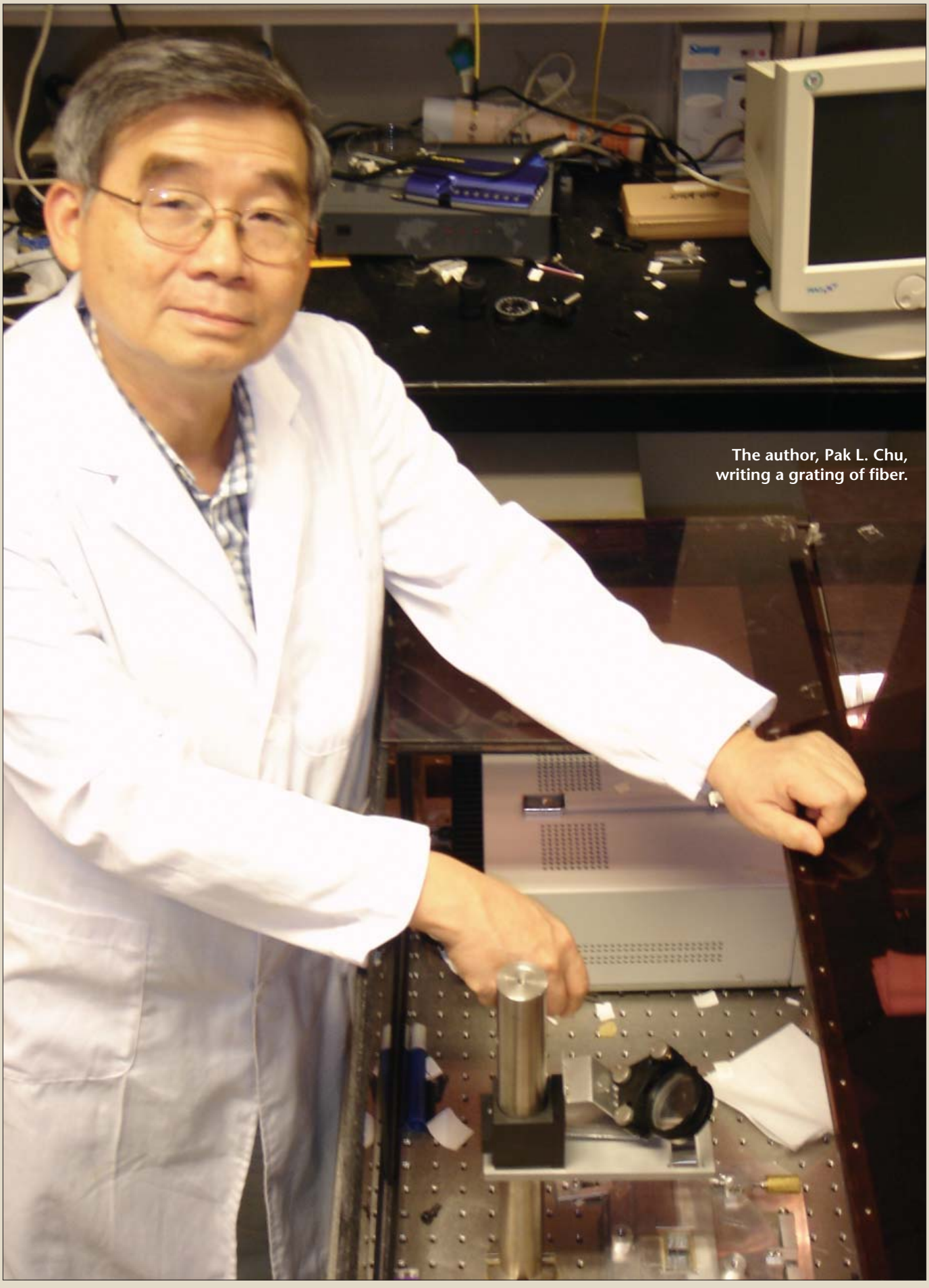

The author, Pak L. Chu, writing a grating of fiber.

