

基于拉曼信号分段重构的分布式光纤测温空间分辨率提升研究

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Research on spatial resolution improvement of distributed optical fiber temperature measurement based on Raman signal segmentation and reconstruction

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基于拉曼信号分段重构的分布式光纤测温空间分辨率提升研究

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摘要: 激光器脉宽是分布式光纤测温系统空间分辨率的主要影响因素之一, 在光脉冲覆盖待测区域的情况下, 系统无法准确解调出待测区域的准确温度。提出了一种拉曼信号分段与重构方法, 通过分析光脉冲在待测区域处的信号特征, 得出了激光脉宽对温度偏差的影响关系, 并根据此关系对不同温度区域原始拉曼信号进行分段, 借助待测区域长度、已知温度和待测温度下的拉曼光强差重构待测区域处的拉曼信号强度, 利用重构后的拉曼信号进行温度解调, 使系统空间分辨率、测温精度大幅提升。使用 20 ns 脉宽的光源 (理论空间分辨率可达到 2 m)、0.72 m 测试光纤进行测试, 结果表明, 在 90 °C 测试温度下, 温度误差从 33.9 °C 减小至 5.8 °C, 系统空间分辨率由 2.27 m 提升至 1.13 m。

关键词: 分布式温度传感器; 空间分辨率; 温度精度; 拉曼信号分段; 拉曼信号重构

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0 引言

分布式光纤拉曼测温系统利用光纤中传输的背向拉曼散射信号实现空间温度场的实时监测^[1-2], 相比于传统测温方法^[3-5], 该技术不仅能够实现长距离温度监测, 还具有抗电磁干扰、响应速度快、易于铺设等优点, 在各领域有着广泛应用^[6-9]。目前分布式光纤测温系统受激光脉冲宽度等因素的影响, 空间分辨率指标无法得到有效提升^[10]。传统方法是通过压缩入射激光脉冲宽度等方法来提高系统空间分辨率, 但激光脉冲宽度不能无限压缩, 且随着脉冲宽度压缩, 系统信噪比也随之变差, 测温精度难以保证^[11-12], 限制了实际应用效果和用范围。

文中对高温区域处的原始拉曼信号进行分析, 根据所在温度区域的不同对拉曼信号进行了分段, 去除分段中已知温度段的信号, 以待测温度段信号作为增益来重构拉曼信号, 该方法通过消除已知温度段信号

串扰来突破激光脉宽对分布式光纤测温系统空间分辨率的限制, 提高测温精度和空间分辨率。

1 温度解调原理与改进

1.1 温度解调方法

分布式光纤拉曼测温系统根据自发背向拉曼散射产生的 Stokes 光和 anti-Stokes 光解析光纤温度信息, 其中 anti-Stokes 光对温度敏感作为信号光, Stokes 光对光敏感度低可作为参照光, 利用 anti-Stokes 光与 Stokes 光比值消除激光器光功率波动等因素^[13], 公式 (1) 为温度解调公式:

$$\frac{1}{T} = \frac{1}{T_0} - \frac{k}{h\Delta\nu} \left[\ln \frac{P_{as}(T)/P_s(T)}{P_{as}(T_0)/P_s(T_0)} \right] \quad (1)$$

式中: P_{as} 为 anti-Stokes 光功率; P_s 为 Stokes 光功率; T_0 为已知温度; T 为待测温度; k 为玻耳兹曼常数; h 为普朗克常数; $\Delta\nu$ 为拉曼频移量。由于系统采集的光强

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值是一段背向拉曼信号的集合,因此当高温区域处光纤长度小于该集合长度时,系统将无法准确解调该区域的温度^[14]。

1.2 拉曼信号分段与重构

拉曼信号分段与重构是通过分析高温区域拉曼信号特征,根据温度梯度将信号分为已知温度段和待测温度段,根据已知温度段与待测温度段的拉曼信号光强差重构高温区域信号。首先要确定待测温度区域的长度,由于 Stokes 光和 anti-Stokes 光对温度变化展现的特性一致,只是敏感度存在区别,且短距离内两路光的传播速度差异可以忽略,为了方便,将 Stokes 信号和 anti-Stokes 信号统称为拉曼信号。图 1 为光脉冲传输过程示意图,将一段长为 L 的测试光纤放入高温区域,其余光纤置于室温下,称为非测试光纤。在脉冲光到达测试光纤之前,光纤温度一致,拉曼信号强度随光纤长度呈指数衰减^[15];在脉冲光到达测试光纤时,受高温区域影响,拉曼信号开始上升, t_i 时刻脉冲光完全覆盖测试光纤;在 $t_i \sim t_k$ 时刻之间,脉冲光移动距离极短,拉曼信号强度可看作一致; t_k 时刻过后,脉冲光开始离开测试光纤,其拉曼信号下降速率受测试光纤与非测试光纤温差影响; t_n 时刻之后,拉曼信号又按指数函数均匀衰减。

