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Fiber-Optic Ground-Truth Thermometer

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by

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ABSTRACT

By making a high accuracy measurement of the optical length of a long fiber optic cable, we can determine the absolute temperature averaged over its length and the temperature of a material in contact with it. We describe how to set up such a measurement and use it to determine the average temperature of the surface of the earth over a large enough area to be useful as a ground truth calibration for a satellite imaging system.

We propose 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 should be sufficient to provide a temperature determination with an accuracy of about 0.1 degree Celsius.

Figure 1 is a schematic drawing of the fiber sensor. It is presumed that an amplitude modulated laser light source is available to drive the system. This amplitude modulation could come from direct control of the driving current, acousto-optic modulation of the laser beam, or modulation of the beam by electro-optic means. The intensity of the laser light source can then 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. If stress induced birefringence acting over the long length of the fibers is a factor in degrading the response of the system these mirrors can be Faraday mirrors so the effect of this birefringence will cancel out.¹ If Faraday mirrors are required this would require that the laser light source operate at $1.3 \mu\text{m}$ or $1.5 \mu\text{m}$ as this is the region where efficient, 80%, mirrors are available. 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 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 $\beta = 5.5 \times 10^{-7}$ and $dn/dT = 1.28 \times 10^{-5}$. These values are valid over the temperature range of interest, -30 to 50°C, so because of the disparity in the magnitude of the terms 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. To develop and test the electronics this fiber could

be separate from the sensor fiber and held at constant temperature. This would however defeat the idea of bonding the two fibers together so that they experience the same mechanical stretching. The 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 $-6.3 \times 10^{-6}/^{\circ}\text{C}$. This however would be a development project as it would require learning how to dope a fiber with those elements which are employed making the FK glasses. An immediate solution is available in the specially coated fibers which have been produced by Simitomo Electric Industries Ltd.² They produce a fiber which is overcoated with a liquid crystal film which is designed to counteract the linear expansion of conventional silica fibers. If the sensor fiber were bonded to such a fiber 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. If these two signals are injected into a double balanced mixer the output will be the product of the two signals

$$V_1 = B_1 A_s A_r \cos \Omega(t + 2L_s n_s/c) \cos \Omega(t + 2L_r n_r/c). \quad (4)$$

The coefficient B_1 is needed to describe the gain of this mixing electronics. V_1 can be rewritten

$$V_1 = B_1 A_s A_r \left[\frac{1}{2} \cos 2\Omega[t + (L_s n_s + L_r n_r)/c] + \frac{1}{2} \cos 2\Omega(L_s n_s - L_r n_r)/c \right] \quad (5)$$

which is the sum of a term which is varying at $2\Omega t$ and an essentially DC term. By simple electronic filtering the high frequency term can be eliminated. This whole procedure can be 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 will be

$$V_2 = \frac{B_2 A_s A_r}{2} \sin 2\Omega \left(\frac{L_s n_s - L_r n_r}{c} \right). \quad (6)$$

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

$$V_3 = \tan \left[\frac{2\Omega(L_s n_s - L_r n_r)}{c} \right] = \tan \phi \quad (7)$$

which is the required result. It is just like a heterodyne interferometer except that we are dealing with the modulation frequency, which we are free to choose, $2\pi\Omega \sim 10^9$ Hz, instead of the frequency of the light, $\nu \sim 10^{15}$ Hz. The signals will go through fringes when the differential length change between the sensor and reference arms have experienced sufficient length 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 entirely due to the change in the index of refraction of the core of the sensor fiber. The expression for this change in fringes will then be

$$\frac{\Delta\phi}{\Delta T} = \frac{2\Omega L_s}{2\pi c} \frac{dn_s}{dT}. \quad (8)$$

By operating at sufficiently high frequency, $\sim 10^9$ Hz, an average temperature change of 0.1°C should be detectable as a $1/250$ of a fringe shift for a kilometer long sensor. The assumption the $B_1 = B_2$ can be very good if a feedback circuit is incorporated in the electronics. The high frequency terms, $\sim \cos 2\Omega$, are linearly proportional to the respective B_x so it should be straightforward to install a feedback circuit in the gains of one of the amplifiers to assure that the required condition is always satisfied.

In all that has been considered up till now there has been the tacit assumption that single mode fibers are being employed. This is true of the comments about Faraday mirrors cancelling the effects of linear birefringence as this will only be true for single mode fibers. If birefringence is not a problem then one should consider the possibility of using multimode fibers.

It would presumably be much easier to produce a multimode fiber with a specific core material, e.g., FK 51, than to make one that is single mode. In any case there has been no constraint on the wavelength of the laser used so one at 1300 nm is a natural choice as this will minimize the effects of chromatic dispersion. The modulation frequency, Ω , should be chosen as high as practical so that maximum sensitivity is achieved. There is however an upper limit to the length of multi-mode fiber which can be employed due to modal dispersion smearing the signals. The time spread due to modal dispersion can be expressed as

$$\tau = 2Ln_o\Delta/c \quad (9)$$

for step index fibers and

$$\tau = 2Ln_o\Delta^2/2c \quad (10)$$

for graded index fibers (assuming a parabolic index profile) where Δ is the index difference between the core and the cladding divided by the cladding index n_o . Typically Δ is on the order of 1%. If we assume that the measurement is destroyed if this spreading is equal to the period of the laser modulation, one can set an upper limit for the length of sensor that could be deployed using a multimode fiber. Setting $\tau = 1/2\pi\Omega$ and $2\pi\Omega = 10^9$ one gets $L = 10$ m for step index profile fibers and 2000 m for parabolic profiles. This indicates that multimode fibers with parabolic index profiles might be of interest but step index fibers are expected to be of no use.

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, could be determined to 0.1°C. If the problem of mechanical stretching can be ignored then no reference arm is needed and the phase shift of the light in the sensor arm could be compared directly to the drive frequency of the voltage which is modulating the laser light. As in interferometry the device is sensitive to changes in temperature/length so electronics should be built to track it through these fringe shifts. From the estimates stated a 25°C change would drive the system through a full fringe. As the range of interest of temperatures exceeds this value one would initially require a drive at lower frequency

to establish which fringe corresponded to the initial state. Operation at the higher frequency would then proceed and the electronics could keep track of the fringes as they go by.

References

- ¹D. A. Kersey et al., *Polarisation-insensitive Fibre Optic Michelson Interferometer*, Electronics Letters **6**, 518 (1991).
- ²T. Kakuta and S. Tanaka, *LCP Coated Optical Fiber with Zero Thermal Coefficient of Transmission Delay Time*, Simitomo Electric Industries Ltd., 1, Tayo-cho, Sakae-ku, Yokohama, 244, Japan.

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

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