Polymer Optical Fiber Bragg Gratings

Pak L. Chu

Silica-based optical fiber Bragg gratings are important in optical signal processing, but they have the disadvantage of being difficult to tune. Now, researchers have developed polymer optical fiber Bragg gratings that can fulfill most of the functions of their silica counterparts, plus greater tunability.

Many kinds of Bragg gratings in silica single-mode optical fiber have been devised, such as chirped gratings, apodized gratings and long-period gratings, which couple the cladding mode of the fiber to the core mode. The technology of writing grating in silica fiber is now very mature and inexpensive.

However, these gratings have always suffered one important disadvantage: a lack of tunability. Because glass is a relatively stiff material with a large Young's modulus of 7.245×10^{10} N/m^2 and a small thermal expansion coefficient, the Bragg wavelength of silica gratings cannot be tuned easily by either mechanical or thermal methods.

In the early 1980s, scientists developed polymer optical fiber based mainly on polymethylmethacrylate (PMMA). However, this material has been viewed as unsuitable for communications applications because of its large attenuation and weak mechanical strength. PMMA fiber has an attenuation figure of around 150 dB/km; it freezes at temperatures below -20° C and softens at temperatures higher than 120° C. Thus, its application is confined to a protected environment.

Despite these disadvantages, polymer optical fiber can be made into optical devices that exhibit properties not found in silica fiber. For example, the nonlinear coefficient of polymer fiber is many times larger than that of silica; hence, optical switches can be constructed. In addition, it has been found recently that the Young's modulus of polymer fiber is about 30 times less than that of silica—which translates to a mechanical tunability for a polymer-based Bragg grating that is about 30 times larger than a Bragg grating in silica fiber.

Similarly, the thermal strain coefficient in polymer fiber is 1.48 pm/με, compared with 1.15 pm/με for silicas. This larger coefficient also allows a wider thermal tuning range in polymer optical fiber Bragg gratings. Since the grating length is short—about 1 cm—the fiber attenuation is immaterial.

The fabrication of gratings in polymer optical fiber relies on the photorefractive effect of the polymer, which differs from that of silica fiber. Scientists have four ways to use light to change the refractive index of the polymer:

- Ablation—the light burns or melts the polymer surface;
- Chain scission—the light breaks the polymer chains and reduces the polymer's density, lowering the refractive index;
- Cross-linking—the light induces free radicals that combine polymer chains to increase the density and refractive index of the polymer; and
- Photopolymerization—the light generates free radicals, causing polymerization of the unreacted monomer, which increases the polymer density and hence the refractive index.

Different types of gratings are created using various techniques. For example, surface grating is made through ablation or chain scission, whereas bulk grating or fiber grating is prepared through cross-linking or photopolymerization. Polymer fiber grating is generally fabricated using photopolymerization as well. This differs from the mechanism used to make gratings in silica fiber.

Photopolymerization in polymer fiber made of PMMA is induced at a wavelength of 325 nm. The process also requires a phase mask to create interference fringes in the fiber core. The periodicity of the mask determines the Bragg wavelength of the grating. The setup for grating fabrication in polymer fiber is similar to that used for writing gratings in silica fiber, as shown in Fig. 1.[1]

The three silica prisms form an optical ring for the first-order diffraction of the phase mask. This diffraction forms the dark and bright fringes on the polymer optical fiber so that the bright fringes change the refractive index of the fiber core and the dark fringes leave the core index unchanged. The grating may be ruined if the zero-order diffraction re-enters the fiber. The beam dumper prevents this from happening.

The amplified spontaneous-emission source launches a wide spectrum of probe light into the fiber through a coupler and two lengths of silica optical fiber. One of the output ports of the coupler is connected to the optical spectrum analyzer to display the reflection spectrum of the grating in the polymer optical fiber. The output end of the silica fiber is also connected to another input of the analyzer, which displays the transmission spectrum of the grating.

