第 19 卷　第 2 期
2011 年 2 月

光学 精密工程
Optics and Precision Engineering

Vol. 19　No. 2
Feb. 2011

文章编号　1004-924X(2011)02-0445-07

用于燃烧场诊断的分子滤波瑞利散射技术

王　晟，刘晶儒，胡志云，张振荣，叶景峰，张立荣
（西北核技术研究所 激光与物质相互作用国家重点实验室，陕西 西安 710024）

摘要：为了测量燃烧场的热力学性质，研究了分子滤波瑞利散射技术。分子滤波瑞利散射技术采用窄线宽激光器、分子滤波器和像增强 CCD 相机，通过分子吸收凹陷检测激光片照射流场产生散射光的频谱，抑制背景杂散光和米散射，解析流场热力学信息。建立了分子滤波瑞利散射诊断系统和分子滤波器，根据测得的滤波图像和碘蒸气吸收光谱，获得了甲烷一空气预混火焰的温度场和密度场。测量结果显示，距离标定燃烧炉表面 15 mm 处火焰的密度为 0.19 kg/m^3，温度为(1827±84) K，与 CARS 法测是结果基本吻合，测温不确定度为 8%。分子滤波瑞利散射技术还成功应用于水雾和高速喷流结构的诊断，获得了激光作用区的湍流结构。实验表明，分子滤波瑞利散射技术能够测量燃烧场温度和密度，并能用于流场可视化。

关　键　词：
中图分类号：O657　　**文献标识码：**A　　**doi：**10.3788/OPE.20111902.0445

Development of filtered Rayleigh scattering for combustion diagnostic application

WANG Sheng, LIU Jing-ru, HU Zhi-yun, ZHANG Zhen-rong, YE Jing-feng, ZHANG Li-rong

(*Northwest Institute of Nuclear Technology*, *State Key Laboratory of Laser Interaction with Matter*, *Xi′an* 710024, *China*)

Abstract: A molecular Filtered Rayleigh Scattering (FRS) diagnostic system was demonstrated to measure thermodynamic properties in combustion environments. The diagnostics system was composed of a narrow line width laser, a molecular/atomic absorption filter and a collection device such as ICCD. The absorption filter was used to modify the spectra of the Rayleigh scattering signal from the flow field illuminated by a laser sheet from a Nd:YAG pulsed laser. The laser was tuned to an absorption line of iodine vapor contained in the filter. This caused Mie scattering and background scattering from solid particles and strong absorption on the surface while much of Doppler broadened Rayleigh scattering was transmitted through the filter. The thermodynamic parameters were deduced from the measured transmission of the molecular Rayleigh scattering. The FRS diagnostic system and the iodine filter cell were described. On the basis of diagnosing FRS image and measuring iodine vapor absorption spectrum, the 2D temperature and density fields of methane/air premixed flame were obtained. The measured density at 15 mm above the burner surface is 0.19 kg/m^3, and temperature is (1

收稿日期：2010-10-08；**修订日期：**2010-10-30.
基金项目：国家重点实验室基金资助项目(SKLLIM0905)

827±84) K, which is good agreement with the results measured by using CARS method in the same condition. The uncertainty of temperature measurement by FRS is less than 8%. Furthermore, FRS technique was used to diagnose the atomization steam and supersonic exhaust flows. The results turbulence structures on the area of laser action were obtained. These demonstrate the abilities of the FRS technique to measure temperature and density fields and to enhance flow visualization in a combustion environment.

