Compact Fizeau wavemeter

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A Fizeau wavemeter using a sealed airspaced wedge is described. Off-axis geometry is employed to produce a compact instrument with good temperature stability. Calibration using a cw multimode dye laser and an argon discharge lamp is described. A precision of 2 in 10^7 and an accuracy better than 2 in 10^6 have been achieved.

I. Introduction

Many modern spectroscopic and diagnostic techniques are based on lasers whose operating wavelength is continuously tunable. A number of methods[1] have been used to measure laser wavelengths to an accuracy approaching the linewidth of the laser. The most common approach is to simultaneously count fringes from the unknown laser, and a reference laser in a Michelson interferometer as the path length is varied. This method is capable of high precision[2] if the two laser beams are parallel in the interferometer, but it is not suitable for pulsed lasers.

Various assemblies[3–5] of static interferometers have been used to determine laser wavelengths without the need to scan path lengths as in the Michelson interferometer. The fringe patterns formed in interferometers of successively higher spacings are measured to provide the wavelength with correspondingly greater accuracy. The laser wavemeter devised by Snyder[6–8] which uses a single Fizeau wedge interferometer whose fringe pattern is measured with a linear detector array is particularly appealing because of its simple form and its potential for high accuracy. This paper describes the construction and performance of a simple compact version of a Snyder-type wavemeter.

II. Principle of Operation

Fizeau wavemeters determine wavelength from a measurement of the fringe pattern formed by two plane coherent wave fronts that have a small degree of tilt between them. Such a pattern is formed with excellent contrast by reflection of an expanded laser beam from a wedge consisting of two separated uncoated glass plates.[7] The pattern is detected with a linear photodiode array and processed to determine both the fringe spacing and the position on the wedge of a fringe minimum.

For plane wave fronts, the fringe spacing is equal to the wavelength in the spacer medium divided by twice the wedge angle. In practice, with wedge angles near 3 min of arc and a 1024-element photodiode array, the fringe spacing can be measured to ~1 in 10^4 accuracy. At any given fringe minimum, the optical path across the wedge is an integral multiple (the order) of half-wavelengths. For a wedge spacing near 1 mm, the order of interference at visible wavelengths is ~3000. Thus the approximate value of wavelength obtained from the fringe spacing can be used to obtain the order of interference and hence allow recalculation of the wavelength to the accuracy with which the wedge separation is known.

Snyder has described two forms of the Fizeau wavemeter,[8] both using an evacuated wedge formed between two glass plates. The first construction used normally incident illumination on the wedge assembly through a beam splitter which directed the reflected beams to the photodiode array. This geometry is sensitive to changes in curvature of the input wave front caused by chromatic aberration in practical beam expanding telescopes. The second form used off-axis illumination in the plane normal to the wedge axis, allowing the detector to be placed at a point of zero shear between the two wave fronts. Then the tilt angle between the two interfering wave fronts is constant, independent of the wave front curvature. However, a significant correction must now be made because dispersion in the front plate of the wedge assembly generates a shift of apparent wedge position along the photodiode array. Also the detector is now mounted a moderately large distance from the wedge, and maintaining the mechanical registration of the two ele-

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ments becomes difficult. Temperature control of a 40- × 45- × 2.5-cm aluminium base plate to 0.5°C and of the wedge assembly itself to 0.05°C was necessary to obtain long-term wavelength precision of 5 parts in 10^7.[9]

Calculation of the effect of wave front curvature on the fringe spacing[10] shows that an acceptable performance can be obtained with practical beam expanding optics if the photodiode array is mounted close to the wedge. Thus an alternative geometry was proposed,[10] using off-axis illumination in a plane parallel to the wedge axis. A wavemeter using such an arrangement has been assembled, and its constructional details and performance are reported here.

III. Construction Details

A number of Fizeau interferometers were made. The optical layout of the final version is shown in Fig. 1. The wedge is formed by optically contacting two fused silica disks (40-mm diameter, 10-mm thickness) to the spacer ring (~1-mm thickness with 3 min of arc wedge). All surfaces except the rear face were polished to better than $\lambda/10$ quality. The leading silica disk was Homosil chosen for its homogeneity. The rear disk was the lower quality Herasil, and it was wedged 5° orthogonal to the spacer wedge so that reflection from the rear face would not interfere with the wanted beams when used near normal incidence. The Homosil disk had parallel faces (<20 min of arc) to avoid correction for changes in the angle of incidence in the central air wedge.