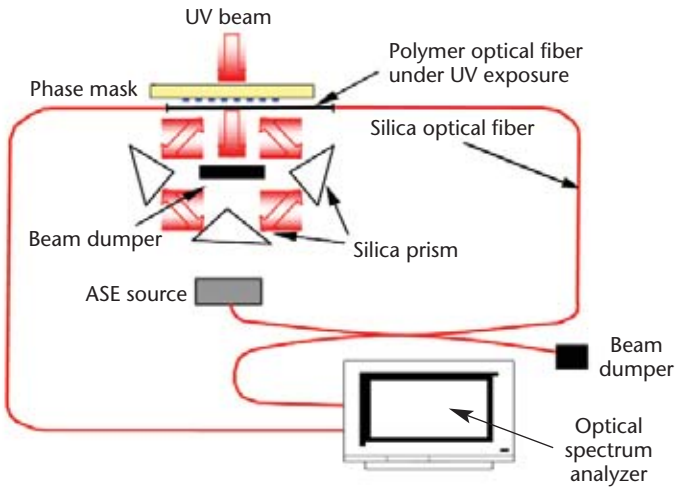

Figure 1. Writing of polymer optical fiber Bragg grating.

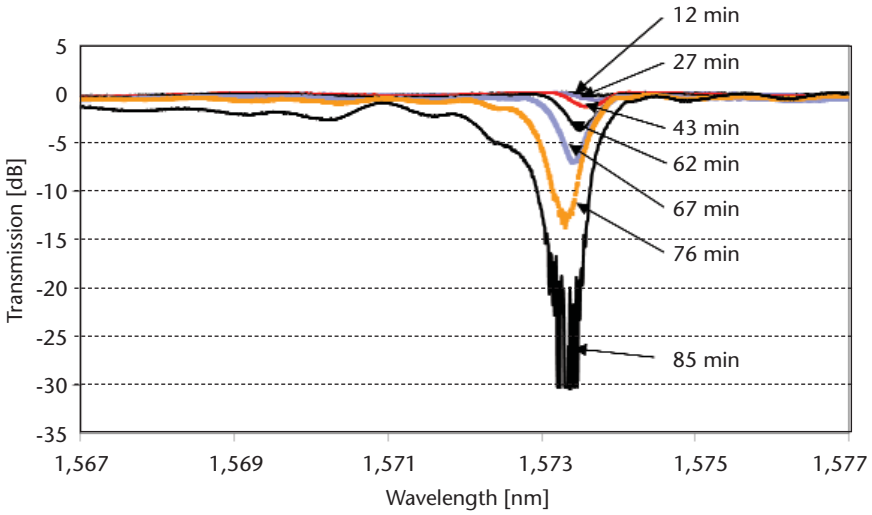

Figure 2. Growth dynamics of polymer optical fiber Bragg grating.

Figure 2 shows the growth dynamics of polymer optical fiber Bragg grating. First, a noticeable change in transmission occurs at around 1,574 nm after a 12-min exposure. The maximum rejection level increases slowly until the 62nd minute. After that, the rejection level increases significantly with further exposure. At the 67th minute, the rejection level is double that at the 62nd minute. At the 85th minute, the transmission at the Bragg wavelength is reduced to the noise level. The spectral width of the stop band at this exposure is 0.5 nm.[2]

The refractive index modulation Δn of the grating can be estimated as a function of the exposure time from the spectra in Fig. 2. This index Δn increases linearly until the 62nd minute. After that, Δn increases nonlinearly to the maximum value at the 85th minute. This phenomenon resembles that in silica fiber gratings. Gratings are designated as type I and type II depending on whether they have undergone linear or nonlinear Δn changes, respectively.

We obtained these type I and type II gratings with relatively strong UV irradiation—about 6 mJ. However, we recently discovered that if the fiber was irradiated at a low energy level (4.5 mJ, for example), we observed an interesting phenomenon.[3]

Initially, as the fiber was irradiated, type I grating began to grow until its reflectivity reached a maximum. As the fiber irradiation continued, the reflectivity started to decrease, indicating an onset of the grating erasing process. This is normal for type I gratings.

When the grating was reduced practically to zero, we turned off the UV irradiation and continued to monitor its status. Amazingly, the grating began to regenerate itself only a couple of minutes later. Its reflectivity continued to grow while the irradiation was off until it reached 61.7 percent after 8 h. After that, it stopped changing.

We are not sure of the mechanism behind this novel polymer-grating growth behavior. However, we believe that the thermal stress that UV irradiation induces in polymer optical fiber plays an important role. Such stress might induce the refractive index change with a sign opposite to that induced by UV photoreactions to the polymer fiber.

