Using Fiberoptics For Practical Sensing

Low-Cost Fibers Open New Applications In Interferometric Temperature And Pressure Sensing

by Scott D. Wohlstein

Recent reductions in production and material costs have made the acquisition of low-cost fiberoptics easier, allowing for more experimentation in the area of sensing. Older techniques – including the use of phosphor-tipped or reaction-type fibers – trade on the inherent fiberoptic advantage of remote location. But these types of sensors cannot be used where interaction by light emission or chemical methods is unacceptable. More innocuous methods have had to be developed. Continuing research and sharply declining prices have led to new levels of fiber-sensor engineering; in particular, the use of low-cost, low-grade optical fibers has proven very successful.

Basic Fiber Transmission

The main element of interest in fiber-optic sensing is the optical fiber itself – in particular, the multimode fiber. While singlemode fiber can be substituted for multimode fiber in almost all sensor systems, a severe sensitivity penalty would have to be paid. For simplicity, this discussion will be restricted to multimode fiber.

The basis of sensing via fiber is the total internal reflection of light propagating through the fiber. Light entering one end of a fiber, within the fiber's numerical aperture (or acceptance cone, as depicted in Figure 1), will undergo TIR at the core-cladding interface repeatedly as it propagates down the length of the fiber.

The typical multimode fiber has a core diameter of 20 to 200 micrometers, and cladding diameter typically ranges from 125 to 400 μm. The cladding, in turn, is usually covered by an outer sleeve or protective covering.

If the cladding is opaque, the only internal reflections that will transmit light through the fiber are bounced from one outside-core/inside-cladding interface through the axial center of the fiber (in any given orientation) to the other outside-core/inside-cladding interface. Although this type of fiber is more sensitive (for use in sensors) than a singlemode optical fiber, it is less sensitive than

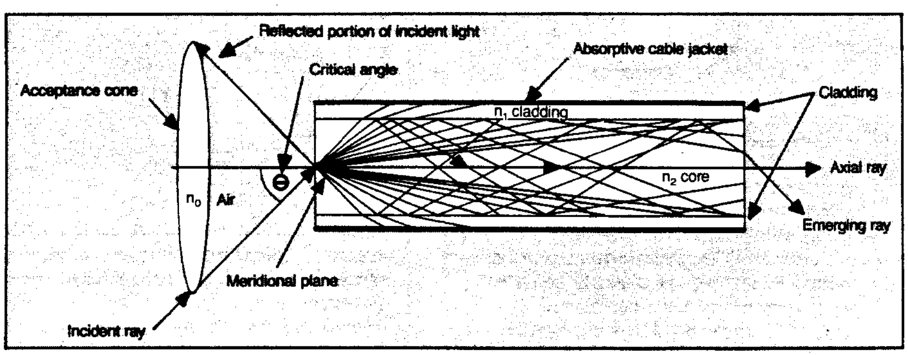

Figure 1. Large-core, solid-clad fiber in axial cross section.

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a multimode fiber with a transparent cladding and an outer opaque covering.

The use of a transparent cladding in a multimode fiber increases sensitivity by introducing an optical interface between glass (or whatever the core material happens to be) and an elastic (plastic is a typical transparent cladding material for sensor applications). Fiberoptic sensing operates on the principle that the more attenuation within the fiber (resulting from the reflection process, not merely poor-quality core material) the better. This is in direct conflict with the standard rule of thumb in the communications field, where the less the attenuation loss is – it is typically about 0.1 dB/km – the better.

Some fiber manufacturers now offer high-loss or high-birefringence fibers for specific use in sensing systems. Sensing systems have been used in such applications as temperature, pressure, strain, acceleration, acoustic waves, fluid depth and volume, electric field, magnetic field, and displacement sensing (in the last case, fiberoptic ring gyroscopes have been used for years). Advantages of fiberoptic sensors over traditional sensing methods include fiber's immunity to electromagnetic and radio-frequency interference, its potential for high data rates, and its electrical passivity in explosive environments.

