

# Auto-correction method for differential attenuation in a fiber-optic distributed-temperature sensor

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A novel method to improve the accuracy of fiber-optic distributed-temperature measurements derived from Raman backscatterings is presented. This method utilizes two light sources with different wavelengths, such that the wavelength of the primary source's return anti-Stokes component overlaps with the incident wavelength of the secondary light source to cancel out the nonidentical attenuations generated by the wavelength differences between Stokes and anti-Stokes. The concept is successfully verified by the experimental results obtained from several sample fibers. The correction can be made automatically and continuously without any interruptions during the whole measurement periods. © 2008 Optical Society of America  
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Optical fiber has been used as the major tool in optical communication for decades. Recently, however, the optical fiber sensing technologies have been growing rapidly owing to its advantages that conventional electrical sensors do not have. The advantages include the capability of handling much higher bandwidth and the inherently safe operation (no generation of electric sparks). Also optical fiber is immune to electromagnetic interference. The most prominent feature is the function of true distributed parameter measurement. Utilizing this technology, the temperature or strain profiles along significant distances, for example, can be monitored over the extended lengths.

When an optical fiber is excited with an input laser light with a center wavelength  $\lambda$ , most of the lights are transmitted, but small portions of incident light are scattered backward and forward along the fiber. They are categorized into three bands, i.e., Rayleigh, Raman, and Brillouin scatterings. For the Raman distributed-temperature sensor (DTS) system, three components— $\lambda_R$  (Rayleigh),  $\lambda_s$  (Stokes), and  $\lambda_{as}$  (anti-Stokes component) are involved. The ratio of temperature-sensitive anti-Stokes intensity to temperature-insensitive Rayleigh or Stokes intensities is the basis of DTS measurement [1,2].

The critical issue of the DTS system has been the ambiguity in the backscattered intensity profile, which is the function of local attenuation affected by physical perturbations as well as of pure temperature effects. For an accurate temperature measurement, the effect of local attenuations should be eliminated at the time of deployment and afterward continuously. This is mainly due to the inherent attenuation difference in  $\lambda_s$  and  $\lambda_{as}$  owing to their wavelengths difference, which ranges from 100 to 200 nm and depends on the light source. It has been observed that fibers from different manufacturers have different attenuation profiles, and the differential attenuation is enhanced when the fiber undergoes perturbations such as bends, tensions, compressions, radiation, and chemical ingressions of hydrogen gas. The hydrogen darkening is commonly encountered in oil fields under high temperatures

and high pressures. This kind of ambiguity usually introduces the error, and it should be corrected for accurate temperature measurement. This issue can be handled with the aid of conventional optical reflectometry methods. To implement this idea to a DTS system, an extra light source (or sources), which has the same wavelength as anti-Stokes and Stokes bands is required. However, either the availability of desired light sources or the issue of the cost have been major obstacles for a practical implementation. A single source method for the issue has been proposed using Rayleigh and anti-Stokes bands [3,4] and a dual-source scheme has also been presented recently [5], but these schemes have a slower response than the proposed scheme and they are not fully automatic processes.

The double-ended (DE) configuration (i.e., both ends of sensing fiber are connected to the DTS unit to cancel out common attenuations) has been used for the automatic correction. However, there are some issues related to this scheme, which requires (1) a two-fold increase in the length of sensing fiber, the optical budget, and the measurement time; (2) an extra DTS channel; and (3) the fact that the deployment is not allowed especially where the space is limited. However, DE configuration has an advantage of redundancy in case of fiber breakage in a section of sensing fiber.

In this Letter, a simpler and fully automatic correction method is presented. The key concept of this novel scheme is utilizing one extra light source, and the wavelengths of the two sources are chosen such that the incident wavelength of the primary source coincides with the Stokes wavelength of the secondary source. This results in Stokes and anti-Stokes signals in the same band and produces the same attenuations in their returned signals, which cancel out the term of differential attenuations automatically. This allows the accurate temperature monitoring without handling of differential attenuation after deployment of the sensing fiber.