With UV irradiation on, the polymer grating is caught between two effects: refractive index change induced by thermal stress and UV photoreaction. After the UV exposure is off, the thermal stress relaxes and its induced refractive index change gradually diminishes.

The UV photoreaction permanently alters the refractive index change; therefore, the regrowing phenomena of the polymer fiber Bragg grating will occur. The grating stabilizes when the thermal stress is completely relaxed—something that also happens to silica fiber Bragg gratings.[4]

Tuning characteristics and applications

The Bragg grating in a polymer optical fiber has a wide tuning range. By stretching the grating to 1.3-percent strain, researchers can shift the Bragg wavelength by 20 nm. On releasing the strain, the wavelength returns to its original value—in other words, no hysteresis effect is observed.[5] Another experiment was carried out by stretching the grating

until it broke. The resulting wavelength shift was 73 nm.[6]

Polymer fiber Bragg gratings also exhibit a broad thermal tuning range. For a change of 50° C—from a room temperature of 20° to 70° C—the Bragg wavelength experiences a blue shift of 18 nm. As the temperature drops from 70° to 20° C, the Bragg wavelength experiences a red shift by retracing the previous tuning curve. In other words, no hysteresis occurs.[7]

Because of their wide tuning range, polymer fiber Bragg gratings have applications with which silica gratings cannot compete.

Simultaneous strain and temperature sensor

A fiber Bragg grating sensor must be able to discriminate against both temperature and strain. However, a single grating cannot do this. Researchers have proposed several kinds of simultaneous sensors: a combination of fiber Bragg grating and long-period grating; two fiber Bragg gratings of different core diameters; the superposition of a polarization-rocking filter onto a fiber Bragg grating; the combination of a fiber Bragg grating and an erbium-doped fiber amplifier; two long-period gratings; and a single Bragg grating straddling the junction of two fibers. All these methods rely on the use of two different silica fiber gratings and are complicated to make. However, a simple sensor can be constructed by combining a silica and polymer grating as shown in Fig. 3.[8]

The setup in Fig. 3 uses a broadband optical source. To sense the temperature change ΔT and a strain change $\Delta\varepsilon$ independently but simultaneously, an optical spectrum analyzer records the Bragg wavelength shift due to each grating as $\Delta\lambda_1$ and $\Delta\lambda_2$, respectively. These quantities can be expressed in terms of the temperature change ΔT and strain change $\Delta\varepsilon$:

$$\begin{bmatrix}\Delta\lambda_1\\ \Delta\lambda_2\end{bmatrix}=\begin{bmatrix}K_{1T} & K_{1\varepsilon}\\ K_{2T} & K_{2\varepsilon}\end{bmatrix}\begin{bmatrix}\Delta T\\ \Delta\varepsilon\end{bmatrix},$$

where K_{1T} and K_{2T} are the temperature sensitivities of gratings 1 and 2, respectively, and $K_{1\varepsilon}$ and $K_{2\varepsilon}$ are the corresponding strain sensitivities. The equation is inverted to obtain ΔT and $\Delta\varepsilon$:

$$\begin{bmatrix}\Delta T\\ \Delta\varepsilon\end{bmatrix}=\frac{1}{K_{1T}K_{2\varepsilon}-K_{2T}K_{1\varepsilon}}\begin{bmatrix}K_{2\varepsilon} & -K_{1\varepsilon}\\ -K_{2T} & K_{1T}\end{bmatrix}\begin{bmatrix}\Delta\lambda_1\\ \Delta\lambda_2\end{bmatrix}.$$

As shown in this equation, if the two gratings in a temperature-strain sensor are of the same kind—both silica or both polymer—the respective sensitivity parameters would have similar values, making the denominator close to zero. Such a sensor would not work very well.

