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Annealing Optical Fiber: Applications, Properties, and Dealing with Detrimental Effects

If done properly, the annealing of optical fiber can produce useful fiber components. Annealing a fiber involves raising the glass to a temperature above the strain point for a short time and cooling slowly back to room temperature. This process reduces stress in the glass, but also initiates a number of physical and chemical changes to the glass. This article discusses a few component examples and covers some of the glass chemistry and physics that occur during annealing. Before describing the effects of annealing, the article presents an application that motivated us to anneal optical fiber: the annealed-fiber coil. Then, after discussing some of the glass chemistry and physics, two applications where annealing's detrimental effects can be made beneficial are described: a fiber depolarizer and increased ultraviolet (UV) photosensitivity.
Optical-Fiber Current Sensing

The annealed-fiber coil is an essential component of optical-fiber current sensors (OCFSs) (also known as optical current transducers). OCFSs have several economic and performance advantages over conventional current transducers in fault detection and metering. The bandwidth and high dynamic range of these sensors provide the power-utility engineer with a diagnostic tool for evaluating the behavior of generators and the transmission grid. Due to their all-dielectric design, installation costs are significantly lower and sensor failure does not pose a threat to power-utility personnel or equipment [1].

The two most common OCFSs are the polarimetric design and the Sagnac interferometric design. Figure 1 shows a schematic of a polarimetric OCFS. The analyzer and analyzer are oriented to convert a rotation of the polarization state into an intensity change at the photodetectors. The Faraday effect provides a rotation of the light's electric field orientation, or polarization state, when a magnetic field is parallel to the optical path in a glass. If the light path is closed around a conductor, or nearly so with an optical fiber, Ampere's law applies, and the Faraday rotation is directly proportional to the current flowing through the aperture of the closed path. Thus, an optical-fiber coil can be used to make a true optical current sensor and not just a magnetic field sensor near a current-carrying line (magnetic field sensors have low isolation to nearby currents and/or magnetic fields). The closed optical path of the OCFS also increases the device's isolation to nearby currents or magnetic fields.

The Sagnac interferometer current sensor can also measure the Faraday rotation. Two counter-propagating light beams in the Sagnac sensor interfere at a coupler. The two beams experience a phase shift, due to an optical path change from current flow. An intensity change at the coupler is proportional to the current flowing through the aperture. A heterodyned Sagnac current sensor is shown in Fig. 2, where a feedback control circuit locks the phase of the interferometer. The current is measured by monitoring the control-circuit output [2].

The simple polarimetric current sensor has a high bandwidth and no saturation, and it is best suited for fault detection and pulse-current metrology. Polarimetric current sensors have been used successfully to measure current pulses of greater than 10 MA with about 1% accuracy. The more complex heterodyned Sagnac current sensor has excellent stability and is best for DC and current metering.

The subtleties of making a practical device with a fiber coil are related to the nature of the Faraday effect and detecting a change in the polarization state of light or phase shift.

1. A schematic of a polarimetric OCT. The two photodetector outputs are summed (\(I_1\)) and the difference (\(I_2\)) taken. The quotient output of the difference divided by the sum (\(\Delta I/I_1\)) removes common-mode noise.

2. A schematic of a Sagnac OCT. Polarization-maintaining (PM) fiber and low-birefringence (Lo-Bi) fiber are used to prepare and preserve the needed polarization states for current measurement.

3. The relative sensitivity versus twist per meter for 7 cm diameter, 29.9 turn fiber sensor coils.
linear state of polarization can be modeled as the superposition of two equal-intensity, right and left circular polarization states. As the linear state propagates through a glass with circular birefringence, the accumulated phase difference rotates the linear state.

Another type of birefringence that is easy to produce in glass is linear birefringence. In a linearly birefringent glass, horizontally and vertically polarized light would propagate at different speeds and again accumulate a phase difference. However, the phase difference changes the polarization from linear to some elliptical state. In polarimetric detection, linear and circular birefringences are not always distinguishable and linear birefringence can easily swamp the effects of circular birefringence. Also, linear birefringence has a large temperature dependence, which destabilizes the sensor. Thus, to measure the weak Faraday effect in optical fiber and make a practical current sensor, we have to remove the linear birefringence from the fiber [1].