Key words: spectroscopy; temperature; density; iodine filter cell; diagnostic in combustion; Rayleigh scattering

1 Introduction

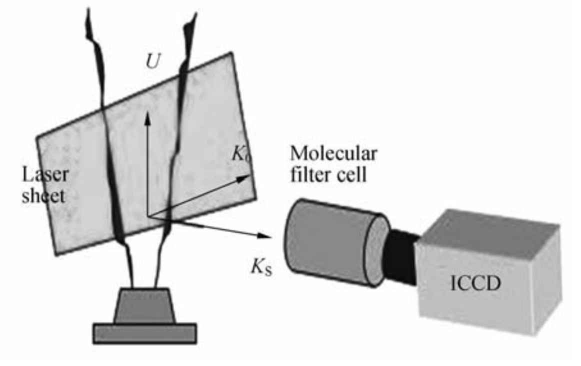
Laser combustion diagnostic techniques are applied to investigate the high temperature combustion flows and turbulent flows for its advantages of non-intrusive, on-line, good temporal and spatial resolution and visualization. These techniques have been developed rapidly in U. S. , France, Germany, Sweden, Australia and other developed countries since 80's of last century[1-4], which played an important role on design and development of engines for automobiles, airplanes, missiles, *etc*.

Laser Rayleigh scattering[5-6] (LRS) technique is an embranchment of laser combustion diagnostic techniques, which was first demonstrated for 2D temperature imaging in flames by Fourguette[7]. LRS has the advantage of simplicity but the disadvantage of weak signal strength, which can be quickly overwhelmed by Mie scattering from solid surfaces, room particulates and soots. Filtered Rayleigh scattering (FRS) is a modification of the LRS technique, first put forth by Miles *et al*.[8], which takes advantage of the full-field, unseeded capabilities of LRS while providing increased rejection of Mie scattering interferences from the illuminating laser line. This significant rejection of background noise is achieved by placing a molecular iodine vapor cell in front of the detector and using an injection-seeded Nd:YAG laser to tune the laser line to an absorption maximum of the hyperfine iodine spectrum. The seeded laser line shape and associated Mie scattering are thereby strongly rejected while a significant portion of the Doppler-broadened Rayleigh signal leaks past the filter and reaches the detector. The FRS technique can be used to enhance flow visualization, or to make quantitative measurements of thermodynamic properties, which is widely applied to sooting flames, plasma, supersonic and hypersonic flows, and so on[9-11].

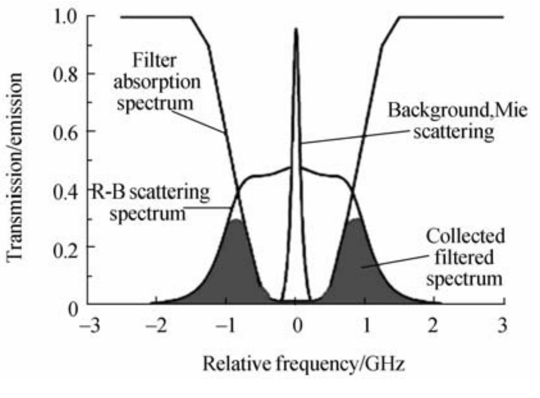
In this work, we present the construction and performance of a FRS instrument for quantitative 2D temperature imaging. The paper begins with a brief summary of FRS working principles, followed by a description of FRS instrument. Results of temperature and density of a premixed flame are presented, which are compared to CARS temperature measurements to validate the accuracy of our FRS measurements. The measurement uncertainty is provided in the discussion. Also, the FRS technique is used to enhance flow visualization of water atomization steam and supersonic exhaust flows.

2 FRS working principle

A schematic diagram of the FRS method is shown in Fig. 1. FRS is an extension of the traditional LRS imaging technique, in which a molecular filter is placed in front of the detector, usually an intensified CCD camera as shown in Fig. 1(a). A frequency-doubled Nd:YAG laser is typically used to measure the Rayleigh scattering. A molecular iodine vapor, which has hyperfine absorption in the vicinity of the 532 nm laser output, is employed as the filter molecule. When the Nd: YAG oscillator is injection seeded, the output line width is an order of magnitude less than the I_2 absorption line width. Injection seeding also allows to tune the laser output over a narrow about 1 cm^{-1} range, so that the laser line can be made coincident with a strong absorption maximum. As seen in Fig. 1 (b), strong Mie scattering and background noise, which have the same spectral profile as the laser line shape, are significantly attenuated by the filter while a significant portion of the Doppler-broadened Rayleigh signal leaks past the filter and reaches the detector.



