the wavelength of light, this quantity must be known at all times. Although the vacuum wavelength, λ_v, of the laser is known and remains constant, the measurement wavelength, λ, is affected by the refractive index, n, of the surrounding air which in turn depends on its temperature, pressure, humidity, and molecular composition.

The measurement wavelength, vacuum wavelength and refractive index are related by

$$\lambda = \frac{\lambda_v}{n} . \tag{6}$$

The function of the optical wavelength compensator is to monitor the change in refractive index of the air from some initial value. It does not measure the absolute refractive index, except under special conditions. This is sufficient in many applications where precision is of primary importance. When absolute accuracy is required, the initial value of the refractive index must be provided by some additional means.

The optical wavelength compensator is made up of two components: an inteferometer similar to the displacement interferometer described earlier and an all quartz measurement cell containing an evacuated tube with a window at one end and a mirror at the other. The optical wavelength compensator is shown in Figure 9. The spatially separated equal path length reference and measurement beams from the main interferometer body are transmitted through the measurement cell. The reference beam travels through the evacuated tube while the measurement beam travels through the surrounding air. The optical path difference, OPD, between the measurement and reference beams for an initial value of the refractive index of the air, n_o is given by,

$$OPD_o = 4L\ (n_o-1), \tag{7}$$

where L is the length of the measurement cell. The optical path difference at a later time is given by,

$$OPD = 4L\ (n-1) \tag{8}$$

where n is the current refractive index of the air. The optical path change is given by

$$\begin{aligned} OPC &= OPD-OPD_o \\ &= 4L(n-n_o). \end{aligned} \tag{9}$$

The system electronics measures the optical path change as given by Eq. (2). Substituting this into Eq. (9) and solving for n gives,

$$n = n_o + \frac{N \lambda_v}{4 L(2^m - 1)} \quad . \tag{10}$$

The first term is the initial value of the refractive index and the second term is the measured change. Equation (10) is used in conjunction with Eq. (6) to calculate the measurement wavelength. For the nominal value of L (280 mm), the smallest detectable refractive index change is $\Delta n = 4.4 \times 10^{-9}$.

Absolute measurement of the refractive index can be made when the optical wavelength compensator is initialized in a vacuum (n_o=1). Figure 10 shows the comparison between the refractive index measured by the optical wavelength compensator and a sensor that calculates the refractive index using Edlen's formula[3] from temperature, pressure, and humidity measurements, after air has been vented into an evacuated chamber.

Errors can be introduced due to the uncertainty in the length of the measurement cell, ΔL. The principal sources of this uncertainty are inaccurate measurement of L, changes in L caused by thermal variations, and misalignment of the measurement cell with respect to the beam which makes the measurement cell appear longer than it actually is. The resultant error in the refractive index is given by

$$\Delta n = \left[\frac{N \lambda_v}{4 L(2^m - 1)} \right] \frac{\Delta L}{L} \tag{11}$$

Under normal atmospheric conditions, the term in brackets can have extreme values of $\pm 10^{-4}$ while the maximum uncertainty in the length from all sources is $\pm 10 \mu m$. This results in a maximum error in the refractive index of $\pm 3.8 \times 10^{-9}$, which is slightly less than the resolution of the optical wavelength compensator.

V. SUMMARY

This paper has described a laser measurement system based on a new laser head and enhanced electronics and interferometers. The significant improvements include a stabilized laser emitting a beam with two orthogonally polarized components that differ in frequency by 20MHz. The electronics measures optical path change in increments of $\lambda_v/(2^m-1)$ which gives a displacement resolution of $\lambda/508$. This resolution is constant for velocities of a movable mirror up to ± 1.8m/sec. A new interferometer body, where the reference and measurement beams are common path, minimizes the effects of thermal and mechanical variations to ensure the highest accuracy. This interferometer body can be configured with remote mirrors to measure displacement and angular change or with an evacuated cell to measure refractive index change for wavelength compensation.

In the near future, interferometers designed to measure other parameters required for precision engineering applications will be introduced.

VI. ACKNOWLEDGEMENTS

Although this project has grown considerably since its inception several years ago, the author would like to thank the core group of individuals that worked with him during the early stages of this project and who are responsible for making it successful. Moshe Schaham was the electronics engineer (presently the project manager) who, with Paul Stasieluk, defined the electronic architecture for the system. Peter Young handled the mechanical and, later, the industrial design of the laser head, interferometers and optical wavelength compensator. Guy Mengel did most of the assembly and testing of the first prototypes. Finally, the general optical and mechanical support of James Morace, from the beginning of the project, is greatly appreciated.

References

1. J. N. Dukes and G. B. Gordon, Hewlett-Packard Journal, 21, 2 (August 1970).
2. A different approach with the same objectives is described by R. R. Baldwin and G. J. Siddall, Proc. SPIE, 480, 78 (1984).
3. B. Edlen, Metrologia 2, 71 (1966).

Figures

Figure 1:	Main components of a laser measurement system.
Figure 2:	Laser head showing major components.
Figure 3:	Laser frequency stability test: Experimental arrangement and results.
Figure 4:	Generation of a beam with two orthogonally polarized components of different frequency using an acousto-optic frequency shifter and a birefringent combining prism.
Figure 5:	Phase measuring technique for determining optical path change.
Figure 6:	Displacement interferometer: simplified plane view (top) and isometric view (bottom).
Figure 7:	Angle interferometer: simplified plane view (top) and isometric view (bottom).
Figure 8:	Plot of angular error due to approximation in Eq. (5).
Figure 9:	Optical wavelength compensator showing the measurement cell.
Figure 10:	Comparison of the refractive index as measured with the optical wavelength compensator and calculated from temperature, pressure, and humidity measurements.