Linear birefringence in fiber arises from stress, applied externally (bending) or internally (drawing process and fiber structure), and from waveguide shape (a noncircular core). Annealing the fiber will relieve all the stress-induced linear birefringence. The waveguide-induced linear birefringence cannot be removed, but its effects can be significantly reduced by twisting the fiber. If the twist rate is about twice the amount of accumulated phase in a given length of fiber, the effects of linear birefringence will be greatly reduced. Figure 3 shows that the combination of twisting and annealing the fiber increases the current sensitivity of an annealed-fiber coil to near that of an isotropic, or perfect, fiber [3]. Several universities and companies are presently exploring the application and production of annealed-fiber OPCSs.

**Detrimental Effects of Fiber Annealing**

As mentioned at the beginning of this article, annealing glass can, under certain conditions, produce undesirable effects in fiber. These effects include increasing the OH concentration in the glass and devitrification (the nucleation and growth of crystals within the glass). The following paragraphs will discuss these effects.

Our fiber annealing is done in an air environment with the acrylate jacket in place. At temperatures between 500 and 600°C, the jacket burns away. The jacket is treated before the annealing cycle with acetone, which causes the jacket to swell. The acetone-treated jacket does not hold the glass tightly, so minimum damage to the glass surface occurs during the jacket combustion. The jacket swells as it burns, stressing the fiber coil. However, with careful winding techniques the fiber coil can survive this stress.

When the jacket burns during annealing, many chemical reactions occur, but the primary species formed is water. At annealing temperatures, water reacts with the glass surface to form OH. OH reduces the strength of the glass and will cause loss at absorption bands around 1390 nm. Also, ambient-air annealing allows water in the air to react with the fiber surface to again produce OH. At temperatures around 850°C, the OH reaction is slow and significant concentrations of OH take over 50 hours to reach the core region of the fiber. At higher temperatures, near 1000°C, the reaction accelerates, and OH can reach the core in only a few
hours. However, above 1000°C the reaction reverses and the glass dehydroxylates, and OH is removed from the glass. The OH and water in the glass also aid in devitrification.

Devitrification in silica can occur through nucleation and crystal growth at temperatures between about 200°C and 800°C, depending on the glass composition. From the nuclei present, crystal growth continues for temperatures near 800°C to a few hundred degrees Celsius below the melting point (about 1800°C in fibers). If the temperature of the glass remains low, nucleation and crystal growth will occur at a negligible rate. However, further thermal processing into the crystal growth temperature range will promote the growth of the nuclei into larger crystals. Devitrification usually starts at the glass-air surface and proceeds inward. This can be due to the presence of surface flaws or due to chemical reaction with water from the air or jacket combustion. At annealing temperatures above 1000°C and heating rates around 5°C/min, the crystal growth is rapid and starts primarily at the surface, propagating into the fiber core.

Devitrification of the fiber increases scattering loss, depolarizes the light, and reduces the strength of the fiber. For our typical annealing cycle (heating at 5°C/min to 850°C, dwell for 4 hours, then cooling at 0.2°C/min to room temperature) the effect of devitrification is small. However, longer annealing times can produce enough depolarization to reduce the current sensitivity of a fiber coil. Figure 4 shows the decrease in coil current sensitivity versus annealing time. The sensitivity scale in Fig. 4 is relative to an ideal current-sensing coil.

For higher annealing temperatures (above 1000°C) and times less than 10 hours, losses in annealed fiber can be due to scattering, fiber fracture, and possibly stress-induced microbending loss from surface crystal growth. At these high temperatures, the optical loss and fiber fragility increase, making current sensing with this type of fiber impractical. Figure 5 shows the transmittance and temperature of a fiber heated to about 1300°C. At this high temperature, the fiber transmittance quickly falls near zero as crystal fracture lines run through the core of the fiber. Figure 6 shows a photograph of the fiber after the annealing cycle. The fiber has many fractures from the random crystal growth.

For fiber heated to temperatures above 1200°C, the OH concentration in the fiber moves rapidly to the core and is seen as an absorption at a wavelength of about 1390 nm. Figure 7 shows the growth of OH concentration in the core of such a fiber. The small peak at 1390 nm and 950°C is associated with the absorption of OH. However, as the fiber is heated beyond 1000°C, the OH concentration decreases due to the OH reaction reversal. Figure 7 also shows that at temperatures above 1200°C, the crystal growth produces broadband loss in the fiber.

