Holographically generated gratings in optical fibers

By W.W. Morey, G. Meltz, and W.H. Glenn

ZAP, ZAP, ZAP...two beams from a pulsed UV laser collide on the side of an optical fiber and a wavelength filter or out-coupling tap is produced. With this method, we have developed a new way for generating periodic modulations of the refractive index, or gratings, in the core of a germania-doped optical fiber. When the wavelength of a guided optical signal in the fiber is twice the grating periodicity (the Bragg condition), a fraction of the signal will be reflected into a counter propagating mode. That is, the grating produces a band rejection filter in the fiber.

K.O. Hill et al.[1,2] were the first to produce such gratings in optical fibers by forming a standing wave pattern with intense visible argon laser light coupled into the end of the fiber. Lam and Garside[3] later showed that this was a two photon process. By going to UV wavelengths and a single photon process, we could achieve much higher writing efficiencies.[4] With UV light a side exposure is required, due to the high absorption of the germania-doped core at these wavelengths. The side exposure has important advantages: it allows the grating spacing and intensity to be varied or modified, and the gratings can be localized and distributed at any position along a length of fiber. The technique is noninvasive and requires only that the buffer coating be temporarily removed for the exposure. Many applications for the gratings in fields such as distributed sensors, data communications, and signal processing should be found.

Method

For the UV source, we used a xenon chloride excimer laser—pumped dye laser with second harmonic generation to the 240-250 nm wavelength band. The laser output is sent to a split beam interferometer that recombines the two beams at an angle onto the side of a fiber. The intersecting beams produce planes of interference perpendicular to the fiber axis. Spacing of the interference planes is set by the angle of the beams and the exposing UV wavelength.

At points in the interference pattern where the optical intensity is most intense, the UV light bleaches the oxygen vacancy defect absorption band at 240-250 nm that is found in germania or germano-silicate glasses. The bleaching process breaks the Ge-Si or Ge-Ge bonds and liberates an electron.[5] The mobile electron eventually falls into neighboring traps to form new absorption centers. A recent model[6] suggests that two Ge traps are important, one giving rise to a strong absorption at shorter UV wavelengths and the other a broadband weaker absorption at longer wavelengths. The weaker absorption center is to some extent photobleachable and annealable, and contributes only a small loss in the important near IR telecommunications bands. Interferometric measurements made by Russell et al.[6] and independently by K.O. Hill[7] have shown that the index of refraction increases with the photobleaching action. Thus, a sinusoidal variation in the index of refraction is produced along the fiber axis in the region of the interfering beams.

Reflection gratings

To date, we have made fiber gratings 5-10 mm long with reflectivities of up to 89% in single-mode fiber that has a germania content of 12.7 mole %. Exposure times are typically from 1-10 min. with average flux levels of 2-4 W/cm^2. The calculated fractional index change corresponding to the 89% reflectivity was 4×10^{-5}. Russell[5] has measured fractional index changes as high as 2×10^{-4} in experiments that measured index changes on exposure to

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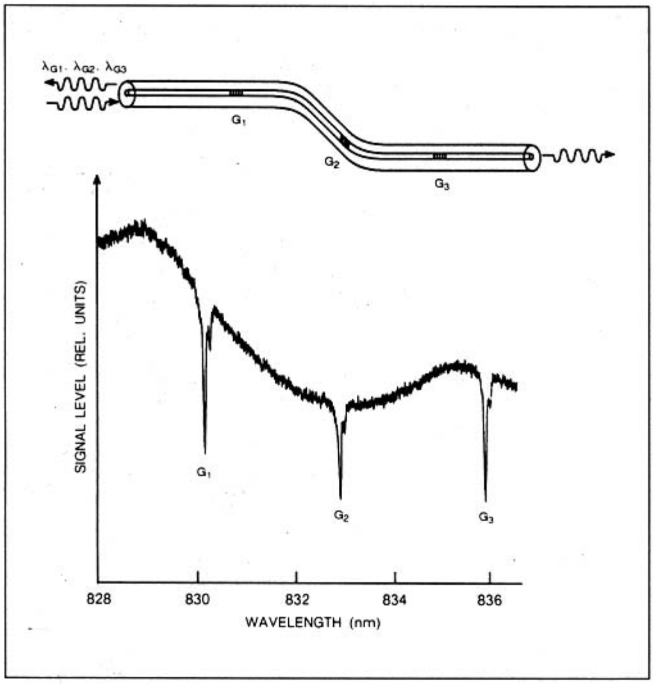