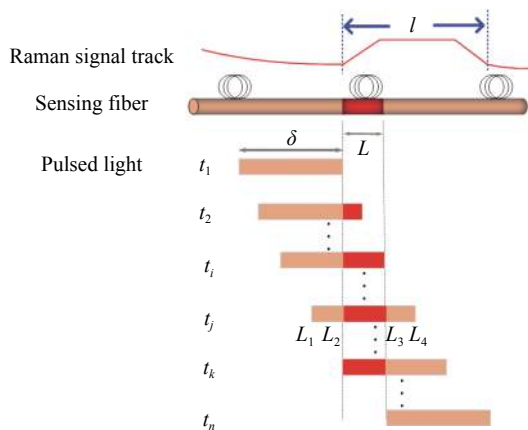


图 1 光脉冲传输过程

Fig.1 Optical pulse transmission process

因此,当激光脉宽为系统空间分辨率的主要制约因素时,可将空间分辨率与测温精度关系分两种情况讨论,当待测区域处测试光纤长度大于等于激光脉冲宽度时,系统测温精度主要与信号信噪比有关。当待测区域处测试光纤长度小于激光脉冲宽度时,测温精度主要与激光脉冲宽度有关,随着激光脉宽的增加,

系统测量温度值逐渐偏离待测区域真实温度值,该理论为空间分辨率受限时,测温精度变差的主要原因。其中该两种情况中受高温区影响的拉曼信号长度 l 、脉冲宽度 δ 和测试光纤长度 L 关系均如公式 (2) 所示:

$$L = l - \frac{\delta c}{2n} \quad (2)$$

式中: c 为光速; n 为光在光纤内的折射率。确定测试光纤长度 L 后即可对该区域拉曼信号进行分段,这里只讨论测试光纤长度 L 小于激光脉宽 δ 的情况。如图 1 所示, t_i 时刻光脉冲所在位置,在 $t_i \sim t_k$ 时刻之间选取任意位置如 t_j 时刻光脉冲所在位置,对此刻的拉曼光强值进行分段,如公式 (3) 所示:

$$P_{t_j} = \int_{L_1}^{L_2} P(T_s) dl + \int_{L_2}^{L_3} P(T) dl + \int_{L_3}^{L_4} P(T_s) dl \quad (3)$$

式中: L_1 为 t_i 时刻光脉冲的起始位置; L_2 为高温区域的起始位置; L_3 为高温区域的结束位置; L_4 为光脉冲的结束位置; $L_1 \sim L_2$ 、 $L_3 \sim L_4$ 为已知温度段; $L_2 \sim L_3$ 为待测温度段; P 为拉曼光功率; T 为高温区域的温度; T_s 为高温区域周围的温度。

当满足高温区域两旁温度相等都为 T_s 时,可拟合出高温区域位置处在 T_s 温度下的拉曼强度值,由于是在短距离下,可使用 t_i 时刻拉曼信号强度值与 t_n 时刻拉曼信号强度值的平均值作为该位置的拉曼强度近似值:

$$P'_{t_j} = \frac{P_{t_i} + P_{t_n}}{2} = \int_{L_1}^{L_2} P(T_s) dl + \int_{L_2}^{L_3} P(T_s) dl + \int_{L_3}^{L_4} P(T_s) dl \quad (4)$$

式中: P'_{t_j} 为高温区域位置处在 T_s 温度下的拉曼强度值; P_{t_i} 为 t_i 时刻采集到的拉曼光强值; P_{t_n} 为 t_n 时刻采集到的拉曼光强值。

那么公式 (3) 和 (4) 的差值就为在长度 L 下,温度为 T 和 T_s 所激发的拉曼光强差:

$$P_{t_j} - P'_{t_j} = \int_{L_2}^{L_3} [P(T) - P(T_s)] dl \quad (5)$$

进一步求出在脉宽尺度 δ 下,温度为 T 和 T_s 所激发的拉曼光强差:

$$\int_{L_1}^{L_4} [P(T) - P(T_s)] dl = \frac{\delta c}{2nL} \int_{L_2}^{L_3} [P(T) - P(T_s)] dl \quad (6)$$

