Differential wavelength meter for laser tuning

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A simple interferometer for matching the wavelengths of tunable lasers is described. Our interferometer uses the angular dispersion of a diffraction grating at the Littrow angle to produce a tilted wavefront with respect to a reference mirror in an opposing arm of a Michelson interferometer. As a first step, the resulting interference pattern is adjusted to produce a null fringe using a reference laser as a wavelength standard. When a tunable laser, such as a laser diode, is used to illuminate the system, the laser is simply tuned to reproduce the null fringe pattern established using the reference laser. When so tuned, the wavelength of the tunable laser is matched to that of the reference laser within about 3 GHz, close enough for optical heterodyning.
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I. INTRODUCTION

In our lab, we have a need to tune diode lasers to within about 10 GHz of stabilized HeNe lasers in order to generate optical heterodyne signals. By servo locking a tunable diode laser to a Fabry–Perot interferometer, we may measure small displacements by observing changes in heterodyne frequency. The implied precision[1] required of the initial tuning operation is approximately $(\Delta\lambda/\lambda)\leqslant 2\times 10^{-5}$ merely to match the lasers closely enough to produce a measurable beat signal. Since many tunable lasers are tuned via hand-operated adjusting screws, we desired a simple, analog tuning indicator that would give us a positive indication of tuning proximity to our reference laser. A fully implemented Michelson wavelength meter,[2] with its attendant moving carriages and digital counters, was deemed inappropriately complex for simple laser comparisons. Static wavelength meters (having no moving parts) such as the Fizeau type[3] require high resolution charge coupled device (CCD) detectors and computer signal processing.

One possible solution that was tried and discarded involved measuring small changes in angle from a diffraction grating via an optical lever arm. Small wavelength changes move a laser spot pattern across a split cell photodiode due to angular dispersion from the grating. If the laser beam is reflected twice off the grating at grazing incidence (approximately the Littman–Metcalf[4] geometry), then dispersion is large and it is easy to detect small ($\approx$100 MHz) changes in laser frequency. Although we achieved excellent results using this system, it is our feeling that the measure and is not as robust as a fringe measurement. When matching two lasers, it is sometimes difficult to match the intensities of the two beams launched into the wavelength comparator. A fringe pattern, we felt, would make a fairly unambiguous indicator no matter what the intensity, especially if a null fringe was selected as the operating point.

II. PRINCIPLE OF OPERATION

The basic design of our fringe pattern wavelength comparator is a Michelson interferometer with a diffraction grating in one arm to provide angular dispersion[5,6] (Fig. 1). Single-mode fiber optics are used to couple light into the interferometer eliminating any influences due to angular misalignments between the reference and measurement lasers. A single 50 mm spherical lens collimates light from the fiber into a 10-mm-diam beam. A dichroic polarizer P after the fiber collimator is used to polarize the light along the plane perpendicular to the grooves in the diffraction grating for higher fringe contrast. The polarized beam then enters a nonpolarizing 50% beam splitter, NPBS. One arm of the interferometer consists of a 25-mm-diam plane mirror on a kinematic adjusting mount. The other arm consists of a 2400 lines per millimeter planar holographic grating at the Littrow autocollimation angle. An inexpensive 6.25 mm diagonal array size CCD camera is used with an appropriate lens to observe and record the resulting fringe patterns. A white card or ground glass screen works equally well. In operation, kinematic adjusting screws on the plane mirror mount are manipulated to produce a null interference pattern on the CCD array. By adjusting the plane mirror, rather than rocking the grating, we maintain alignment of any etalons or Fabry–Perot interferometers placed in the path of the zeroth-order diffracted beam for additional diagnostics.

It is important to note that the path lengths of the two interferometer arms are nearly equal. Making the two arms equal effectively cancels many of the aberrations induced by the fiber optic collimating lens. In our case, using the single element lens at $f/5$, we would normally expect significant spherical aberration to be present in the interferograms. However, with nearly equal path lengths aberrations effectively cancel out.

Basically, our wavelength meter behaves like a Fizeau interferometer in which the separation of the two flat plates is the path difference and the apparent tilt of one plate is a function of wavelength because of the grating dispersion. Adding a path difference between the two arms would increase the rate of fringe ''rolling'' but not the fringe spacing. Although a larger path difference might increase the sensitivity of the interferometer, the simplicity would be compromised as well as adding to the complexity of the collimating lens system.

