Temperature sensitivity enhancement in a standard optical fiber with double coatings at low temperature

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ABSTRACT

The thermomechanical behavior of a standard optical fiber with double coating is theoretically analyzed at room temperature and ~ 220 K. As the primary coating becomes stiffer at low temperature, the impact of the thermal expansion of the coatings is no longer negligible and contributes to the thermal response of the fiber sensor. The temperature sensitivity enhancement is validated by distributed fiber sensors based on Brillouin scattering and coherent Rayleigh scattering at 220 K; the experimental results agree well with the theoretical analysis.

Keywords: Fiber optics sensors, distributed fiber sensing, Brillouin scattering, Rayleigh scattering.

1. INTRODUCTION

Distributed fiber sensors (DFS) based on various scattering processes have been proposed over the past 30 years and are now commercialized in different fields[1]. Raman-based sensors are able to retrieve the temperature distribution based on the optical power ratio between anti-Stokes and Stokes/Rayleigh waves. For Brillouin sensing, the Brillouin frequency is measured along the fiber to acquire the environmental information. For DFS based on coherent Rayleigh scattering the cross-correlation spectrum of the Rayleigh traces will shift due to the environmental variations. While a Raman sensor is sensitive only to temperature, DFS based on Brillouin and Rayleigh scatterings can measure both temperature and strain; this feature broadens their application area but introduces cross-sensitivity problems. It is interesting to notice that the thermal response of all the DFS techniques becomes weak in cryogenic environments[2] due to different reasons. On the one hand, spontaneous Raman scattering is a thermally-activated process and the anti-Stokes Raman component vanishes at low temperature, while the relation between Brillouin frequency shift and temperature becomes non-monotonic under cryogenic conditions. On the other hand, the thermal response of the Rayleigh-based DFS decreases at low temperature because of a weaker thermo-optic effect. The cross-sensitivity between temperature and strain can however be used as an advantage to improve the temperature sensitivity, which is sustained by the thermal expansion of the coatings, especially in cryogenic environments. The ambient temperature variations cause expansion or shrinkage of the fiber coating, resulting in a thermally-induced strain in the fiber glass, so that the thermal response can be enhanced. This method has been widely used to improve the sensitivity of fiber Bragg gratings (FBG), and is supposed to have the same effect on distributed sensing techniques, except for Raman sensing, which is strain-insensitive. So far, most of the research has focused on selecting special coatings, while standard coatings have been widely overlooked, though they actually show a good thermal expansion and adhesion to the fiber.

In this paper, the thermomechanical behavior of a standard single-mode fiber (SMF) with ordinary telecom-grade acrylate coating is theoretically analyzed, and the results show a non-negligible thermally-induced strain from ~ 220 K and downwards, around the glass transition of the primary soft coating. A higher temperature sensitivity is then expected under this thermal condition for the relevant distributed sensing techniques. Experiments based on Brillouin and coherent Rayleigh sensing confirm this sensitivity enhancement and show a good agreement with the theoretical analysis.

2. THEORY

Nowadays, a standard SMF always presents a dual-layer coating to mechanically protect the fiber, following the cross-section depicted in Fig. 1. The primary soft coating (inner coating), adhering to the fiber glass, is designed to reduce the attenuation caused by microbending, while the secondary harder coating (outer coating) provides the mechanical protection to the fiber[3]. Visco-elastic materials are typically used for primary coating, which are very soft at room temperature. Thus the thermal expansion of the dual-layer coating has nearly no impact on the fiber. However, the

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polymers making the primary coating exhibits a glass behavior at low temperatures, and its corresponding Young's modulus increases as the temperature drops from ~ 273 K to ~ 220 K, to then remain constant and independent on temperature[3]. This introduces extra microbending loss to the fiber and, more importantly, causes non-negligible strain in the fiber when the temperature changes, thus affecting the overall thermal response of distributed fiber sensors, such as Rayleigh and Brillouin-based sensors.

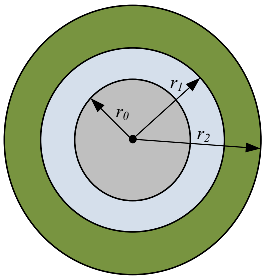

Figure 1. Cross-section of a standard single-mode fiber with double coatings.