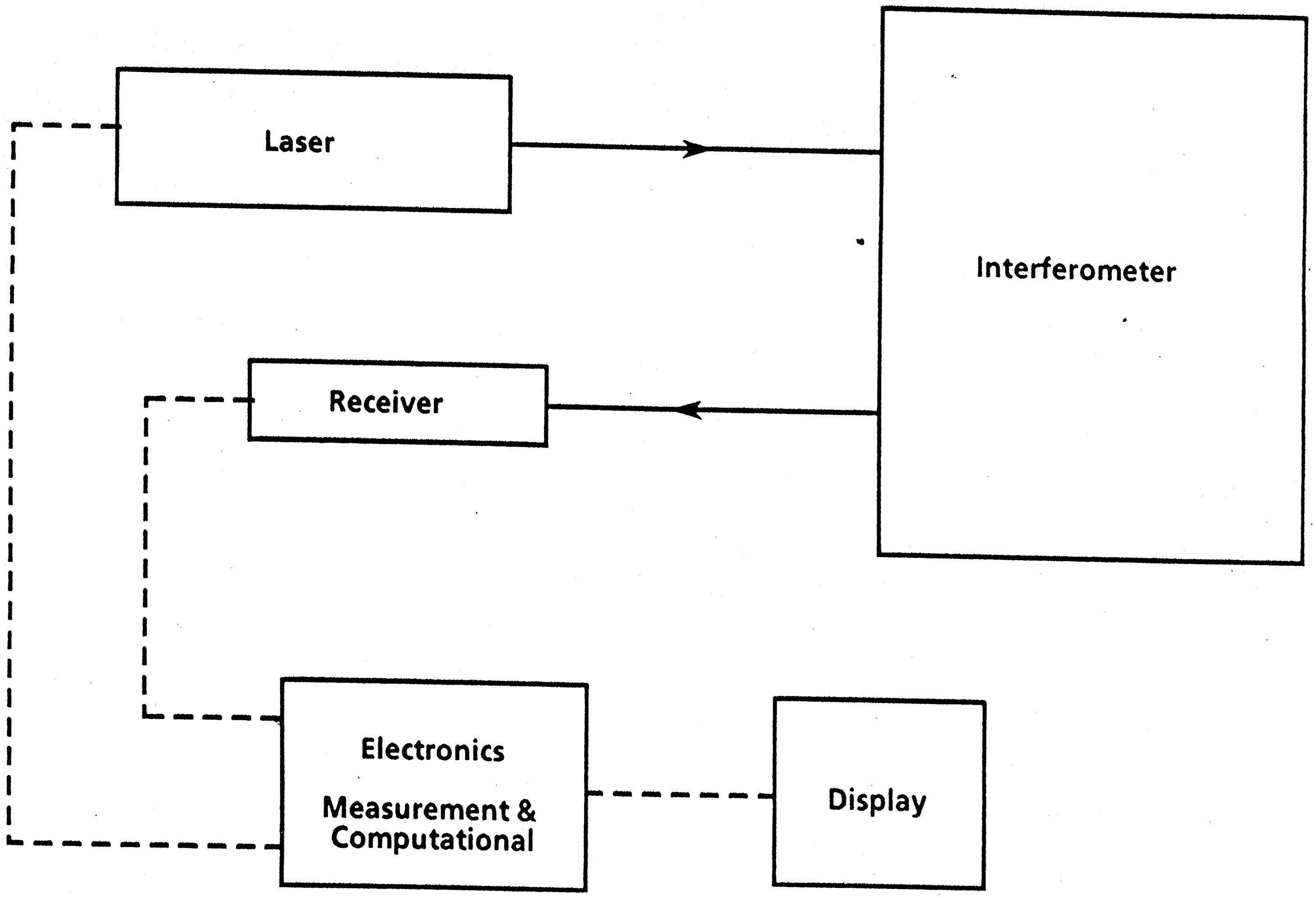

Laser
Interferometer
Receiver
Electronics
Measurement &
Computational
Display

FIGURE 1

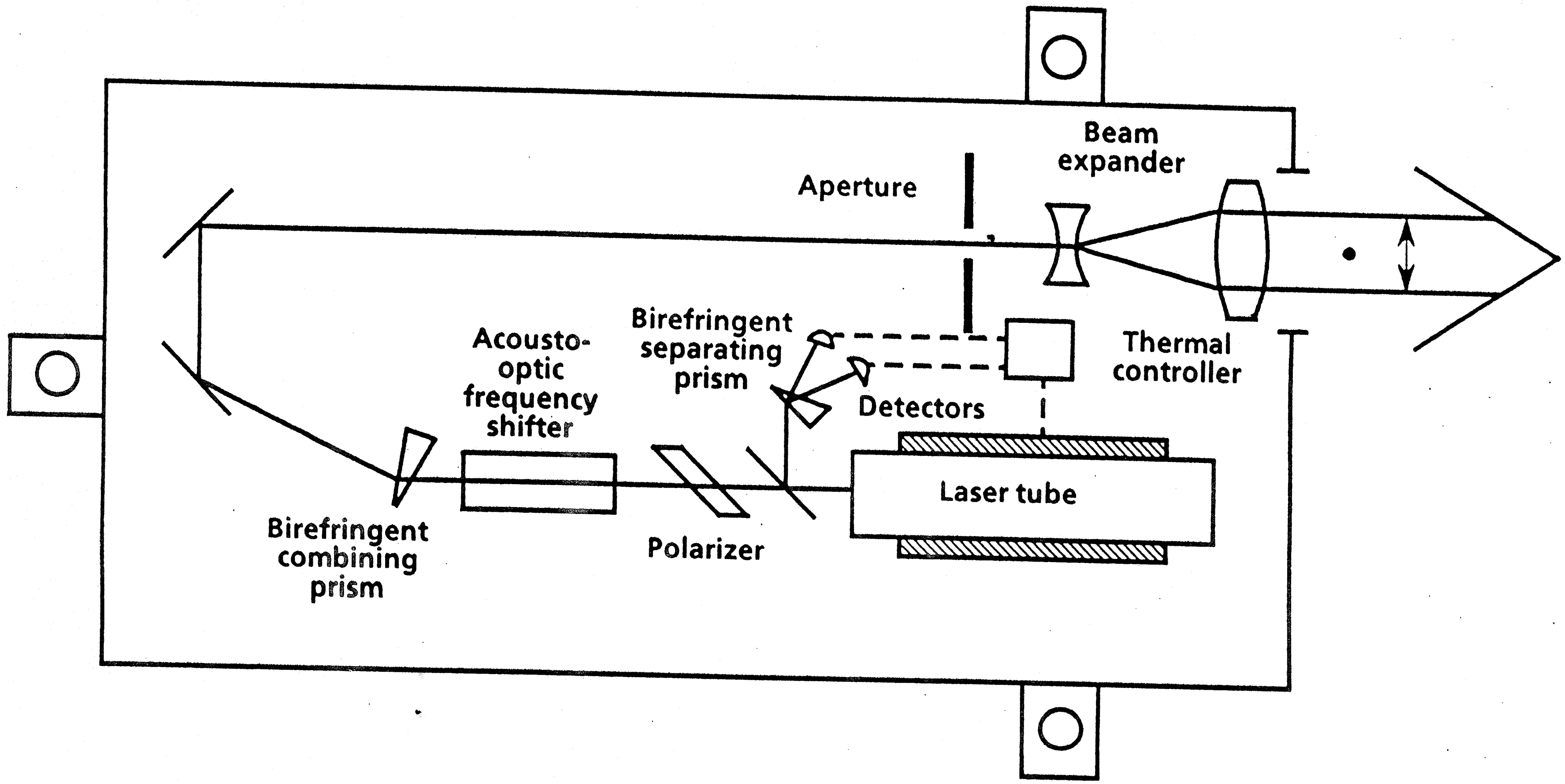
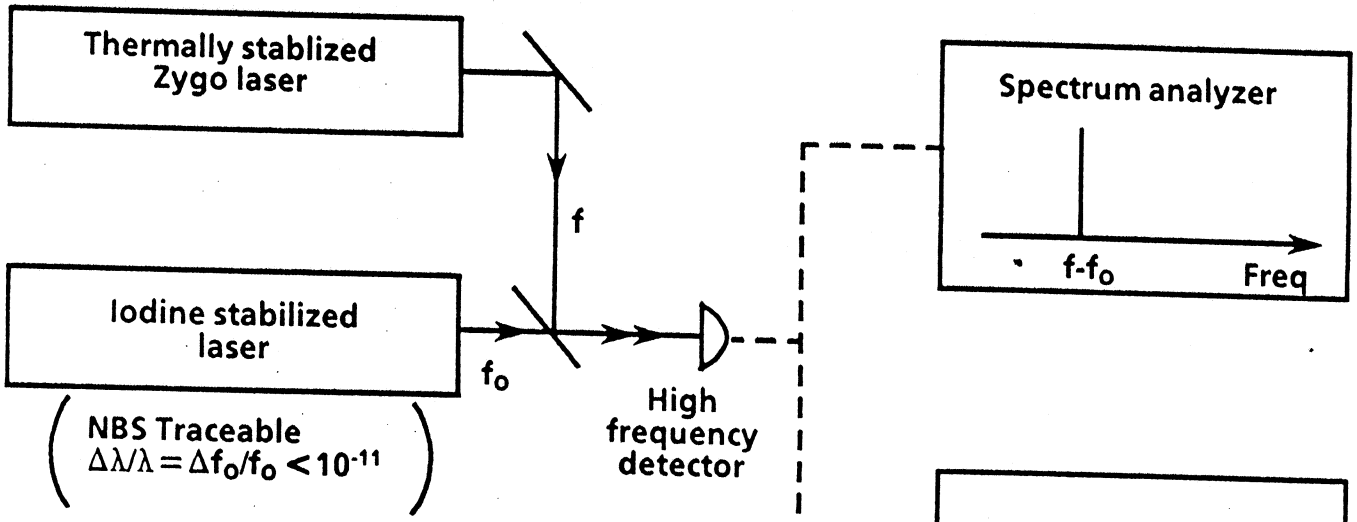

Beam expander
Aperture
Thermal controller
Birefringent separating prism
Acousto-optic frequency shifter
Detectors
Laser tube
Birefringent combining prism
Polarizer

FIGURE 2



Experimental results:

