Hybrid multiple wavelength reference using fiber gratings and molecular absorption

W.C. Swann, M.A. Hubbard, and S.L. Gilbert
National Institute of Standards and Technology, M/S 815.03, 325 Broadway, Boulder, CO 80303
Phone: (303)497-7381, Fax: (303)497-7621, Email: swann@boulder.nist.gov

The development of dense wavelength division multiplexed systems at wavelengths between 1300 and 1600 nm has created a demand for wavelength references throughout this region. The fundamental absorption lines of atoms or molecules are insensitive to environmental conditions and provide stable wavelength references; acetylene and hydrogen cyanide absorption lines in the 1510-1565 nm region are good examples.[1,2] Although there are other atomic and molecular reference lines in the 1300-1600 nm region, it is difficult to achieve full coverage. Artifact references such as fiber Bragg gratings or etalons can produce references at arbitrary wavelengths, but suffer from large thermal, strain, and pressure sensitivity. Stabilized references over limited wavelength ranges have been demonstrated using a Fabry-Perot resonator[3] and a frequency comb generator.[4] In this paper we present a wavelength reference based on multiple superimposed fiber Bragg gratings, one of which is locked to a molecular absorption line.

Principle of operation: Multiple fiber Bragg gratings are superimposed[5] at a specific location within an optical fiber. One grating is written near an acetylene or hydrogen cyanide absorption line in the 1500 nm region. This grating is actively stabilized to the molecular absorption line using a feedback loop to control its temperature or strain. The other gratings have Bragg wavelengths in other spectral regions; for WDM applications this may be in the L-band (above 1560 nm) or in the 1300-1500 nm region. Because the other gratings are superimposed on the absorption-referenced grating, they experience the same environment and their wavelengths are similarly controlled. Thus, after an initial calibration measurement of their wavelengths, they can be used as stable wavelength references. Wavelength references in other regions, such as near 850 nm or 980 nm, can also be produced using this technique.

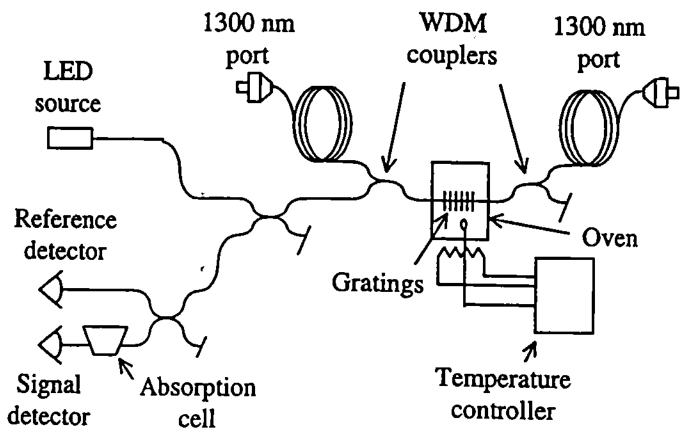

Fig. 1: Apparatus arrangement showing principal components.

Experimental details: We wrote a pair of superimposed fiber gratings with Bragg wavelengths at 1549 and 1303 nm using a cw 244 nm source. The gratings were written in commercial photosensitive fiber with a cutoff wavelength of around 1200 nm. The 1549 nm grating was written first. The second (1303 nm) grating's inscription caused a 20 % reduction in the reflectance and 0.1 nm change in the wavelength of the 1549 nm grating.

We incorporated the grating pair into the apparatus shown in Fig. 1. Light from a 1550 nm LED is reflected off the reference grating and is then sent to a fiber splitter. Half of this light passes through a gas absorption cell to a signal detector, and the other half passes directly to a reference detector. Intensity noise is removed by dividing the signal by the reference; this normalized transmittance is a function of the absorption of the reflected light by the molecular absorption line. The reference grating has a room temperature center wavelength of 1548.9 nm, a full width at half maximum (FWHM) of 0.30 nm, and a reflectance of 0.6. The grating pair resides in a temperature-controlled oven.

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The grating wavelength is located conveniently close to the P9 absorption line of the $2\nu_3$ transition of hydrogen cyanide ($H^{13}C^{14}N$). We use a NIST Standard Reference Material absorption cell[2] (22 cm path length, 13 kPa pressure of $H^{13}C^{14}N$); line P9 of $H^{13}C^{14}N$ has a center wavelength of 1548.9554(6) nm, a FWHM of 0.045 nm, and an approximate absorption depth of 50 %. Figures 2-4 show pictorially how the power received at the detector depends on the grating temperature. Thermally tuning the grating over the absorption line produces a plot of transmittance vs. temperature, as shown in Fig. 5, where a 1 °C temperature change corresponds to 9 pm in wavelength.

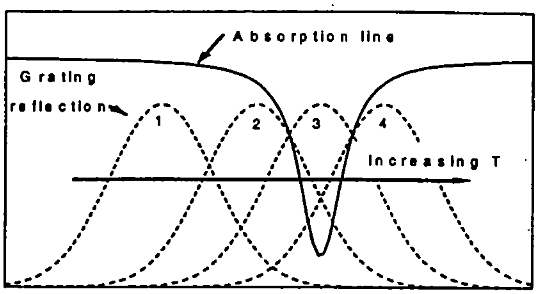

Fig. 2: Grating reflection spectrum relative to the absorption line. Shown are the grating spectra for four different temperatures.

