# Improved Calibration Method for Raman Distributed Temperature Sensor

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**Abstract**— We propose an improved calibration technique that simultaneously and simply determines an accurate Raman shift wave number and the differential loss of the sensing fiber in order to take highly accurate temperature measurements over a wide range of temperatures.

## 1. INTRODUCTION

The Raman Distributed Temperature Sensor (DTS) has recently been successfully adopted in the oil & gas fields, site safety, assets monitoring, and facilities maintenance [1]. According to the DTS principle, local temperature $T_s$ can be determined by knowing the temperature $T_0$ in the temperature reference fiber, the ratios of the anti-Stokes and Stokes intensities, and the Raman shift wave number of the sensing fiber. However, the optical device characteristics such as the light source (wavelength), optical filter, photodiode, reference thermometer (uncertainty), optical switch, optical connector, splice, and sensing fiber under actual conditions may affect the temperature measurement accuracy. We already reported on a novel calibration technique to determine the accurate Raman shift wave number of the sensing fiber (fiber having the differential characteristics from a built-in fiber) to perform highly accurate temperature measurements over a wide range of temperatures although the conventional linear approximation method is only effective over a small temperature range [2]. However, the deferential loss (attenuation difference at the Stokes and anti-Stokes wavelengths) needs to be corrected beforehand.

We propose an improved calibration method in this paper that automatically, simultaneously and simply calculates the calibration parameters such as the Raman shift wave number and the differential loss of the sensing fiber.

## 2. PRINCIPLE [3]

Raman scattering occurs due to the interaction between the light and optical phonons present in a continuum medium. In such an interaction, the medium can lose energy (anti-Stokes) or acquire energy (Stokes) by means of scattering. The molecular vibrational states — the phonons — obey the Bose-Einstein statistics distribution, which is a function of the temperature. The Stokes and anti-Stokes intensities $(I_{st}, I_{as})$ are given by Equation (1)

$$I_{st} \propto (\nu_0 - \Delta\nu)^4 (1 + n(\Delta\nu, T)) \qquad I_{as} \propto (\nu_0 + \Delta\nu)^4 n(\Delta\nu, T), \tag{1}$$

where $\nu_0$ is the wave number of incident light, $\Delta\nu$ is the Raman shift wave number, and $n$ is the number of photons as expressed by Equation (2)

$$n(\Delta\nu, T) = \frac{1}{\exp(hc\Delta\nu/kT) - 1}, \tag{2}$$

where $h$ is the Plank's constant, $k$ is the Boltzmann's constant, and $c$ is the speed of light. The Raman shift wave number is determined by the molecular structure of the medium. The Raman spectrum has a peak at around 400–500 $\mathrm{cm}^{-1}$ in the silica optical fiber. The ratio of the anti-Stokes to Stokes intensities can be expressed as

$$R(T) = I_{as}/I_{st} = \frac{(\nu_0 + \Delta\nu)^4}{(\nu_0 - \Delta\nu)^4} \exp\left(-\frac{hc\Delta\nu}{kT}\right) \tag{3}$$

Using the temperature in the built-in fiber (for temperature reference) $T_0$,

$$R(T)/R(T_0) = \exp\left(-\frac{hc\Delta\nu}{kT}\right) / \exp\left(-\frac{hc\Delta\nu}{kT_0}\right). \tag{4}$$

Equation (5) is obtained by taking the logarithm of both sides

$$T = \frac{hc\Delta\nu}{k}\left[\frac{1}{-\ln R(T) + \ln R(T_0) + \frac{hc\Delta\nu}{k}\frac{1}{T_0}}\right]. \tag{5}$$

Local temperature $T_s$ can be determined by priorly knowing $T_0$, $R(T_0)$, $R(T)$, and $\Delta\nu$. We assume here that the deferential loss (attenuation difference at the Stokes and anti-Stokes wavelengths) is corrected beforehand and the sensing fiber has the same characteristics as the built-in fiber. Moreover, we assume that the optical connector does not experience differential loss.

## 3. HIGHLY ACCURATE MEASUREMENT USING HIGHLY ACCURATE $\Delta\nu$ [2]

Let us connect the sensing fiber (fiber having differential characteristics from built-in fiber) to the interrogator (Figure 1). The measured temperature $T'_s$ at the point of scattering can be calculated by measuring $R_r(T_0)$ and $R(T_s)$. Here, $T_s$ is the true temperature and the Raman shift wave number of the sensing fiber is set to the same value as the built-in fiber. $R_r(T_0)$ and $R(T_s)$ are the ratios of the anti-Stokes to Stokes intensities of the built-in fiber and the measured position.

$$T'_s = \frac{hc\Delta\nu_r}{k}\left[\frac{1}{-\ln R(T_s) + \ln R_r(T_0) + \frac{hc\Delta\nu_r}{k}\frac{1}{T_0}}\right]. \tag{6}$$

The actually measured $R(T_s)$ can be expressed by using Equation (7)

$$R(T_s) = \Delta L_{conn}\frac{(\nu_0 + \Delta\nu_s)^4}{(\nu_0 - \Delta\nu_s)^4}\exp\left(-\frac{hc\Delta\nu_s}{kT_s}\right), \tag{7}$$

where $\Delta L_{conn}$ is the differential loss of the connecter and $\Delta\nu_s$ is the Raman shift wave number of the sensing fiber. Then $R_r(T_0)$ is given by using Equation (8)

$$R_r(T_0) = \frac{(\nu_0 + \Delta\nu_r)^4}{(\nu_0 - \Delta\nu_r)^4}\exp\left(-\frac{hc\Delta\nu_r}{kT_0}\right), \tag{8}$$

where $\Delta\nu_r$ is the Raman shift wave number and $T_0$ is the absolute temperature of the built-in fiber.

