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Compact diffraction grating laser wavemeter with sub-picometer accuracy and picowatt sensitivity using a webcam imaging sensor

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We describe a compact laser wavelength measuring instrument based on a small diffraction grating and a consumer-grade webcam. With just 1 pW of optical power, the instrument achieves absolute accuracy of 0.7 pm, sufficient to resolve individual hyperfine transitions of the rubidium absorption spectrum. Unlike interferometric wavemeters, the instrument clearly reveals multimode laser operation, making it particularly suitable for use with external cavity diode lasers and atom cooling and trapping experiments. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4765744]

I. INTRODUCTION

The use of tunable lasers, in particular extended-cavity diode lasers (ECDLs), has become ubiquitous in atom optics. Knowledge of the wavelength is critical, for example, so that the laser can be tuned to an atomic transition of interest. The spectral width of atomic transitions is typically $10^6$ times smaller than the tuning range of the laser, and to find the Doppler-broadened line in a vapor reference cell requires wavelength measurement with picrometer (1 part in $10^6$) absolute accuracy. Wavemeters with the necessary precision and accuracy are readily available commercially, but they are expensive and often excessive when the required measurement range is only a few nanometers. There are also many excellent descriptions of self-constructed interferometers with resolution of $10^6-10^{11}$ but they can be large and complex. Two-color photodiodes have not achieved accuracy better than 25 pm. Moreover, all of these devices are prone to error if the laser is operating in multiple longitudinal modes, a common problem with ECDLs.

Grating spectrometers are low in cost, reliable, readily available commercially, and simple enough to construct in the lab, but they are generally considered to have insufficient resolution, typically no better than 50 pm (25 GHz). Here we reconsider the grating spectrometer for high resolution measurement, although over a relatively narrow spectral range. Grating spectrometers are usually designed for broad spectral range, linear dispersion, high optical efficiency, and high optical resolution so that adjacent wavelengths can be distinguished. For measurement of a laser wavelength, these characteristics are less important. The tuning range of an ECDL is typically no more than 10 nm and linear dispersion is of little value when the light source is at one frequency only. The extremely high sensitivity of semiconductor imaging sensors means that high optical efficiency is not needed for bright laser sources. With a laser, there is no need to resolve closely spaced lines and thus we can accept a relatively wide wavelength resolution and use computer interpolation to find the line center.

This report describes a simple grating-based spectrometer with an off-the-shelf consumer HD (high definition) “webcam” imaging sensor, a small (15 mm × 15 mm) reflective diffraction grating, one or two lenses, and a single mode fiber. The usefulness of webcams in grating spectrometers has been described elsewhere with emphasis on their application to undergraduate laboratory projects, here we emphasize the application for laser wavelength measurement. The absolute accuracy is ±0.7 pm (1 standard deviation) with correction for the measured air temperature and pressure, corresponding to 350 MHz, which is smaller than the Doppler broadened width of a single hyperfine transition in room-temperature rubidium vapor. The CMOS webcam sensor has very high sensitivity: the optical power required to saturate the sensor at a frame rate of 10 Hz is only 1 pW. Accurate measurements can be obtained with a bare single-mode fiber placed in a 10 nW laser beam without input collimation lens. The fiber core also forms a very small “slit” for high resolution imaging in the spectrometer.

II. DESIGN

The design is shown schematically in Fig. 1. Light from the single-mode fiber expands and is collimated by lens $f_1$ before striking an 1800 line/mm planar reflective holographic grating. The diffracted beam passes through a second lens $f_2$ that reimages the fiber core onto the bare camera sensor (lens and IR filter removed). Achromatic doublet lenses were used because they provide higher resolution, particularly off-axis, in comparison to spherical singlets.

We used 25 mm diameter lenses and a 15 mm × 15 mm diffraction grating to create a compact device. The first lens focal length $f_1$ was chosen to fill the grating. The beam divergence from the fiber is $\sin^{-1}(NA)$, where $NA = 0.12$ is the numerical aperture of the fiber, and hence the beam diameter is 15 mm at a distance of 65 mm. The lens focal length $f_1$ should then be longer than 65 mm; we used $f_1 = 120$ mm. The second lens determines the image magnification and hence the wavelength range and resolution. For
$f_2 = 200 \text{ mm}$ and sensor width of $6.0 \text{ mm}$, the practical wavelength range was about $6.7 \text{ nm}$. A single-lens configuration with grating angle in near-Littrow configuration ($\theta_1 \sim \theta_2$) was also successful.

