Optical Fiber Technology 40 (2018) 165–171

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

Regular Articles

Optimization design of the tuning method for FBG spectroscopy based on the numerical analysis of all-fiber Raman temperature lidar

Li Wang, Jun Wang, Dong Bao, Rong Yang, Qing Yan, Fei Gao, Dengxin Hua*

School of Mechanical and Precision Instrument Engineering, Xi'an University of Technology, Xi'an 710048, China

ARTICLE INFO

Keywords:
All-fiber Raman temperature lidar
Fiber spectroscopic system
Fiber Bragg grating
Wavelength tuning method

ABSTRACT

All fiber Raman temperature lidar for space borne platform has been proposed for profiling of the temperature with high accuracy. Fiber Bragg grating (FBG) is proposed as the spectroscopic system of Raman lidar because of good wavelength selectivity, high spectral resolution and high out-of-band rejection rate. Two sets of FBGs at visible wavelength 532 nm as Raman spectroscopy system are designed for extracting the rotational Raman spectra of atmospheric molecules, which intensities depend on the atmospheric temperature. The optimization design of the tuning method of an all-fiber rotational Raman spectroscopy system is analyzed and tested for estimating the potential temperature inversion error caused by the instability of FBG. The cantilever structure with temperature control device is designed to realize the tuning and stabilization of the central wavelengths of FBGs. According to numerical calculation of FBG and finite element analysis of the cantilever structure, the center wavelength offset of FBG is 11.03 nm/°C with the temperature change in the spectroscopy system. By experimental observation, the center wavelength offset of surface-bonded FBG is 9.80 nm/°C with temperature changing when subjected to certain strain for the high quantum number channel, while 10.01 nm/°C for the low quantum number channel. The tunable wavelength range of FBG is from 528.707 nm to 529.014 nm for the high quantum number channel and from 530.226 nm to 530.547 nm for the low quantum number channel. The temperature control accuracy of the FBG spectroscopy system is up to 0.03 °C, the corresponding potential atmospheric temperature inversion error is 0.04 K based on the numerical analysis of all-fiber Raman temperature lidar. The fine tuning and stabilization of the FBG wavelength realize the elaborate spectroscope of Raman lidar system. The conclusion is of great significance for the application of FBG spectroscopy system for space-borne platform Raman lidar.

1. Introduction

Temperature is one of the important parameters that describe the state of the atmosphere. The global atmospheric temperature detection technology based on satellite platform is highly concerned by scientists and governments as an effective means for dealing with global climate change and the spread of pollution. The pure rotational Raman lidar has been widely applied in atmosphere temperature measurement due to its higher temporal and spatial resolution [1–8]. The spectroscopy systems of the Raman lidar mainly are grating monochromator or polychromator [1–3], narrowband interference filters [4] and Fabry-Perot etalon. In recent years, the development of the space-borne lidar is rapid and has become the future development direction and trend of optical active remote sensing. In order to satisfy the requirement of lightweight and miniaturization of space-borne lidar, an all-fiber pure rotational Raman lidar based on the FBG spectroscopic system has been proposed and developed by our group for profiling the atmospheric temperature with 1 K accuracy [5,6].

The principle of Raman lidar is the temperature dependence of the Raman scattering spectral intensity of atmospheric molecules. The rotational Raman scattering signals of different quantum numbers are extracted to retrieve the atmospheric temperature. The central reflective wavelengths of FBGs should be strictly equal to the selected the wavelength of high and low quantum numbers. As the filter of Raman signal, FBG is mainly used to extract the temperature dependent rotational Raman signal. The fine tuning and control of the FBG center wavelength is the key technology to realize the all fiber Raman lidar. However, the central wavelength of fabricated FBG usually has a certain error and its central wavelength is easily affected by the ambient temperature, which will directly lead to instability of the all fiber Raman lidar system.