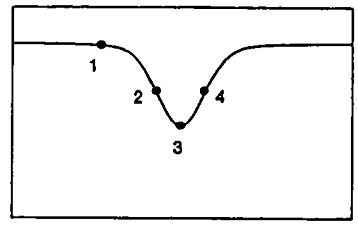

Fig. 3: Total detected power vs. grating temperature. The 4 points refer to the 4 temperature-dependent grating positions shown in Fig. 2.

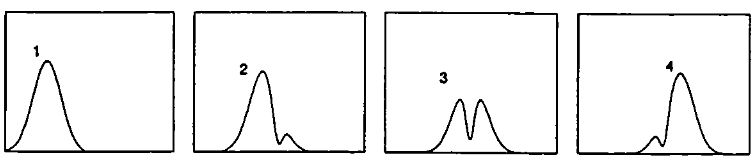

Fig. 4: Spectrum after reflected light passes through the absorption cell, for the four temperatures shown in Fig. 2. The power received by the detector is the integral of each spectrum shown.

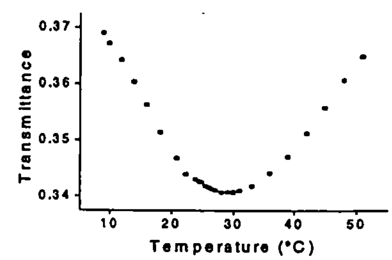

Fig. 5: Experimental data showing transmittance as the grating is temperature-tuned across line P9.

In the operating condition where the 1549 nm grating is stabilized to the molecular absorption line using thermal feedback, any anomalous change in strain will be compensated by an appropriate change in temperature. However, this temperature change may not exactly cancel the strain-induced wavelength change of the 1300 nm grating. In general, a grating subjected to both a strain $\Delta\varepsilon$ and temperature change ΔT will be wavelength-shifted by

$$\Delta\lambda = (C_T \Delta T + C_\varepsilon \Delta\varepsilon)\lambda, \quad (1)$$

where λ is the grating center wavelength, $C_T = (1/\lambda)d\lambda/dT$ is the grating temperature coefficient, and $C_\varepsilon = (1/\lambda)d\lambda/d\varepsilon$ is the strain coefficient. For the reference grating (referred to here as grating 1) locked to the absorption line, $\Delta\lambda_1 = 0$. An applied strain $\Delta\varepsilon$ will be compensated by a corresponding temperature change of

$$\Delta T = -(C_{\varepsilon 1} / C_{T1})\Delta\varepsilon . \quad (2)$$

With substitution of Eq. (2) into Eq. (1), the wavelength shift of the 1300 nm grating (grating 2) is

$$\Delta\lambda_2 = \lambda_2(-C_{T2}\frac{C_{\varepsilon 1}}{C_{T1}} + C_{\varepsilon 2})\Delta\varepsilon . \quad (3)$$

We measured the temperature and strain coefficients for both of the gratings. Grating shift values were obtained by doing polynomial fits to the central portion of the grating transmittance at different temperature and strain values. We found that C_{T1} = 6.06(3) x 10^{-6}/°C, C_{T2} = 5.96(5) x 10^{-6}/°C, $C_{\varepsilon 1}$ = 0.764(5) per unit strain, and $C_{\varepsilon 2}$ = 0.760(2) per unit strain. Using these values, we find that if the gratings are subjected to a strain of 80 x 10^{-6} (80 $\mu\varepsilon$) the feedback loop will reduce the grating's temperature by ΔT = 10 °C to maintain the lock of grating 1. Substituting these temperature and strain values into Eq. (3), we find that grating 2 will undergo a wavelength shift $\Delta\lambda_2$ of 0.9 pm. We conducted a similar test on a second grating pair and found that the wavelength shift of the unstabilized grating would be only 0.1 pm under the same conditions. Thus, it appears that if the grating strain is constant to within 1 x 10^{-4}, the wavelength error due to dissimilar temperature and strain coefficients will be about 1 pm or less.

Stabilization: We are designing and implementing a system for the stabilization of grating 1 to the absorption line. In one scheme that we are considering, the grating is strain-dithered with a piezo-electric transducer (PZT), imparting a wavelength modulation to the light reflected from the grating. The wavelength-modulated light can then be locked to the absorption line using a phase-locked loop (PLL) and feedback to the temperature or PZT control. Alternatively, a slow thermal dither could be produced using the temperature controller, and the same PLL techniques can be applied; in this case the loop is much slower, and the PLL would be implemented digitally. The advantage of the thermal dither lock is that it eliminates the need for a PZT and associated electronics, as well as eliminating the problems associated with bonding the fiber to an actuating mechanism. One drawback to both of these stabilization schemes is that the wavelengths of the gratings are being modulated (in the range of ±1 to ±10 pm). Thus, the references themselves are dithering slightly in wavelength.

In an alternative scheme, a tunable diode laser, instead of an LED, is used as the light source. Here, the laser frequency is dithered, and the laser is locked directly to the absorption line using a PLL that feeds back to the laser's wavelength control. The grating is then locked to the laser, using a second PLL that feeds back to the temperature control of the grating. Since the frequency dither necessary for both of the PLLs is produced by dithering the laser's drive current, this scheme avoids modulating the grating wavelengths. However, it has the disadvantage of the added cost of a tunable diode laser.

Conclusion: We have presented a novel wavelength reference device based on multiple superimposed fiber Bragg gratings. The device has the flexibility to provide references in any wavelength region where fiber gratings can be produced. We are currently working on improving the sensitivity and implementing the absolute stabilization. In particular, the sensitivity would be improved by more closely matching the grating width to that of the absorption line. We also plan to examine the polarization sensitivity and evaluate the absolute accuracy of this technique.

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