Multiple-wavelength reference based on interleaved, sampled fiber Bragg gratings and molecular absorption

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We present a wavelength calibration reference based on interleaved, sampled fiber Bragg gratings stabilized to a molecular absorption line. Such a hybrid reference can provide multiple stable calibration peaks over a wide range of wavelengths. We demonstrate a wavelength reference that has at least 20 peaks suitable for use as calibration references in each of three wavelength regions: 850, 1300, and 1550 nm. We monitored the stability of a 1300-nm reflection peak and found that the standard deviation of the peak wavelength was 0.7 pm over a 70-day period. © 2004 Optical Society of America

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1. Introduction

Wavelength calibration references are needed in a variety of wavelength regions to calibrate wavelength-measuring instruments such as optical spectrum analyzers. Molecular absorption lines can provide stable and accurate calibration points, but convenient references are not available in some wavelength regions. Artifacts such as etalons and fiber Bragg gratings can provide references at arbitrary wavelengths, but can also suffer from large sensitivity to temperature, strain, and pressure. We developed a hybrid multiple-wavelength reference that incorporates the wavelength flexibility of artifact references and the stability of fundamental molecular absorption references. We generated a series of customized reflection peaks by writing interleaved, sampled fiber Bragg gratings. One of the reflection peaks is actively stabilized to a molecular absorption line, which results in the stabilization of the entire ensemble of peaks. We used this approach to produce wavelength references in the 850-, 1300-, and 1550-nm regions. Although our device is limited to these three specific wavelength regions, it demonstrates the feasibility of hybrid wavelength references over the near-infrared (IR) region. Because this approach provides many calibrated reflection peaks in each region, the reference can be used for single-point and scan-linearity calibration within each region.

2. Gratings

A sampled fiber Bragg grating (SFBG),[1] created when a long-period square-wave amplitude modulation is imposed on the refractive-index profile of a regular fiber Bragg grating, produces a reflection spectrum that is a series of regularly spaced peaks under a broad central envelope with small sidelobes. Interleaved, sampled fiber Bragg gratings (ISFBGs)[2,3] consist of two or more SFBGs with different grating periods that are interleaved so that the gratings are contained in the same length of fiber but their inscribed sections are offset from each other. Figure 1 shows the reflection spectra for ISFBGs with two different wavelength combinations: 850 and 1550 nm and 1300 and 1550 nm. We wrote the 1300- and 1550-nm ISFBG [Fig. 1(b)] with the phase-mask method described in Ref. 3. The grating was written with a continuous-wave 244-nm laser beam focused to a line through the back of a phase mask and onto an ~1-cm length of the fiber. The H_2-loaded, single-mode standard communication fiber was in contact with the phase mask's front face. Opaque metal strips that plate the front face of the phase mask provided the sampling by blocking off sections of the ultraviolet (UV) beam. We wrote one SFBG at a time using the appropriate sampled phase

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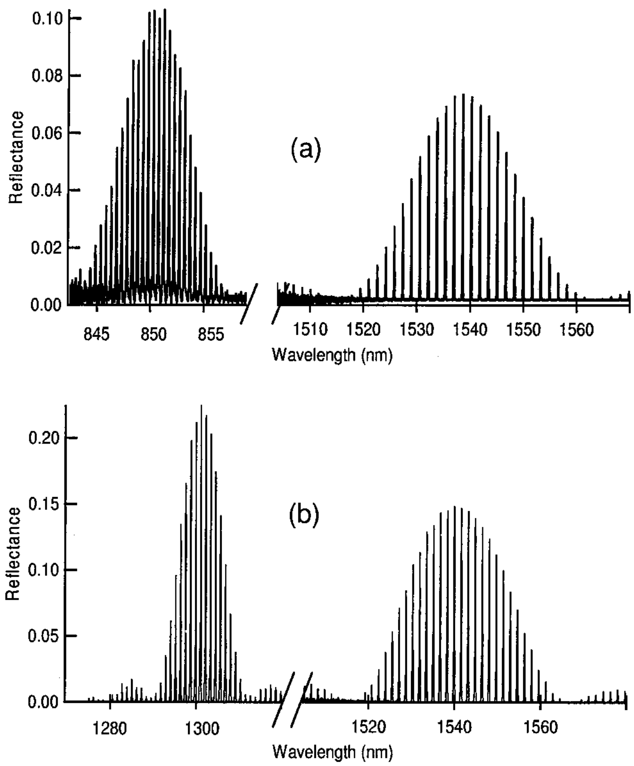