The model presented hereafter is derived from the original work of Lagakos *et al*[4], later adapted to the situation under question by Gu *et al*[5], and is simply repeated here for clarity. The optical fiber, primary and secondary layers show different responses to a temperature change ΔT, and the thermally-induced stresses in radial, tangential, axial dimensions [σ^i_r, σ^i_θ, σ^i_z] of each layer can be described by the so-called Lamé solutions[4,5]:

$$\begin{bmatrix}\sigma_r^i\\ \sigma_\theta^i\\ \sigma_z^i\end{bmatrix}=\begin{bmatrix}\lambda_i+2\mu_i & \lambda_i & \lambda_i\\ \lambda_i & \lambda_i+2\mu_i & \lambda_i\\ \lambda_i & \lambda_i & \lambda_i+2\mu_i\end{bmatrix}\begin{bmatrix}\varepsilon_r^i-\alpha_i\Delta T\\ \varepsilon_\theta^i-\alpha_i\Delta T\\ \varepsilon_z^i-\alpha_i\Delta T\end{bmatrix}, \tag{1}$$

where i represents the layer index, λ_i and μ_i are the Lamé parameters, written as:

$$\lambda_i=\eta_i E_i\Big/\big[(1+\eta_i)(1-2\eta_i)\big],\quad \mu_i=E_i\Big/\big[2(1+\eta_i)\big], \tag{2}$$

with the corresponding Poisson's ratio η_i, Young's modulus E_i and linear thermal expansion coefficient α_i for each layer; and [ε^i_r, ε^i_θ, ε^i_z] represent the strain in radial, tangential, axial dimension ,expressed as

$$\varepsilon_r^i=U_i+V_i\big/r^2,\ \varepsilon_\theta^i=U_i-V_i\big/r^2,\ \varepsilon_z^i=W_i, \tag{3}$$

where U_i, V_i and W_i are constants that can be determined by the boundary conditions:

$$\begin{aligned}&\sigma_r^i(r_i)=\sigma_r^{i+1}(r_i)\quad i=0,1,\quad \mu_r^i(r_i)=\mu_r^{i+1}(r_i)\quad i=0,1\\ &\sigma_r^2(r_2)=0,\quad \sum_{i=0}^{2}\sigma_z^i\cdot A_i=0,\quad \varepsilon_z^0=\varepsilon_z^1=\varepsilon_z^2=\varepsilon_z\end{aligned}, \tag{4}$$

where r_i and A_i are the radius and the cross-section area of the i^{th} layer, respectively. As the optical fiber is axisymmetric, $\varepsilon^0_r=\varepsilon^0_\theta$, this leads to $V_0 = 0$.

Table 1. Relevant physical parameters of a standard single-mode fiber and its dual-layer acrylate coating.

r_0	r_1	r_2	η_0	η_1	η_2	E_0	E_2	α_2
62.5 μm	95 μm	125 μm	0.17	0.4995	0.452	72 GPa	1 GPa	7.93×10^{-5} K^{-1}

According to literature, the thermal expansion coefficient of fused silica SRM 739 is 0.45×10^{-6} K^{-1} at room temperature and 0.21×10^{-6} K^{-1} when T = 220 K[6]. For the primary coating, the thermal expansion coefficient and Young's modulus are measured to be 2.11×10^{-4} K^{-1} and 1 MPa at room temperature, and 1.18×10^{-4} K^{-1} and 2.6 GPa at the temperature of the glass transition point[3,7]. The other parameters used in the model are assumed temperature-independent and are listed in Table 1. Consequently, the thermally-induced strain under these different conditions can be calculated by inserting the corresponding parameters into Eqs. (1)-(4). Particularly, the strains in axial and radial directions are of great importance because they have been proven to affect the fiber sensing response. At room temperature, ε_z and ε^0_r are calculated to be 1.78 με and −0.09 με per 1 K change, respectively. The small thermally-induced strain in the glass fiber is due to the softness of the primary coating, which inhibits the transfer of the thermal expansion from both coatings to the fiber. However, as a result of the large increase of the Young's modulus in the primary coating at ~ 220 K, the strains increase to 7.41 με and −0.46 με in the axial and radial directions, respectively. The generated strains may therefore sustain the thermal response of the fiber. Actually, such a sensitivity enhancement has been observed by COTDR sensing in this temperature range[2].