重构温度为 T 下的拉曼信号,包含温度为 T_s 时的拉曼光强和温度为 T 和 T_s 所激发的拉曼光强差:

$$P_{t_j}(T) = P'_{t_j} + \int_{L_1}^{L_4} [P(T) - P(T_s)] dl \quad (7)$$

将采集的 Stokes 和 anti-Stokes 强度值分别用公式 (3)~(7) 进行修正, 将修正后的拉曼信号代入公式 (8) 进行温度解调, 得:

$$\frac{1}{T} = \frac{1}{T_s} - \frac{k}{h\Delta\nu} \left[\ln \frac{P_{astj}(T)/P_{stj}(T)}{P'_{astj}/P'_{stj}} \right] \quad (8)$$

式中: $P_{astj}(T)$ 、 $P_{stj}(T)$ 分别为修正后的 Stokes 和 anti-Stokes 值; P'_{astj} 、 P'_{stj} 为公式 (2) 中拟合的 Stokes 和 anti-Stokes 值。该方法去除了拉曼信号集合中的已知温度段信号串扰, 提高了空间分辨率和测温精度。

2 温度解调原理与改进

2.1 系统结构

为了验证拉曼信号分段与重构后的温度修正效果, 搭建了实验测试平台, 如图 2 所示。该平台由脉冲激光器、波分复用器 (Wavelength Division Multiplexing, WDM)、光电探测器 (Avalanche Photo Diode, APD)、数据采集卡 (Data Acquisition Card, DAC)、传感光纤、智能恒温槽 (Intelligent Thermostat Tank) 组成。

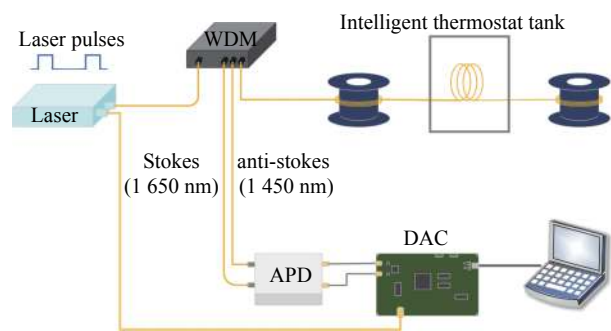


图 2 系统结构图

Fig.2 System structure diagram

2.2 高温区域长度测试

用两组脉冲宽度来验证公式 (2) 高温区域长度检测方法的实际效果, 实验中取 14 圈周长为 0.24 m 的测试光纤放入智能恒温槽, 温度设定为 80.0 °C, 其余光纤放置在室温 (21.0 °C) 下, 智能恒温槽内光纤长度即为高温区域长度。第一组实验将激光器脉宽设定为 20 ns, 第二组实验将激光器脉宽设定为 50 ns。如图 3(a)、(b) 所示, Ratio 为采集的 anti-Stokes 与 Stokes 的比值。受高温区域影响的拉曼信号长度为光脉冲刚接触高温区域至刚好完全离开高温区域, 如图 1 中即为 $t_1 \sim t_n$ 时刻之间对应的距离。其中图 3(a) 受高温区域影响的拉曼信号长度为 5.52 m, 求得高温区域长度

为 3.52 m, 误差为 0.16 m; 图 3(b) 受高温区域影响的拉曼信号长度为 8.68 m, 求得高温区域长度为 3.68 m, 误差为 0.32 m, 可以看出该方法可有效地检测出高温区域的长度。