When the temperature is measured at the scattering position, it is calculated by using Equation (6) and the true temperatures are set to $T'_1$ and $T_1$. Then, for another temperature measurement, the temperature calculated by using Equation (6) and the true temperature are set to $T'_2$ and $T_2$ as well. Next, a highly accurate Raman shift wave number of the sensing fiber can be determined by using Equation (9)

$$\Delta\nu_s = \Delta\nu_r\frac{T'_1 - T'_2}{T'_1T'_2}\frac{T_1 \cdot T_2}{T_1 - T_2}. \tag{9}$$

Then, the highly accurate temperature can be determined using Equation (10)

$$T_s = \Delta\nu_s\frac{1}{\frac{\Delta\nu_r}{T'_s} - \frac{\Delta\nu_r}{T'_1} + \frac{\Delta\nu_s}{T_1}}. \tag{10}$$

On the basis of the above examination, we evaluated the temperature measurement accuracy using a highly accurate $\Delta\nu_s$. First, we determined the highly accurate Raman shift wave number $\Delta\nu_s$ of the sensing fiber by using Equation (9) at 80°C ($T_1$) and 300°C ($T_2$). The measured temperature difference between the DTS and the reference thermometer was within $+/-0.2$°C in the wide temperature range from 80–300°C (Figure 2).

## 4. IMPROVED CALIBRATION METHOD

As mentioned above, a highly accurate $\Delta\nu_s$ is very important for taking highly accurate temperature measurements. However, we assume that the deferential loss (attenuation difference at the Stokes and anti-Stokes wavelength) is corrected beforehand. There are several methods for determining the differential loss of the sensing fiber. 1) Differential loss $\Delta\alpha_s$ (dB/km) can be determined by calculating the temperature so that it matches the temperature at two different positions where

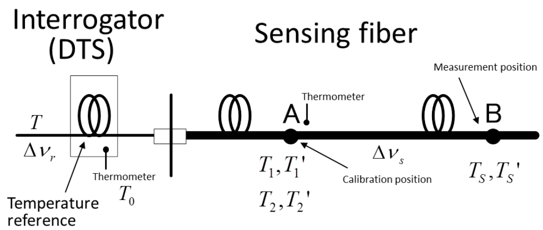



Figure 1: Measurement set-up.

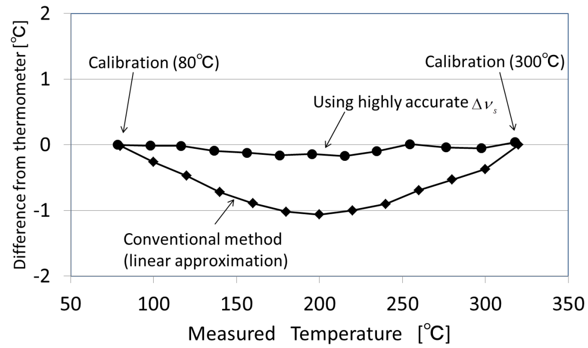



Figure 2: Evaluated results using highly accurate $\Delta\nu_s$.

the temperatures are set to the same level Since the calculated temperature has various parameters and there is a complicated relation between all of them, the temperatures from two positions need to be the same. 2) At a position in the near end where the differential loss is neglected, the highly accurate $\Delta\nu_s$ can be determined by using the above mentioned method. After that, the differential loss can be determined by calculating the temperature at the far end so that it is the same as the true temperature. However, every method has a complicated step, and needs much more time and labor to complete it.

We propose an improved method here for simultaneously and simply determining a highly accurate $\Delta\nu_s$ and $\Delta\alpha_s$ using the temperatures at three positions.