For a single-light Raman DTS system, the temperature is measured by the intensity ratio,  $R(T)$ , between anti-Stokes ( $I_{AS}$ ) and Stokes ( $I_S$ ) signals,

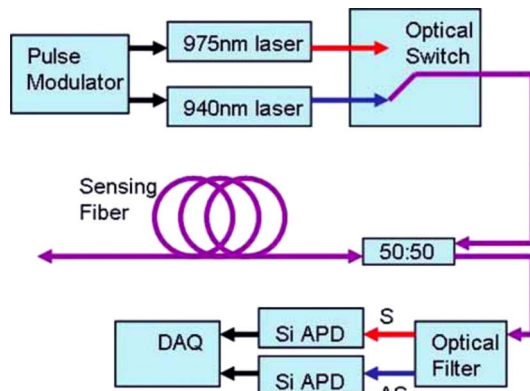


Fig. 1. (Color online) Block diagram of the dual-light auto-correction setup. DAQ, data acquisition.

which is expressed as [6]

$$R(T) = \frac{I_{AS}}{I_S} = \left( \frac{\lambda_s}{\lambda_{as}} \right)^4 \exp\left(-\frac{hcv'}{kT}\right), \quad (1)$$

where  $\lambda_s$  and  $\lambda_{as}$  are the Stokes and anti-Stokes wavelengths,  $v'$  is their wavenumber separation from the input wavelength,  $h$  is Planck's constant,  $c$  is the velocity of the light,  $k$  is Boltzmann's constant, and  $T$  is the absolute temperature.

In a typical DTS system, the input light is guided along the fiber to the measurement location, and the scattered signals travel back to a detector along the same fiber with different attenuations between  $\lambda_s$  and  $\lambda_{as}$ . This requires an addition of attenuation terms to Eq. (1) as

$$\frac{I_{AS}}{I_S} = \left( \frac{\lambda_s}{\lambda_{as}} \right)^4 \exp\left(-\frac{hcv'}{kT}\right) \frac{f(\lambda_{as}, l)}{f(\lambda_s, l)}, \quad (2)$$

where  $f(\lambda_{as}, l)$  and  $f(\lambda_s, l)$  represent the attenuation profile of anti-Stokes and Stokes backscattering.

Aside from nonlinear effects, optical fibers generally exhibit higher attenuation for shorter wavelength, and the anti-Stokes signals usually have higher attenuation than Stokes signals. As a result, the backscattered signals need to be adjusted for differential attenuation to derive accurate temperature measurement. The typical method of applying an ex-

ponential factor [7] to a Stokes signal corresponds to the difference in attenuation between anti-Stokes and Stokes. Although this works for fibers in a good physical condition, the physical perturbations, and/or radiation, chemical ingress causes the variations in differential attenuation continuously or intermittently. In such cases, applying a single-static differential-attenuation-factor correction method is no longer accurate or effective.

For the new dual-light auto-correction scheme, we may designate their input wavelengths as  $\lambda_1$  for the primary source (longer wavelength) and  $\lambda_2$  for the secondary source (shorter wavelength). The use of the Stokes signal backscattered from the secondary source in place of the Stokes signal backscattered from the primary source requires Eq. (2) to include the attenuation term contributed by forward direction and the input intensity. Considering this, Eq. (2) can be modified as following equation:

$$\frac{I_{1,AS}}{I_{2,S}} = \frac{I_1}{I_2} \left( \frac{\lambda_{2,s}}{\lambda_{1,as}} \right)^4 \exp\left(-\frac{hcv'}{kT}\right) \frac{f(\lambda_1, l) f(\lambda_{1,as}, l)}{f(\lambda_2, l) f(\lambda_{2,s}, l)}, \quad (3)$$

where  $I_1$  and  $I_2$  are input light intensities of the primary and the secondary source and  $\lambda_{1,as}$  and  $\lambda_{2,s}$  are wavelengths of anti-Stokes and the Stokes of the primary and the secondary light source, respectively.