To determine the sensitivity of the grating interferometer for our equal path case, we first assume the standard relation for two overlapping planar wavefronts of equal intensity tilted at an angle α, see Fig. 2(a). A normalized intensity I,

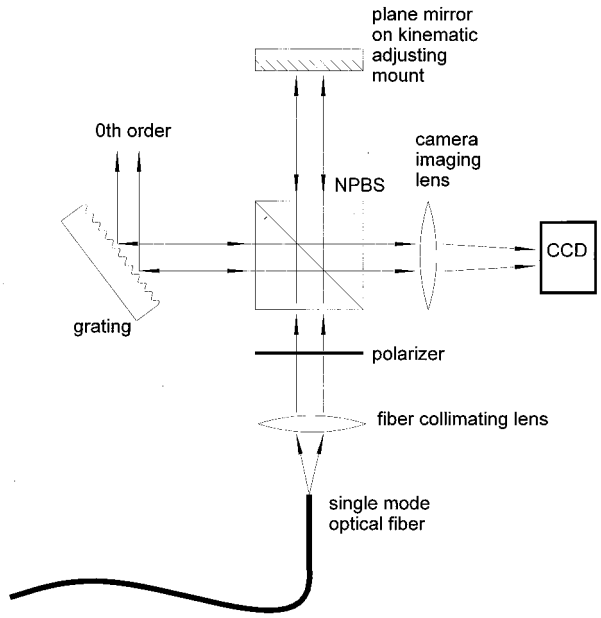

FIG. 1. Schematic diagram of the wavelength comparator showing single-mode fiber input coupling to provide consistent input beam conditions.

along one of the wavefronts at position x and wavelength λ is given as

$$I=1+\cos\left(\frac{2\pi x\alpha}{\lambda}\right), \tag{1}$$

where the tilt angle α, is a function of the angular dispersion D from a diffraction grating detuned $\Delta\lambda$ from null. Thus

$$\alpha=D(\Delta\lambda), \tag{2}$$

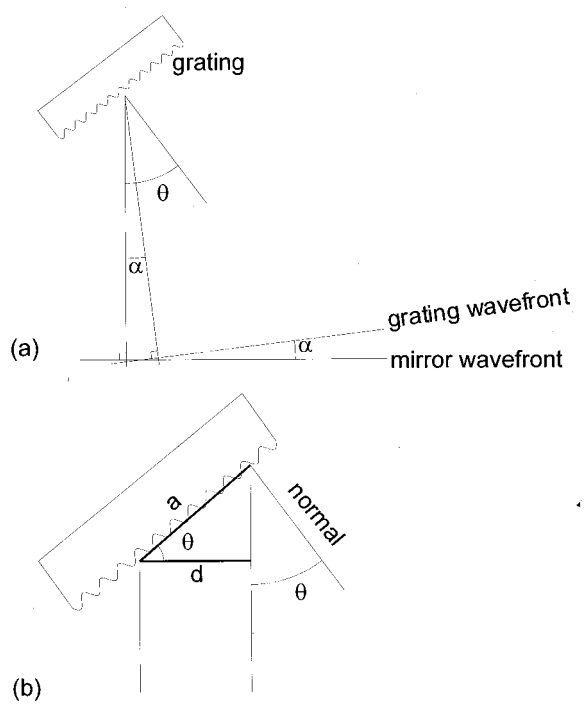

FIG. 2. Geometrical relationships of the grating and tilted wavefronts (a) and relationship of grating lines to input diameter and Littrow angle.

where D is defined as

$$D=\frac{\partial\theta}{\partial\lambda}=\frac{m}{p\cos\theta}, \tag{3}$$

given that p is the groove spacing of the grating, approximately 417 nm for a 2400 lines per millimeter grating, and m is assumed to be first order, or one. The grating angle of incidence, θ_L, is at the angle for autocollimation, or Littrow angle

$$\theta_L=\sin^{-1}\left(\frac{m\lambda}{2p}\right). \tag{4}$$

Although the final measurand, fringe spacing, is a nonlinear function of wavelength, we may assume linearity for small excursions around the null wavefront condition, which is a single dark or light fringe (Fig. 3).