For Brillouin sensing, temperature and strain change the acoustic velocity inside the fiber, which in turn generate a Brillouin frequency shift (BFS). According to the above analysis, the BFS change Δf_B may not only be induced by the temperature variation ΔT, but also by the extra strain:

$$\Delta f_B = S_T^B \cdot \Delta T + S_{\varepsilon,z}^B \cdot \varepsilon_z + S_{\varepsilon,r}^B \cdot \varepsilon_r^0 , \tag{5}$$

where S^{B}_{T}, $S^{B}_{\varepsilon,\mathrm{r}}$ and $S^{B}_{\varepsilon,\mathrm{z}}$ represent the temperature, radial and axial strains sensitivities of the Brillouin sensor, respectively. The temperature and axial strain sensitivities of a Brillouin sensor are classically taken as ~ 1 MHz/K and 0.05 MHz/με, respectively, at room temperature for a standard SMF, while the radial strain sensitivity $S_{\varepsilon,r}$ is reported to be 0.029 MHz/με[8]. The axial strain sensitivity demonstrates no large variation in the temperature range from 300 K to 200 K[9] and the radial sensitivity $S_{\varepsilon,r}$ is assumed to have the same behavior. Based on the analysis above, the axial strain will contribute to the thermal response of the fiber sensor, even though the radial strain counteracts this effect a little bit. With the calculated radial and axial strains, the actual sensitivity $S^{B}_{T}{}' = \Delta f_B/\Delta T$ is enhanced by 0.09 MHz/K and 0.36 MHz/K when the temperature is 300 K and 220 K, respectively. As expected, the thermal expansion of the coating has almost no influence on S_T at room temperature because the soft primary coating isolates the fiber from the thermally-induced strain. However, since the primary coating turns stiff at ~ 220 K, it can transfer the thermal expansion from to coating to the fiber, resulting in an enhanced temperature sensitivity.

In a coherent optical time-domain reflectometry (COTDR), the random interference leads to a speckling aspect of the obtained Rayleigh trace, which is reproducible and restorable. The whole process can be locally modelled as a long and weak FBG with random modulation and period. Coherent Rayleigh sensing therefore exhibits the same sensitivity as a FBG sensor. The Bragg wavelength change $\Delta\lambda_B$ due to temperature and strain variations is expressed as[10]:

$$\Delta\lambda_B = \lambda_B \left(\left\{ 1 - n^2/2 \cdot \left[P_{12} - \eta_0 \left(P_{11} + P_{12} \right) \right] \right\} \varepsilon_z + \left(\alpha_0 + \frac{1}{n}\frac{dn}{dT} \right) \Delta T \right) = \lambda_B \left(S_\varepsilon^R \varepsilon_z + S_T^R \Delta T \right), \tag{6}$$

where λ_B is the Bragg wavelength of the grating, n is the refractive index of the fiber, P_{11} and P_{12} are Pockel's coefficients of the stress-optic tensor, dn/dT represents the thermo-optic coefficient, S^{R}_{T} and S^{R}_{ε} are the corresponding temperature and strain sensitivities. The factor $\{1-n/2[P_{12}-\eta_0(P_{11}+P_{12})]\}$ has a value of ~ 0.22 and the thermo-optic coefficient can be obtained from the Sellmeier model in different temperature environments[11]. It has to be pointed out that, Eq. (6) not only considers the axial strain ε_z, but also radial strain ε_r through the Poisson's ratio. Since the coherent Rayleigh sensor demonstrates the same working principle as a FBG, Eq. (6) can also be used to calculate the frequency shift of the cross-correlation spectrum between the Rayleigh traces so that the modified temperature sensitivity $S^{R}_{\mathrm{T}}{}'$ of a COTDR sensor can be obtained accordingly.

According to Eq. (6), the temperature sensitivity of a COTDR sensor is calculated to be −1.22 GHz/K at room temperature and −0.98 GHz/K at 227 K. The strain sensitivity is measured to be −150 MHz/με and is experimentally confirmed to be temperature-independent[12]. Considering the thermally-induced strain, the temperature sensitivity is enhanced to −1.48 GHz/K and −2.02 GHz/K when the ambient temperature is 300 K and 227 K, respectively.