Fig. 1. Reflection spectra of ISFBGs, measured with an optical spectrum analyzer with superluminescent diodes used as light sources. (a) Spectrum of an ISFBG with 850- and 1550-nm peaks. (b) Spectrum of an ISFBG with 1300- and 1550-nm peaks.

mask for the wavelength region desired. We shifted the fiber before writing the second SFBG so that the new grating was written in the previously unexposed region. The sampling on–off periodicity Λ_{MOD} was 500 μm (approximately 1000 times the regular grating's index period), and the length of the individual inscribed regions D_{ON} was 50 μm for the 1300-nm grating and 30 μm for the 1550-nm grating. The spacings between peaks, which scale inversely with Λ_{MOD}, were 1.2 and 1.6 nm for the 1300- and 1500-nm regions, respectively. The individual peaks' width scales inversely with the total length of the grating. These widths were 110 pm (120 pm) for the peaks in the 1300-nm (1550-nm) region. The broad envelope widths, which scale inversely with D_{ON}, were 10 and 30 nm for the 1300- and 1550-nm regions, respectively. The spectrum has more than 20 peaks in the 1300-nm region and more than 25 peaks in the 1550-nm region that are strong enough to be suitable for use as wavelength calibration references.

Demonstrating an alternative approach, we used a free-space interferometric method to make the 850-nm SFBG shown in Fig. 1(a). The grating was written in single-mode fiber at 850 nm; single-mode fiber provides a clean set of peaks that can be identified by relative amplitude without contamination by secondary peaks of varying amplitude, which would occur in multimode fiber. In the interferometer, two beams were focused to a line 1 cm long where they intersect and form the interference pattern for writing the grating. To produce the on–off modulation of the grating, an amplitude mask was placed in front of the fiber. We used a commercial metal mask (~100 μm thick) that was photochemically machined with grooves ~200 μm wide and spaced 500 μm apart. This mask was held in contact with the fiber. Because of its thickness, the mask blocked a significant amount of the intersecting beams (an angle of 35° for 850 nm). With this geometry, the length of the individual interference sections D_{ON} was only approximately 30 μm. After the 850-nm SFBG was written, we interleaved a 1550-nm SFBG using the phase-mask method described above. Figure 1(a) shows the reflection spectrum for the 850- and 1550-nm ISFBG. The peaks in the 850-nm spectrum were 90 pm wide and spaced by 0.5 nm. At least 20 of these peaks are suitable for use as wavelength calibration references.

3. Wavelength Reference

Previously we demonstrated a hybrid wavelength reference based on superimposed gratings.[4] Here we use ISFBGs instead of superimposed fiber Bragg gratings and two feedback loops to stabilize the wavelength of the grating's peaks. Figure 2 shows the components of the hybrid wavelength reference. First, a laser is locked to a molecular absorption line, then one peak of the 1550-nm SFBG is locked to this laser. This two-lock method allows us to stabilize the fiber gratings without dithering the grating's spectrum. As shown in Fig. 2, a fiber-coupled 1550-nm distributed-feedback diode laser is frequency modulated and a portion of its output is directed though a fiber-coupled cell filled with hydrogen cyanide ($H^{13}C^{14}N$) gas at a pressure of 13.3 kPa (100 Torr). Because the frequency modulation also introduces amplitude modulation, this signal is normalized by a reference signal that does not pass through the absorption cell. Hydrogen cyanide has numerous accurately measured absorption lines in the 1530–1560-nm region and is used as a National Institute of Standards and Technology wavelength calibration Standard Reference Material.[5] From the normalized absorption signal a lock-in amplifier extracts an error signal that is fed back to the laser's temperature controller to lock the laser to one of the HCN lines. By monitoring the error signal with the system locked, we found that the laser's central wavelength stays within ±1 pm of the set value; with a wavelength meter we verified that this value corresponded to the center of the HCN line.