If the wavelengths of two laser are selected such that  $\lambda_{1,as} = \lambda_2$  and  $\lambda_{2,s} = \lambda_1$ , Eq. (3) is simplified as

$$\begin{aligned} R(T) &= \frac{I_{1,AS}}{I_{2,S}} = \frac{I_1}{I_2} \left( \frac{\lambda_{2,s}}{\lambda_{1,as}} \right)^4 \exp\left(-\frac{hcv'}{kT}\right) \frac{f(\lambda_{2,s}, l) f(\lambda_{1,as}, l)}{f(\lambda_{1,as}, l) f(\lambda_{2,s}, l)} \\ &= \frac{I_1}{I_2} \left( \frac{\lambda_1}{\lambda_2} \right)^4 \exp\left(-\frac{hcv'}{kT}\right), \end{aligned} \quad (4)$$

Consequently, the attenuation profiles  $f(\lambda_1, l)$  and  $f(\lambda_2, l)$  are totally canceled by the attenuation profiles of two chosen incident lights, and the equation becomes free of an attenuation term. This enables the temperature measurement without a handling of the differential attenuation.

To calculate the absolute temperature, the reference fiber coil located in a DTS unit is maintained at

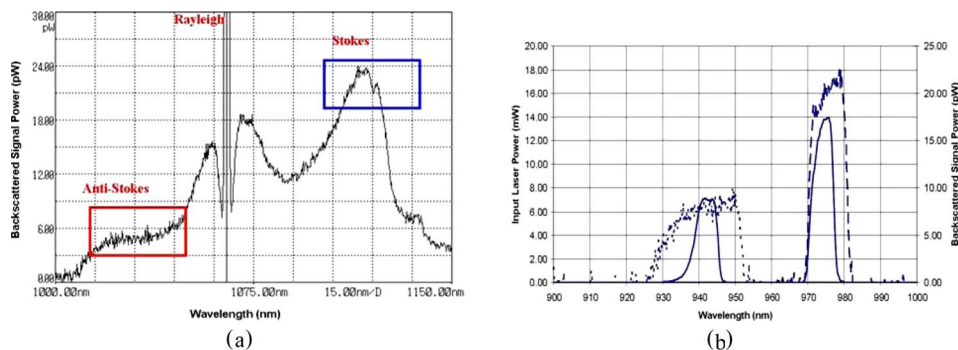


Fig. 2. (Color online) Backscattered spectra of a conventional 1064 nm (a) single-source system [4] and the (b) dual-source auto-correction system. In (b), two input lights centered around 975 nm and 940 nm (solid curve), the backscattered signals whose anti-Stokes signal at around 940 nm (dotted curve) generated by 975 nm input light, and Stokes signal at around 975 nm (dashed curve) generated by 940 nm input light are displayed.

a known temperature  $\theta$ . Then unknown temperature  $T$  along the arbitrary section of the sensing fiber can be calculated by rearranging the above equation as

$$T = \left[ \frac{1}{\theta} - \frac{k}{hcv'} \ln \left( \frac{R(T)}{R(\theta)} \right) \right]^{-1}, \quad (5)$$

where  $R(T)$  and  $R(\theta)$  are the backscattering ratios measured at the arbitrary section of the sensing fiber and at the reference fiber coil, respectively. The intensity terms  $I_1, I_2$  in Eq. (4) are integrated into  $R(T)$  and  $R(\theta)$  in Eq. (5).

A block diagram shown in Fig. 1 illustrates the overall architecture of the dual-light auto-correction system. Two laser sources of 975 nm and 940 nm are operated in pulse mode and selected alternatively using an optical switch, and the scattered signals are collected in sequence by a Si avalanche photodiode (APD). The anti-Stokes signal is collected with a 975 nm laser connection, while the Stokes signal is collected with a 940 nm laser. Backscattered spectra of the single source [5] and the proposed dual-source system are plotted in Fig. 2.

