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Fiber-optic spectroscopic rotational Raman lidar with visible wavelength fiber Bragg grating for atmospheric temperature measurement

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ABSTRACT

A fiber-optic spectroscopic rotational Raman lidar is demonstrated with the visible wavelength fiber Bragg grating technique for profiling the atmospheric temperature. Two-channel pure rotational Raman optical signals are extracted from lidar echo signals by two sets of visible wavelength fiber Bragg gratings. The rejection-type of fiber Bragg grating in visible region is successfully fabricated through the zero-order nulled phase mask. Its most significant parameter, out-of-band rejection, for fiber-optic spectroscopic system is tested to ensure the spectral purity of rotational Raman channel. A temperature profile up to a 0.7-km height is obtained by pure rotational Raman lidar with 300-mJ laser pulse energy, and a 250-mm telescope. Preliminary results of observations show that this fiber-optic spectroscopic scheme with high mechanical stability has $>$70-dB suppression to elastic backscattering in lidar echo signals.

1. Introduction

Temperature is one of the important parameters describing the atmospheric state in meteorology. The vertical profile of atmospheric temperature has a specific significance in atmosphere physics. The pure rotational Raman lidar (PRRL) technique was proposed for temperature measurement in 1972. Now PRRL has been widely applied in atmosphere science due to its higher temporal and spatial resolution [1–3].

The high spectral purity extraction of pure rotational Raman signal (PRRS) from lidar echo optical signals is one of the most crucial techniques in PRRL. Therefore the pure rotational Raman spectroscopic system requires at least 70–80 dB suppression to elastic backscattering signals. Several rotational Raman spectroscopic systems had been proposed such as double-grating monochromator or polychromator [4,5], double interference filters [2], grating spectrometer together with atomic-vapor filter [6]. It is clear that these spectroscopic systems adopt two cascades of bulk optical devices to achieve approximately 70–80 dB suppression to elastic backscattering signals. With requirement of global-scale temperature measurement in climate and weather research, space-borne PRRL has become a significant development trend [7]. However, complex adjustments and large volumes or weights of these conventional bulk-optic spectroscopic systems hinder the development of space-borne PRRL.

Fiber Bragg grating (FBG) is an optical-fiber device possessing excellent spectroscopic properties and inherent compatibility with optical-fiber. It has been widely applied in optical communication system and optical-fiber instrumentation including fiber sensors and fiber lasers [8,9]. In order to propel the development of space-borne lidar, Vann et al. had applied firstly FBG technique to a differential absorption lidar (DIAL) for atmospheric water vapor

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measurement, and fabricated successfully a narrowband fiber-optic phase-shifted Fabry–Perot Bragg grating filter at 946-nm wavelength [10]. Mao et al. in our research group had also proposed a pure rotational Raman lidar with FBG spectroscopic system in visible region for profiling atmospheric temperature, and its performances were only simulated through numerical calculation [11]. To our knowledge, most research on FBG technique is focus on near infrared region, whereas a few reports involve visible wavelength FBGs. Lindner et al. had designed a complex combination of phase mask and interferometric inscription technique to fabricate successfully visible wavelength FBG [12]. Carver et al. had applied broadband visible FBGs in confocal spatial scan field [13]. Some previous simulative research on PRRL with fiber-optic spectroscopic system is implemented [14,15].

In this paper, for propelling the PRRL development, a fiber-optic spectroscopic system with high mechanical stability and small volume or weight is configured by two sets of rejection-type FBGs and several fiber couplers (FCs) in visible region. They can extract two-channel PRRSs from lidar echo signals for probing the atmospheric temperature. Their spectral parameters such as out-of-band rejection, central wavelength (CW), maximum reflectivity, and full width at half maximum (FWHM) are tested by experiments. Some preliminary experiments of this fiber-optic spectroscopic rotational Raman lidar have been carried out at Xi'an University of Technology (34.25°N, 108.99°E), and several vertical profiles of atmospheric temperature are demonstrated and discussed to verify the efficient suppression to elastic backscattering.