There are two fiber gratings in the system, one with peaks at 1300 and 1550 nm and one with peaks at 850 and 1550 nm. Depending on which wavelength region is desired, an optical switch connects the correct grating to the system. These fibers are held in a strain-free configuration in a temperature-controlled copper block. Given the temperature tunability of the grating, 10 pm/°C, any grating peak can be matched with a HCN line (~800-pm spacing) by the heating or cooling of the grating over a range of 80 °C. To lock the grating to the HCN line, another portion

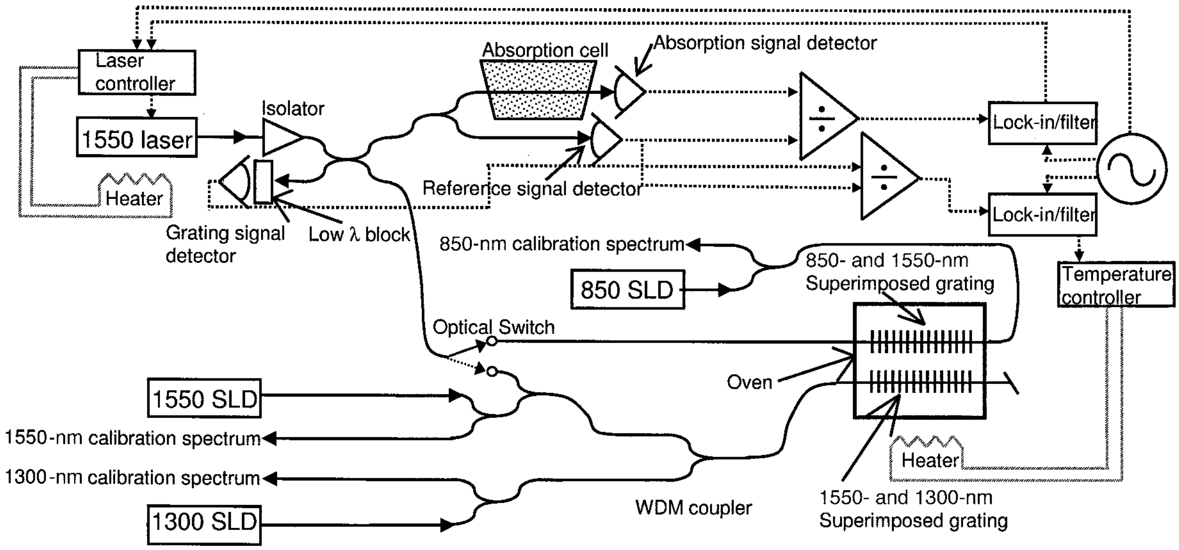

Fig. 2. Diagram of the hybrid wavelength reference. The upper section contains the components used to stabilize both a laser to a HCN line and a 1550-nm grating peak to this laser. The lower section contains the ISFBGs. Superluminescent diodes (SLDs) illuminate the fiber gratings, and the light reflected off the gratings is observed at the calibration spectrum ports. An optical filter prevents 850-nm SLD light from reaching the grating signal detector. WDM, wavelength division multiplexing.

of the 1550-nm laser light is reflected off the grating and detected with the grating signal photodiode. As with the first lock loop, the normalized grating signal is demodulated with a lock-in amplifier, filtered, and then fed back to the grating's temperature controller, which stabilizes the grating to its reflection maximum. We monitored the grating error signal and determined that the grating was stabilized to within 1 pm of the set value.