In this paper, the configuration of the all fiber Raman lidar system and the principle of atmospheric temperature detection are firstly proposed. The method of the temperature inversion error caused by the

* Corresponding author.
E-mail address: dengxinhua@xaut.edu.cn (D. Hua).

https://doi.org/10.1016/j.yofte.2017.11.010
Received 27 May 2017; Received in revised form 18 October 2017; Accepted 11 November 2017

instability of FBG is analyzed. The cantilever structure with temperature control device is designed to realize the tuning and stabilization of the central wavelength of FBGs. According to the numerical calculation of FBG and the finite element analysis of the cantilever beam structure, the wavelength adjustment and temperature control parameters of the FBG spectrum system are optimized. Results and analysis of wavelength adjustment and temperature control experiment for FBG spectroscopic system are presented. Finally, based on the requirement of the accuracy of the temperature measurement of all fiber Raman lidar, the temperature measurement error of the system is evaluated by use of the optimization control parameters of FBG. The temperature control accuracy of spectroscopic system in all-fiber Raman temperature measurement lidar is obtained to be 0.03 °C, corresponding to the atmospheric temperature inversion error of 0.04 K, which can also be negligible against to requirement of whole system temperature inversion error within 1 K.

2. Principle of rotational Raman lidar for temperature measurement

Rotational Raman temperature measurement lidar is based on the theory of the rotational Raman scattering spectral intensity of single gaseous molecule with different quantum numbers relating to temperature to inverse atmospheric temperature profiles. Fig. 1 shows the changes of Raman scattering cross section of the Stokes and the anti-Stokes branch of the N_2 induced by the 532 nm laser and the reflection spectrum of the filter FBG. In Fig. 1, the rotational Raman scattering intensity of N_2 changes with temperature. The spectral intensity of low quantum number increases and the spectral intensity of high quantum number decreases with the temperature increases. Rotational Raman spectrum $\lambda_L = 530.54$ nm and $\lambda_H = 528.96$ nm are chosen respectively as the center reflection wavelength of FBG, which also are called as low and high quantum number (wavelength).

The rotational Raman scattering spectrum normalization function is $G(\lambda)$, the reflection spectrum functions of FBG of two Raman channels are $h_H(\lambda)$ and $h_L(\lambda)$ respectively. After the FBG filtering, the rotational Raman scattering spectrum functions $f_H(\lambda)$ and $f_L(\lambda)$ can be expressed as the convolution of the two

$$f_H(\lambda) = \int h_H(\lambda' - \lambda) G(\lambda') d\lambda' \tag{1}$$

$$f_L(\lambda) = \int h_L(\lambda' - \lambda) G(\lambda') d\lambda'. \tag{2}$$

The lidar equation is

$$p(z) = K \cdot E_0 \cdot \frac{c \cdot \tau}{2} \cdot \frac{Ar}{z^2} \cdot Y(z) \cdot \beta(z) \cdot \exp\left[-2\int_0^z \alpha(z) dz\right] \tag{3}$$

where, K is optical system efficiency, E_0 is laser pulse energy, τ is laser

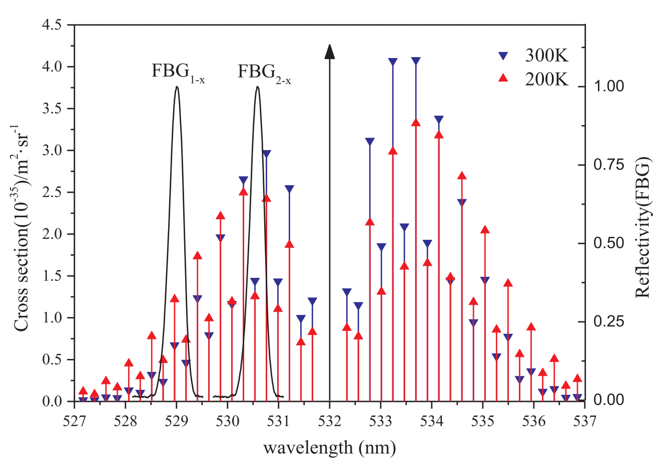

Fig. 1. Changes of Raman scattering cross section of N_2 at different wavelengths.

