Pressure-sensitive blackbody point radiation induced by infrared diode laser irradiation

Feng Qin,[1,2] Hua Zhao,[3,5] Yangdong Zheng,[1] Zhemin Cheng,[1] Peng Wang,[1] Changbin Zheng,[1] Ying Yu,[1] Zhiguo Zhang,[1,2,6] and Wenwu Cao[2,4,7]

[1]*Department of Physics, Harbin Institute of Technology, Harbin 150001, China*

[2]*Laboratory of Sono- and Photo-theranostic Technology, Harbin Institute of Technology, Harbin 150001, China*

[3]*School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China*

[4]*Materials Research Institute, The Pennsylvania State University, Philadelphia, Pennsylvania 16802, USA*

[5]*e-mail: Zhaoh@hit.edu.cn*

[6]*e-mail: Zhangzhiguo@hit.edu.cn*

[7]*e-mail: dzk@psu.edu*

Received March 24, 2011; revised April 1, 2011; accepted April 11, 2011; posted April 12, 2011 (Doc. ID 144733); published May 9, 2011

Ultrabroadband radiation from Yb_2O_3 at ambient and low air pressures was investigated under the excitation of a 980 nm diode laser. The radiation was confirmed to be blackbody radiation, and it is sensitive to environmental air pressure in the way that the integrated radiation intensity decreases linearly with increasing air pressure. An ideal gas model may be employed to interpret the linear dependence. The pressure-sensitive radiation characteristic provides a potential method for noncontact measurement of air pressure with high accuracy.

OCIS codes: 350.5610, 290.6815, 280.6780, 280.5475.

Trivalent rare-earth ions, due to their unique spectral properties of the 4*f* electrons, have been widely used to activate luminescence, and they have found extensive applications in fluorescent lamps, solid-state lasers, and optical amplifiers in fiber optics. [1,2]. In recent years, there has been an increasing interest in studying optical properties and related physical mechanisms of rare-earth-doped materials by laser excitation spectroscopy [3,4]. Among rare-earth ions, the trivalent ytterbium (Yb^{3+}) ion is the most interesting element. First, the Yb^{3+} ion has the simplest energy structure compared to other trivalent rare-earth ions with only two energy levels. Second, the energy structure of the Yb^{3+} ion matches well with the widely used commercial 980 nm diode laser, which makes it an excellent sensitizing ion [5]. Third, by irradiation of well-matched infrared (IR) lasers upon the Yb^{3+} ions, ultrabroadband luminescence can be excited, which could be used as a blackbody radiator [6]. In this Letter, we report a study on high-temperature blackbody radiation of Yb_2O_3 at ambient and low air pressures under the excitation of a 980 nm diode laser. The blackbody radiation point source made by our method can have a much smaller size ($<1\,mm^2$) than traditional blackbody sources. More importantly, the optical excitation method for blackbody radiation is noncontact, which has many advantages compared to traditional electrical driven blackbody sources used for spectrum calibration. The integrated intensity of the ultrabroadband emission is very sensitive to the environmental air pressure, and, therefore, one may utilize the sensitive pressure-dependence emission for noncontact measurement of air pressures [7].

Broadband emissions from oxide nanopowders doped with Yb^{3+} ions and other rare-earth ions have been reported [6,7]. In order to eliminate the effects of other active ions, and focus on the essential nature of Yb^{3+} ions, raw Yb_2O_3 powders of 99.99% purity were used for our study, which were obtained from the National Engineering Research Center of Rare-Earth Metallurgy and Function Materials (Inner Mongolia, China). The Yb_2O_3 powders were pressed under 100 MPa pressure into a smooth and flat disk. The disk was mounted inside a closed chamber connected to a vacuum pump. The ultimate minimum pressure of the closed system was 200 Pa. A 980 nm diode laser with maximal output power of 1 W was used as the excitation source. The collimated IR laser was focused on the disk by a convex lens with a focal length of 5.0 cm. The induced bright luminescence was analyzed by a miniature fiber optic spectrometer (Ocean Optics, USB 2000) and recorded by a connected computer. The fluorescence measurement system was calibrated by a tungsten filament lamp (12 V, 1.685 A, 243 lm).