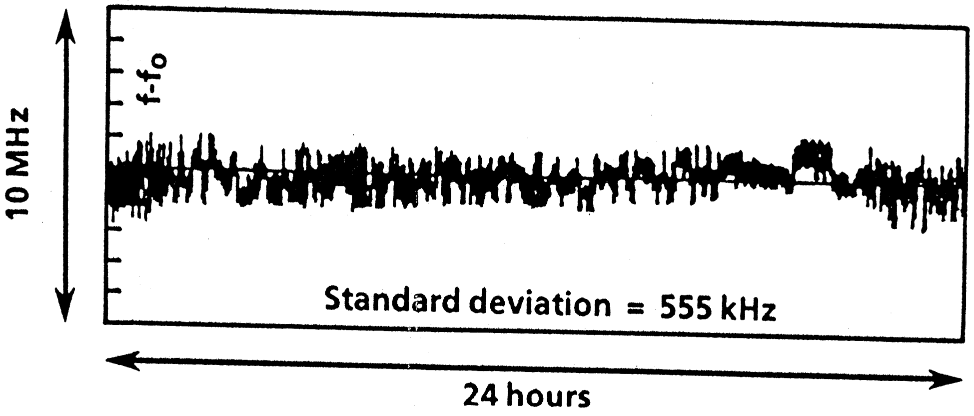


FIGURE 3

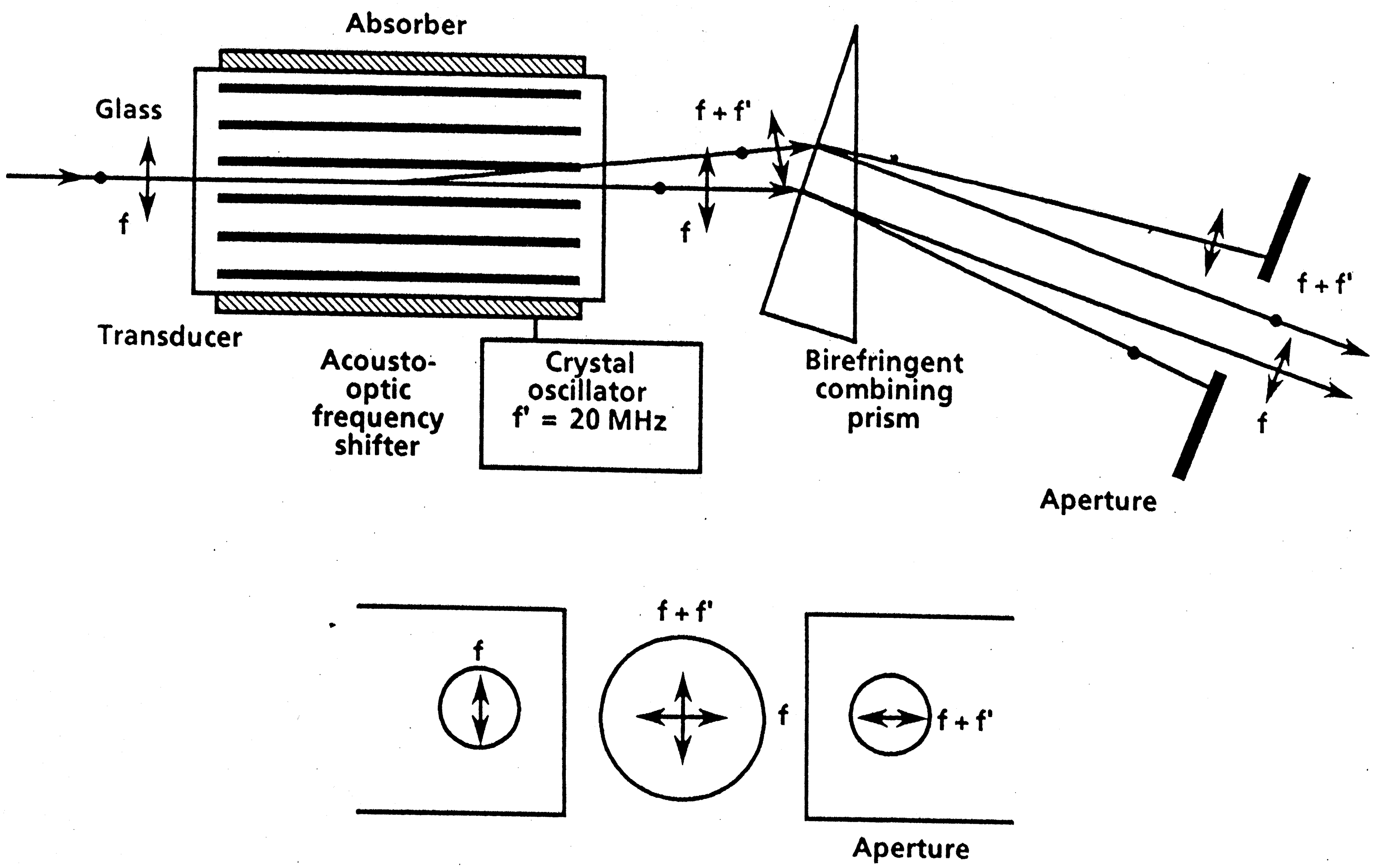

Absorber
Glass
f
Transducer
Acousto-optic frequency shifter
Crystal oscillator
f' = 20 MHz
f + f'
f
Birefringent combining prism
f + f'
f
Aperture
f
f + f'
f
f + f'
Aperture

