Dual-purpose, compact spectrometer and fiber-coupled laser wavemeter based on a Wollaston prism

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A fiber-coupled, compact laser wavemeter based on a modified Wollaston prism has been constructed and evaluated. The path difference between orthogonal polarization states of the input light varies smoothly across the aperture of the prism forming an interferogram in the spatial domain that is recorded with a CCD detector array. A Fourier transform of this interferogram gives the spectral distribution of the incident light. Alternatively, for a narrow-linewidth source a fringe period measurement technique is used to obtain precision measurement of the center wavelength. Using 752 interferogram data points we obtain a wavelength precision of 1 part in 10^6. The elimination of moving parts from the design makes the recorded interferogram inherently stable. © 1998 Optical Society of America

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1. Introduction

With the development and increased utilization of tunable lasers in areas such as spectroscopy and photodynamic therapy has come the need for instruments that can conveniently and accurately determine their wavelengths. The highest-accuracy measurements of laser frequency have been achieved by use of direct-frequency measurements. Elaborate frequency synthesis chains have been designed to compare selected laser frequencies to an atomic clock that produce results with uncertainty of only a few parts in 10^{10}.[1] However, the complexity of such frequency chains means that they do not lend themselves to routine laboratory use. Rather than measure the laser frequency directly it is possible to determine frequency from a measurement of the laser wavelength. Such an instrument is termed a laser wavemeter, and for reasons of practicality it should have accuracy, speed, and portability.

Michelson interferometers are often used as laser wavemeters in which the precision of the wavemeter is set by the number of fringes within the interferogram. These interferometrically based instruments usually require high-precision scanning mechanisms and stable designs, which inevitably implies high cost and substantial bulk. This has led to considerable research into designs of instruments having no moving parts, where an interferogram formed in the spatial domain is recorded with a detector array. These static instruments have the advantage of use with both cw and pulsed lasers. Some of these are based on Fizeau wedges, where the wavelength is determined from a measurement of the CCD-recorded fringe pattern formed by reflection of an expanded laser beam from a wedge consisting of two separated, uncoated glass plates with a small degree of tilt between them. Alternatively, birefringent wedges can be used to introduce a variable path difference between orthogonal polarization states of the input light.

Recently, novel static Fourier-transform spectrometers (SFTS's) based on Wollaston prisms have been developed that have no moving parts and are consequently extremely robust and compact instruments.[2,3] The operating principles of SFTS's based on Wollaston prisms have been reported earlier,[2,4] and it suffices to state here that a Wollaston prism comprises two similar wedges of birefringent material joined by their hypotenuse to form a rectangular block. The optic axes within the two wedges are aligned perpendicular to each other and parallel to the entrance–exit faces of the composite block. The angle of refraction at the internal interface of the prism depends on the polarization state of the light and hence leads to the customary use of a Wollaston prism as a polarizing beam splitter. Of interest to the spectroscopist is the introduction of a path differ-

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ence between orthogonally polarized components of the incident light that varies linearly with the lateral position across the prism. Thus, when illuminated between polarizers, interference fringes are produced parallel to the sides of the Wollaston prism. For an extended source, the fringes are localized within the prism itself.[5] Early designs of spectrometers used a lens to image the fringes on a detector array.[2,3] Subsequently, the lens was replaced by a second Wollaston prism that relocalizes the fringe plane to a position behind the exit face of the second prism where it can be recorded directly.[4] The removal of the lens from the design allows a significant reduction in optical length of the instrument and eliminates the possible distortion of the interferogram from chromatic aberrations that are due to the lens. A further reduction in size is possible by modifying the Wollaston prism itself, by inclining the optic axis in the Wollaston prism such that the fringes are localized behind the exit face without the need for either a lens or a second prism.[6]

Unfortunately, the number of the pixels on the CCD array sets a limit on the number of fringes that can be recorded within the interferogram, thus limiting the resolution of the spectrometer. In addition, the fast-Fourier-transform method is problematic with so few data points, as it yields information about the period of a sinusoid only indirectly and is known to suffer from systematic errors, or bias, that interfere with the real spectrum.[7] However, the lack of moving parts within the spectrometer itself results in an extremely stable interferogram. This inherent stability can be used to increase the precision beyond that dictated by the number of fringes within the interferogram. If it is assumed that the input light is quasi-monochromatic then a measurement of the fringe period gives the wavelength of the source to an arbitrary high accuracy.