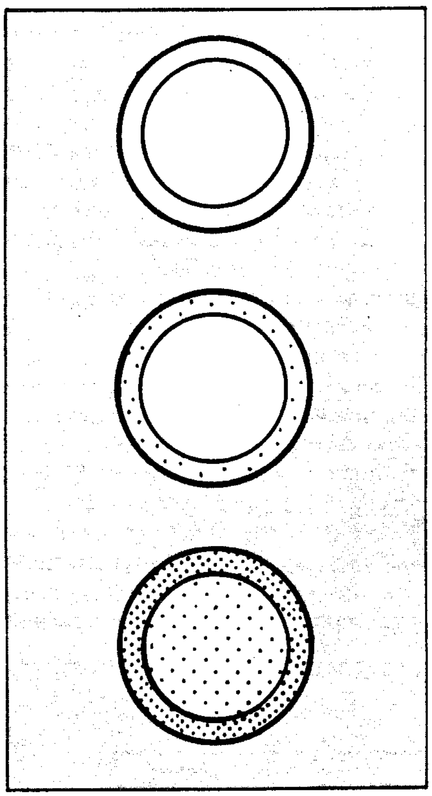

Figure 2. Graphic depiction of changes in speckle interference pattern with increase in temperature. Top, equilibrium ambient temperature yields no pattern. Center, the temperature has begun to climb; the speckle lies mostly in the region of the core/cladding interface. Bottom, the temperature climbs further; the speckle pattern moves toward the core.

Temperature Sensing

Temperature sensing with a fiberoptic sensor relies on the change of the coefficient of thermal expansion at the core/cladding interface (Figure 2). As the temperature of the cable increases or decreases, the thermal equilibrium at the core/cladding interface is disturbed, because the core and cladding expand (or contract) at different rates. In instances where the optical fiber forms one arm of an interferometer, this effect manifests itself as a proportionate gradient in the contrast of the interferometric matrix (speckle) – as a "spiralling" effect. As the temperature increases, the "spiralling" rotates toward the center of the core; when the temperature decreases, the "spiralling" effect rotates away from the center of the core.

Sensing temperature with fiberoptics is a dual-conversion process. The first step of the process is to convert the sensing temperature into the relative linear or axial change in the fiber core and cladding. This dimensional change is then converted into the corresponding fringe/-interference generation.