FIGURE 4

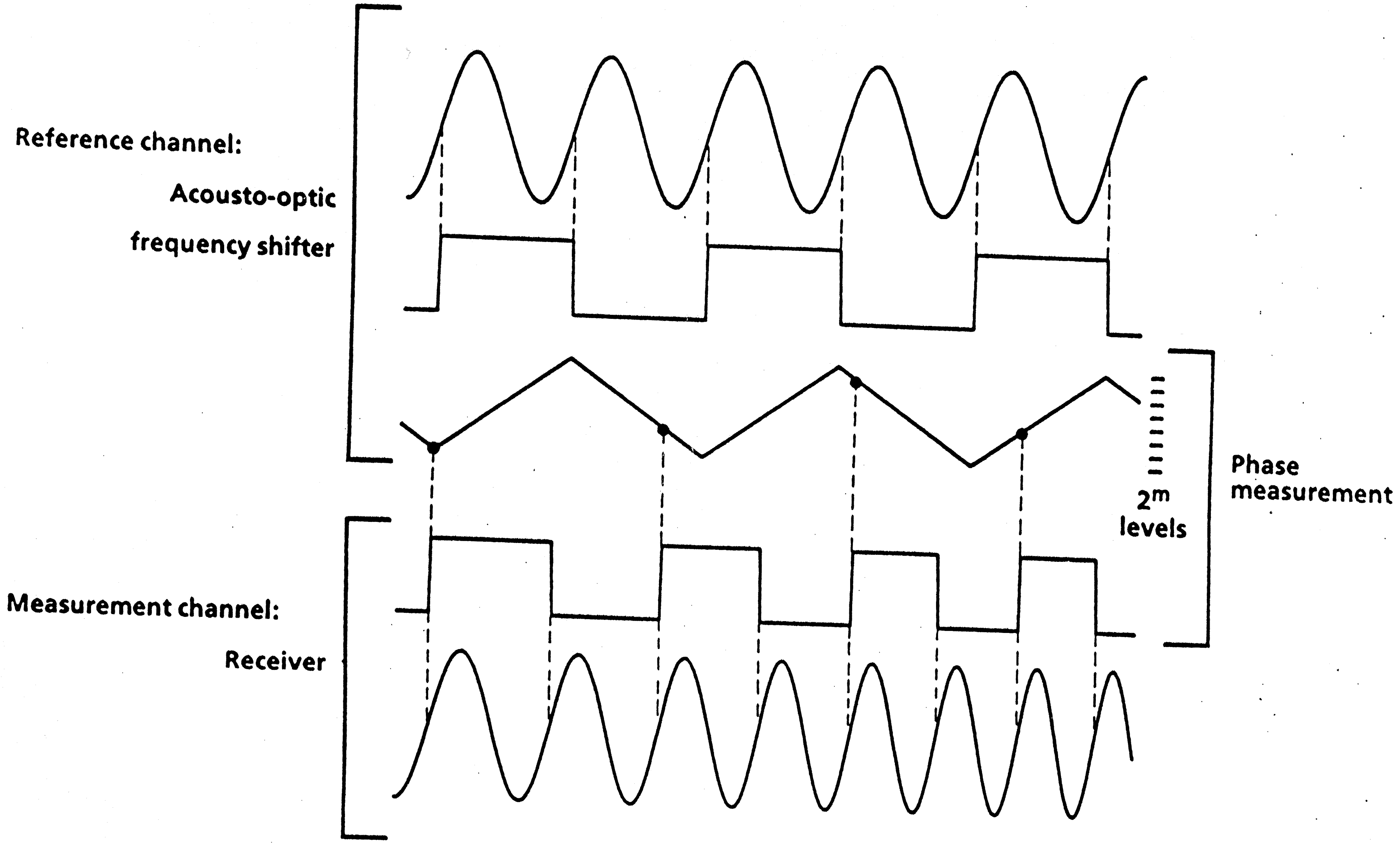

Reference channel:
Acousto-optic
frequency shifter
2^m
levels
Phase
measurement
Measurement channel:
Receiver

