The study of radiation effect on Raman Distributed optical fiber Temperature Sensor

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Abstract. The rapid development of big data and artificial intelligence technology is inseparable from the acquisition of massive basic data, and the data is acquired by sensors. The Raman Distributed optical fiber Temperature Sensor (RDTS) is a kind of sensor with many advantages, such as: anti-electromagnetic interference, intrinsic safety, small size, water and high temperature resistance. It has been applied in many fields for fast and continuous temperature measurement. However, due to the rapid attenuation of transmitted light and the temperature error in radiated environment, it has not been applied in nuclear field. Therefore, in order to improve the temperature accuracy of RDTS in radiated environment and provide basic data for advanced control. This paper studies the radiation effect on RDTS. Analyzes the radiation damage mechanism and radiation damage influencing factors of RDTS. Proposes measures to improve the anti-radiation performance and provides four useful calibration method for temperature error. Among them, two calibration methods have been proved right by experiments.

1. Introduction
At present, Sensors provide a large amount of basic data for the rapid development of big data and artificial intelligence technology. RDTS is a kind of sensor that can measure distributed temperature quickly and continuously. RDTS has all the advantages of optical fiber sensors, such as: no electricity, anti-electromagnetic interference, intrinsic safety, small diameter, light weight, water and high temperature resistance [1]. In addition, RDTS is unique in that it utilizes the fiber itself as both a sensing unit and a signal transmission medium. Due to the low transmission loss of optical signals along fiber, the span of optical fibers can reach several tens of kilometers. Therefore, an optical fiber can cover a monitoring range of several tens of kilometers, which is equivalent to thousands of ordinary sensors [2,3]. It has been used for temperature measurement in the field of electric power, petroleum, chemicals, bridges, tunnels, and large storage tanks that store flammable, explosive, toxic, and harmful gases.

However, compared with other fields, the most prominent feature of nuclear field is nuclear radiation, and nearly every equipment used in nuclear power plants need to consider radiation problems. Literatures show that the transmitted light in optical fiber attenuates greatly under radiated environment, which causes the light intensity to decrease, and finally causes a large temperature error or even instrument failure [4]. Therefore, in order to improve the temperature accuracy of RDTS in
radiated environment, this paper analyzes the mechanism of radiation damage, the influencing factors of radiation damage, the measures to improve the anti-radiation performance and the calibration method for RDTS in nuclear fields.

2. The principle of RDTS

When light travels through an optical fiber, three scattering occurs, namely Rayleigh scattering, Brillouin scattering and Raman scattering. Rayleigh scattering is insensitive to temperature. The Brillouin scattering is sensitive to both temperature and stress, which is easily interfered by external factors. Raman scattering is only related to temperature and the scattering signal is easy to acquire and analyze [5].

To achieve distributed temperature measurement, it is first necessary to ensure that the temperature modulates the transmitted light in the fiber and converts the change in temperature into a change in optical signal. Secondly, it is necessary to locate the temperature in order to obtain the spatial distribution of temperature. RDTS is based on Raman scattering effect and Optical Time Domain Reflectometer (OTDR), the Raman scattering effect realizes temperature measurement, and the OTDR technology realizes temperature positioning [6].

Figure 1 is the structure of RDTS. The light emitted by light source enters sensing fiber through wavelength division multiplexer. The light generates Raman scattering throughout the fiber. Then the temperature-adjusted backward Raman scattered light enters photodetector through wavelength division multiplexer, then the temperature information is extracted.

![Figure 1. The structure of RDTS.](image)

The backward Raman scattered light includes two different frequencies of light, the higher frequency is anti-Stokes light, which is sensitive to temperature changes, the lower frequency is Stokes light, which is insensitive to temperature. In order to eliminate the influence of source power fluctuation, fiber bending and other factors, the ratio of the two light intensities is usually calculated to obtain the temperature.