The complete interaction between

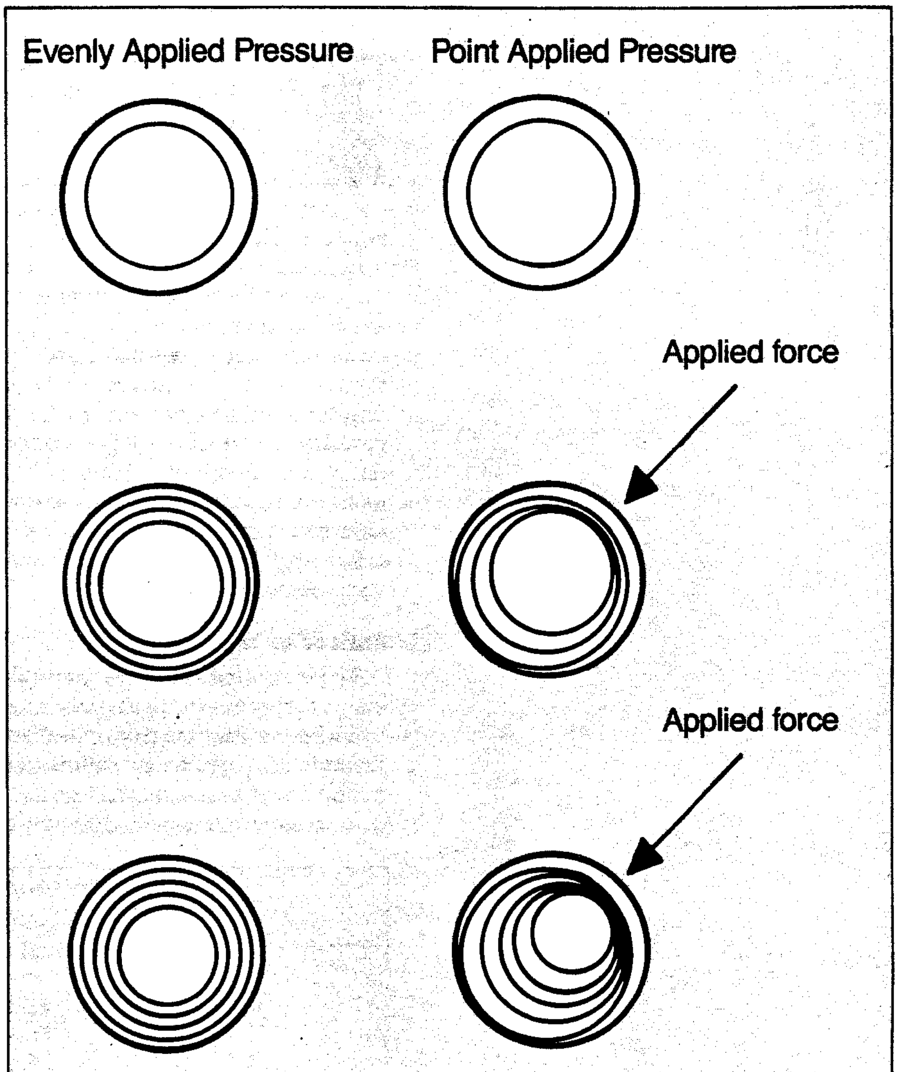

Figure 3. Graphic depiction of changes in shelling effect pattern with change in pressure. Top, equilibrium ambient pressure yields no pattern. Center (left), ambient pressure increases, forming "shells" in cladding. Center (right), applied point force to fiber increases, forming eccentric rings in cladding. Bottom (left), further increase in pressure creates "shelling" effect to be noticed in center core. Bottom (right), applied point force increases eccentric "shelling" effect observed in core.

dimensional change and fringe changes for the core and cladding can be described as a two-step calculation process. In the first step, calculate the fringe changes separately for the core and cladding, using the following formula:

$$Fc_{\text{core or clad}} = [(n - 1)\,\alpha\, L\, \Delta T]/\lambda \quad (1)$$

where n is the refractive index of the core or cladding material [no units], α is the coefficient of thermal expansion of core or cladding material for the temperature range 0 to 100° C [in units of /°C], L is the length of the sensing piece [cm], ΔT is the change in temperature [° C], and λ is the source wavelength [nm].

The second step involves calculating the overall (average) system fringe changes, using the following formula:

$$Fc_{\text{system}} = [(n_{avg} - 1)(\Delta L_{avg})]/\lambda \quad (2)$$

where n_{avg} is the average refractive index of core and cladding material [no units], ΔL_{avg} is the average change in linear dimension of core and cladding material [cm], and λ is (again) the source wavelength [nm].

Equation 1 yields ≈ 3 fringe changes for a core material of fused quartz-glass and ≈ 360 fringe changes for a cladding material of Teflon TFE (both materials with a 100° C change in temperature). Solving Equation 2 yields ≈ 189 fringe changes, which confirms the result of the average of Equation 1 solved for both the components.

Simple reduction suggests that this system can resolve ≈ 1 fringe change per 0.5° C change in temperature. Resolutions of 1 fringe change per 0.1° C change in temperature can be obtained, depending upon the setup, conditions, mounting, and other such factors. The system accuracy is directly related to the definition of α. Repeatability of the system is directly related to the elastic memory of the core and cladding materials used.

Pressure Sensing

Pressure sensing via optical fiber relies on the applied compressibility or coefficient of volumetric elasticity of the optical fiber (Figure 3). As the pressure on the cable increases or decreases, the differential between the core and cladding causes the core/cladding interface to be disrupted. This is manifested by a proportionate disturbance on the interference matrix — call it a "shelling" effect. As the pressure increases, the "shelling" collapses toward the center of the core; as the pressure decreases, the "shelling" moves away from the center of the core.

Sensing pressure with optical fibers involves a tri-conversion process. The first step is to convert the sensed pressure into relative volumetric change. Second, convert the volumetric information into linear or axial change. Third, convert this dimensional change into corresponding fringe/interference generation.

The complete interaction between dimensional change and fringe changes for both the core and cladding can be described in the following manner. First, calculate the fringe changes for the core, using Equation 3:

$$Fc_{\text{core}} = [(n - 1)\,((\Delta PV)/B\pi r^2)]/\lambda \quad (3)$$

where n is the refractive index of the core material [no units], ΔP is the change in pressure [kg/cm²], V is the volume of core material in the sensing piece [cm³], B is the bulk modulus of the core material [kg/cm²], r is the radius of the core material [cm], and λ is the source wavelength [nm].

Next, calculate the fringe changes separately for the cladding, using Equation 4:

$$Fc_{\text{clad}} = [(n - 1)((\Delta PV)/B\pi(R^2 - r^2))]/\lambda \quad (4)$$

where n is the refractive index of the cladding material [no units], R is the outer radius of the cladding material [cm], and the other parameters are as defined above.

Next, calculate the overall (average) system fringe changes, using Equation 5:

$$Fc_{\text{system}} = (n_{avg} - 1)(\Delta L_{avg})/\lambda \quad (5)$$

where n_{avg} is the average refractive index of the core and cladding [no units], ΔL_{avg} is the average change in linear dimension of core and cladding material [cm], and λ is the source wavelength [nm].