(a) FRS imaging configuration



(b) Spectral profiles of molecular filter and nitrogen Rayleigh line shapes

Fig. 1　FRS working principle

The FRS signal must be related to the physical variable of interest such as laser intensity and thermodynamic properties of flow, which can be written as

$$S = CI_0 n \sum_k x_k \frac{d\sigma}{d\Omega}(\varphi)_k \int R_k(v, \Delta v_D, p, T, M_k)\tau(v)dv \ , \tag{1}$$

In Eq. 1, S is the intensity of FRS signal which most generally depends upon temperature, pressure, and the local chemical composition, C is a calibration constant associated with the FRS optical system, I_o is the local laser light-sheet intensity, $n=p/kT$ is the local number density, x_k is the mole fraction of the kth species present locally in the flow field, $(d\sigma/d\Omega)_k$ is the differential Rayleigh cross section for the kth species, M_k is the molecular weight of the kth species, v is the light frequency, $\tau(v)$ is the measured transmission spectrum of the molecular filter, $\Delta\nu_D$ is frequency shift of scattering, and $R_k(\nu, \Delta\nu_D, p, T, M_k)$ is the normalized Rayleigh line-shape function for the kth species calculated from the S_6 model of Tenti *et al*.[12].

Frequency shift of scattering due to the Doppler shift can be given by

$$\Delta\nu_D = \frac{1}{\lambda} | \boldsymbol{v} \cdot (\boldsymbol{e}_s - \boldsymbol{e}_o) | \ . \tag{2}$$

Where $\boldsymbol{e}_o$ and $\boldsymbol{e}_s$ are the incident and observed unit light wave vectors, respectively, and $\boldsymbol{v}$ is the flow velocity vector.

By the measure image divided by a reference image recorded in room-temperature air, the optical calibration constant and local laser-beam intensity dependence can be removed. For constant-pressure flow fields, this process yields the following expression for the normalized FRS signal,

$$\frac{S}{S_{ref}} = \frac{T_0}{T} \frac{\sum_k x_k \sigma_k(T)}{0.21\sigma_{O_2}(T_0) + 0.79\sigma_{N_2}(T_0)} \ , \tag{3}$$

Where T_0 is the reference temperature (usually 300 K) and σ_k is defined as a temperature dependent FRS cross section,

$$\sigma_k(T) = (d\sigma/d\Omega)_k \int R_k(v, p, T, M_k)\tau(v)dv, \tag{4}$$

FRS signal curves are shown in Fig. 2. Each curve has been calculated from Eq. 3 for methane/air premixed flame of different equivalence ratios. In Fig. 2, density can be calculated by the equation $\rho=\bar{\mu}p/RT$, where $\bar{\mu}$ is an average molecular mole mass.

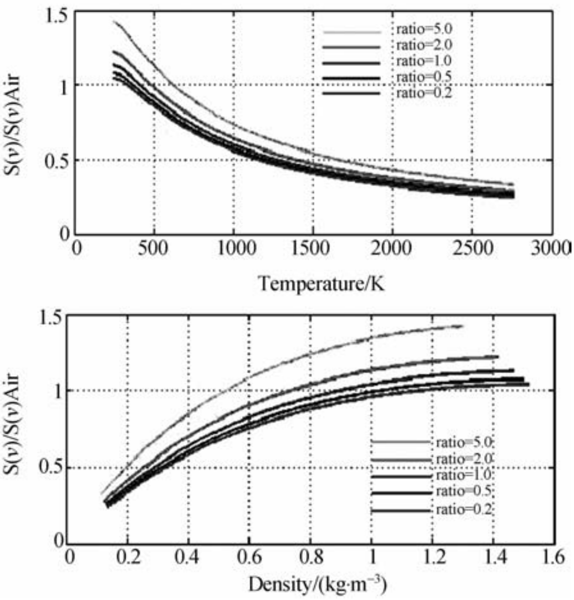


Fig. 2 FRS signal curves as a function of temperature and density calculated for methane/air premixed flame of different equivalence ratios