Figure 1 shows the emission spectra of the sample induced by the IR laser (red curve), and the luminescence spectrum of the tungsten filament lamp (black curve) for comparison. One can see that the sample generated similar wideband radiations as that of the tungsten filament lamp although the luminescence intensity from the lamp is much higher than that from the sample. The color temperature of the tungsten filament lamp is 2742 K. According to the spectrum distributing of the standard lamp given by the manufacturer, the relative response of the measurement system can be acquired. By dividing the system response spectrum, the calibrated photoluminescence spectrum has been acquired as shown in Fig. 2. Based on the Planck radiation formula, the color temperature of the Yb_2O_3 radiator is fitted to be 1778 (10) K. Therefore, the tungsten filament lamp is brighter than the Yb_2O_3 radiator not only because of larger radiation area, but also because of the higher color temperature. Because of the limitations of our spectrometer, the measured data only constitute a small portion of the whole blackbody radiation spectra.

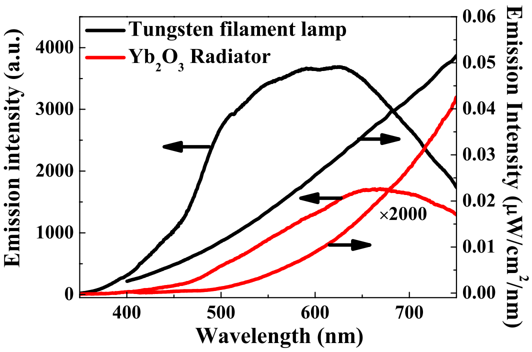

Fig. 1. (Color online) Measured radiation spectra of the Yb_2O_3 radiator (red curve) and the tungsten filament lamp (black curve). The left scale is for the original measured spectra and the right scale is for corresponding calibrated spectra.

Since the calibrated spectrum corresponds well with the Planck's law, the wideband emission can be considered as blackbody radiation. However, the photoinduced blackbody radiation mechanism is still not clear at the moment. We believe that the matching between the pumping light energy and the energy gap of Yb^{3+} plays an important role in the observed photoinduced blackbody radiation, but the exact mechanism still needs to be worked out in the near future.

There are only two energy states for trivalent ytterbium ion, i.e., the ground state $^2F_{5/2}$ and the first excited state $^2F_{7/2}$. When the $^2F_{5/2}$ state of Yb^{3+} is excited by a 980 nm laser, the $^2F_{5/2}$ level can be populated. The population of the $^2F_{5/2}$ state could be kept stable through the balance of decay processes, spontaneous radiation, and nonradiative multiphonon relaxation. With the increase of the pumping power, the population of the excited state is increased. When the pumping laser power exceeds a threshold, photoinduced blackbody radiation occurs, which agrees with the power-dependence curves illustrated in Figure 4 of [6].

Since the photoinduced radiation is thermal radiation, the collision of air molecules on the radiation area would greatly affect the radiation intensity, i.e., the radiation should be sensitive to the surrounding air pressure. To verify the effect of the environmental pressure on the

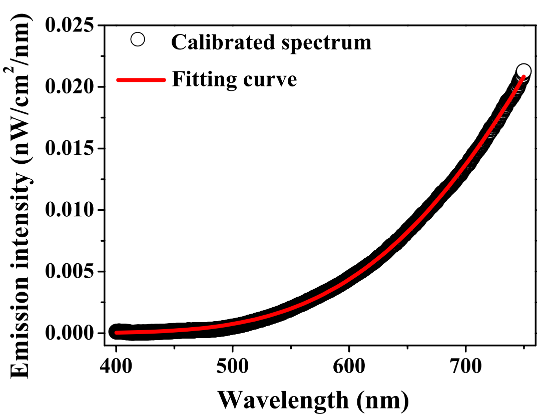

Fig. 2. (Color online) The discrete black circles are the calibrated emission spectrum of the Yb_2O_3 radiator under atmospheric pressure. The red solid curve is a Planck distribution fit ($T = 1778 \pm 10$ K).