Optical contacting to both sides of the spacer disk provided a sealed air gap to avoid changes in refractive index caused by ambient temperature or pressure changes, leaving only the dispersion in air contributing to the uncertainty of the refractive index in the wedge medium,[10] at the level of 3 parts in 10^8. Spacer disks were made of both Herasil and Zerodur, the latter having a smaller coefficient of thermal expansion. No effects attributable to strain caused by differential expansion of the glasses were noticed. The mount containing the wedge assembly included provision for temperature control to better than 0.1°C, although no special precautions were taken to minimize radiation losses from the faces of the disks. In practice, temperature control was not required for Zerodur spaced wedges in our laboratory, where the air temperature was controlled to within 1°C.

Different spacer disks were made with the central holes cut as circular and rectangular shapes, the latter aligned to the photodiode array axis. A rectangular slit minimizes the strain in the cover plates caused by changes in ambient air pressure, but greater care must be taken in forming the optical contact over the larger area involved. Deformation of the wedge due to changes in barometric pressure may be estimated using the formulas given by Roark[11] for a plate with fixed edges under uniform loading. For fused silica of 10-mm thickness, a pressure differential of 13 Pa (1 cm Hg) would deflect the center of a 30-mm circular plate by 3×10^{-6} mm and the center of a 5- × 30-mm rectangular plate by 3×10^{-10} mm. The latter is negligible, whereas the former would represent a significant change in the average separation of a 1-mm wedge.

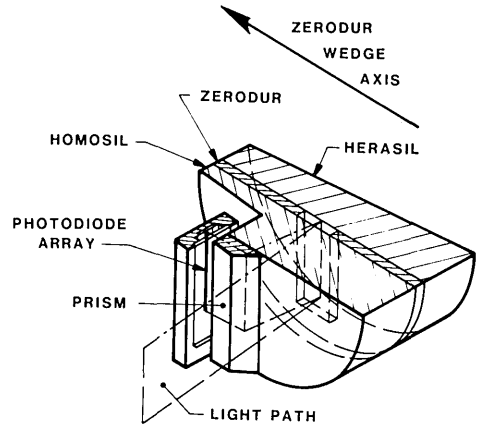

Fig. 1. Isometric view of the optical assembly sectioned through the center.

The beam expander consisted of a Kyowa 60× microscope objective, a 30-μm pinhole as a spatial filter, and a 100-mm achromat lens. This arrangement resulted in a beam ~30-mm diameter from a Coherent 699-05 ring dye laser. A 4% uncoated wedged glass beam splitter diverted the laser beam onto steering mirrors and thence into the wavemeter. A Glan-Thompson prism was used to attenuate the polarized laser beam to prevent saturation of the photodiode array (Reticon RL1024G, 1024 elements). The beam expander lenses were aligned with a shearing plate interferometer, which was also used to check the degree of collimation through the scanning range of the rhodamine 590 dye used. The radius of curvature of the wave front remained >300 m over this range requiring that the photodiode array be placed within ~30 mm of the wedge for the fringe spacing to be measured to 1 in 10^4 accuracy.[10]

The simplest method of obtaining this close proximity was to mount the photodiode array almost in contact with the front wedge cover plate. The minimum angle of incidence of the laser beam on the wedge is then ~30° for the beam to clear the mounting package of the photodiode array. Parasitic reflections from the front and rear wedge plates do not interfere with the wanted beams, and the total assembly is compact and rigid. However, the optical path difference in the air wedge varies as the cosine of the angle of incidence α, and the relative path difference for small changes in angle varies as $\tan\alpha d\alpha$. Reasonable performance was obtained provided the laser beam was centered in the spatial filter. Without constant readjustment as the wavelength was altered, errors at a level of 1 in 10^5 were encountered. This angular sensitivity was reduced by a factor of 17 by reducing the angle of incidence to 2° using the arrangement shown in Fig. 1. The Homosil disk was cut as shown to receive the photodiode array, and a small prism was cemented to the disk to deflect

the beams reflected from the air wedge onto the photodiode array by total internal reflection. All the prism surfaces were polished to reduce scatter, and a wedge of ~2° was maintained in the gap between the photodiode cover plate and the exit face of the prism to avoid interfering reflections. The resulting assembly was compact and readily mounted to maintain good registration between the diode array elements and the position in the wedge.

The signal from the photodiode array was recorded and stored with a Z-80 microprocessor under the control of a separate computer. The microprocessor was also programmed to convolve the data using the algorithm described by Snyder,[12] determine the position of the turning points of the fringe pattern, and linearly fit these data vs fringe (turning point) number. Each convolution and fit required ~300 msec. The residuals between the fitted and actual values of the turning points showed that the wedge whose performance is detailed below was significantly convex. The departure from linearity was 40 nm at the wedge center compared with the edges. Computer simulation of this effect showed that little error was introduced by a linear fit to the turning points; i.e., the returned fringe spacing and intercept represented average values over the whole fringe pattern.