3 FRS optical system

3.1 System optical layout

Fig. 3 shows a schematic diagram of the FRS optical arrangement. An injection seeded frequency-doubled Nd:YAG laser is used in FRS system. The output of the laser can be tuned by applying a bias voltage to the heater circuit of the CW seed laser. This tuning capability allows the seeded Nd : YAG output be matched to the hollow center of I_2 absorption spectrum so that the narrow band Mie scattering light produced by the flame can be absorbed and the broadened Rayleigh scattering can be passed partly to provide a detected signals. The output of the YAG laser is split into two ways. The 3% of the laser energy is used to detect the laser power and frequency on-line. The laser beam with 97% of energy passes through a half-wavelength plate that is used to change the polarization of the laser beam, and a spherical lens and a cylindrical lens which are used to form a laser sheet and then travels through the flame. The Rayleigh scattering from the combustion is then imaged through an iodine filter cell and a narrow band-pass filter onto a 12-bit intensified CCD camera.

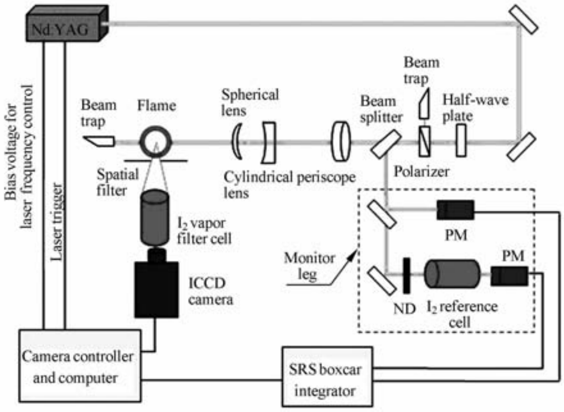


Fig. 3 Schematic of molecular FRS system

3.2 Iodine filter cell

Configuration of the molecular iodine filter cell is shown in Fig. 4. The iodine filter is a glass cylinder with optically flat windows on each end. Iodine vapor is formed in the cell by placing a small amount of iodine crystals in the side arm of the cell and evacuating the cell. The cell temperature is raised above the ambient temperature so that no iodine crystallizes on the windows. The cell temperature is elevated with insulated electrical heat tape. The coldest point in the cell is set in a side arm. The temperature of the side arm controls the vapor pressure

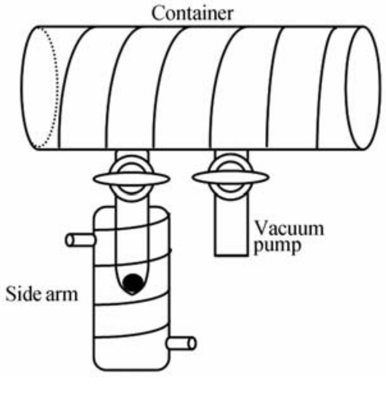


Fig. 4 Schematic of iodine filter cell

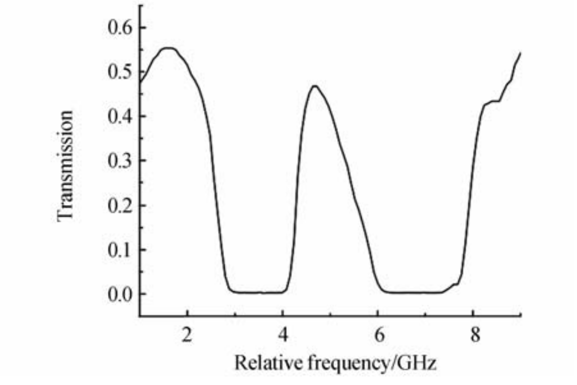


Fig. 5 Measured absorption line of iodine

(number density) of the iodine in the filter cell.