Resolution of the device may be estimated as follows. Assume we can, by unaided eye, resolve one fringe across the viewing field. Referring to Eq. (1), as position x is varied from 0 to pupil diameter d [Fig. 2(b)], we may set

$$\frac{d\alpha}{\lambda}=1. \tag{5}$$

Substituting Eq. (2) and Eq. (3) into Eq. (5) we obtain

$$\frac{\lambda}{\Delta\lambda}=\frac{dm}{p\cos\theta_L}. \tag{6}$$

Referring to the geometry shown in Fig. 2, the number of grating lines illuminated are

$$N=\frac{a}{p}=\frac{d}{p\cos\theta_L}, \tag{7}$$

where a is the illuminated grating length.

Substituting Eq. (7) into the previous relation, we arrive at the well-known Rayleigh criterion:

$$\frac{\lambda}{\Delta\lambda}=mN. \tag{8}$$

Thus, a resolution corresponding to a single fringe is equivalent to the Rayleigh resolution, a convenient method to estimate resolution. For our case of a beam diameter of about 10 mm, we estimate illuminating just over 40×10^3 grating lines with a corresponding frequency resolution of 11.2 GHz per fringe using a 670 nm nominal laser wavelength. In the next section, the experimental scatter will be shown to be approximately 0.25 fringe using visual interpretation of the fringe information.

III. EXPERIMENTAL RESULTS

Before the wavelength interferometer could be used, the fiber optic collimator lens focus was adjusted with the aid of a shear plate interferometer. As a repeatability test, light from a 670 nm tunable diode laser[7] was coupled into the wavelength indicator via the optical fiber. The laser was then repeatedly tuned up and down in frequency to obtain first five fringes, then ten fringes, back through null to five fringes (-5) and finally, back to the null fringe. At each position, laser tuning was recorded using a known, 1 m path