When one reflection peak of an ISFBG is stabilized, the rest of the ensemble is also stabilized. Once the wavelengths of the reflection peaks are measured, they can all be used as wavelength calibration references. We access the multiple stabilized peaks of the ISFBG by way of the calibration spectrum ports shown in Fig. 2.

4. Results

To check how well the ensemble of grating reflection peaks is stabilized when one of the grating's 1550-nm peaks is locked to the HCN reference, we imitated harsh environmental conditions by straining the fiber grating and then checking the response of the system. The fiber grating was held between two fiber chucks, one on a micrometer, to apply a calibrated strain to the fiber. With the system locked, it compensated for a change in strain $\Delta\varepsilon$ with a change in the temperature of the grating ΔT so that the Bragg wavelength λ_B remained unchanged:

$$\Delta\lambda_B = (C_T \Delta T + C_\varepsilon \Delta\varepsilon)\lambda_B = 0. \tag{1}$$

Here C_T is the grating's temperature coefficient and C_ε is the grating's strain coefficient. For the system to serve as a calibration reference, the temperature change that compensates the 1550-nm grating for the added strain must also be close to the correct amount to cancel the strain-induced change at 850 and 1300 nm. We tested this by measuring the shift in the wavelengths of peaks at 850 or 1300 nm as we strained the fiber with the system locked. We monitored the wavelength of a peak by scanning over the central portion with a laser that was calibrated with a wavelength meter and measuring the reflected power. We used the center of a Gaussian fit to this data as a measure of the peak's wavelength. Figure 3 shows how the wavelength of selected peaks changed as the fiber was strained by up to 6×10^{-4} (600 $\mu\varepsilon$). For the 850- and 1550-nm fiber, Fig. 3(a), the 850-nm grating shift coefficient was 1.6 pm/100 $\mu\varepsilon$. Figure 3(b) shows the data for the 1300- and 1550-nm fiber; the 1300-nm grating shift coefficient was 0.2 pm/100 $\mu\varepsilon$. If the system were unlocked, the 1300-nm grating would shift by approximately 100 pm/100 $\mu\varepsilon$. To compensate for 100 $\mu\varepsilon$ of strain, the system changed the grating's temperature by approximately 10 °C. This was an extreme test; we would expect the fiber gratings to experience strains of no more than 20 $\mu\varepsilon$ when packaged within the instrument.

A polarization-dependent wavelength (PDW) shift of the grating can affect the accuracy of the wavelength reference. If the wavelength of a grating peak depends on the input polarization, then the calibration spectra can shift as the polarization changes. We measured the PDW shift of our gratings as described in Ref. 6, using both a 4-state method and a 26-state approximation to all polarization states to measure the wavelength of the reflected peak versus polarization. The PDW shift of a grating was the maximum deviation between the grating wavelength values for the different polarizations. We then selected two fiber types that produced low-PDW gratings, one for the 1300- and 1550-nm gratings and one