For a sinusoidal holographic grating, the diffraction angle is given by the grating equation

$$\sin \theta_1 + \sin \theta_2 = \frac{\lambda}{d} \quad (1)$$

for wavelength $\lambda$, where $\theta_1, \theta_2$ are the incident and output angles and $d$ is the grating pitch. The displacement at the sensor is $x = -f_2 \theta_2$ and the dispersion is

$$\frac{dx}{d\lambda} = \frac{f_2}{d} \left[ 1 - \left( \frac{\lambda}{d} - \sin \theta_1 \right)^2 \right]^{-1/2}, \quad (2)$$

which is approximately $8.4 \times 10^5$ for the configuration in Fig. 1 ($\theta_1 = 30^\circ, \theta_2 = 65^\circ$). That is, at $\lambda = 780 \text{ nm}$, a wavelength change of $3.5 \text{ pm}$ will shift the image by one pixel on the sensor ($3 \text{ mm}$).

The wavelength resolution of the spectrometer is determined by a convolution of the effective slit aperture size, the grating dispersion, and the imaging resolution. The minimum size of the image of the fiber core, assuming diffraction limited lenses and specular reflection, is $w_{\text{sensor}} = (f_2/f_1)w_{\text{core}} = 8.3 \text{ mm (1/e^2)}$, equivalent to $3.5 \mu\text{m}$ full-width at half maximum (FWHM). This width is small compared to the width of the grating diffraction function, approximately $d\lambda = \lambda/N$ where $N$ is the number of grating rulings illuminated ($15 \times 1800 = 27000$); i.e., $d\lambda = 0.03 \text{ nm}$, corresponding to 8 pixels = 25 $\mu\text{m}$ full width or $11 \mu\text{m}$ FWHM at the imaging sensor. The measured width (see Fig. 2) was $21 \mu\text{m}$ FWHM, corresponding to a wavelength resolution of $24 \text{ pm}$.

The resolution of a spectrometer is usually defined in terms of this spectral width, but laser linewidths are typically much smaller than the spectrometer linewidth. When using the device as a wavemeter we can interpolate the diffracted image to find the center with much greater precision than defined by its spectral width, and as shown in our results, the resolution can be improved by a factor of 30.

III. CALIBRATION

Spectra were acquired using the `videoinput` function of MATLAB. Each image was converted to grayscale and averaged over several image rows; an example of an acquired spectrum is shown in Fig. 2. The peak center was found by fitting to a Gaussian function. The spectrometer was calibrated using a tunable laser at a series of wavelengths spanning the extent of the imaging sensor, while simultaneously measuring the wavelength with a commercial wavemeter (absolute accuracy $\pm 0.1 \text{ pm}$); see Fig. 3. Up to 100 measurements were averaged at each wavelength.

The wavelength is related to the pixel location by Eq. (1), which is linear to one part in $10^7$ over the limited wavelength range. Spherical aberration caused deviation from the linear relationship by up to $\pm 0.01 \text{ nm}$. A second-order polynomial fit to the calibration data improved accuracy by a factor of 30; the calibrated wavelength was then accurate to $\pm 0.7 \text{ pm}$.

If a high-precision wavemeter is not available, the spectrometer can be calibrated with reference to known transitions as described in a later section.

The absolute value of the wavelength measurement depends on structural stability and environmental variables including temperature, pressure, and relative humidity (RH). Calibration consistency from day to day requires solid
structure stability of the camera mount in relation to the grating and fiber input. The most significant environmental factor is temperature, which directly affects the grating line spacing through thermal expansion of the substrate. The variation was measured (Fig. 4) to be approximately $-4.3 \text{ pm/K}$, which corresponds to a grating spacing variation of $7.7 \times 10^{-6} / \text{K}$, in good agreement with the thermal coefficient of expansion for the BK-7 borosilicate glass of our grating ($7.1 \times 10^{-6} / \text{K}$).