FIGURE 1. Transmission spectrum of a fiber with three distributed Bragg gratings. The light source for the spectral measurement was a xenon arc lamp. Two polarization modes can be seen for each grating.

visible and 266 nm perturbing light.[6] Consequently, stronger gratings should ultimately be possible with our side exposure UV writing technique.

Gratings made in a fiber that propagates two modes will show two reflection peaks corresponding to the Bragg condition being satisfied for the different effective indices of the modes in the fiber. Single-mode, elliptical core, polarization maintaining fiber also has separate Bragg reflectances for the two polarization modes. Figure 1 shows a transmission spectrum of an elliptical core fiber with three gratings placed at different locations along the fiber. A xenon arc lamp was used as the probing light source for the spectral measurement. Notches occur at the Bragg wavelengths shown for each grating. The light source was unpolarized so that each of the two polarization modes for each grating can be seen in the spectrum. One mode gives a stronger line due to the polarization response of the spectrometer.

Tilted gratings

The Bragg condition is also satisfied by radiation modes at shorter wavelengths, causing light to diffract out of the fiber. For reflection gratings, the efficiency of this process is very low. One can see very weak out-coupling, for example, with He-Ne and visible dye laser light from an 800 nm band reflection grating. A conical pattern about the fiber is observed in this case. As with a standard diffraction grating, different wavelengths emerge at different angles. However, we can significantly improve the out-coupling efficiency if the grating planes are tilted or blazed at an angle to the fiber axis by tilting the fiber in the UV interference planes during exposure.[8] The radiation pattern changes from a full conical azimuth fan to a 40° azimuthal segment.

The cover photo shows light from an argon laser emerging from a 5 mm long grating where the planes were tilted at 40° to the fiber axis. Out-coupling efficiencies were 0.2%. When the camera was focused in the far field, the different wavelengths were separated into narrow lines as shown by the second exposure in the photo. Not only do different wavelengths emerge at different angles, but the different modes at the same wavelength emerge at slightly different angles due to their different propagation constants or effective indices. In the cover photo, the argon laser green wavelength has two modes and the blue wavelength three modes propagating in the fiber. Wavelength resolution for this out-coupling grating was 0.15 nm.

Applications

Since the refractive index of the fiber changes with temperature and strain-optic effects, the fiber grating's Bragg wavelength is sensitive to both temperature and strain. Figure 2 shows a plot of the temperature and strain response for typical gratings. Measurements of strain and temperature for this plot were made on different fibers and for gratings at different wavelength bands. The maximum strain produced on the grating for the test corresponds to

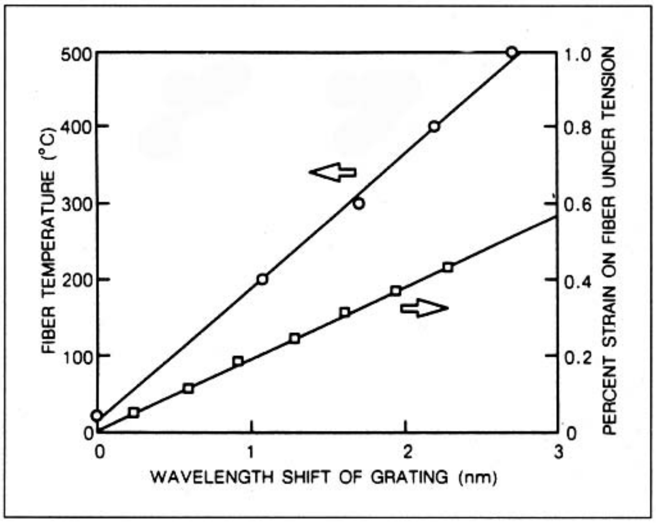

FIGURE 2. Wavelength shift of a fiber grating with temperature and strain.

a fiber stress of 310 MPa (45kpsi). Of particular importance is the fact that the fiber gratings were taken to 500°C, cycled, and held at this temperature for periods of 18 hours. Within our measurement accuracy, no significant change was observed in the grating characteristic. That is, the gratings appear to be permanent.