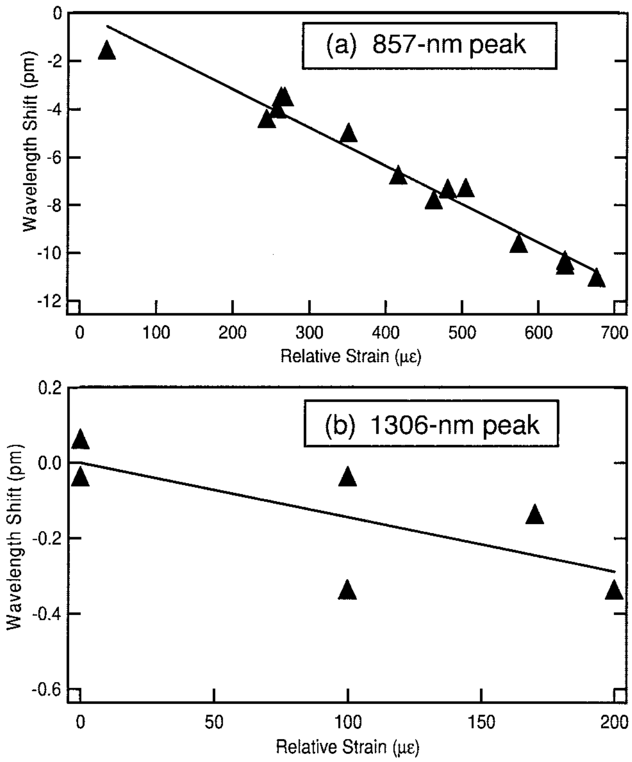

Fig. 3. Wavelength of stabilized grating as strain is applied (1 $\mu\varepsilon = 1 \times 10^{-6}$). (a) The 857-nm peak of the 850- and 1550-nm ISFBG. (b) The 1306-nm peak of the 1300- and 1550-nm ISFBG.

for the 850- and 1550-nm gratings.[7] These fibers had low intrinsic birefringence. The PDW values were predominantly due to UV-induced birefringence[8] from the grating writing rather than the fibers' intrinsic birefringence. Our measured PDW values for the selected fibers were typically 1–3 pm in the three wavelength regions.

We checked the performance of the wavelength reference over a period of 70 days. Figure 4 shows how the wavelength of the monitored 1300-nm peak changed over time. Each data point represents an average of approximately ten measurements made within a few hours; the error bars on the data points are the standard deviation of these measurements (typically 0.1–0.2 pm). The long-term fluctuations in wavelength are greater; the standard deviation of the wavelength over the 70-day period was 0.7 pm, and the maximum deviation was less than 3 pm. These long-term fluctuations were expected because we do not control the polarization of either the laser for locking the 1550-nm grating or the laser probing the 1300-nm grating. This long-term check tested the stability of the locking scheme for the whole system, which is the same for both gratings. For both fiber systems the wavelength stability is currently limited by the PDW shift.

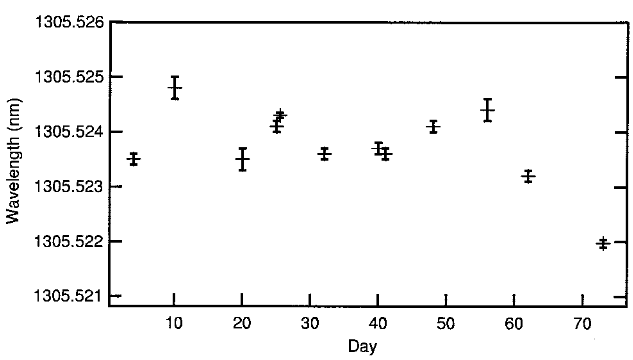

Fig. 4. Wavelength of a 1300-nm wavelength reference peak over 70 days.

5. Conclusion

We have described a hybrid wavelength reference that provides multiple calibrated reflection peaks in the 850-, 1300-, and 1550-nm regions with a stability of better than 3 pm. By using ISFBGs we can lock a grating peak in the 1550-nm region to a HCN absorption line, which stabilizes the entire ensemble of fiber grating peaks. For this stabilization to work at wavelengths differing from 1550 nm, the grating's temperature and strain coefficients must work to create nearly the same compensation at both wavelengths. We have shown that this is true for wavelengths as short as 850 nm. The system described here is intended for calibration of an optical spectrum analyzer, but the approach could also be used for tunable laser calibration by substitution of the user's tunable laser for one of the superluminescent diodes. We believe that this approach can be extended to other wavelength regions that can be guided in single-mode optical fiber. Although we interleaved only two SFBGs in a fiber, multiple SFBGs can be interleaved in the same section of fiber, and all the wavelength regions can be stabilized by means of stabilizing one peak of the 1550-nm grating. Our 3-pm stability is limited by the PDW shift of the gratings; we could achieve subpicometer stability by scrambling the polarization of the light sources, controlling the polarization using polarization-maintaining fiber, or producing lower-PDW gratings.

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