However, if one of the gratings is silica and the other polymer, the parameters are very different. This makes the denominator far from zero, and it is then possible to sense both temperature and strain changes more accurately. For polymer gratings, K_{1T} = -149 pm/°C and $K_{1\varepsilon}$ =1.5 pm/με, and for silica gratings, K_{2T} =10.47 pm/°C and $K_{2\varepsilon}$ =1.17 pm/με. If the optical spectral analyzer's resolution is $\Delta\lambda_1 = \Delta\lambda_2 = 0.01$ nm = 10 pm, the minimum detectable temperature is $\Delta T = 7.7$° C and strain $\Delta\varepsilon = 0.07$ με.

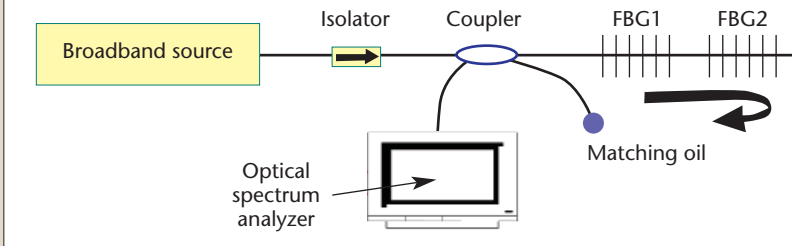

Figure 3. Sensor with a combination of polymer and silica fiber gratings.

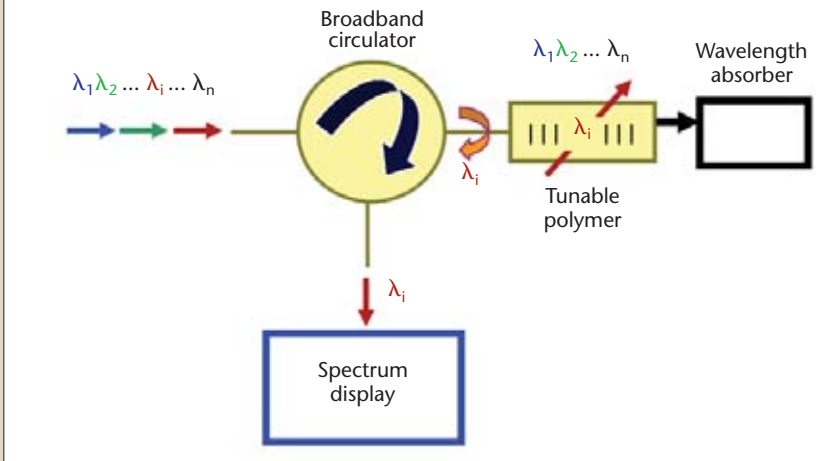

Figure 4. A simple optical spectrum analyzer.

Tunable add-drop multiplexer-demultiplexer

Two basic configurations of optical add-drop multiplexers are based on fiber Bragg gratings. One configuration consists of a fiber Bragg grating sandwiched between two broadband circulators. The wavelength to be added or dropped is determined by the Bragg period of the grating. If silica fiber Bragg grating is used, this wavelength is not easily tunable.

On the other hand, if it is replaced by a polymer fiber Bragg grating, the wavelength can be tuned over 20 nm by either mechanical or thermal means. The other possible configuration for an optical add-drop multiplexer is the Mech-Zehnder construction, in which a pair of identical fiber Bragg gratings forms the two arms. Again, the Bragg wavelength of the