2. Instrument Construction

The compact design of the SFTS is realized by matching the Wollaston prism and the polarizers to an appropriate detector. We use a highly integrated CCD monochrome video camera,[8] which has a 752 × 582 array sensor with a total active area of 7.95 × 6.45 mm. It also includes the necessary drive circuits to deliver a formatted video signal. The detector array of the camera is mounted behind the exit face of the Wollaston prism to coincide with the fringe plane.

In the optimized, computer-modeled design[9] both the Wollaston prism and the polarizers are manufactured with an aperture of 10 mm. The Wollaston prism, manufactured from calcite,[10] is 1.5 mm thick and has an internal wedge angle of 2.8°. The optic axis in the first wedge is inclined at an angle of 16.0° to the prism entrance face (18.8° to the wedge interface). Adhering the polarizers to the faces of the prism with their polarization axes aligned at 45° to the edges gives a single optical component spectrometer approximately 3 mm thick. The fringe pattern forms approximately 2.0 mm behind the exit face of the prism, coincident with the position of the detector array. This optical arrangement gives a maximum path difference of approximately 50 μm across the aperture of the detector. The Nyquist criterion means that for a 752-element array the shortest measurable wavelength is 320 nm.

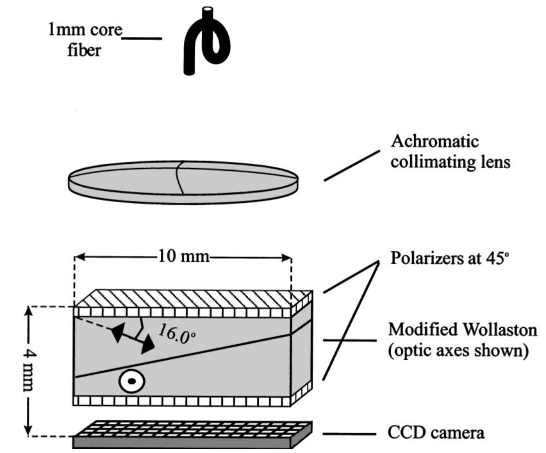

Fig. 1. Optical layout of the wavemeter/spectrometer.

One of the main advantages of a Fourier-transform spectrometer is its higher optical throughput or étendue. This can be as much as 190× greater than that for a dispersive instrument for equivalent resolutions.[11] However, for laser wavemeter applications optical throughput is usually not an issue. When configured as a wavemeter we use a large 1-mm-diameter core fiber to couple light into the instrument. This not only gives a convenient, easily aligned instrument, but the fiber coupling ensures uniform intensity across the interferogram, which in turn gives greater measurement stability. The optical layout of the wavemeter/spectrometer is illustrated in Fig. 1.

The camera outputs data to a desktop or laptop computer by a frame grabber card and appropriate software. The raw data from the camera is a two-dimensional image of the interference fringes that is averaged down the frame to give a single 752-element data array. Averaging the data over the 582 lines of the array reduces the effect of fixed-pattern noise on the resulting interferogram. For ease of use, the control and data-processing software was written for a Microsoft Windows environment. Through simple mouse button clicks the user can control the wavemeter or spectrometer. A photograph of the complete instrument interfaced to a laptop computer is shown in Fig. 2.