3. EXPERIMENTAL RESULTS

To confirm this theoretical analysis, a Brillouin optical time domain analyzer (BOTDA) and a COTDR systems are set up to measure a 14-m long standard SMF with a dual-layer coating. Due to the short length of the fiber, the spatial resolution is chosen to be 1.7 m. The sensing fiber is loosely coiled in a copper box with a diameter of 9 cm to avoid temperature gradients in the fiber. A Pt-1000 thermal probe is placed in the middle of the box to monitor and calibrate the temperature. For room temperature measurements, the box is placed in a thermal bath filled with water which can be controlled with a 0.1 K accuracy. Smaller temperature variations can be even achieved by the natural thermal exchange between the water and the ambient air. Low temperature measurements are realized using a container filled with liquid nitrogen, and temperatures setting over a large range can be achieved by adjusting the box elevation above the nitrogen.

The experimental results obtained by the different sensing techniques are shown in Fig. 2. The BFS obtained by BOTDA and the frequency shift measured by COTDR demonstrate a good linear relation with temperature under distinct thermal environments. According to Fig. 2(a), the sensitivity of a Brillouin sensor is found to be 1.1 MHz/K at room temperature, which is very close to the theoretically predicted result. However, a steeper slope between BFS and temperature is observed at ~ 220 K as a result of the larger thermally-induced strain from the coating. Thus a higher sensitivity of 1.5 MHz/K is obtained, which is fairly close to the prediction made in the previous section (less than 10% deviation).

A good agreement is also observed for coherent Rayleigh sensing at room temperature: Fig. 2(b) shows a temperature sensitivity of −1.46 GHz/K, which is very close to the theoretical prediction of −1.48 GHz/K. Fig. 2(c) indicates the thermal response enhancement of the COTDR at ~ 227 K due to the thermally-induced strain. In this case, the measured sensitivity is −2.29 GHz/K, some 12% higher than the theoretical prediction. Generally speaking, the experimental results match well the theoretical prediction at room temperature, but small deviations are observed at low temperature in both Brillouin and coherent Rayleigh sensing, which is probably due to the inaccurate knowledge of the actual coating parameters used for the analysis.

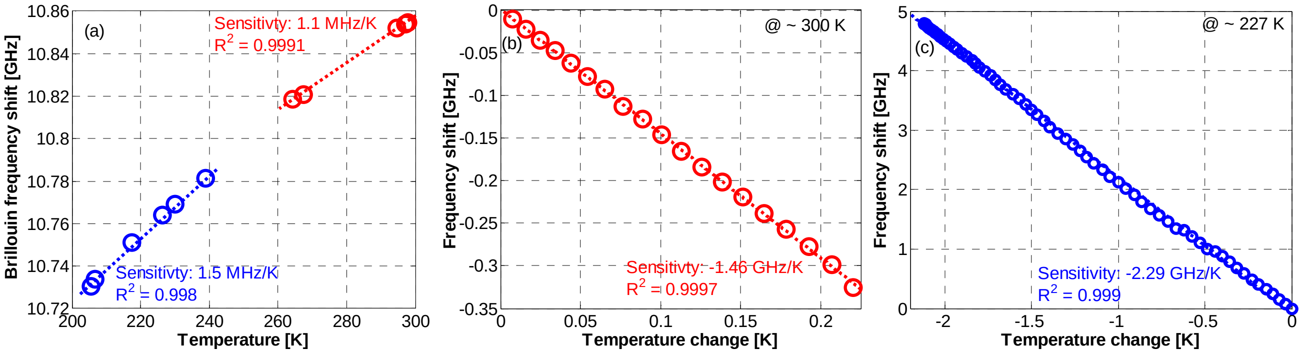

Figure 2. Measured (a) Brillouin frequency shift and cross-correlation spectrum shift in Rayleigh sensing at (b) 300 K and (c) 227 K as a function of temperature.

4. CONCLUSIONS

In this paper the temperature-dependent strain induced by the coating and its contribution to the overall thermal response of distributed fiber sensors have been studied and theoretically predicted at both ambient and cryogenic temperatures using a known thermomechanical model for a standard dual-layer coating around a SMF. The theoretical description and experimental results show that the temperature sensitivity of both Brillouin and coherent Rayleigh distributed sensors is enhanced at ~ 220 K, due to a glass transition occurring in the soft acrylate coating. Results based on the presented thermomechanical model also illustrate that the thermal response of the sensor depends on eventual local variations of the coating parameters. This way, distributed sensing techniques can also offer the possibility to evaluate the longitudinal non-uniformity of the fiber coating when placed in a container at low temperatures.

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