In mild environment, the attenuation is not considered, therefore, the ratio of anti-Stokes intensity to Stokes intensity is as follows.

\[
R(T) = \frac{I_a(T)}{I_s(T)} = \frac{S_a v_a^4}{S_s v_s^4} \left[ 1 - \exp(-h \Delta v / kT) \right] / \left[ \exp(h \Delta v / kT) - 1 \right]
\]

\[
= \left( \frac{v_s}{v_a} \right)^4 \exp(-h \Delta v / kT)
\]

(1)

Among them, \(I_a\) and \(I_s\) are the anti-Stokes intensity and the Stokes intensity, respectively. \(S_a\) is the backscattering factor of fiber. \(v_a\) and \(v_s\) are the anti-Stokes frequency and the Stokes frequency, respectively. \(\Delta v\) is the Raman frequency shift. \(h\) is Planck constant. \(k\) is Boltzmann constant. \(T\) is the thermodynamic temperature value at any point on the fiber.

A reference fiber is placed at the beginning of fiber. Its temperature is \(T_0\).

\[
R(T_0) = \frac{I_a(T_0)}{I_s(T_0)} = \frac{K_a}{K_s} \left( \frac{v_s}{v_a} \right)^4 \exp(-h \Delta v / kT_0)
\]

(2)

The temperature of fiber is obtained by dividing formula (1) and formula (2) [7]
The positioning principle of RDTS is OTDR, which is similar to radar technology. It assumes that the light is injected into the fiber at the starting time, after time $t$, the backward Raman scattered light is received, and the position of Raman scattering is $L$. Then, by measuring time $t$, $L$ can be calculated.

$$L = \frac{v t}{2}$$  \hspace{1cm} (4)

$V$ is the speed of light [8].

3. Radiation damage mechanism of RDTS

Under the action of high-energy rays, the optical fiber core will undergo physical and chemical changes (discoloration, hardening, embrittlement, decomposition, destruction, etc.), and various defects will be generated in the core. Therefore, the optical transmission performance of optical fiber is deteriorated. The main performances are as follows: (1) The color center is formed, the fiber is blackened, the loss in the visible light band is rapid, and even the fluorescence is excited. (2) The change of the glass density inside the fiber and the change of the corresponding refractive index are caused, so that the refractive index distribution of the fiber changes, affecting the transmission characteristics and bandwidth of the optical fiber. (3) Destroy the coating layer of the optical fiber, affecting the mechanical strength and wear resistance of the optical fiber, high-dose radiation will cause the cladding layer to become brittle [9].

The most important performance above is the first one. In the manufacturing process of optical fiber, due to fiber doping, drawing and impurities existing in the fiber itself, the fiber will have a defective structure. In a high-energy ray environment such as gamma radiation, gamma rays directly interact with the optical fiber atom through photoelectric effect and the Compton effect, causing the atoms in the fiber to ionize electron-hole pair. When the electron-hole pair is trapped by defects and impurities, a new defect center is created, these defect centers are also called color centers. The color centers have a specific absorption spectrum for the transmitted light, which increases the fiber loss [10].

4. Influencing factors of radiation damage on RDTS

The factors affecting the radiation damage of RDTS are shown in Table 1. Next, we will analyze these major factors.

| Radiation source     | Radiation process          | External factors | Internal factors |
|----------------------|----------------------------|------------------|------------------|
| Nucleon              | Dose rate                  | Ambient temperature | Fiber material |
| Charged particles    | Total dose                 | Light intensity   | Dopant           |
| High-energy          | Continuous radiation/      | Wavelength        | Impurities       |
| electromagnetic      | Pulse radiation            |                  |                  |

(1) Radiation source

Common radiation sources include nucleons (protons, neutrons), charged particles (positive and negative electrons, $\alpha$ particles, heavy charged particles), high-energy electromagnetic radiation (X-rays, $\gamma$-rays), etc. The penetrating power of different types of radiation is very different. The alpha ionization ability is strong but the penetrating power is very weak. It can be shielded by only a thin paper. The penetrating power of beta rays is much larger than that of alpha rays. It causes defects on the surface of material. High-energy electromagnetic radiation has a very strong penetration ability, especially gamma rays. Even after passing through a few centimeters of lead plate, some rays still exist. Different radiation particles will also cause significant differences in the formation of color center of fiber, thereby affecting light attenuation. For example, charged particles can only cause
ionization damage to the atoms in fiber, high-energy electromagnetic radiation can cause atom displacement of fiber, and neutrons can undergo nuclear reactions with atoms to generate secondary radiation particles, and secondary interaction with the fiber.