The tunable narrowband Nd : YAG laser with a narrow line width at a wavelength of 532 nm can be tuned across the absorption bands of iodine. Fig. 5 presents a measured absorption line of iodine at 18 788.4 cm^{-1}.

4 Results and discussion

4.1 Methane/air premixed flame

As a first step toward applying the FRS instrument for combustion thermometry, the temperature field in the premixed methane/air flame provided by a Hencken burner is measured. On the basis of diagnosing FRS images and measuring iodine vapor absorption spectrum, temperature and density of methane/air premixed combustion is obtained. Fig. 6 shows the typical measurement results of temperature and density in methane/air premixed combustion field for $\phi=1$. It is seen that the measured density at 15 mm above the burner surface is 0.19 $\mathrm{kg/m^3}$, and the temperature is (1 827±84) K which is good agreement with the result measured by using CARS method in the same condition[13]. The relative uncertainty of temperature measurement by FRS is less than 8%[14].

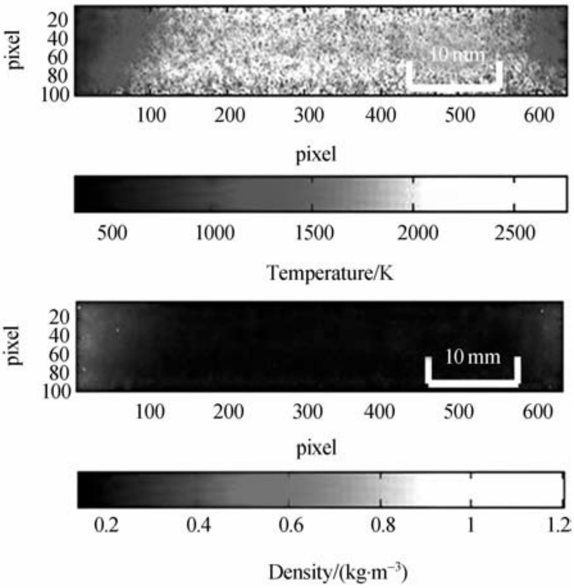


Fig. 6 Temperature and density of methane/air flame ($\phi=1$, $d=15$ mm) measured by FRS

4.2 Water atomization steams

The water atomization steams are diagnosed using FRS. Fig. 7 shows the turbulence structures on the area of laser action. In general, there are two sources of unwanted scattering: surface scattering due to walls and windows and scattering due to particles present in the flow. If the iodine filter is not present, the images of the pulverization flows would be saturated by particle and background scattering. Using the iodine filter, the scattering from walls and windows could be significantly absorbed. Since molecular Rayleigh scattering experiences thermal broadening, a portion of the scattering can pass outside of the absorption profile, even when the center of the profile coincides with line-center of the iodine transition.

