Design of optical fiber-grating spectrum-dividing system for NO_2-DIAL

Xu Ben*, Yang Kai, Fang Dawei, Li Jinsong, Li Xiaoyan, Huang Jie
College of Optical and Electronic Technology of China JiLiang University, Hangzhou, 310018

ABSTRACT

Differential Absorption Lidar for detecting atmospheric NO_2 (NO_2-DIAL) is used extensively for its high precision and spatial resolution, and the measurement can be done real-time with a wide range. The design of spectrum-dividing system is a key component of lidar. According to characters of DIAL, such as adjacency of laser wavelength and weakness of received signal, a set of optic fiber-grating spectrum-dividing system is developed. The system has the advantages such as high spectral resolution, efficiently divide lidar echo signals in different wavelengths, weak attenuation, receive and process signals in two channels synchronously, etc. So the SNR of receiving system has improved.

Key words: Atmosphere Optics, lidar, optical fiber, blazed grating, optical design

1. INTRODUCTION

NO_2, as a by-product of industrialization, is harmful to human health and the environment, and its concentration in atmosphere has been increasing in the past few years. Therefore, how to measure the concentration accurately and real time is very important to protect environment and human health[1]. The methods reported in some articles include colorimetric determination coulomb primary cell, chemiluminescence, optical absorption spectroscopy, differential absorption lidar, and so on[2,3]. NO_2-DIAL is used extensively because of its high precision and spatial resolution, and the measurement can be done real time with a wide spatial range[4,5].

Stimulated Raman scattering is generated with a Raman cell full of D_2 pumped by the third harmonic of Nd: YAG laser(354.7nm). The frequency of scattering radiation is

$$\upsilon_{mn} = \upsilon_P + m\upsilon_V + n\upsilon_R \tag{1}$$

where υ_P and υ_{mn} are the frequency of pumped laser and scattering radiation, υ_V and υ_R are the vibrational and rotational Raman frequency-shift of D_2, m, n are the order of stimulated vibrational and rotational Raman scattering. Rest pumped laser (354.7nm) and the first pure rotation Raman scattering(359.9nm , $m=0,n=1$) are absorbed strongly and weakly separately by NO_2, which are chosen as the laser source of NO_2-DIAL[6]. The difference of two beams echo intensity is due to the absorbing of NO_2 but not influenced by air molecule and aerosol. So it is probable to retrieve the distribution of NO_2 according to the difference of two beams echo intensity. The expression of NO_2 concentration can be given as[5]

$$N(z) = \frac{1}{2[\delta_{354.7}(T) - \delta_{359.9}(T)]} \times \{\frac{d}{dz}[-\ln\frac{P_{354.7}(z)}{P_{359.9}(z)}] + B_A + E_A + E_M\} \tag{2}$$

$\delta_{354.7}(T)$ and $\delta_{359.9}(T)$ are the temperature dependent absorption cross-sections of NO_2, T is the temperature. $P_{354.7}(z)$ and $P_{359.9}(z)$ are the photon numbers, corrected terms of B_A and E_A are due to aerosol backscattering and extinction at height of z. They are neglected generally. Term E_M is due to air molecular extinction at the height of z and can be corrected with radiosonde data or atmospheric molecular model. correction factor of atmospheric molecular. The capital letter N(z) is the number density of NO_2 molecules.

Two beams are emitted simultaneously via Raman cell, and propagate along the same path in atmosphere. So the lidar

* xuben@cjlu.edu.cn; phone +8613858080370

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echo signals of two beams are simultaneous acquisition by two channels for retreating atmosphere onflow disturbance. Using double narrow band filters, signal noise ratio (SNR) is low and unsuitable to receive and analyse because of the lower transmissivity transitivity of filters(less than 20%), so that the signals are attenuated seriously, the intensity input to photoelectric detectors is less than 10% of that all received from telescope. A set of optic fiber-grating spectrum-dividing system is designed to resolve the problems above.