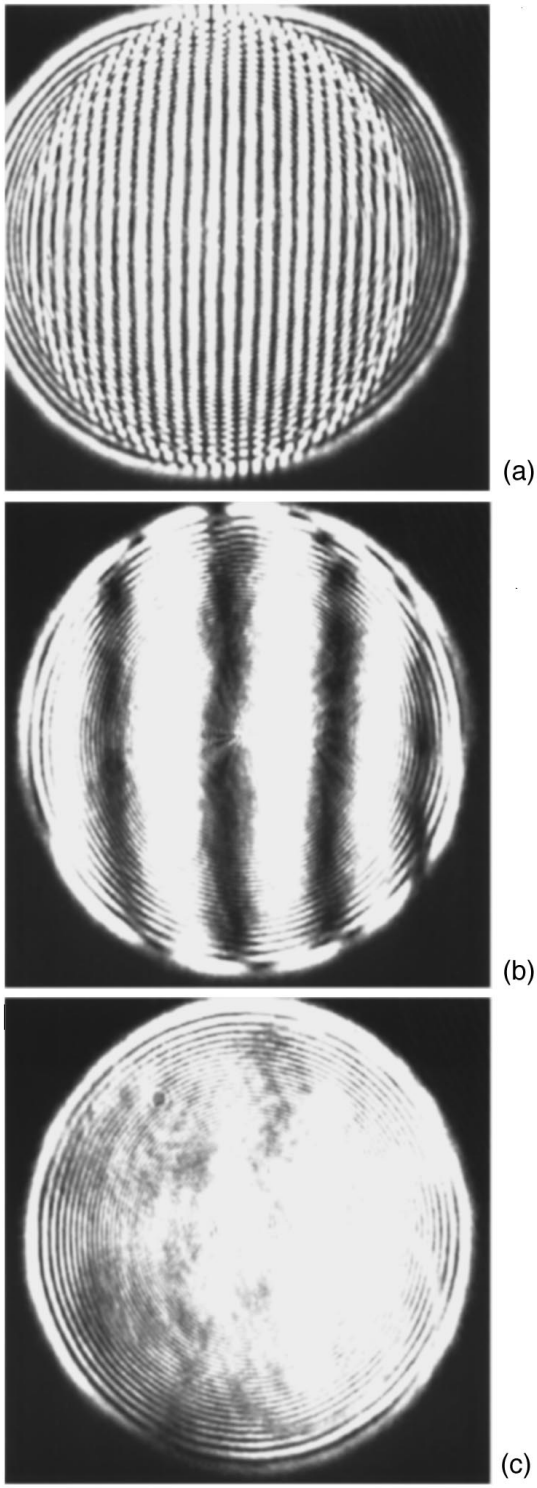

FIG. 3. Interferograms captured by the CCD array showing (a) significant detuning, (b) slight detuning, and (c) a null fringe indicating matched wavelengths. The circular fringes in the interferograms are due to defocusing of the fiber collimator and aperture induced effects from the polarizer.

interferometer and fringe counting system. The data are shown in Fig. 4. It is interesting to note that the null fringe pattern has the smallest standard deviation, just less than 3 GHz. It would appear that the null can be set to a smaller fraction of a fringe than initially anticipated.

In a second experiment, light from a frequency stabilized

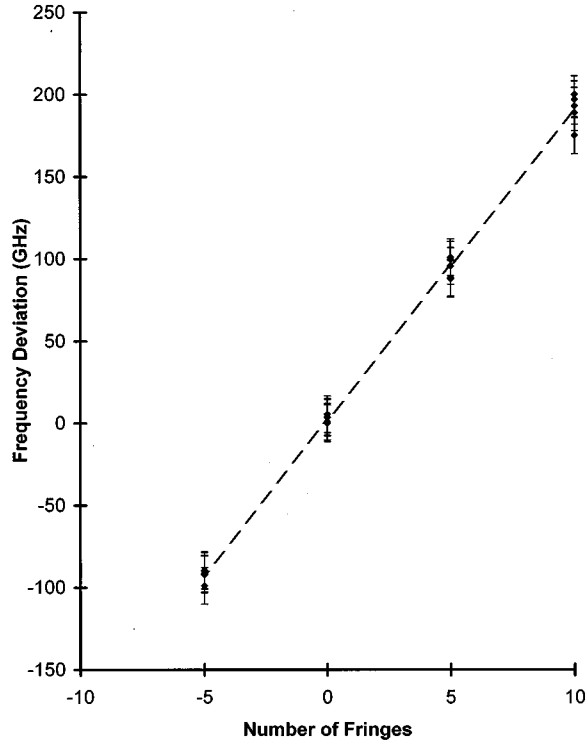

FIG. 4. 670 nm diode laser tuning experiment to determine instrument repeatability. Note the reduced scatter of the points around the null fringe, about 3 GHz. The error bars represent one fringe spacing, or the Rayleigh resolution.

HeNe laser was used to null the wavelength interferometer. Light from a 633 nm tunable diode laser was then coupled into the system and the diode was fine tuned to obtain another null fringe. The elapsed time for this reference setting and tuning operation was approximately 2 min, so instrumental drifts due to sloppy optomechanics were minimized.

Finally, the reference HeNe laser and the diode laser were mixed together in a beam splitter and used to illuminate an avalanche photodiode resulting in the production of a beatnote despite the limited 1.5 GHz bandwidth of our rf spectrum analyzer.

IV. DISCUSSION

The interferometer has proved to be very useful for tuning a variable laser to the same wavelength as a fixed laser. The strength of the device is that it provides good wavelength sensitivity and a visual display that gives an immediate, easily interpreted figure indicating quantitatively how far the laser needs to be tuned; the detuning of the laser is proportional to the number of fringes observed in the interferogram. Laser mode hops are clearly discerned as the fringes are seen to ''jump''; multimode behavior degrades the fringe contrast. In practice, it is easy to make a visual inspection of the fringe pattern and decide if a laser is functioning properly.

The proof that one fringe in the system is equivalent to the Rayleigh resolution is merely a convenient means of conveying resolution estimations. Although we estimate our resolution to be approximately 0.1 fringe (about ten times

better than the Rayleigh criterion), there are many instances where the so-called ''resolution limit'' has been circumvented by making use of phase information[8] as we have done here.

[1] In this article, all frequency measurements are referred to vacuum wavelengths using the nominal value of $c = 3 \times 10^8$ m s^{-1}. Wavelength and frequency units are interchanged for convenience and readability.

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