Fiber gratings, then, can be used as transducer elements that detect changes in temperature and strain.[9] The grating sensor responds with a wavelength change and is independent of signal amplitude. This feature is an advantage over many other fiber sensor devices that depend on signal amplitude for their sensor response. Moreover, several gratings can be easily placed along a length of fiber to produce a distributed sensing element. Wavelength, time, or frequency division multiplexing techniques can be used to interrogate or resolve the individual grating sensors. The grating strain response can be used in conjunction with other devices such as a diaphragm to detect pressure. One should also be able to enhance the sensitivity of the grating sensors with the use of two gratings in a Fabry-Perot interferometer arrangement, for instance. In this case, the measurand could affect the fiber segment between two grating reflectors. Different types of coatings could be used to detect different measurands. The grating, therefore, could be a generic sensor type to measure different quantities with the sensor elements multiplexed on a single fiber lead.

Another important application for the fiber grating is in laser diode wavelength control. Bandwidths of the gratings made to date are typically 20 GHz (0.05 nm). The bandwidth can be adjusted to some extent by varying the length of the grating or the grating spacing (chirping). Tests we performed, with a 58% reflecting fiber grating and a simple butt coupling of the fiber to a standard laser diode chip, forced the laser to emit at the Bragg wavelength of the grating. By stretching the grating, the laser could be tuned over a range of 2 nm with a 0.43% strain (45 kpsi). The diode laser's linewidth was narrowed to 250 kHz as measured with a self heterodyne test.

Since the temperature stability of the fiber grating (.006 nm/°C) is much greater than that of a diode laser (.3 nm/°C), the wavelength stability of the laser can be improved with a fiber grating reflector. Moreover, the temperature sensitivity of the grating could be controlled in a special housing to cancel the grating's temperature response. The stabilized laser diodes could be used as sources and local oscillators in a coherent communications system. Other potential applications for wavelength-narrowed and stabilized laser diodes should emerge in optical fiber systems.

Out-coupling with the fiber grating has obvious applications to data communications as a wavelength multiplexed tap. With wavelength resolutions of 0.15 nm, many channels could be generated with a grating tap. Other applications of the tilted gratings could be in special wavelength filter designs, signal processing loops, and possibly with fluorescence chemical sensing and analysis.

REFERENCES

1. K.O. Hill, Y. Fujii, D.C. Johnson, and B.S. Kawasaki, Appl. Phys. Lett. **32**, 1978. pp. 647.
2. B.S. Kawasaki, K.O. Hill, D.C. Johnson, and Y. Fujii, Opt. Lett. **3**, 1978. pp. 66.
3. D.K.W. Lam and B.K. Garside; Appl. Opt. 20, 1981. pp. 440.
4. G. Meltz, W.W. Morey, and W.H. Glenn, "Formation of Bragg gratings in optical fibers by a transverse holographic method," Opt. Lett. **14**, 1989. pp. 823.
5. E.J. Friebele and D.L. Griscom, Proceedings of the Materials Re search Society Symposium (Materials Research Society, Pittsburgh, Penn., 1986). pp.319.
6. D.P. Hand and P. St. J. Russell, Opt. Lett. **15**, 102, 1990.
7. K.O. Hill, private comm., 1990.
8. G. Meltz, W.W. Morey, and W.H. Glenn, "In-fiber Bragg grating taps," Paper TUG1, OFC '90, San Francisco, January 1990.
9. W.W. Morey, G. Meltz, and W.H. Glenn, "Fiber optic Bragg grating sensors," Paper 1169-12, SPIE's 1989 Boston Symposium OE/FIBERS '89.

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