2. SYSTEM STRUCTURE

The schematic of spectrum-dividing system of NO_2-DIAL is shown in Fig.1(a). Lidar echo signals received from telescope are coupled into fiber 1, which are multi-wavelength including 354.7nm and 359.9nm. The other side of fiber 1 is set in the focal plane of collimating lens. The light beam transmitting from collimating lens is parallel, and then is dispersed by a blazed grating Which blaze wavelength is 354.7nm. The diffracted beam maintain parallel and converge to focal plane of collimating lens. For different wavelength has different diffraction angles, 354.7nm and 359.9nm optical wave will focus on different spot. In order to avoid beam coupling into fiber 1 again, fiber 1 is placed slightly inclined relative x axis. Then the focused spots of 354.7nm and 359.9nm optical are shown in Fig.1 (c). Fiber 2 and 3 are used to receive the diffracted beams at the two wavelengths, and the other ends of them are connected with PMT1 and PMT2 separately to realize the data acquisition in two channels synchronously.

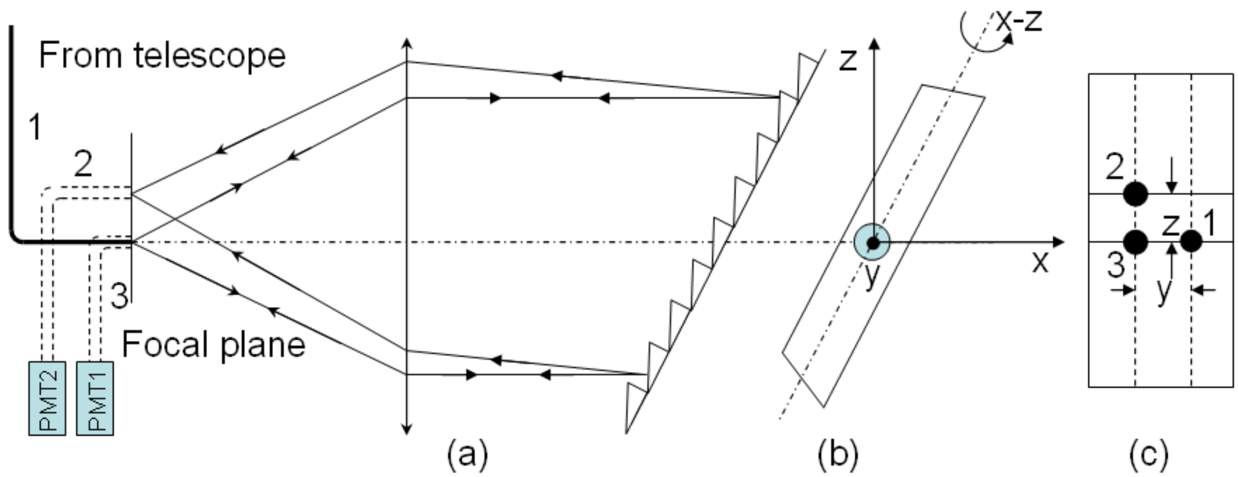

Fig.1 Schematic of the system

3. COMPONENTS

Optical Fiber

The numerical aperture(NA.) is one of important parameters of optical fiber representing the ability of receiving light and the divergence of light output. So it is necessary to consider NA. for higher coupling efficiency.

The divergence of light output from fiber 1 should be as small as possible to make it easier to design lens, fiber 1 is chosen with NA=0.22. The bigger of the fiber diameter, the easier of telescope coupling, on the other hand, the spherical aberration of lens would be bigger. Avoiding the focused spot of two beams in focal plane is bigger than the core diameter of fiber 1, the incident fiber is set with core diameter 0.8mm.

It is useful for fiber 2 and 3 to improve their coupling efficiency with bigger core diameter and NA., and the angular dispersion required of the grating and spectral resolution of the system are dependent on the two factors. Finally, fiber 2 and 3 are set with core diameter 1.3mm and NA.=0.37.

Lens

A lens is used for collimation and imaging in the system. The spherical aberration of lens is considered and color aberration is neglected while design the lens because of the adjacency of laser wavelength. Generally, the former is difficult to correct for single lens, and it may be solved if the core diameter of receiving fiber is bigger than that of the incident to ensure the focused spot of diffracted radiation is smaller than the core diameter of receiving fiber. Applying software ZEMAX, a convexo-convex lens is designed with ZS-1 ultraviolet quartz glass, and its radius of curvature of spherical surface is 373mm and -54mm, aperture is 50mm, focal length is 100mm. The simulated results show the maximum width of focused spot in focal plane via lens is 1.1mm, which is smaller than the core diameter (1.3mm) of receiving fiber.