FIGURE 5

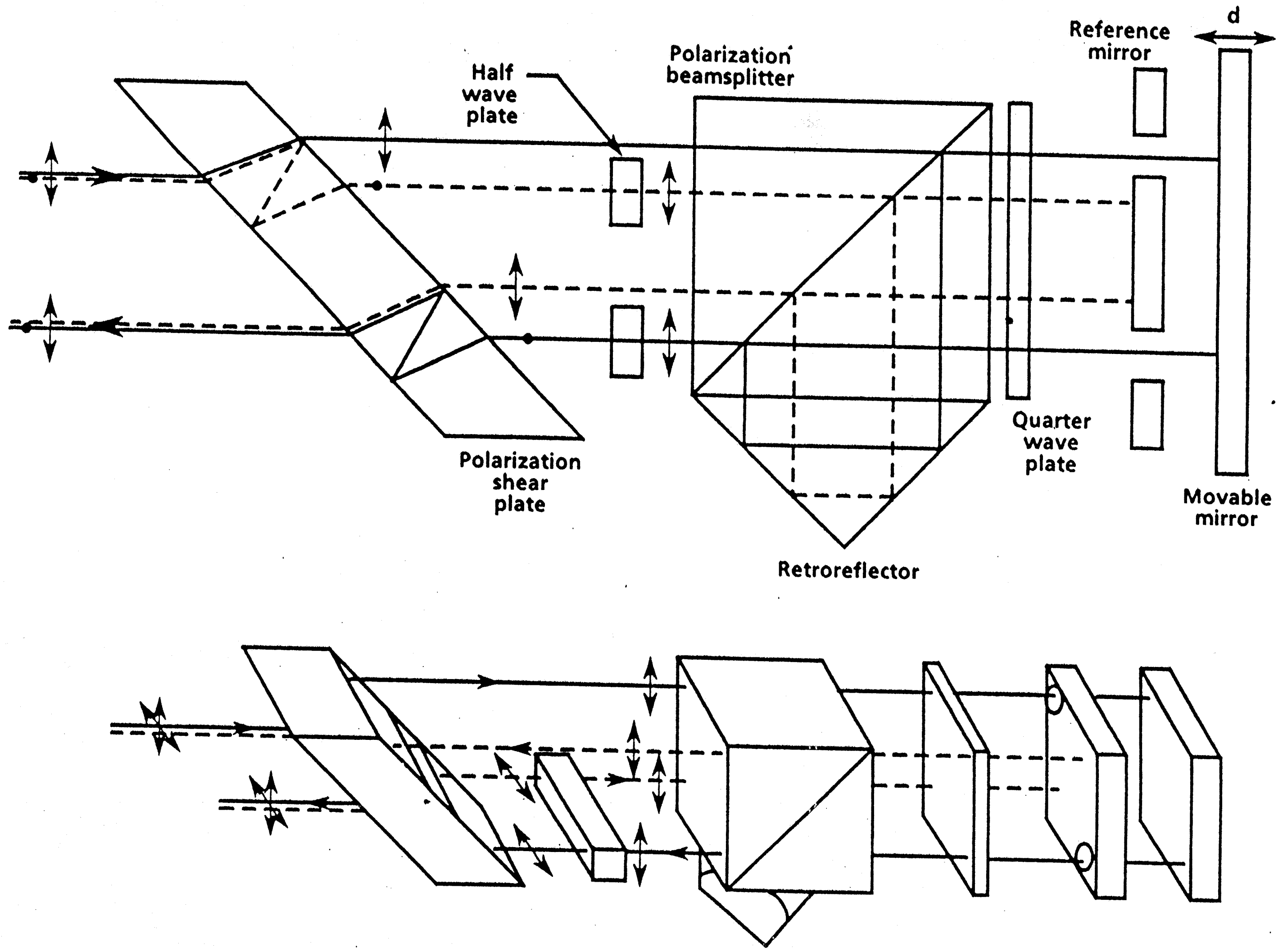

Half wave plate
Polarization beamsplitter
Reference mirror
d
Polarization shear plate
Retroreflector
Quarter wave plate
Movable mirror

FIGURE 6

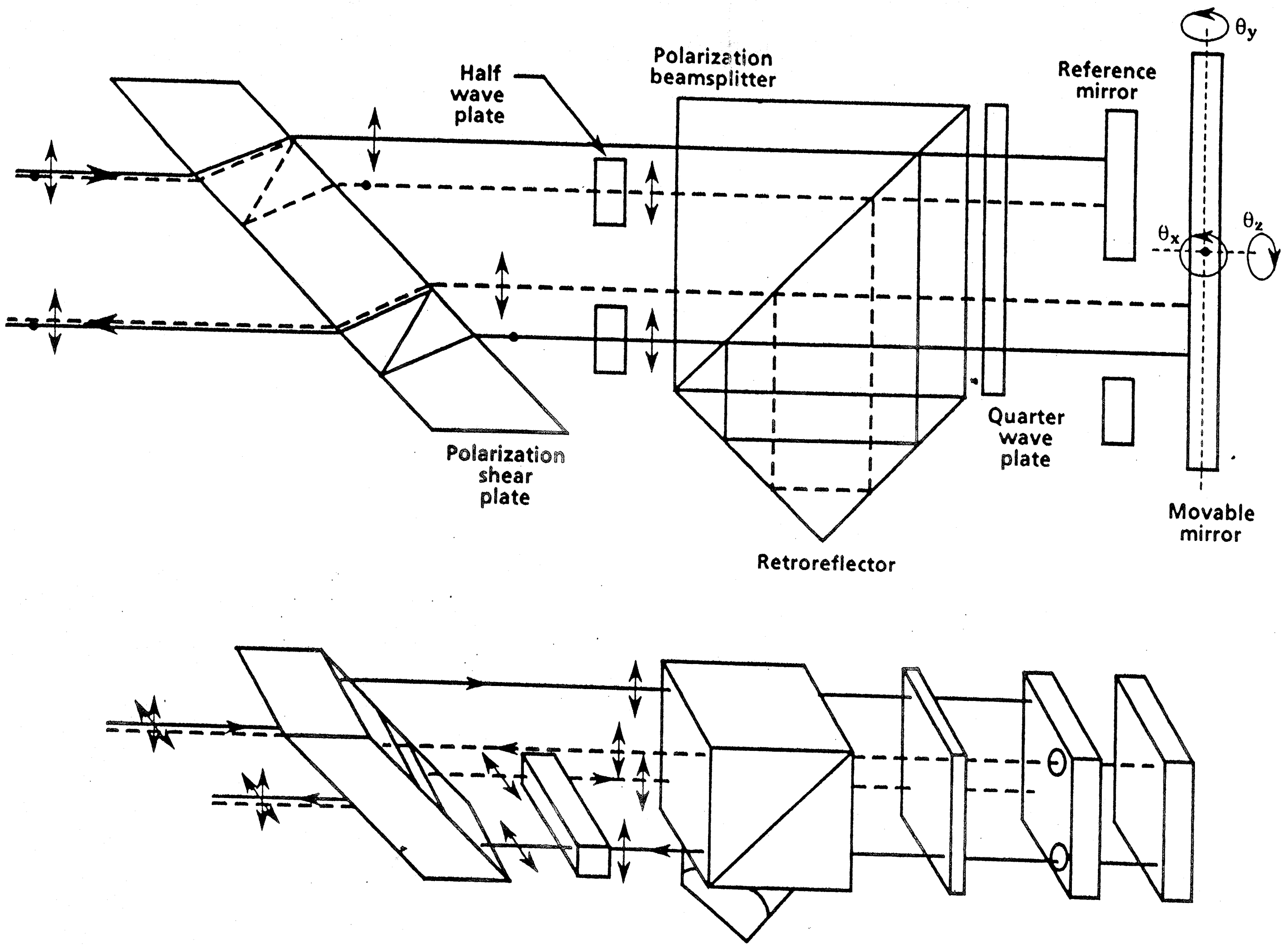

θy
Half wave plate
Polarization beamsplitter
Reference mirror
θx
θz
Quarter wave plate
Polarization shear plate
Movable mirror
Retroreflector