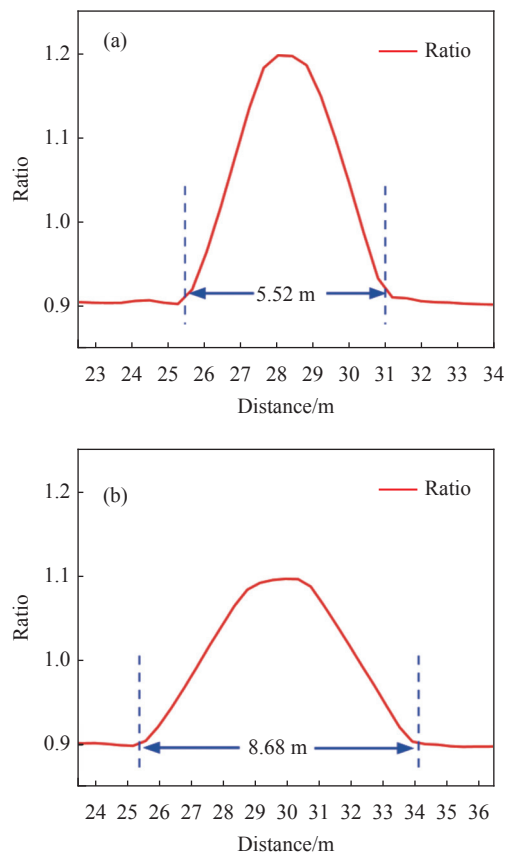


图 3 (a) 在激光脉宽 20 ns 下的 Ratio 曲线; (b) 在激光脉宽 50 ns 下的 Ratio 曲线

Fig.3 (a) Ratio curve at a laser pulse width of 20 ns; (b) Ratio curve at a laser pulse width of 50 ns

2.3 拉曼信号分段重构测试结果

下面进行一个高温区域温度测试来验证该拉曼信号重构的实际效果。在实验中激光脉宽设置为 20 ns, 数据采集卡采样速率为 250 MSPS, APD 带宽为 100 MHz, 根据侯培国^[6]给出的理论计算公式, 系统理论空间分辨率经计算结果为 2.27 m, 由 APD 和数据采集卡限制的空间分辨率为 1.07 m。取 3 圈周长为 0.24 m、总长为 0.72 m 的测试光纤放入智能恒温槽, 智能恒温槽中实际温度为 92.1 °C, 传统解调算法下的温度曲线如图 4 所示, 可以看出, 传统温度解调算法下的测试光纤温度为 58.2 °C, 温度误差为 33.9 °C。根据拉曼信号轨迹确定智能恒温槽影响的温度范围

为 1.13 m, 经拉曼信号重构后温度解调结果为 86.3 °C, 实测温度达到了实际温度的 90% 以上^[17]。此前已有多次报道温度精度优于 1 °C 的实验^[18-19], 这些方法是基于测试光纤足够长的情况下 (大于空间分辨率), 针对提升信噪比来优化测温精度。文中方法主要解决了当测温区域长度小于激光脉冲宽度的条件下造成的测温偏移, 对于小范围泄漏监测具有突出优势。其中温度误差主要来源于 APD 带宽不足, 该方法可随 APD 带宽的提高逐渐缩短可准确测量的温度区域长度和温度精度。

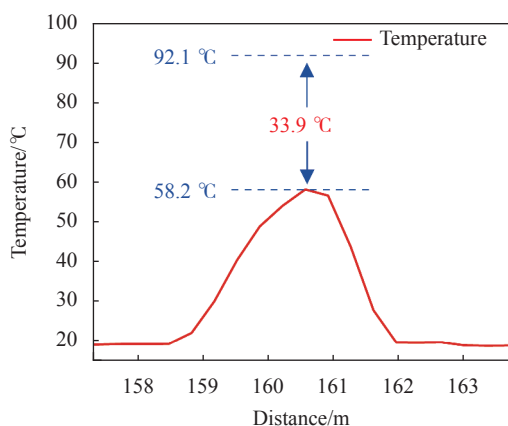


图 4 92.1 °C 下的测温曲线

Fig.4 Temperature measurement curve at 92.1 °C

测试该方法不同的温度点, 表 1 为 40~90 °C 的实验测试, 图 5 为传统解调方式下和拉曼信号重构后温度解调下的误差对比, 图中左轴为传统解调方法温度误差, 右轴为拉曼信号分段重构方法的温度误差。由于系统空间分辨率不足, 在传统解调方法下产生了较大的测温误差, 经该方法提升空间分辨率后, 温度误差由最大的 33.9 °C 提升至 5.8 °C 以内, 在 0.72 m 的

表 1 传统温度解调与重构后温度解调对比

Tab.1 Comparison of traditional temperature demodulation and reconfigured temperature demodulation

Actual temperature/°C	Traditional demodulation/°C	Raman signal reconstruction/°C
40.7	31.0	39.8
50.7	36.1	48.5
61.6	41.7	58.2
71.8	46.9	67.1
81.9	52.7	77.2
92.1	58.3	86.8