Blazed grating

It is possible to shift energy out of the useless zeroth order into one of the higher-order spectra using a blazed grating[7]. The schematic is shown in Fig.2, where n and N are normal to the grating groove surfaces and grating plane, α and β are the incident angle and diffracted angle of light wave, φ is the angle of incident light wave which is normal to the grating groove surfaces. The relation of these parameters can be given as

$$\sin\alpha + \sin\beta = m\lambda/d \tag{3}$$

which is known as the grating equation. m denotes the order of the various principal maxima, d is grating constant. The spectrum intensity is considerable at the range of wavelength around of blazing wavelength. Generally, when a incident wavelength is 2/3 to 2 times to blaze wavelength, the diffraction efficiency is high enough.

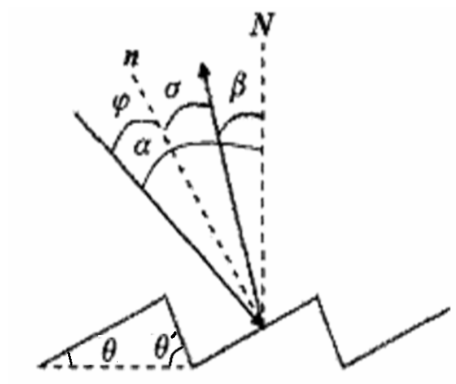

Fig.2. Section of a blazed reflection grating.

The spectrum-dividing system in this paper is used to separate two beams at 354.7nm and 360nm. For saving the cost of grating, we choose a common blazed grating blazing at 354.7nm.

Differentiating the grating equation (3) yields,

$$\cos\alpha d\alpha + \cos\beta d\beta = \frac{m}{d} d\lambda \tag{4}$$

The two beams output from the end of fiber 1 propagate along the same path via the lens, So $d\alpha = 0$ if the focus length difference between two beams is neglected. Grating angular dispersion can be obtain

$$\frac{d\beta}{d\lambda} = \frac{1}{\cos\beta} \cdot \frac{m}{d} \tag{5}$$

The linear dispersion of the diffraction grating D is dependent on the focus length *f* of lens, and it is given as

$$D = f\frac{d\beta}{d\lambda} = f\frac{1}{\cos\beta} \cdot \frac{m}{d} \tag{6}$$

The two adjacency fibers are used to receive the beams with wavelength 354.7nm and 359.9nm separately, so the distance of two focus spots should be equal to the diameter of fibers A (=1.3mm) at least.

$$f\frac{1}{\cos\beta}\cdot\frac{m}{d}\cdot\Delta\lambda\geq A$$

(7)

where $\Delta\lambda=359.9-354.7=5.2nm$, f=100mm. The blazing angles resolved based on eq.(7) and eq.(3) with d=1/600 mm and d=1/1200 mm at 354.7nm separately are shown in table 1.

Tabel1. Range of diffractive angle relative to the order of grating and the calculated blazed angle relative to the order of grating

Order of grating	d=1/1200 mm		d=1/600 mm	
	Arrange of angle of meeting of the necessity of optical system / (°)	Calculated blazed angle / (°)	Arrange of angle of meeting of the necessity of optical system / (°)	Calculated blazed angle / (°)
1	>61.3146	12.2877	>76.1135	6.1084
2	>16.2602	25.1912	>61.3146	12.2877
3	Any	39.6771	>43.9455	18.6164
4	Any	58.3512	>16.2602	25.1912
5		nonentity	Any	48.1479

From the table above, it can be concluded

(1) For the 2nd order, the two beams light can be separated if d=1/1200mm. The distance z=1.31mm between the two spots in the focus plan is obtained theoretically applying eq.(7),and it is just bigger than the core diameter of fiber 2(1.3mm). Considering of the thickness of cladding, the difficulty of fabricating the fiber with high precision, and spectral width of lights coupled into fiber 2 and 3, it is unsuitable for extraction and analysis of lidar signal to choose the 2nd order diffraction light.

(2) For the 3rd order, the distance z=2.43mm is obtained theoretically if d=1/1200mm, which is bigger more than the core diameter of fiber 2 or 3. And the whole spectral width $\Delta\lambda'$ of lights coupled into the two fibers can be given based on the following expression

$$f\frac{1}{\cos\beta}\cdot\frac{m}{d}\cdot\Delta\lambda'\leq 1.3 \tag{8}$$

The result is $\Delta\lambda'\leq 2.78nm$, which meets the requirement of lidar.