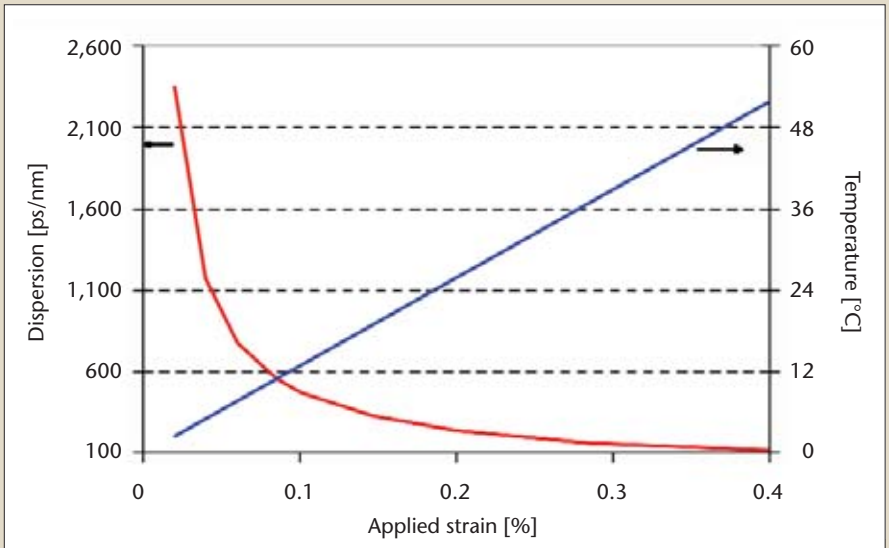

Figure 5. Dispersion tuning by applied strain and the required temperature tuning to remove wavelength shift.

gratings determines the add-drop wavelength. To make the multiplexer tunable, we can again replace the silica fiber Bragg gratings by a pair of polymer fiber Bragg gratings.

Simple optical spectrum analyzer

If we remove the second broadband circulator in the optical add-drop multiplexer, we achieve the basic structure of an optical spectrum analyzer, as shown in Fig. 4. The second circulator is now replaced by a wavelength absorber, which can simply be a piece of black velvet attached to the end of the fiber Bragg grating. This absorber prevents light from reflecting back to the input end of the grating, thus interfering with the signal delivered to the spectrum display unit.

Instead of the absorber, an optical fiber isolator may be inserted between the first circulator and the fiber grating. Of course, the tuning of the polymer optical fiber grating needs to be calibrated in order to produce a relationship between the amounts of tuning and the wavelength shift. Mechanical tuning is preferred because it is faster than thermal tuning. Researchers can incorporate this simple optical spectrum analyzer into a personal computer so that they can use software to control experiments and collect data.

Linearly chirped polymer fiber Bragg gratings for dispersion compensation

Fiber grating dispersion compensation of the transmission fiber in a long-distance optical communication system is a good alternative to the dispersion management technique used extensively in the field, particularly if it is made tunable.[9]

To do this, scientists have developed a way to chirp-tune fiber Bragg gratings by external strain or temperature perturbation. However, these methods suffer from the large Bragg wavelength shift during tuning. The large thermal tunability of polymer fiber Bragg gratings can be used to eliminate the wavelength shift.

The linear chirping of the grating can be achieved by first writing a regular grating into the core of the fiber. Next, its cladding is tapered into a specified function of its axial distance by chemically etching the fiber and withdrawing it at a given speed. The slope spectrum of the group delay of this tapered grating can be tuned by applying tension. However, as the tension rises, the Bragg wavelength experiences a red shift. Subjecting the grating to thermal tuning can counteract this effect because this tuning tends to introduce a blue shift.

Figure 5 shows the dispersion introduced by the grating as a function of applied strain, as well as the required temperature tuning to maintain the Bragg wavelength unchanged. It clearly indicates that a very large range of dispersion can be achieved—from 2,400 ps/nm at 0.02 percent, for example, to 110 ps/nm at 0.4 percent. Meanwhile, the required maximum temperature rise to offset the Bragg wavelength shift is small. For example, to offset the wavelength shift induced by the 0.4 percent applied strain, the required temperature rise is only 51° C. This is well within the operating temperature range for polymer optical fiber Bragg gratings. In contrast, a linearly chirped silica fiber Bragg grating taper would need a temperature change of 300° C if the applied strain is only 0.25 percent.

Polymer optical fiber gratings are evolving into an important optical signal processing component. They can perform more functions than silica ones because of their large mechanical and thermal tuning ranges. The large attenuation figure of polymer optical fiber is irrelevant in this case because the length of the grating is only 1 or 2 cm. The fabrication of polymer fiber Bragg gratings is similar to that for silica fiber Bragg gratings except for the difference in the irradiation wavelength.

Recently, a new polymer material has debuted in the laboratory: the perfluorinated polymer. Optical fibers made using this substance have an attenuation figure as low as 10 dB/km. In fact, the theoretical attenuation of this fiber can be as low as 0.3 dB/km at 1,550 nm—close to that of silica fiber. Hence, researchers have renewed their interest in using this fiber for short-distance communications, such as home and automobile networking.

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