FIGURE 7

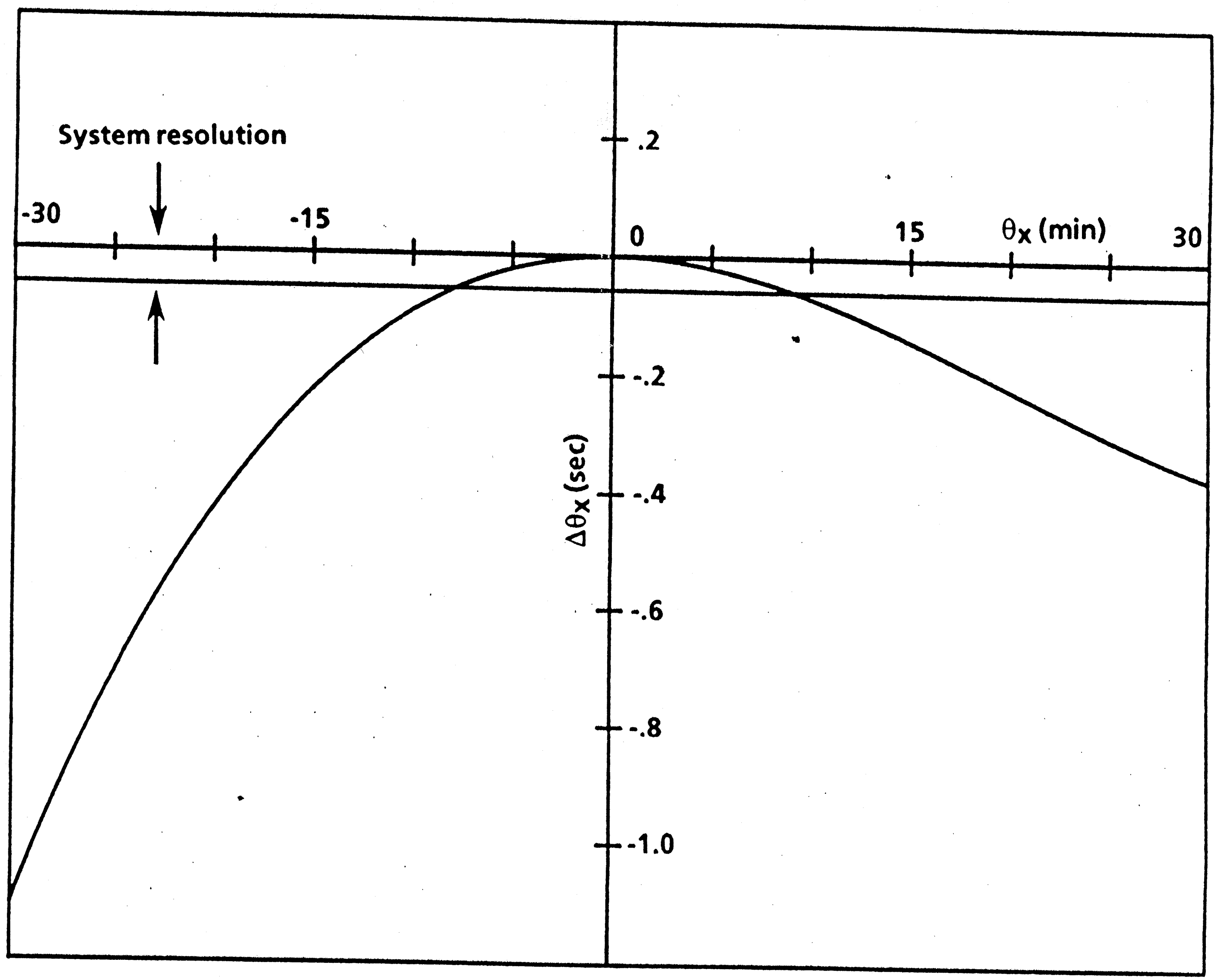

System resolution
-30
-15
0
15
θ_x (min)
30
.2
-.2
$\Delta\theta_x$ (sec)
-.4
-.6
-.8
-1.0