Four different multimode fibers are used as the test probes: three fibers in normal condition from different manufacturers and one fiber that is hydrogen darkened in an oil well (all in 50/125/250 GI MM fibers: OFS, 5 km; Spectran, 4.5 km; Corning, 2 km; and hydrogen darkened, 800 m). All the fiber spools are kept under room temperature and a 30 s optical time-domain reflectometry (OTDR) trace and a 2 min temperature trace are taken with each fiber operated by regular DTS and the self-correction mode consecutively. Figure 3 shows the comparison in OTDR traces produced by the fibers, which clearly show different attenuations from fiber to fiber, and it also shows locally generated nonlinear attenuation in the darkened fiber. Then all probe fibers are connected consecutively, and the temperature traces are derived without taking any actions to correct the differential attenuations. The resulting temperature profiles produced by normal and the auto-correction mode are plotted in Fig. 4. While the normal operations show calculation errors among different fibers

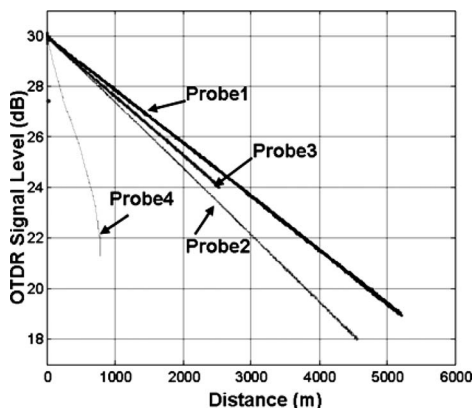


Fig. 3. OTDR traces of test fibers. Probe 1, OFS; probe 2, Spectran; probe 3: Corning; probe 4, hydrogen darkened. All probe fibers are 50/125/250 GI MM fibers with NA  $\sim 0.2$ .

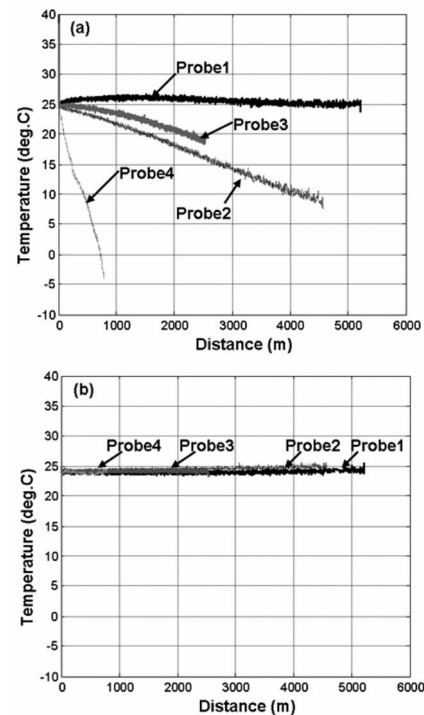


Fig. 4. Comparison of temperature traces between (a) conventional DTS modes and (b) dual-source auto-correction mode.

[in Fig. 4(a)] due to differential attenuation, the temperature traces measured by the dual-light auto-correction mode display correct temperature profiles [in Fig. 4(b)] for all fibers.

A novel correction method based on the self-cancellation of differential attenuations utilizing dual-light source is introduced for a Raman DTS application. This method can provide the accurate temperature calculation by eliminating the ambiguity (between the effects of attenuation and temperature) in a backscattered profile, which varies continuously with time in real situations. The concept was verified by the experimental results of several sample fibers, which have nonidentical attenuation characteristics in a whole length or in a section. As clearly shown in the result, the proposed method can calculate accurate temperature profiles automatically and continuously in DTS applications.

This idea of this paper is patent pending.

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