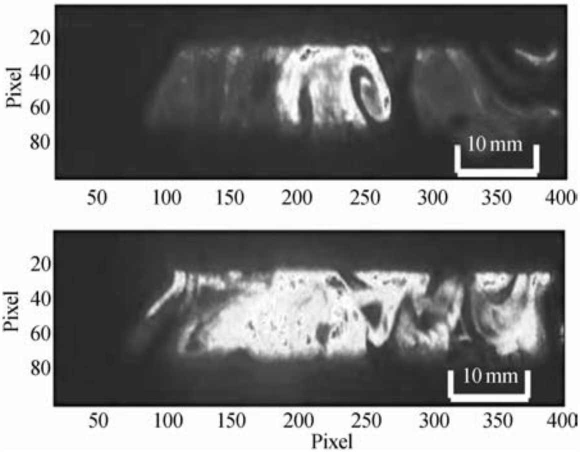


Fig. 7 Images of water atomization steam using FRS

4.3 Supersonic exhaust flows

Another example shows the potential of FRS to improve the flow visualizations. The supersonic exhaust flows were diagnosed using FRS. Considering the Doppler shift effect, observation, incident laser and stream wise directions are accomplished orthogonally each other so that the Mie scattering is not shifted completely out of the absorption line, as shown in Fig. 8. With this arrangement, the FRS system is not sensitive to Doppler shift in the stream wise direction. Thus, the scattering intensity variations results primarily from density and temperature variations.

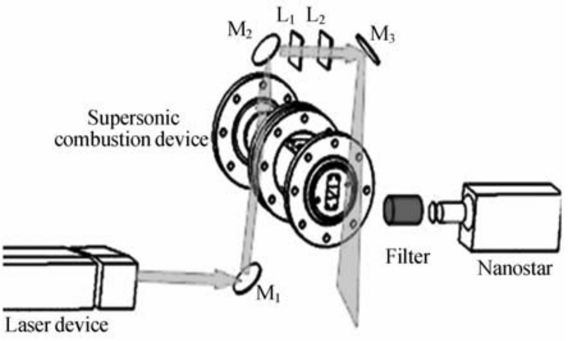


Fig. 8 Schematic of FRS applied to supersonic exhaust flows

The supersonic exhaust flow is from right to left and the laser sheet propagation direction is from top to bottom of the image, as shown in Fig. 9. Using the iodine filter, the signal-to-noise ratio is sufficient to observe the turbulence structures in the flow field.

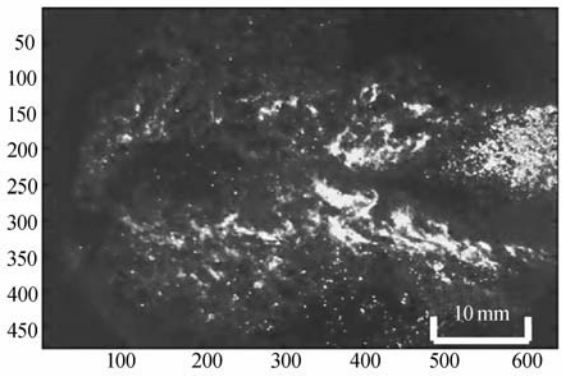


Fig. 9 Visualization of supersonic exhaust flows

5 Conclusions

On the basis of diagnosing FRS images and measuring iodine vapor absorption spectrum, the methane/air premixed flames were diagnosed and the 2D temperature and density fields were obtained. The measured density at 15 mm above the burner surface is 0.19 kg/m^3, and temperature is (1 827±84) K which is good agreement with the results measured by using CARS method in the same condition. The uncertainty of temperature measurement by FRS is less than 8%. Water atomization steams and supersonic exhaust flows were diagnosed for flow visualization. These demonstrate the abilities of the FRS technique to measure the temperature and density field and to enhance flow visualization in a combustion environment.

References:

[1] ZHANG P, CHENG XL. Recent Development on Combustion Diagnostics Technique[J]. *Journal of Solid Rocket Technology*, 1998,21(2):66-70. (in Chinese)

[2] LIU CH W, CHENG W M, LIU J. Intelligent control and application of two-dimensional counting-tracing LDA measurement system[J]. *Opt. Precision Eng.*, 2002,10(6):639-643 . (in Chinese)

[3] HU ZH Y, LIU J R, GUAN X W, *et al.*. Study on laser diagnostics applied to combustion and flame [J]. *High Power Laser and Particle Beams*, 2002,14(5):702-706. (in Chinese)

[4] ZHU L, XU J L, KONG F R, *et al.*. Effect of hydrogen/air ratio on combustion performance of micro combustor[J]. *Opt. Precision Eng.*, 2008,16(11):2214-2221 . (in Chinese)

[5] JIANG L Y, SISLIAN J P. Rayleigh Scattering in Supersonic High Temperature Exhaust Plumes[C]. *38th AIAA Aerospace Sciences Meeting & Exhibit*, 10-13 *January* 2000, *Reno*, *Nevada*, *AIAA*-2000-0779.