FIGURE 8

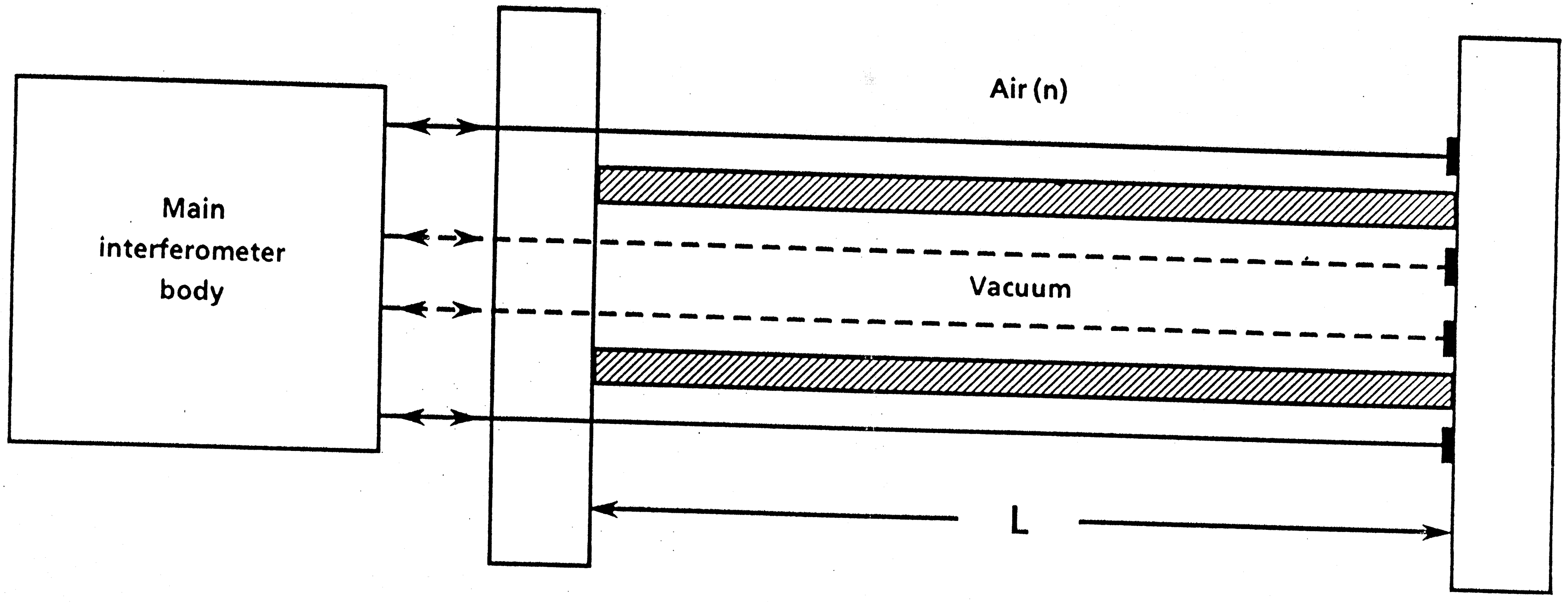


FIGURE 9

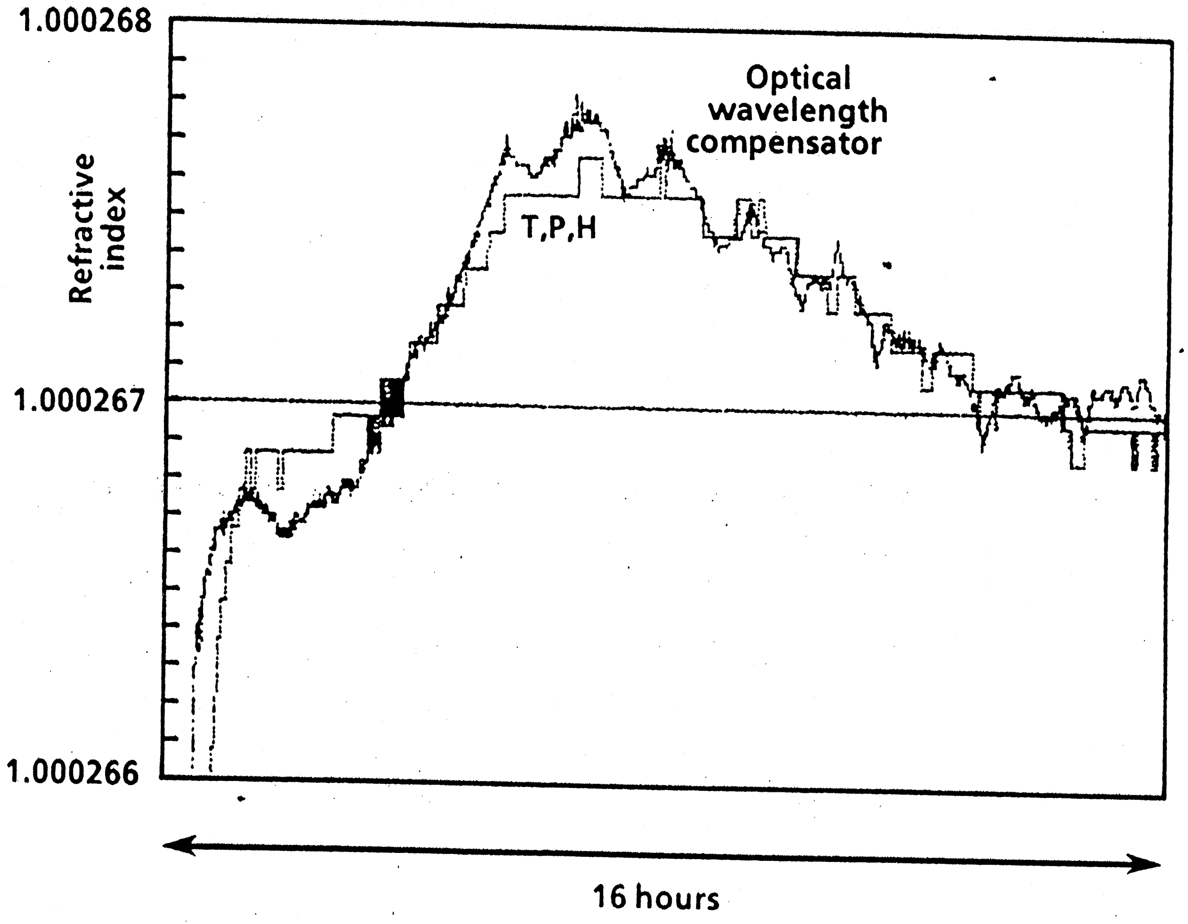

1.000268
1.000267
1.000266
Refractive index
Optical wavelength compensator
T,P,H
16 hours

FIGURE 10