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FIBER-OPTIC LARGE AREA AVERAGE TEMPERATURE SENSOR

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Fiber-Optic Large Area Average Temperature Sensor

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In many instances the desired temperature measurement is only the spatial average temperature over a large area; eg. ground truth calibration for a satellite imaging system, or average temperature of a farm field. By making an accurate measurement of the optical length of a long fiber-optic cable, we can determine the absolute temperature averaged over its length and hence the temperature of the material in contact with it.

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Much effort has been devoted to using fiber-optic sensors to measure temperature as a function of position along the fiber. The results of this work are impressive but the equipment is expensive. In many instances the desired measurement is only the spatial average temperature over a large area; eg. ground truth calibration for a satellite imaging system, or average temperature of a farm field. By making an accurate measurement of the optical length of a long fiber optic cable, we can determine the absolute temperature averaged over its length and hence the temperature of the material in contact with it.

We study a fiber-optic temperature sensor which will determine the average temperature of a fiber of considerable length, a few kilometers, which can be deployed in environmental studies to measure the average temperature over an area of several thousand square meters. The measurement is based on determining the optical length of the fiber. With suitable characterization and calibration, the change in index of refraction with temperature of the fiber core provides a temperature determination with an accuracy of about 0.1 degree Celsius.

Figure 1 is a schematic drawing of the fiber sensor. An amplitude modulated laser light source is available to drive the system. The intensity of the laser light source can be written as $I_0 \sim \cos \Omega t$ where Ω is the constant modulation frequency which we are free to choose. This output is first split by a 3 dB coupler and then directed to two fiber sensors again through 3 dB couplers. The two fiber sensors are intimately bonded, one to the other, so that any mechanical change in length, stretching, is common to both of them. The light is reflected by mirrors attached to the ends of the sensor fibers. The two fiber sensors are different in that they respond differently to a change in temperature.

The sensor section is ordinary silica fiber, e.g., Corning SMF-28(TM). The change in the optical length, $\mathcal{L}$, of physical length, L , and index n of this fiber is described by

$$\frac{d\mathcal{L}}{dT} = \frac{d(nL)}{dT} = L \frac{dn}{dT} + n\beta L \quad (1)$$

where β is the linear coefficient of expansion. Typical values for a silica fiber are $\beta = 5.5 \times 10^{-7}/^{\circ}C$ and $dn/dT = 1.28 \times 10^{-5}/^{\circ}C$. These values are valid over the temperature range of interest, -30 to 50°C, so the response of the fiber is essentially linear over this region.

The reference fiber is required to have a response which is different than that of the sensor fiber. An ideal fiber sensor would be a single fiber with two well separated cores. Mechanical stretching would be dominated by the bulk of the fiber which is the cladding, and the twin cores would act as the sensor and reference arms. If one core were to be normal silica, the other could be something like Schott glass, FK 51. This glass has a *negative* coefficient of refractive index in the temperature range of interest of about $-6.3 \times 10^{-6}/^{\circ}C$. This however would be a development project so for this preliminary work a temporary solution is to employ the specially coated fibers which have been produced by Simitomo Electric Industries Ltd.[1] They produce a fiber which is overcoated with a liquid crystal film which is designed to counteract the linear expansion of conventional silica fibers. When the sensor fiber is bonded to this reference the combination should be sensitive to temperature while insensitive to mechanical strain.

Assuming that the laser output is proportional to $\sim \cos \Omega t$, the signal detected from the sensor arm will be shifted by twice the fiber transit time, $2L_s n_s/c$, giving

$$V_s = A_s \cos \Omega(t + 2L_s n_s/c) \quad (2)$$

and the reference fiber signal is

$$V_r = A_r \cos \Omega(t + 2L_r n_r/c) \quad (3)$$

where the L_x are the lengths of the fibers, n_x the index of refraction of the fibers, c the velocity of light, and the A_x are constants which take into account all the differences in gains and coupler differences, etc. These two signals are injected into a double balanced mixer. The output is the product of the two signals.

$$V_1 = B_1 A_s A_r \left[\frac{1}{2} \cos 2\Omega[t + (L_s n_s + L_r n_r)/c] + \frac{1}{2} \cos 2\Omega(L_s n_s - L_r n_r)/c \right] \quad (4)$$

which is the sum of the first term which is varying at $2\Omega t$, and a very slowly varying, (essentially DC) term. The coefficient B_1 is needed to describe the

gain of this mixing electronics. By simple electronic filtering the high frequency term is eliminated. This whole procedure is repeated with a second double balanced mixer but with the additional feature of electronically introducing a phase shift of $\pi/2$ into the reference signal. The resulting signal after filtering is

$$V_2 = \frac{B_2 A_s A_r}{2} \sin 2\Omega \left(\frac{L_s n_s - L_r n_r}{c} \right). \quad (5)$$

Assuming $B_1 = B_2$ the ratio of these signals is then

$$V_3 = \tan \left[\frac{2\Omega(L_s n_s - L_r n_r)}{c} \right] = \tan \phi \quad (6)$$

which is the required result. It is just like a heterodyne interferometer[2] except that one is dealing with the modulation frequency, which one is free to choose, $2\pi\Omega \sim 10^9$ Hz, instead of the frequency of the light, $\nu \sim 10^{15}$ Hz. When the differential length change between the sensor and reference arms have experienced sufficient change the signals will go through a fringe change. By recording both the sine and the cosine of the phase shifts the direction of change can be monitored and uniquely determined. To first approximation the change in ϕ will be due to the change in the index of refraction of the core of the sensor fiber. The expression for this change in fringes is then

$$\frac{\Delta\phi}{\Delta T} = \frac{2\Omega L_s}{2\pi c} \frac{dn_s}{dT}. \quad (7)$$

By operating at sufficiently high frequency, $\sim 10^9$ Hz, an average temperature change of 0.1°C is detectable as a $1/250$ of a fringe shift for a kilometer long sensor.

In all that has been considered up till now there has been the tacit assumption that single mode fibers are being employed. The use of multimode fibers is attractive, however, there is an upper limit to the length of multimode fiber which can be employed due to modal dispersion smearing the signals. If we assume that the measurement is destroyed when this spreading is larger than the period of the laser modulation, we estimate that an upper limit for the length of a sensor with a parabolic index profile is $\sim 2km$.

Summary

By modulating the amplitude of a laser light source at high frequency, a kind of fiber interferometer can be formed which exhibits fringe shift behavior at a wavelength commensurate with the modulation frequency, not the wavelength of the laser itself. Using long lengths of single mode fibers the average temperature, as inferred from the optical length of the fiber, can be determined to 0.1°C using simple electronics.

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Fig.1. The long fibers, sensor and reference, are shown schematically as separated, but in fact, they are bonded together.

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