2. Fiber-optic spectroscopic rotational Raman lidar

The principle of PRRL to measure atmospheric temperature is that pure rotational Raman spectral lines of atmospheric molecules have different sensitivities to temperature. Two PRRSs with different quantum-numbers is usually adopted to retrieve the atmospheric temperature [1–4]. A block diagram of the fiber-optic spectroscopic rotational Raman lidar is shown in Fig. 1. When a pulsed laser light at 532-nm wavelength is transmitted into the atmosphere, the echo signal collected by telescope is transferred to the fiber-optic spectroscopic system to extract two PRRSs. Then these PRRSs are detected by two photomultiplier tubes (PMTs), respectively. Some specification parameters of PRRL are listed in Table 1.

The lidar echo signal is coupled into a single-mode fiber (SMF) through an aspheric lens and then transferred to fiber-optic spectroscopic system, and its outputs are SR_2, SR_{11} and SR_{12}, respectively. There are two sets of FBGs in this fiber-optic spectroscopic system, i.e. FBG1x (x=1–8) and FBG2x (x=1–4). It is noted that each set of FBGs must possess the same CW and similar FWHM. Therefore this fiber-optic spectroscopic system can extract two-channel PRRSs from lidar echo signals, SR_{11} and SR_{12}, SR_2. The utilization of FC1 results in the separation of the low-quantum-number rotational Raman signal into two parts, SR_{11} and SR_{12}. Such two parts are both extracted to improve SNR of PRRL.

CW of each FBG set corresponds generally to certain quantum-number rotational Raman spectral line of nitrogen molecule. The anti-Stokes branch of PRRS is chosen to avoid the influence of atmospheric fluorescence generated from laser excitation. For example, CW of FBG1x in Fig. 1 is 530.4 nm corresponding to quantum-number J=6, whereas that of FBG2x is 529.5 nm corresponding to J=10. FWHM of all FBGs should be theoretically close to spectral line-width of rotational Raman to filter out more background noise. However, it is difficult for FBG fabricating technique, and the typical value of FWHM is approximately 0.2 nm. The relationship between FBG reflective spectra and rotational Raman spectral lines of nitrogen (N_2) and oxygen (O_2) molecules is shown in Fig. 2.

Owing to the absence of optical circulator (OC) in visible region to our knowledge, FC is used to transfer optical signal in fiber-optic spectroscopic system, and then introduces more power loss. The dual-FC FBG unit shown in Fig. 3 is the basic unit of fiber-optic spectroscopic system. Its four FBGs have similar reflective spectra, i.e. the same CW and FWHM. Each FC has four ports, PA, PB, PC, and PD. Clearly, the fiber-optic spectroscopic system shown in Fig. 1 may be build up by three dual-FC FBG units.

The input signal P_i through PA of FC1 is divided into two parts. The optical signal with Bragg wavelength of FBG1 and FBG2 will be reflected, and then divided into two parts

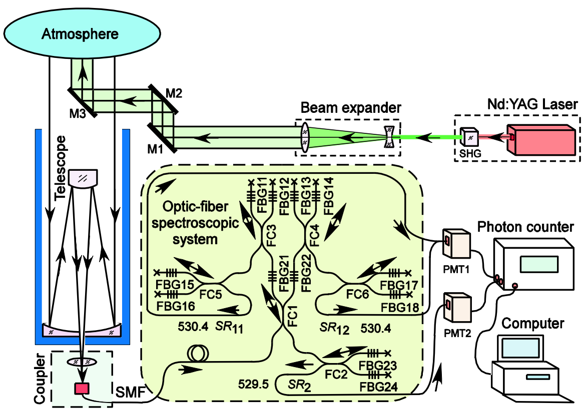

Fig. 1. Layout of fiber-optic spectroscopic rotational Raman lidar.

Table 1
Specification parameters of the fiber-optic spectroscopic rotational Raman lidar.

Laser wavelength	532.0 nm
Laser energy per pulse	300 mJ
Pulse repetition rate	20 Hz
Telescope diameter	250 mm
Coupler	Aspheric lens
Fiber Bragg grating	(wavelength, FWHM)
FBG11018 (Raman-1)	530.4 nm, 0.23 nm
FBG21024 (Raman-2)	529.5 nm, 0.25 nm
Detector	
Photomultiplier tubes	Hamamatsu R7400U-02
Acquisition device	Licel TR40-160
Bin width	25 ns(3.75 m)