(2) Radiation process

Generally, at the initial moment of radiation, the formation of the color center dominates, and the attenuation of the fiber increases rapidly with time. However, at the same time, the color center also degenerates due to heat, and the attenuation of fiber increases slowly. Finally, the formation and degradation of color center are balanced, and the light attenuation is saturated. Under same total dose, the faster the dose rate, the shorter the fiber recovery time, thus, the loss caused by radiation is higher and the total radiation dose that the fiber can withstand is lower. Therefore, the high pulse radiation causes greater damage than continuous radiation [11].

(3) External factors

The optical fiber has a radiation damage recovery effect, that is, the color center of fiber gradually fades with time under certain temperature and light conditions. The principle of radiation recovery effect is that the trapped charges are released due to the effect of heat and light, and the radiation damage is also restored, that is, the so-called annealing occurs. But only the unstable color center can be restored, and the stable color center will cause permanent damage to the fiber material.

(4) Internal factors

Radiation-induced attenuation is the result of interaction between radiating particles and the atoms of fiber. Therefore, almost all fiber parameters affect the formation and degradation of the color center, which affects the radiation-induced attenuation effect on the fiber, such as fiber materials, fabrication processes, and fiber Core/cladding doping, purity, coating materials, etc [12].

5. Measures to improve the anti-radiation performance of RDTS

According to the influence factors of radiation damage on RDTS, we summarized several measures to improve the anti-radiation performance of RDTS.

(1) Fiber material

The fiber whose core is pure silica and cladding is fluorine-doped has better radiation resistance [13], besides, the content of colored ions (Fe, Cr, Mn, Cu, Co, Ni, Pb) should be controlled during the manufacturing process, then, the processed optical fiber has better anti-radiation performance. In addition, the outer coating of optical fiber has a great influence on radiation resistance. If the outer surface of the optical fiber is coated with a fluoropolymer, the phenomenon of "breaking" is less likely to occur when radiated. If a protective sleeve (such as a copper mesh) is added to the fluorocoated fiber, the radiation resistance can be greatly improved.

(2) The wavelength of light source

The absorption of color center is mostly concentrated in ultraviolet and visible range, and its tail can extend to the near infrared region, and the absorption intensity decreases with the increase of wavelength, that is, the radiation damage received by the system when working at a long wavelength is much smaller. Generally, the wavelength of light source is selected to be 1550 nm.

(3) Fiber size

Large-diameter optical fibers transmit higher optical power, and their anti-radiation performance is better than small one, and the light annealing is more significant [14]. Since the radiation-induced attenuation increases along the length of fiber, so the length of each fiber should be shortened and the number of fibers can be increased when measuring.

(4) Post-treatment process

Pre-radiation: A higher dose of pre-radiation of fiber makes the fiber less sensitive to radiation, which is called anti-radiation hardening [15]. That is to say, the radiated fiber is less damaged when it is radiated for the second time. When the pre-radiated fiber is radiated with the same dose at the same rate as the not pre-radiated fiber, the radiation-induced attenuation of the former fiber can be 2 to 3 times lower. Therefore, repeated pre-radiation of fiber can improve its radiation resistance.

Thermal annealing: Under certain temperature conditions, the color center formed in the optical
fiber includes stable one and unstable one. Once the stable color center is formed, it will not retreat, and it can stably exist in fiber and form stable light absorption, but the proportion of stable color center is not large, just about 20%. Most color centers are unstable, and unstable color centers are prone to degradation under heat. The higher the temperature, the more significant the thermal annealing effect [16].

Light annealing: The color center degradation is also affected by the light in fiber. If the transmitted light is changed from "weak light" to "high light" in fiber radiation process, the color center will degrade, which is called light annealing. The stronger the optical power, the more obvious the effect of light annealing.