3. Wollaston Prism-Based Static-Fourier-Transform Spectrometer Operating as a Laser Wavemeter

Instruments that utilize the fast-Fourier-transform algorithm to determine wavelengths have been produced[12] with an accuracy of ≈1 part in 10^8. The principal advantage of such systems is their ability to measure the wavelength of several single-mode and multimode lasers simultaneously. However, a

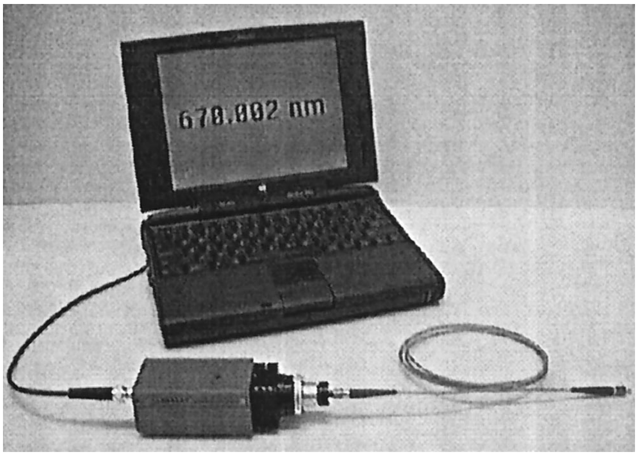

Fig. 2. Fiber-coupled, ultracompact SFTS and wavemeter interfaced to a laptop computer.

static instrument with a restricted number of data points for the fast Fourier transform has a somewhat limited level of accuracy. When a single monochromatic laser source is assumed, this allows the possibility of higher-accuracy methods.

A method that utilizes the SFTS based on a single Wollaston prism and an imaging lens has recently been proposed by Jiang *et al.*[13] The essence of the system involves putting a known reference laser and unknown signal into a standard Wollaston prism spectrometer.[3] The spatial intensity distribution is a superposition of the two sets of interference fringes from the two wavelengths and thus fringe beating is observed. By use of autocorrelation and Gaussian filtering techniques, a variation between the two wavelengths can be measured. The system achieves a precision as high as 0.01 nm. For this system to work it is required that the wavelengths of the two light sources be within 15 nm. If a large measurement range is required, the resolution drops. For example, a measurement range of 110 nm gives a resolution of only 1 nm. In addition, the interference pattern produced by two light sources can be distorted because intensity differences and spectral characteristics of the optics.

Our approach does not require a reference source. We measure the fringe period of the interferogram to determine the wavelength of laser light directly. This not only simplifies the instrument but also gives a wavelength measurement range of several 100 nm with no loss of accuracy.

The path difference Δ introduced by a Wollaston prism between orthogonally polarized components of the incident light is given by[5]

$$\Delta = 2d[\Delta n(\lambda)]\tan \vartheta, \tag{1}$$

where d is the displacement from the center of the prism, $\Delta n(\lambda)$ is the wavelength-dependent birefringence of the prism material, and ϑ is the wedge angle.

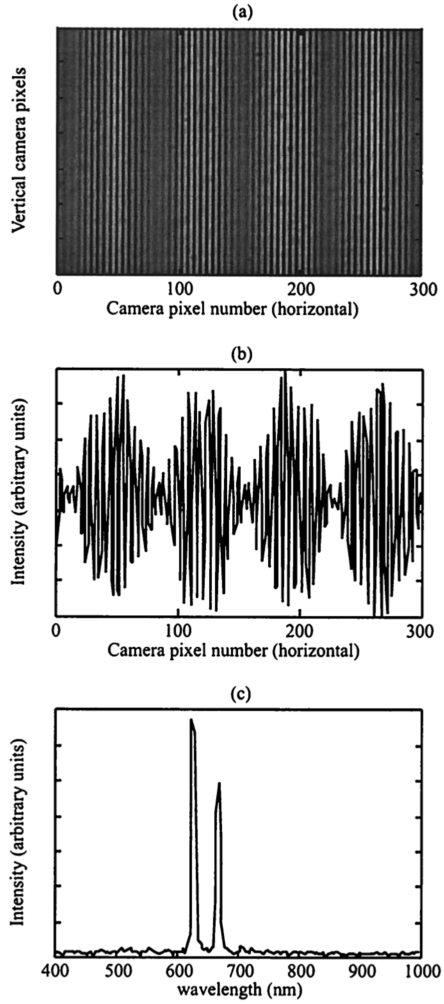

Fig. 3. Sample results when the instrument is used as a spectrometer while illuminating with He–Ne and diode lasers. (a) A section of the two-dimensional fringes as recorded by the detector array, (b) the corresponding one-dimensional interferogram, (c) the Fourier-transformed result.