pulse interval time, Ar is receiving area of telescope, $Y(z)$ is overlap coefficient of optical path of transmitter and receiver, z is detection height, $\beta(z)$ is backscatter coefficient at height z, $\alpha(z)$ is atmospheric extinction coefficient at height z. The Raman scattering signal energy of the high and low quantum number received by the telescope are

$$p_1(z) = K \cdot E_0 \cdot \frac{c \cdot \tau}{2} \cdot \frac{Ar}{z^2} \cdot Y(z) \cdot N(z) \cdot \sigma_1(J_1, T) \cdot \exp\left[-2\int_0^z \alpha(z) dz\right] \tag{4}$$

$$p_2(z) = K \cdot E_0 \cdot \frac{c \cdot \tau}{2} \cdot \frac{Ar}{z^2} \cdot Y(z) \cdot N(z) \cdot \sigma_2(J_2, T) \cdot \exp\left[-2\int_0^z \alpha(z) dz\right] \tag{5}$$

where, T is the atmospheric temperature, J_1 and J_2 are the rotation quantum numbers of the Raman scattering signal of the high and low quantum channel respectively, $N(z)$ is the density of atmospheric molecules, $\sigma_1(J_1, T)$ and $\sigma_2(J_2, T)$ are the intensity of the scattering cross sections of the rotational Raman scattering signal with rotation quantum number J_1 and J_2 respectively at temperature T. Then the signal energies detected by the two Raman channels are

$$P_H(T, z) = P_1(T, z) \cdot f_H \tag{6}$$

$$P_L(T, z) = P_2(T, z) \cdot f_L \tag{7}$$

The energy ratio of the scattering signals of two Raman channels is

$$H(T, z) = \frac{P_H(T, z)}{P_L(T, z)} = \exp\left\{-\left[\frac{A}{T^2(z)} + \frac{B}{T(z)} + C\right]\right\} \tag{8}$$

According to the above equation, the expression of atmospheric temperature can be described as

$$T(z) = -\frac{B \pm \sqrt{B^2 - 4A\{\ln[H(T, z)] + C\}}}{2\{\ln[H(T, z)] + C\}} \tag{9}$$

The main factor that affects the inversion accuracy of atmospheric temperature is the spectral extraction accuracy of the all-fiber spectral system, while the central wavelength shift of FBG is mainly affected by temperature. Therefore, it is very important to study the temperature response characteristic of the all-fiber optical system. The effective refractive index and the grating period of the uniform FBG are constant. When the incident light passes through a uniform fiber Bragg grating, which satisfy the Bragg phase-matching condition yield high-reflection, the rest of the light transmitted. The spectrum of a specific wavelength can be efficiently extracted by this characteristic. The wavelength of the reflected light can be expressed as

$$\lambda_B = 2n_{eff}\Lambda \tag{10}$$

where, n_{eff} is the effective refractive index of the grating and Λ is the grating period. When the ambient temperature changes, FBG effective refractive index and grating period are both changed due to thermal expansion effect and thermal effect, and the center wavelength of FBG is shifted. The relationship between the offset and the temperature change is expressed as

$$\Delta\lambda_B = 2n_{eff}\frac{\partial \Lambda}{\partial T} \cdot \Delta T + 2\Lambda\frac{\partial n_{eff}}{\partial T} \cdot \Delta T = (\alpha + \xi) \cdot \Delta T \cdot \lambda_B \tag{11}$$

where, α is the coefficient of thermal expansion of the fiber and ξ is the thermal coefficient. The base material of FBG introduces additional strain to make the strain of FBG change due to the effect of thermal expansion and contraction, causing the grating modulation period changes and elastic effect, making the effective refractive index and the grating period change, and resulting in the offset of the central wavelength of FBG. Among them, the relationship between the offset and the strain of the center wavelength is

$$\Delta\lambda_{B\varepsilon} = (1 - P_e) \cdot \varepsilon\lambda_B \tag{12}$$

where, P_e is the effective elastic coefficient of the fiber material, and ε is the strain subjected by FBG. The relationship between the offset of the center wavelength caused by base material and temperature is