6. The calibration methods for temperature error of RDTS

In mild environment, we do not consider the attenuation of anti-Stokes light and Stokes light, but in radiated environment, the attenuation of the two beams is large and different, which causes temperature error. Therefore, the attenuation of the two beams must be considered in radiated environment. Currently, there are four useful calibration methods for temperature error.

(1) The two-point multi-section method

The method was originally proposed by Atsushi Kimura from Japan [17]. After improved, it can realize multi-stage calibration. As shown in figure 2, the ac segment is a fiber placed in radiated field, 1 is any point on ab, and the temperature of point 1 is the temperature to be calibrated. The accurate temperature of point a (T_a) and b(T_b) can be measured by Resistance Temperature Detector (RTD) or thermocouple in radiated field. the calibrated temperature is T_1'. The temperature of point a, 1 and b measured by RDTS is T_a', T_1', T_b', respectively.

![Figure 2](image)

**Figure 2.** The structure of two-point multi-section method.

In mild environment, the ratio of anti-Stokes intensity and Stokes intensity at point b is as follows:

$$\frac{I_{sat}}{I_{sat}} = \left(\frac{v_a}{v_b}\right)^4 \exp(-h\Delta\nu/kT_b)$$

(5)

In radiated environment, the ratio of anti-Stokes intensity and Stokes intensity at point b is as follows:

$$\frac{I_{sat}}{I_{sat}} = \left(\frac{v_a}{v_b}\right)^4 \exp(-h\Delta\nu/kT_b)$$

Compared to mild environment, the ratio is exponentially decayed in the radiated environment:

$$\frac{I_{sat}}{I_{sat}} = \frac{I_{sat}}{I_{sat}} \exp(-h\Delta\nu/kT_b)$$

(6)

$$A_s - A_b$$ is the average radiation-induced attenuation for unit length of anti-Stokes and Stokes light (So, the method is suitable for environments with the same radiation-induced attenuation), $A_{sat} - A_{sat}$ is radiation-induced attenuation of anti-Stokes and Stokes light between RDTS system and point a.

Solved by the combination of (5), (6), and (7), we get $T_b$.

$$\frac{1}{T_b} = \frac{1}{T_a} - \frac{k}{h\Delta\nu} \left( (A_s - A_b) L_{ab} + (A_{sat} - A_{sat}) \right)$$

(8)

Similar equations are acquired for point a and point 1.
$$\frac{1}{T_s} = \frac{1}{T_e} + \frac{k}{h\Delta v}(A_{att} - A_{iab})$$

$$\frac{1}{T_s} = \frac{1}{T_e} + \frac{k}{h\Delta v}[(A_j - A_i)L_{St} + (A_{iab} - A_{iab})]$$

From formula (8),(9),(10), we can get

$$\frac{1}{T_i} = \frac{1}{T_s} + \frac{T_s}{T_a} - \frac{1}{T_s} + \frac{T_s}{T_a} - \frac{T_s}{T_a} + \frac{T_s}{T_a}$$

This is the temperature of point $1$ after calibration. Similarly, the temperature of point 2 can be calibrated by the temperature of point b and c. This method does not need to know the specific radiation induced attenuation, only the temperature at both ends of the calibration point. But this method can only be used in the environment of stableradiation dose rate.

(2) Loop method

Figure 3 shows the structure of loop method. The sensing fiber is arranged in a loop form. A and D are close together, so the temperature and radiation dose rate of A and D are nearly the same. The same is true for BC. Besides, the length of AB is equal to CD. $T_0$ is reference temperature, $T_1$ is the temperature to be calibrated. $T_0$ and $T_1$ is the temperature of points A and B measured by RDTS respectively. By comparing the temperature values of point A and D measured by RDTS, the radiation induced attenuation between AD is known. Similarly, by comparing the temperature values of point B and C measured by RDTS, the radiation induced attenuation between BC is known. Since the radiation induced attenuation between AB and CD is the same, the radiation induced attenuation between AB can be obtained. Finally, combine the reference temperature $T_0$ at point A and the radiation induced attenuation between AB, the calibration temperature $T_1$ at point B can be calculated.