For a monochromatic source, the fringe spacing S is therefore given by

$$S = \frac{\lambda}{2[\Delta n(\lambda)]\tan \vartheta} = C(\lambda)\lambda. \tag{2}$$

The denominator in Eq. (2) relates to the calibration of the instrument and can be measured explicitly. Rearranging Eq. (2) to give the wavelength in terms of a measured fringe spacing gives

$$\lambda = C'(S)S. \tag{3}$$

The calibration of the wavemeter is carried out with several sources of known wavelength and corresponding fringe spacing. A functional form of C' (S) is obtained. This can then be used to calculate C' for any observed fringe spacing enabling the corresponding wavelength to be determined.

We use an algorithm for measuring the fringe period that was proposed by Snyder.[7] The basis of the

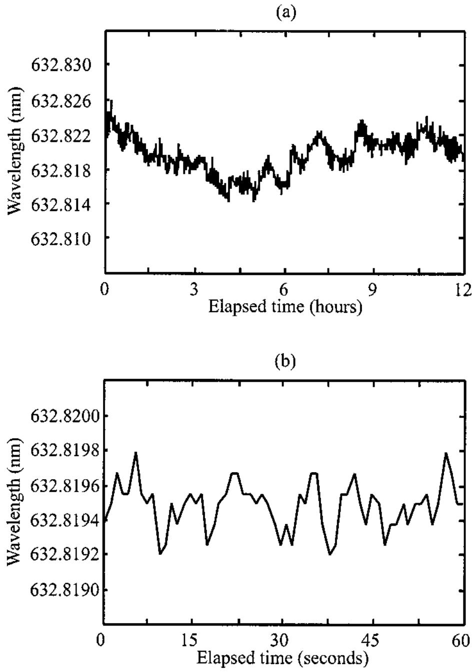

Fig. 4. Sample results from the wavemeter. Wavelength measurement was of a commercial He–Ne laser over (a) a 12-h period that demonstrated a stability of the instrument of approximately 2 parts in 10^5, and (b) a short-term recording over 60 s that demonstrated an accuracy and stability of approximately 1 part in 10^6.

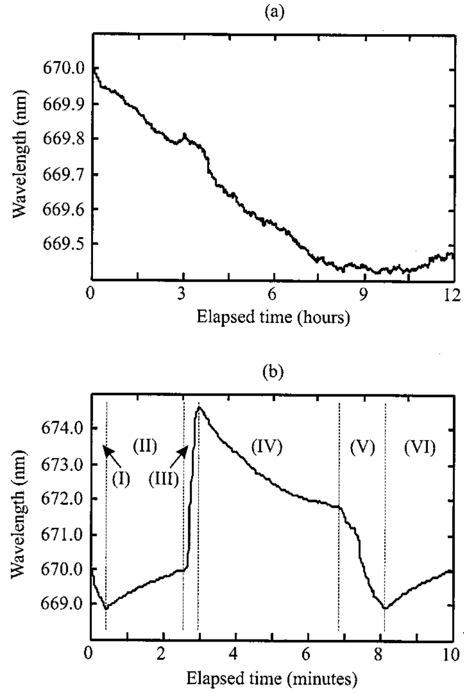

Fig. 5. Sample results from the wavemeter for a commercial laser diode operating at a nominal wavelength of 670 nm. (a) Recorded over a 12-h period and shows the wavelength drift of the diode as the ambient room temperature changes. (b) Recorded over a period of 10-min while the diode was subjected to forced heating and cooling. Section (I) is a period of forced rapid cooling; in section (II) the diode heated up naturally followed in section (III) by a period of forced rapid heating. The diode was allowed to cool unaided in section (IV) until it was rapidly cooled again in section (V), and finally allowed to heat up again to its preferred operating temperature in section (VI).