测试光纤下达到了真实温度的 90% 以上, 可以看出, 经重构后系统温度精度和空间分辨率都得到了较高的提升。

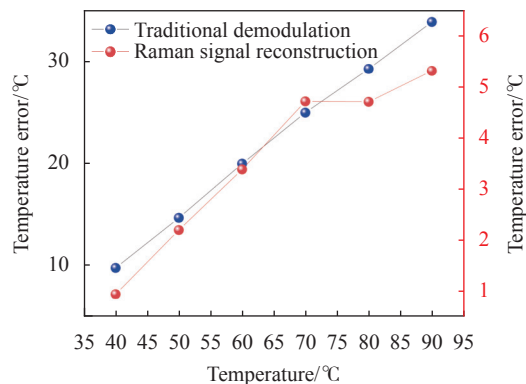


图 5 传统解调方法与拉曼信号分段与重构方法温度误差对比

Fig.5 Temperature error between conventional demodulation method and Raman signal segmentation and reconstruction method

3 结论

文中分析了分布式光纤测温系统激光脉冲覆盖的高温区域拉曼信号特征, 提出了一种拉曼信号分段与重构方法, 根据温度梯度对高温区域拉曼信号进行分段, 分为已知温度段和待测温度段, 根据不同温度下待测温度段与已知温度段的拉曼信号强度差值实现信号重构。并采用 20 ns 脉宽激光光源与 0.72 m 光纤测试段进行了不同温度实验, 结果表明, 使用该方法后系统空间分辨率从 2.27 m 提升至 1.13 m, 测试段光纤最大温度误差从 33.9 °C 减小到 5.8 °C。该方法可为油气储罐密封圈火灾、高温炉体裂缝等高空分辨率温度监测应用提供有力支撑。

参考文献:

- [1] He Zuyuan, Liu Yinping, Ma Lin, et al. Raman distributed temperature sensor using multimode fiber with reduced core size [J]. *Infrared and Laser Engineering*, 2019, 48(4): 0422002. (in Chinese)
- [2] Xu Yang, Li Jian, Zhang Mingjiang. Research progress of Raman distributed optical fiber temperature sensor [J]. *Journal of Applied Sciences*, 2021, 39(5): 713-732. (in Chinese)
- [3] Liao Guangmeng, He Jianxin, Zhu Yuqin, et al. Fiber grating sensor and application [J]. *Equipment Environmental Engineering*, 2022, 19(11): 142-149. (in Chinese)
- [4] 杨甜甜, 郭涛, 陈展等. 温度传感器的应用研究[J]. 内江科技,

- 2020, 41(3): 38-42.
- [5] Zhang Lijun. Temperature measurement principle and fault analysis of industrial thermocouple [J]. *Science & Technology Information*, 2022, 20(2): 42-44. (in Chinese)
- [6] Xu Yang, Li Jian, Zhang Mingjiang, et al. Pipeline leak detection using Raman distributed fiber sensor with dynamic threshold identification method [J]. *IEEE Sensors Journal*, 2020, 20(14): 7870-7877.
- [7] Li Zhen, Leng Xianlun, Yin Qiuyu. Research on the temperature distribution characteristics of tunnel fire based on distributed optical fiber monitoring [J]. *Modern Tunnelling Technology*, 2022, 59(6): 132-139. (in Chinese)
- [8] Liu Xiang. Applications of distributed optical fiber temperature sensor system in nuclear power plants [J]. *Application of Electronic Technique*, 2022(S1): 38-43. (in Chinese)
- [9] Zhou Bocheng, Fan Xinyu, He Zuyuan. Raman distributed temperature sensor based on intensity modulated chirped pulse compression [J]. *Optical Communication Technology*, 2021, 45(10): 30-33. (in Chinese)
- [10] Soto M A, Ramirez J A, Thévenaz L. Intensifying the response of distributed optical fibre sensors using 2D and 3D image restoration [J]. *Nature Communications*, 2016, 7: 10870.
- [11] Bazzo J P, Pipa D R, Martelli C, et al. Improving spatial resolution of Raman DTS using total variation deconvolution [J]. *IEEE Sensors Journal*, 2016, 16(11): 4425-4430.
- [12] Silva M S P E, Alves H P, Nascimento J F, et al. Impact of pulse width on the sensitivity and range of a Raman-based distributed fiber-optic temperature sensor [J]. *Journal of Microwaves*, *Optoelectronics and Electromagnetic Applications*, 2018, 17(4): 539-551.
- [13] Lu Jiahui, Wan Chenggong, Jin Kai, et al. Research on optimizing accuracy and real-time performance of distributed optical fiber temperature sensor system [J]. *Laser Journal*, 2023, 44(1): 62-67. (in Chinese)
- [14] Zhang Rushan, Wu Shuo, Tu Qinchang, et al. Design and application of high spatial resolution distributed temperature sensing system [J]. *Optical Instruments*, 2015, 37(1): 79-82. (in Chinese)
- [15] Sun Miao, Yang Shuang, Tang Yuquan, et al. Distributed fiber optic temperature sensor based on dynamic calibration of Raman Stokes [J]. *Acta Physica Sinica*, 2022, 71(20): 200701. (in Chinese)
- [16] Hou Peiguo. Theory and experiment research on fiber optic distributed temperature sensor system[D]. Qinhuangdao: Yanshan University, 2003. (in Chinese)
- [17] Wang Dingrui, Deng Xiao, Zhang Jun, et al. High spatial resolution distributed optical fiber temperature measurement system for ice cover profile [J]. *Applied Optics*, 2021, 42(5): 941-948. (in Chinese)
- [18] Wang Yanping, Sun Xiaohong, Qi Xue, et al. The study of the Raman-based optical fiber-folded distributed temperature sensing system with simplex code [J]. *Optics Communications*, 2018, 420: 200-204.
- [19] Wang Honghui, Wang Xiang, Cheng Yi, et al. Research on noise reduction method of RDTS using D-SVD [J]. *Optical Fiber Technology*, 2019, 48: 151-158.