\[ \frac{I_{SXR}}{I_{St}} = \exp[-2(A_{iab} + A_{iab})] \]

Similarly, the ratio of Stokes light intensity between point D and point A is as follows.

\[ \frac{I_{SXR}}{I_{St}} = \exp[-2(A_{iab} + A_{iab}) + (A_{iab} + A_{iab})] \]

Among them, $I_{SXR}$ is the anti-Stokes light intensity at X point in radiated environment. $I_{St}$ is the Stokes light intensity at X point in radiated environment. $A_{iab}$ is the radiation induced attenuation of anti-Stokes between X and Y, $A_{iab}$ is the radiation induced attenuation of Stokes between X and Y. $A_{iab}$ is the radiation induced attenuation of incident light between X and Y.

By dividing formula (12) and formula (13), we can get:

\[ \frac{I_{SXR}}{I_{St}} = \frac{I_{SXR}}{I_{St}} - \exp[-2(A_{iab} + A_{iab}) + (A_{iab} + A_{iab})] \]

Similarly, for BC:

\[ \frac{I_{SXR}}{I_{St}} = \frac{I_{SXR}}{I_{St}} - \exp[-2(A_{iab} + A_{iab}) + (A_{iab} + A_{iab})] \]

From equations (14) and (15), the radiation induced attenuation between AB can be obtained as:
\[
\exp[-(A_{\text{at}} - A_{\text{st}})] = \sqrt{\frac{(I_{\text{at}}/I_{\text{st}})(I_{\text{at}}/I_{\text{st}})}{(I_{\text{at}}/I_{\text{st}})(I_{\text{st}}/I_{\text{at}})}}
\] (16)

Similar to equation (9), for point A:
\[
\frac{1}{I_a} = \frac{1}{I_o} - \frac{k}{h\lambda V}(A_{\text{at}} - A_{\text{st}})
\] (17)

Similar to equation (8), for point B:
\[
\frac{1}{I_b} = \frac{1}{I_o} - \frac{k}{h\lambda V}[2(A_{\text{at}} - A_{\text{st}}) + (A_{\text{at}} - A_{\text{st}})]
\] (18)

where \( A_{\text{at}} - A_{\text{st}} \) is the radiation induced attenuation from the RDTS system to point A.

Solve equations (16), (17), and (18) simultaneously, then we get:
\[
\frac{1}{T_1} - \frac{1}{T_2} = \frac{1}{T_1} - \frac{1}{T_2} + \frac{k}{2h\lambda V} \ln \left( \frac{I_{\text{at}}/I_{\text{st}}(I_{\text{at}}/I_{\text{st}})}{(I_{\text{at}}/I_{\text{st}})(I_{\text{st}}/I_{\text{at}})} \right)
\] (19)

This is the temperature at point B calibrated by loop method. It is not necessary to install thermocouples. It can be used in the case where the radiation dose rate changes. Just get the Stokes and anti-Stokes light intensity at four points and combine the reference temperature, the calibrated temperature can be obtained.

(3) Double source method

The double source method was originally proposed by KwangSuh from the United States [18], he used two light sources, whose wavelength are 940nm and 950nm respectively. Since the fiber radiation damage is lower when the wavelength of light source is longer, so the method is improved by using two light sources whose wavelength are 1450nm and 1550nm, respectively, the two light sources are called light source 1 and light source 2. As shown in figure 4, two light sources are controlled by an optical switch to sequentially reach the wavelength division multiplexer and enter the sensing fiber. The anti-Stokes light and Stokes light in sensing fiber successively return to the wavelength division multiplexer, and are divided into two paths, which are respectively sent to the APD to be converted into electrical signals and be processed by computer.