Equation 3 yields ≈ 146 fringe changes for a core material of fused quartz-glass, and Equation 4 yields ≈ 1635 fringe changes for a cladding material of Teflon TFE (both materials undergoing a change of pressure of 1000 kg/

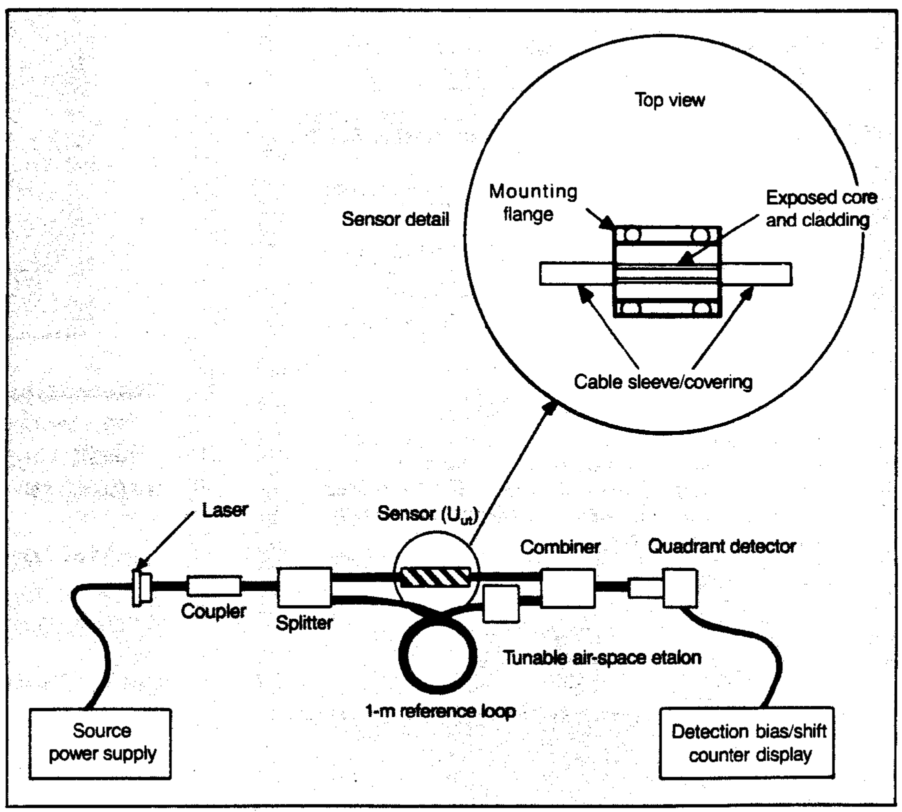

Figure 4. Complete system layout for a fiberoptic temperature or pressure transducer system.

cm²). Solving Equation 5 yields ≈ 2616 fringe changes, which confirms the result of three times the average of Equations 3 and 4.

Simple reduction illustrates that this system can resolve ≈ 1 fringe change per 0.38 kg/cm². Resolutions of 1 fringe change per 0.10 kg/cm² can be obtained, depending upon the setup, conditions, mounting, and related factors. The system accuracy is directly related to the definition of B. System repeatability is directly related to the elastic memory of the core and cladding materials used.

System Theory

Start with a diode laser coupled to a splitter via a multimode fiber pigtail (Figure 4). The light emerging from the splitter in one path traverses a reference loop of one meter of fiber. This loop encompasses an in-line tunable air-space etalon, which compensates for any mismatching or interference caused between the sensor and reference loop prior to readings. The etalon also compensates for any biasing required for calibration.

The other path, after exiting the splitter, connects to the sensor (U_{ut}). The sensor is placed in direct contact with the subject area to be gauged for temperature or pressure (or both).

Both the sensor arm and the reference arm (with the tunable air-space etalon) recombine at a mixer; the single resultant output fiber is imaged onto a quadrant wavelength-matched photodetector. As the path differential changes in response to the external stimulus, the resulting interference pattern(s), in the form of a speckle interferogram, will be imaged onto the quadrant detector. If there is a temperature-induced shift, the quadrants of the detector will be active successively towards or away from the center or null point. If there is a pressure-induced shift, the quadrants will be active in varying degrees over the face of the detector, only to become more concentrated near the center or null point of the detector.

The electronics to decipher the detection include biasing, scanning and phase-matching circuitry (to de-emphasize the expansion/contraction effects associated with the cooling/heating pressurization/depressurization).

Applications of the system include vacuum, radioactive, hazardous chemical and other hostile environments. Since there are no "component" parts other than the core and cladding composition, maintenance is minimal.

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