Research on spatial resolution improvement of distributed optical fiber temperature measurement based on Raman signal segmentation and reconstruction

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Abstract:

Objective Currently distributed fiber optic temperature sensor has become an important tool for oil and gas storage tank seal ring fires, high temperature furnace crack detection, and thermal pipeline leakage detection. Most detection methods are judged by the temperature threshold and temperature rise rate. And when the leak area is too small and the system spatial resolution is insufficient, the temperature and temperature rise rate will be

much lower than the actual value. As one of the main factors of the spatial resolution of the distributed optical fiber temperature measurement system, the pulse width of the laser determines whether the sensor can detect the occurrence of accidents in time. Therefore, it is necessary to use a method to reduce the impact of laser pulse width on the spatial resolution of the system.

Methods A Raman signal segmentation and reconstruction method is proposed. By analyzing the signal characteristics of the laser pulse in the optical fiber at the region to be measured, the relationship between the laser pulse width and the temperature deviation is obtained. According to this relationship, the original Raman signal at different temperature regions is segmented into known temperature segments and temperature segments to be measured, and the Raman signal intensity at the region to be measured is reconstructed from the signal of the temperature segment to be measured with the help of a fitted signal to eliminate the Raman signal offset at the known temperature segment.

Results and Discussions The method was tested using a laser source with 20 ns pulse width (the theoretical spatial resolution is about 2 m) and 0.72 m test fiber. The results show that within the test temperature range of 40-90 °C, the temperature error is reduced from a maximum of 33.9 °C to below 5.8 °C, and the spatial resolution of the system was improved from 2.27 m to 1.13 m.

Conclusions By analyzing the signal characteristics of the laser pulses passing through the high-temperature region, a Raman signal segmentation reconstruction method is proposed. By dividing the high temperature area covered by the laser pulse into the known temperature region and the temperature region to be measured, the signal offset of the known temperature segment is removed and the signal of the high temperature area is reconstructed according to the signal intensity of the temperature segment to be measured. A test is carried out using 20 ns laser pulses and 0.72 m test fiber. The results show that the temperature error is reduced from 33.9 °C to 5.8 °C at 90 °C, and the spatial resolution of the system is improved from 2.27 m to 1.13 m. This method mainly solves the temperature measurement error when the length of the optical fiber in the area to be measured is less than the laser pulse width, and has outstanding advantages for small-scale leakage monitoring. The remaining temperature error mainly comes from insufficient APD bandwidth. This method can gradually shorten the measurable temperature region length and temperature accuracy with the increase of APD bandwidth.

Key words: distributed temperature sensor; spatial resolution; temperature accuracy; Raman signal segmentation; Raman signal reconstruction

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