In addition, temperature, pressure, and humidity affect the refractive index of the air and hence the effective wavelength. For typical laboratory conditions (20%–80% RH), the effects of variations in humidity are below the precision of the spectrometer. The refractive index $n_p$ corrected for temperature and pressure is then sufficiently well approximated by

$$n_p = 1 + \frac{(1.04126 \times 10^{-5})p}{1 + 0.003671 T}(n_s - 1), \quad (3)$$

where $T$ is temperature in °C, $p$ is pressure in Pa, and $n_s$ is the refractive index at $15$ °C and 1 atm ($1.01325 \times 10^5$ Pa); $n_s = 1.000275163$ at $\lambda = 780$ nm. Under these conditions, the wavelength variations with temperature and pressure are approximately $1 \text{ pm/°C}$ and $1 \text{ pm/500 Pa}$. We used a consumer “weather station” to measure temperature and pressure with $0.1$ °C and $100 \text{ Pa}$ resolution to determine the corrected in vacuo wavelength via Eq. (3).

**IV. APPLICATIONS**

A spectrometer of this precision is particularly useful when tuning an extended-cavity-diode laser system to atomic transitions. At a wavelength of $780$ nm, an uncertainty of $0.7$ pm corresponds to $350$ MHz, well below the Doppler width of absorption lines in rubidium vapor. The spectrometer can then be used to tune the laser unambiguously to the different hyperfine transitions in the rubidium D1 and D2 manifolds. Fig. 5 shows wavelength measurements using a laser frequency-locked to four $^{85}$Rb and $^{87}$Rb hyperfine transitions around 780 nm with locking stability better than $\pm 1 \text{ fm}(0.5 \text{ MHz})$.

A particular advantage of a spectrometer in comparison to interferometric wavegters is the ability to see multiple wavelengths simultaneously. ECDLs will often simultaneously support two or more closely-spaced longitudinal cavity modes with the total output power split between modes such that the effective power is substantially reduced, yet without the multimode operation being readily apparent. Figure 6 shows an example with two modes separated by $40$ GHz, which corresponds to the free spectral range of the bare diode; that is, the cavity formed by the front and rear facets of the laser diode semiconductor.

The spectrometer can also be effective for undergraduate teaching laboratories, where the high resolution and sensitivity allow measurements of atomic structure such as the sodium doublet spacing, again using the bare single mode fiber without collection lens, in this case simply placed near a sodium discharge lamp. Other appropriate experiments might include measurement of the hydrogen/deuterium isotope shift or measurement of the vibrational constant of the cesium dimer ground state. Note that calibration of the separation between lines depends on the focal length of the lens and the grating spacing, which can be measured using a reference at a very different wavelength.

The wavelength range of the device as configured in Fig. 1 has been sacrificed to achieve high resolution, but by rotation of the $1800$ /mm grating alone the device can access any wavelength between the $370$ nm wavelength used...
in Yb$^+$ ion trapping (\(\theta_1 = 2.9^\circ\)) and the 960 nm which is used via second harmonic generation to access Rydberg states in rubidium (\(\theta_1 = 47.4^\circ\)). We have also successfully used a wireless internet camera to create a network-connected device and a digital single lens reflex camera with 24 mm wide sensor which provided 28 nm range, sufficient to acquire the full spectrum of a femtosecond laser.

V. CONCLUSION

The spectrometer is compact, readily constructed from commonly available components without requiring special machining, and yet sufficient to resolve the hyperfine spectrum of the rubidium absorption spectrum with only 1 pW of optical power. In a research environment, these features would allow incorporation of a separate spectrometer to monitor each laser in a complex laser atom cooling experiment. In the undergraduate teaching context, construction and calibration of the spectrometer can provide a useful learning experience in itself and also a precision apparatus for probing the quantum nature of atomic structure.

16We used a Newport 1800 l/mm gold-coated holographic grating, Melles-Griot doublet lenses, a Microsoft Lifecam Studio webcam, and a HighFinesse WS-6 Fizeau wavemeter. Commercial equipment, instruments, and materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement, nor does it imply that the materials or equipment are necessarily the best available for the purpose.