algorithm is to first smooth the data by processing with a simple adaptive filter that locates the symmetry points of the fringe pattern (i.e., the zero axis crossing points of the sinusoid). By use of a least-squares method, a straight line is then fit to the set of symmetry point positions. The period (or frequency) of the fringe pattern is related directly to the slope of the straight line fit to the data. The scaling between fringe period and wavelength is set by the pitch of the CCD array and the wedge angle of the Wollaston prism. Therefore the calibration of the instrument does not change significantly with time, and good performance can be obtained without a reference laser.

4. Results

As with earlier designs of the instrument it can be used as a general purpose laboratory spectrometer where the Fourier transform of the interferogram gives an estimate of the power spectrum of the incident light. The use of a single birefringent element only 1.5 mm thick results in a large angular acceptance of $\pm 5°$. Representative performance of the spectrometer is given in Fig. 3 that shows the recorded interferogram and the Fourier-transformed spectrum of a He–Ne laser and a 670-nm diode laser simultaneously incident onto the input aperture. The resolution of the spectrometer is set by the number of pixels and corresponding maximum path difference.[4] With a selection of narrow-band interference filters, the resolution of the spectrometer was measured to be 5 nm at 633 nm. The operating spectral range of the instrument of 400–900 nm is limited by the specification of the polarizers. The data-acquisition rate of approximately 25 frames/s was dictated by the speed of the camera–computer interface.

As discussed above, when used as a laser wavemeter, the incident light is fiber coupled into the instrument. This not only gives a convenient instrument but also ensures a uniform and consistent illumination of the Wollaston prism. When operating as a laser wavemeter the key performance criteria are short time-scale precision and long time-scale stability. Figure 4 shows the wavelength of a He–Ne laser measured by a 1-s averaging time. This shows the short-term stability of the wavemeter to be approximately 1 part in 10^6 which should be compared with the inherent stability of a standard He–Ne laser of approximately 1 part in 10^6. Over a 12-h period, Fig. 4 shows that the observed stability is 2 parts in 10^5.

Figure 5 shows the wavelength of a diode laser with a nominal emission wavelength of 670 nm recorded as a function of time. Figure 5(a) shows wavelength measurement over a 12-h period; the change in wavelength arises from the change in ambient temperature. Figure 5(b) shows the wavelength change arising from deliberate heating and cooling of the laser diode.

5. Conclusions

We have reported the design, construction, and initial evaluation of a SFTS and a laser wavemeter based on a modified Wollaston prism configuration. The operating spectral range of 400–900 nm is set by the choice of polarizers, but alternative polarizers and detector array selection would allow operation anywhere within the transparency window (220–2200 nm) of the calcite Wollaston prism.

When used as a laboratory spectrometer, the large field of view and large aperture give an instrument with a large optical throughput. Thus the Jacquinot advantage of Fourier-transform spectroscopy can be realized in this novel design.

When used as a laser wavemeter, fiber coupling gives convenient use and ensures uniform intensity across the interferogram. Rather than use a Fourier transform of the interferogram data we used an algorithm to measure the fringe period and hence the wavelength to an arbitrary high precision. By recording the wavelength of a He–Ne laser that is inherently stable to better than 1 part in 10^6 we showed that the 1-s measurement time stability of our instrument is approximately 1 part in 10^6. The long timescale stability is 2 parts in 10^5, which we believe to be limited by the temperature coefficient of the birefringence of the calcite. Windows environment software gives a user-friendly instrument when used in either spectrometer or laser wavemeter configuration.

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