**Figure 4.** The structure of double source method.

The light source 1 enters from the end face of sensing fiber, and the incident light intensity is \( I_{10} \). At the measured point L, its Stokes intensity is:
\[
I_{\text{st}}(T) = I_{10}S \lambda_{\text{st}}^+ \frac{1}{1 - \exp(-h\lambda_{\text{st}}/kT)} \exp[-(\alpha_{\text{st}} + \alpha_{\text{at}})L]
\] (20)

Among them, \( \lambda_{\text{st}} \) is the wavelength of Stokes light of light source 1. \( \lambda_{\text{at}} = \lambda_{\text{st}} = 1550nm \). \( \alpha_{\text{st}} \) and \( \alpha_{\text{at}} \) are the transmission loss coefficients of incident light and Stokes light of light source 1, respectively. \( L \) is the position of any point on the optical fiber.

Next, the light source 2 enters from the end face of sensing fiber, and the incident light intensity is \( I_{20} \). At the measured point L, its anti-Stokes intensity is:
\[
I_{\text{ats}}(T) = I_{20}S \lambda_{\text{ats}}^+ \frac{1}{1 - \exp(h\lambda_{\text{ats}}/kT)} \exp[-(\alpha_{\text{ats}} + \alpha_{\text{at}})L]
\] (21)

Among them, \( \lambda_{\text{ats}} \) is the wavelength of anti-Stokes light of light source 2. \( \lambda_{\text{ats}} = \lambda_{\text{at}} = 1450nm \). \( \alpha_{\text{ats}} \) and \( \alpha_{\text{at}} \) are the transmission loss coefficient of incident light and anti-Stokes light of light source 2, respectively. \( L \) is the position of any point on the optical fiber.

Calculate the ratio of anti-Stokes light intensity of light source 2 to the Stokes light intensity of
light source 1 in the radiated field,

\[ R_s(T) = \frac{I_{sm}}{I_s} = \frac{I_{sm}K_m}{I_sK_s} \frac{\lambda_m}{\lambda_s} \exp\left(\frac{-\Delta\nu}{kT}\right) \exp\left[-(\alpha_{so} + \alpha_{sz})L\right] \]  

(22)

Because \( \lambda_s = \lambda_{so} \), similarly \( \lambda_s = \lambda_{sz} \), then formula (22) can be simplified to

\[ R_s(T) = \frac{I_{sm}}{I_s} = \frac{I_{sm}K_m}{I_sK_s} \frac{\lambda_m}{\lambda_s} \exp\left(\frac{-\Delta\nu}{kT}\right) \]  

(23)

According to formula (23), the difference attenuation of anti-Stokes light and stokes light in radiated environment can be directly eliminated. A reference fiber is placed at the beginning of the fiber. Its temperature is \( T_0 \).

\[ R_s(T_0) = \frac{I_{sm}}{I_s} = \frac{I_{sm}K_m}{I_sK_s} \frac{\lambda_m}{\lambda_s} \exp\left(\frac{-\Delta\nu}{kT_0}\right) \]  

(24)

The temperature of the fiber is obtained by dividing formula (23) and formula (24)

\[ \frac{1}{T} - \frac{1}{T_0} = \frac{k}{\hbar\Delta\nu} \left( \frac{R_s(T)}{R_s(T_0)} \right) \]

(25)

This is the temperature at any point along the fiber obtained by double source method. It is not necessary to install thermocouples nor an optical fiber loop arrangement, just need two light sources. It can be used in the case where the radiation dose rate changes.

(4) Double-ended method

The structure of double-ended method is shown in figure 5. The sensing fiber is arranged in a loop, and the 1*2 optical switch is used to make the incident light enter from both ends of the fiber. First, the pulsed light enters sensing fiber from point 1, the ratio of anti-Stokes light to Stokes light intensity is \( R_1 \), due to the influence of radiation, \( R_1 \) can no longer accurately reflect the temperature. Then the incident light is switched to sensing fiber from point 2 and get the ratio of anti-Stokes light to Stokes light intensity \( R_2 \), due to the influence of radiation, \( R_2 \) can no longer accurately reflect the temperature. Finally, calculate the geometric mean value of \( R_1 \) and \( R_2 \) and we get \( R = \sqrt{R_1R_2} \) R is the light intensity ratio that cancels the influence of radiation, and can be used to calculate the accurate temperature.