In the measurement setup shown in Figure 1, Equation (6) is rewritten as Equation (10) by taking the differential loss into consideration.

$$T'_n = \frac{hc\Delta\nu_r}{k}\left[\frac{1}{-\ln R(T_n, L) - \ln\left(10^{\frac{\Delta\alpha_s L}{5}}\right) + \ln R_r(T_0) + \frac{hc\Delta\nu_r}{k}\frac{1}{T_0}}\right], \tag{11}$$

where $\Delta\alpha_s$ (dB/km) is the differential loss of the sensing fiber and $L$ (km) is the distance from the interrogator to the measured position. The distance of the three measured positions are $L_1$, $L_2$, and $L_3$ and the true temperatures at the three positions are $T_1$, $T_2$, and $T_3$. Using Equations (9) and (11), $\Delta\nu_s$ and $\Delta\alpha_s$ are calculated as

$$\begin{aligned}\Delta\nu_s &= \Delta\nu_r\frac{T'_1 - T'_2}{T'_1T'_2}\frac{T_1T_2}{T_1 - T_2} \\ &= \frac{T_1T_2}{T_2 - T_1}\frac{k}{hc}\ln\frac{R(T_2, L_2)}{R(T_1, L_1)}10^{\frac{\Delta\alpha_s(L_2-L_1)}{5}} = \frac{T_1T_3}{T_3 - T_1}\frac{k}{hc}\ln\frac{R(T_3, L_3)}{R(T_1, L_1)}10^{\frac{\Delta\alpha_s(L_3-L_1))}{5}}\end{aligned} \tag{12}$$

and

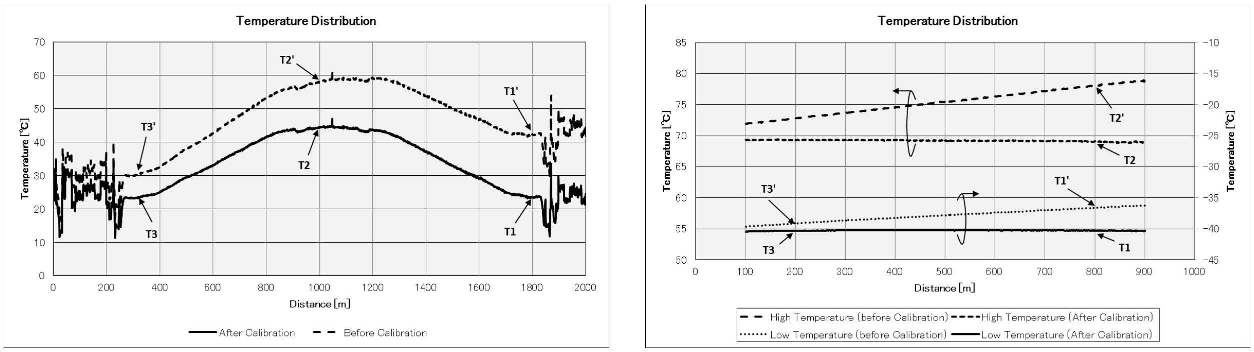
$$\Delta\alpha_s = \frac{5\left(\ln\frac{R(T_1,L_1)}{R(T_3,L_3)} - \frac{T_1-T_3}{T_3}\frac{T_2}{T_2-T_1}\ln\frac{R(T_2,L_2)}{R(T_1,L_1)}\right)}{\ln(10)\left((L_3 - L_1) + \left(\frac{T_1-T_3}{T_3}\right)\left(\frac{T_2}{T_2-T_1}\right)(L_2 - L_1)\right)} \tag{13}$$

## 5. EXPERIMENT

We evaluated two cases based on the above study.

The temperature measurement was conducted on the installed and turned up in the oil well (Figure 3(a)). The initial values used in Equation (11) are $\Delta\nu_s = \Delta\nu_r = 386\,\text{cm}^{-1}$, $\Delta\alpha_s = 0.28\,\text{dB/km}$. Using Equations (10), (12) and (13) for three temperatures at three positions, $\Delta\nu_s = 379\,\text{cm}^{-1}$ and $\Delta\alpha_s = 0.18\,\text{dB/km}$ were found to be highly accurate. The temperature distribution agreed well with the actual temperature.

Figure 3(b) shows a calibration example using two positions and three temperatures. The initial values used in Equation (11) were $\Delta\nu_s = \Delta\nu_r = 392\,\text{cm}^{-1}$, $\Delta\alpha_s = 0.30\,\text{dB/km}$. $\Delta\nu_s = 394\,\text{cm}^{-1}$ and $\Delta\alpha_s = 0.21\,\text{dB/km}$ were calculated using Equations (10), (12) and (13) for three temperatures at two positions. Figure 3(b) indicates there is a good agreement in both the high and low temperature ranges after calibration.




(a) (b)

Figure 3: (a) For three positions and three temperatures and (b) two positions and three temperatures for calibration.

## 6. CONCLUSION

We proposed an improved calibration method that automatically simultaneously and simply calculates the calibration parameters such as the Raman shift wave number and the differential loss of the sensing fiber. The demonstrated results agreed well using the proposed method.

## REFERENCES

1. Hartog, A. H., "Raman sensors and their applications," *Proc. 22nd International Conf. on Optical Fiber Sensors, SPIE*, 8421, 2012.
2. Fukuzawa, T., H. Shida, K. Oishi, N. Takeuchi, and S. Adachi, "Performance improvements of raman distributed temperature sensor," *Photonic Sensors*, Vol. 3, No. 4, 314–319, 2013.
3. Dakin, J. P., D. J. Pratt, G. W. Bibby, and J. N. Ross, "Distributed optical fiber raman temperature sensor using a semiconductor light source and detector," *Electron. Lett.*, Vol. 21, 569–570, 1985.