IV. Calibration Method

Data returned to the host computer were the slope and intercept of the line fitted to the turning points and indicated whether the intercept corresponded to a fringe intensity maximum or minimum. If a maximum, the slope of the line, i.e., the distance along the array between turning points, was added to the intercept. The resultant value represents the array (and hence wedge) position of a fringe minimum, averaged over the fringe pattern, and the slope represents the half-fringe separation. These two quantities depend on the wedge separation and the wedge angle, respectively.

It was intended to calibrate the wedge parameters using the optogalvanic effect in a uranium hollow cathode discharge lamp as the wavelengths of the uranium lines are accurately known.[13] However, the lamp chosen had an argon gas fill, and the discharge was oscillatory and noisy over a wide frequency range. The only spectral lines detected were those corresponding to argon resonance transitions. The wavelengths of many of these lines are known to sufficient accuracy[14] to be used for calibration at the 1 in 10^7 level.

The cw dye laser was operated multimode with a linewidth of ~2 GHz. Many of the argon lines detected showed halfwidths greater than this, the broadest being ~6 GHz. The broader lines were not used in determining the wedge separation. A number of lines showed saturation line shapes and line reversals as described for the optogalvanic effect in neon.[15] Thus, for each line used, the line profile (normalized to the laser power) was recorded by scanning the laser wavelength with the intracavity tilting Brewster plate, and the line center was determined with a 25-point Savitsky-Golay routine.[16] The laser was then stepped to the line center, and the fringe information was averaged over ten readings.

The argon reference vacuum wavelengths were converted to air values using the air dispersion formulas of Jones.[17] The wedge angle was then determined from the fringe spacing and an average struck over the calibration set. Typical uncertainty levels (3σ) in this value were ~1.5 in 10^4, sufficiently accurate to estimate reliably the order of interference at a fringe minimum.

The wedge separation was determined by a grid-search least-squares fit to order residuals. A reference value was assigned to the spacing of the wedge at the position corresponding to that seen by the zeroth photodiode. At each wavelength, the increase in separation to the position of the representative fringe minimum, calculated from the known wedge angle, was added to the reference value. The order of interference at the fringe minimum, given the reference value, was determined and subtracted from the nearest integer. The reference spacing was altered until the sum of squares of these order residuals over the set of calibration wavelengths was a minimum. For the wavelengths used near 600 nm, a local minimum occurs every ~300-nm increment in the wedge separation. A step of 100 nm determined the approximate region of the true minimum, which was then unambiguously determined with a step size of 10 nm, followed by 0.1-nm steps to obtain the best fit. In principle, two wavelength values may be used to find the wedge separation,[18] but this does not allow for systematic errors caused by wave front curvature or small changes in angle, which influence the optical path difference in the wedge gap.

V. Performance

The results of a typical calibration run are shown in Table I. Once the wedge angle has been calibrated, these data may be acquired in ~1 h by rapidly stepping the laser wavelength to the vicinity of each of the required lines and then fine scanning until the line is found. The error column represents the difference between the known wavelength and that calculated from the fringe information and the fitted values. The mean relative error is 6 in 10^7 with the largest error 1.7 in 10^6. These errors are well within the laser linewidth of 2 GHz or 4 in 10^6 at these wavelengths. The wedge parameters derived from this calibration were wedge angle 22.9866 nm/diode (where the diode separation is 25 μm) and wedge separation 936160.4 nm at the reference position.

Repeated calibrations proved the wedge separation to be stable to ~5 in 10^7 over several weeks with no temperature control other than the normal high-quality laboratory air-conditioning. The rate of change of the wedge separation with temperature was determined to be 4 in 10^7/°C. This represents an order of magnitude improvement over the zero-shear instrument of Snyder[9] largely because of the compact form of the present instrument. Readings of the position of

Table I. Vacuum Wavelengths of Ar Calibration Lines and Calibration Error

Wavelength (nm)	Error (pm)
573.95207	−0.48
577.21160	−0.47
580.20809	−0.17
583.42660	−0.37
586.03118	−0.20
588.26250	0.84
588.85851	−0.36
597.16036	−1.00
598.73027	−0.04
599.90004	−0.05
600.57246	0.76
601.36790	0.71
602.51515	0.26
603.21291	0.02
604.32254	−0.24
605.27234	0.04
605.93735	0.29
610.56354	−0.26

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the fringe minimum taken over a few seconds showed a typical variance of 0.01 diodes corresponding to a short-term precision of 2 in 10^7.

VI. Conclusion

The Fizeau wavemeter described above is a simple compact instrument producing results comparable to the more complex instruments described elsewhere. Good wavelength accuracy has been achieved without the use of a vacuum wedge. The compact form possible with off-axis geometry leads to improved temperature insensitivity compared with zero shear instruments. Reliable calibration has been obtained without the need for frequency-narrowing etalons in the laser cavity.

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