Crystal growth at the surface is greatly affected by the treatment and type of jacket on the annealed fiber. As the jacket burns, the surface of the glass is altered to promote crystal growth through chemical attack. Therefore, for fiber that endures fire or other high-temperature processing, the jacket material becomes critical to the fiber survivability and loss. Silica fiber sensors of any kind are not practical for long-term use above 1000°C.
Fiber Depolarizer

The crystal growth in heat-treated fibers can be used to make a depolarizing fiber. For optical systems that measure the polarization-dependent loss of a component, the detector must be insensitive to the polarization state. With the proper heat treatment, an annealed multimode fiber can be made to depolarize or scramble the polarization state of the light passing through it to the photodetector. Figures 8 and 9 show the effect of polarization-state scrambling on two Poincaré spheres. A polarization state is represented as a point on the Poincaré sphere. In Fig. 8, linear states lie on the equator, circular states on the poles, and elliptical states elsewhere. Figure 8 shows the polarization state motion of a 45 m piece of multimode fiber as the fiber is moved by hand. The polarization state moves along well-defined paths on the sphere due to stress-induced birefringence. The 1 m fiber in Fig. 9 was annealed for 8 hours at 950°C. Because of scattering on crystal sites in the fiber core, the polarization-state motion is like a random walk on the Poincaré sphere. In Fig. 9 the Poincaré sphere has been rotated to better show the polarization state motion of the annealed multimode fiber as it is moved by hand. Both the unannealed and annealed fibers have similar depolarization effects; reducing a 30% degree of polarization on the input to 1.5% at the output of the fiber.

Fiber Bragg Gratings

Fiber Bragg gratings (FBGs) are an optical component that can filter a band of light. FBGs reflect the light off of an index grating or a periodic index structure in the fiber. The period of the index modulation is a little more than twice the wavelength of the reflected light. In the case of 1.5 μm telecommunications, it is about 4 μm. The reflected band of an FBG is proportional to the Fourier transform of the periodic index modulation along the length of the fiber. Thus, for an FBG that has a "flat top" reflection bandwidth, the index modulation strength along the fiber could follow a sinc function.

What makes FBGs so useful in optical-fiber communication networks is the combination of both optical filtering (for add/drop and multiplexed/demultiplexed connections) with dispersion and polarization mode dispersion (PMD) correction. Optical-fiber links have dispersion and PMD, both of which act to temporally spread a pulse of light. With enough pulse spreading, adjacent pulses "run into each other" so that data is lost and bit-error rates rise. FBGs can be used to actively correct for dispersion and PMD as they change with the fiber link's environmental conditions. Thus, FBGs become powerful components that allow multiple wavelengths on a single fiber and corrections for fiber nonlinearities so that data rates can be kept high.

The periodic index structure in the fiber that creates the FBG is made by exposing an optical fiber to ultraviolet (UV) light. Depending on the type of UV light (wavelength = 157 nm, 193 nm, 248 nm, 334 nm, 488 nm, pulsed or continuous and power level) and glass, various changes will occur in the glass to increase or decrease the index. There are a number of interactions between the glass and the UV light to make the index change. All the interactions are related to molecular bond changes in the exposed region of the glass.17

A typical method of making an FBG is to form an interference pattern with UV light on the fiber via an interferometer or phase mask. In addition to the UV interference pattern, the intensity of the pattern is varied or apodized along the length of the fiber to change the performance of a grating's passband and dispersion characteristics. A full discussion of the apodization process can be found in (17).
However, the annealed fiber accomplishes this depolarization with a much shorter length of fiber and the polarization-state motion is random.

**Increased Photosensitivity**
Fiber Bragg gratings (FBGs) are a basic optical filter in fiber telecommunication systems. An FBG written in a fiber can reflect or block a wavelength band of light passing through the fiber. An FBG can also correct for dispersion in fiber systems and is an excellent strain sensor. FBGs are made by exposing a fiber to a periodic pattern of UV light, which produces an index modulation in the fiber (see box). The period and depth of the index modulation and modulation profile determine the optical characteristics (center wavelength, bandwidth, reflectance, etc.) of the FBG. Oven annealing fibers above 1000°C increases the photosensitivity of a fiber to UV, so shorter exposure times and larger index changes can be achieved. One mechanism for UV photosensitivity arises from defects in the glass matrix. Annealing a fiber above 1000°C would form many crystal defects sites in the fiber for increased photosensitivity [6].

**Conclusion**
Annealing optical fibers has made the optical-fiber current sensor practical for monitoring and diagnostics by utility companies. To produce an annealed-fiber coil for this application, the annealing process must be held within time and temperature bounds or devitrification and OH absorption will degrade coil performance. Annealed-fiber devitrification can produce other useful fiber components, such as a fiber depolarizer and increased photosensitivity for FBG production.

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**References**