![Figure 5. The structure of double-ended method.](image)

As shown in figure 6, the total length of sensing fiber is \( Z \), the distance from the point of raman scattering to end 1 is \( L \), and the distance from the point of raman scattering to end 2 is \( Z-L \).

![Figure 6. The principle of double end method.](image)

First, the incident light enters sensing fiber from end 1, and the ratio of anti-Stokes light intensity to Stokes light intensity is obtained.

\[ R_1(T) = \frac{I_{so}}{I_s} = \left( \frac{\nu_s}{\nu_o} \right)^4 \exp\left(-\frac{\hbar\Delta\nu}{kT}\right) \exp\left[-(\alpha_{so} + \alpha_{sz})L\right] \]  

(26)

Then, the incident light is switched to sensing fiber from end 2, and the ratio of anti-Stokes light intensity to Stokes light intensity is obtained.

\[ R_2(T) = \frac{I_{so}}{I_s} = \left( \frac{\nu_s}{\nu_o} \right)^4 \exp\left(-\frac{\hbar\Delta\nu}{kT}\right) \exp\left[-(\alpha_{so} + \alpha_{sz})Z-L\right] \]  

(27)
The geometric mean of $R_s(T)$ and $R_l(T)$ is
\[
R_s(T) = \sqrt{R_r(T)R_l(T)} = \frac{K_s}{K_r}\left(\frac{v_s}{v_r}\right)^{\alpha_s} \exp\left(-\frac{\Delta \nu}{kT}\right) \exp[-(\alpha_s - \alpha_l)Z]
\]
(28)

Since $Z$ is the total length of sensing fiber, $Z$ is unchanged, so $\exp[-(\alpha_s - \alpha_l)Z]$ is a certain value and does not change with $L$, which eliminates the effect of radiation.

Assuming the temperature at reference fiber is $T_0$, the ratio of light intensity at reference fiber is
\[
R_s(T_0) = \frac{K_s}{K_r}\left(\frac{v_s}{v_r}\right)^{\alpha_s} \exp\left(-\frac{\Delta \nu}{kT_0}\right) \exp[-(\alpha_s - \alpha_l)Z]
\]
(29)

Equation (28) divided by (29) gives the temperature on sensing fiber as
\[
\frac{1}{T} = \frac{1}{T_0} + \frac{k}{\hbar \nu} \ln \frac{R_s(T)}{R_s(T_0)}
\]
(30)

This is the temperature at any point along the fiber obtained by double-ended method. It is not necessary to install thermocouples nor an optical fiber loop arrangement, just need an optical switch. It can be used in the case where the radiation dose rate changes.

7. Discussion
Among the above four calibration methods, we verified the correctness of two-point multi-section method and loop method by fiber radiated experiment with a total dose of 2MGy of γ-ray. The results show that the two methods can calibrate the highest error 38.9°C to below 2°C for the total sensing fiber, this is consistent with the results of other researcher’s experiments, so, the first two calibration methods are proved to be available, but the verification of double source method and doubleended method require further experimentation.

Each of the four methods has advantages and disadvantages, the two-point multi-section method can only be used in places where the radiation dose rate is stable, and thermocouples need to be installed. The loop method can be used in places where the radiation dose rate changes, and the loop fiber arrangement is required. The double source method and double-ended method can be used in places where the dose rate changes, without the need for thermocouples or loop arrangements, but requires two light sources or optical switches. So, we should choose the appropriate one according to the actual situation.

8. Conclusion
According to the research on radiation effect on RDTS, we can obtain the RDTS with high accuracy in radiated environment in three steps: (1) Select the core material as pure silica, the cladding material is a fluorine-doped silica fiber (2) Make several times of pre-radiation and thermal annealing of the optical fiber to obtain an optical fiber with better radiation resistance. (3) Select the appropriate calibration method according to the measuring environment. These three steps improve the anti-radiation performance of the fiber from three aspects of material, post-treatment process and calibration. Thus, we can obtain a RDTS with higher accuracy in radiated fields.

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