The radiation collection efficiency of grating is defined as the energy ratio of one order diffraction radiation to all the monochromic, and it is equal to the energy ratio of one order diffraction radiation G_k to the sum of diffraction,

$$E_\lambda(k)\approx\frac{G_k}{\sum G} \tag{9}$$

According to the formula of energy distribution of diffracted radiation obtained by Roland [8]

$$G_k\sim\lambda^2[\sin\frac{\pi a(\mu-cl)}{\lambda}]^2\times[\frac{\sqrt{1+c^2}}{\mu-cl}-\frac{\sqrt{1+c'^2}}{\mu+c'l}]^2 \tag{10}$$

Where $c=\tan\theta,\mu=\frac{k\lambda}{d}=\sin\alpha+\sin\beta,l=\cos\alpha+\cos\beta$, and $c'=\tan\theta'$. Under the condition of autocollimation, it can be concluded that only the zeroth, 1st, 2nd, and 3rd order spectra are exist applying eq.(3), and the radiation collection efficiency of grating for the existent can also be obtained using eq.(9) and eq.(10). The result is shown in fig.3. The radiation collection efficiency of the 3rd order to 354.7nm and 359.9nm is bigger with the increase of θ', and it reaches the biggest when θ' is a certain value, then it will decrease if θ' increases further. When $\theta' \approx 70^o$, the radiation collection efficiency of the 3rd order to 354.7nm and 359.9nm is almost equal (94.5%) , which is close to the biggest efficiency of each.

Considering the reflection on the surfaces of lens, optic fiber and grating, some kinds of reflection or anti-reflection Films are coated on them.

The length and width of grating is described as following,

$$a = \tan(\arcsin 0.22) \times 100 \times 2 = 45.1mm$$
$$b = 45.1 / \cos 39.6771^0 = 58.6mm \tag{11}$$

The blazing angle for the 3rd order of 354.7nm radiation is equal to the 1st order of 1064nm radiation, so we can choose a blazed grating for the 1st order to 1064nm, which is a standard and popular product, and needn't to design blazed grating specially, then the cost can be saved.

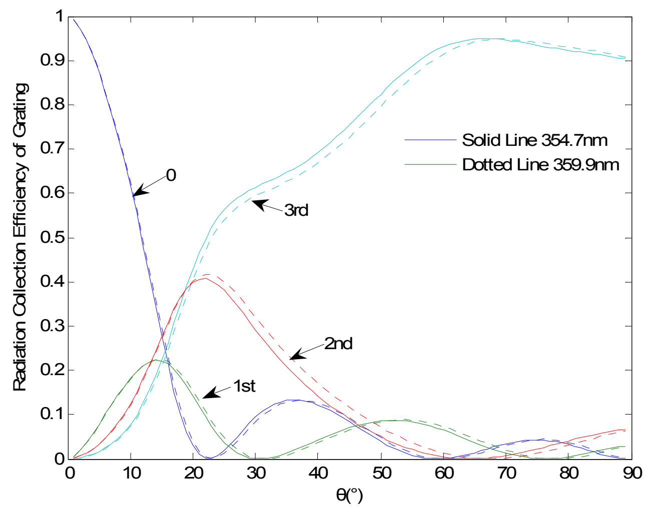

Fig.3. The radiation collection efficiency of grating VS the degree of grooves θ' of grating.

(3) If d=1/600mm, the 4th order is blazed, which is equal to the 2nd order for d=1/1200mm, and the analysis is presented above. For the 5th order, z=2.34mm in theory, higher the order of blazing radiation, lower the diffraction efficiency, so it is unsuitable for lidar to detect the weak signal. Furthermore, the area of grating is required to be larger as the order increases, which make it more difficult and expensive to produce a big grating.

From the above discussion, a blazed grating is proposed, and the 3rd order of 354.7nm radiation is blazed with d=1/1200mm.

4. CONCLUSIONS

According to characters of NO_2-DIAL, such as adjacency of laser wavelength and weakness of received signal, a set of optic fiber-grating spectrum-dividing system composed with several optic fibers, a lens and a blazed grating is designed. Some numerical results imply the proposed system can divide the two beams of 354.7nm and 359.9nm efficiently and its attenuation is weak. The SNR of lidar is improved instead of using interference filters. The system is also suitable for other DIAL systems with little modification.

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