[6] YUAN X Q, ZHAO Q, CHEN Y R, *et al*.. Scattering method applied to detect the particle properties in a multiple particle field[J]. *Opt. Precision Eng.*, 2005,13:5-8. (in Chinese)

[7] FOURGUETTE D C, ZURN R M, LONG M B. Two-Dimensional rayleigh thermometry in a turbulent nonpremixed methane-hydrogen flame [J]. *Comb. Sci. Tech*, 1986,44:307-317.

[8] MILES R B, LEMPERT W R, FORKEY J N. Instantaneous velocity fields and background suppression by filtered Rayleigh scattering[C]. 29*th AIAA Aerospace Sciences Meeting & Exhibit*, 7-10 *January* 1991, *Reno*, *Nevada*, *AIAA*-1991-0357.

[9] HOFFMAN D, MUNCH K U, LEIPERTZ A. Two-dimensional temperature determination in sooting flames by filtered Rayleigh scattering[J]. *Opt. Letters*, 1996,21(7):525-527.

[10] ELLIOTT G S, GLUMAC N, CARTER C D. Two-dimensional temperature field measurements using a molecular filter based technique [J]. *Comb. Sci. Tech*, 1997,125:351-369.

[11] ELLIOTT G S. Toward Multiple Property Measurements [C]. 39*th AIAA Aerospace Sciences Meeting & Exhibit*, 8-11 *January* 2001, *Reno*, *Nevada*, *AIAA* 2001-0301.

[12] TENTI G, BOLEY C D, RASHMI C D. On the kinetic model description of rayleigh-scattering from molecular gases[J]. *Canadian Journal of Physics*, 1974, 52(4):285-290.

[13] ZHANG Z R, HU ZH Y, HUANG M SH, *et al*.. Measurement of temperature in a combustion field by Boxcars[J]. *High Power Laser and Particle Beams*, 2003,15(4):323-325. (in Chinese)

[14] WANG S, LIU J R, HU Z Y, *et al*.. Molecular filtered Rayleigh scattering diagnostic for meaurement of temperature and density in flame [J]. *High Power Laser and Particle Beams*, 2008, 20(12):2001-2005. (in Chinese)

作者简介:

王　晟(1977—),男,山东乳山人,工程师,1999 年于天津大学获得学士学位,2008 年于西北核技术研究所获得硕士学位,主要从事激光技术及应用方面的研究。E-mail: pplunum1@163.com

刘晶儒(1945—),女,辽宁沈阳人,研究员,1967 年毕业于哈尔滨工业大学,主要从事激光技术及应用方面的研究。E-mail: liujingru2k3@vip.sina.com

胡志云(1969—),男,河南 人,博士研究生,高级工程师,1993 年于哈尔滨工业大学获得学士学位,1998 年于西北核技术研究所获得硕士学位,主要从事激光技术及应用方面的研究。E-mail: ninthzy@163.com

张振荣(1974—),男,陕西蒲城人,副研究员,1997 年于西北工业大学获得学士学位,2004 年于西北核技术研究所获得硕士学位,主要从事激光技术及应用方面的研究。E-mail: nintzzr@163.com

叶景峰(1979—),男,河南西平人,助理研究员,2001 年于国防科技大学获得学士学位,2004 年于国防科技大学获得硕士学位,主要从事激光技术及应用方面的研究。E-mail: leafey1979@163.com

张立荣(1980—),男,北京人,助理研究员,2003 年于天津大学获得学士学位,主要从事激光技术及应用方面的研究。E-mail: oreelue@163.com