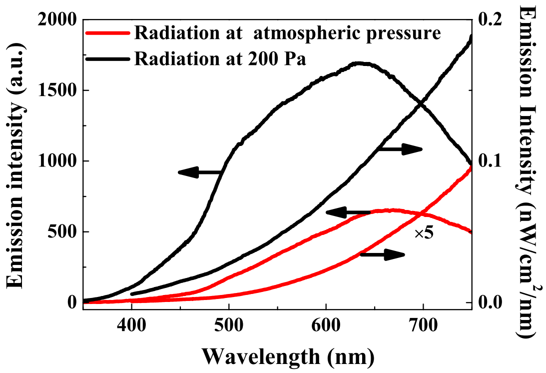

Fig. 3. (Color online) Comparison of radiation under 200 Pa pressure (black curve) with that under atmospheric pressure (red curve). The left scale is for the original measured spectra and the right scale is for corresponding calibrated spectra.

photoinduced blackbody radiation, we have performed an experiment in a closed chamber connected to a vacuum pump. Our measurement results indicated that the intensity of the fluorescence at 200 Pa was 14 times stronger compared to the fluorescence at ambient pressure as shown in Fig. 3, and the color temperature of the Yb_2O_3 radiator was fitted to be 2304 (10) K.

For an ideal gas, the gas pressure can be expressed as $P = nkT$. Here, n is the number density of the molecules, k is the Boltzmann constant, and T is the temperature in Kelvin. According to the Maxwell distribution of molecular velocity, the mean molecular velocity may be given by

$$\bar{\nu} = \sqrt{\frac{8kT}{\pi m}}, \tag{1}$$

and the mean square velocity is

$$\bar{\nu}^2 = \frac{3kT}{m}. \tag{2}$$

The average number of molecules collided on unit area per unit time is given by

$$n_0 = \frac{1}{4} n\bar{\nu}. \tag{3}$$

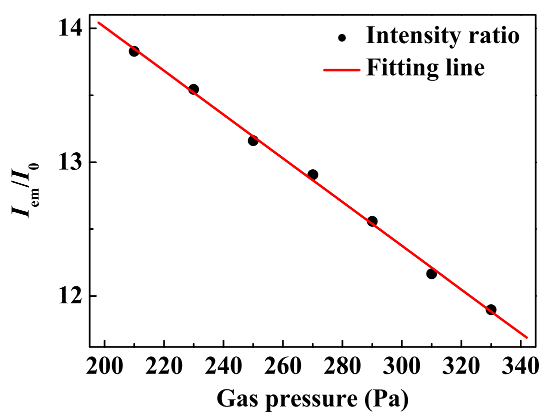

Fig. 4. (Color online) The blackbody emission integrated intensity ratio versus gas pressure.

Table 1. Corresponding Color Temperatures Fitted by the Planck's Law under Different Pressures

Gas pressure (Pa)	210 (10)	230 (10)	250 (10)	270 (10)	290 (10)	310 (10)	330 (10)
Color temperature (K)	2291 (10)	2286 (10)	2278 (10)	2274 (10)	2262 (10)	2256 (10)	2250 (10)

In our case, the initial environmental temperature is T_0, the mean molecular velocity is $\bar{v}_0$, and the mean square velocity is $\bar{v}_0^2$. After the molecules collide with the radiative surface of temperature T, the mean molecular velocity and the mean square velocity are $\bar{v}$ and $\bar{v}^2$, respectively. Hence, the energy taken away from the radiative area through molecular collision is given by

$$\Delta E = n_0 A\left(\frac{1}{2}m\bar{v}^2 - \frac{1}{2}m\bar{v}_0^2\right) = \frac{3}{4}\sqrt{\frac{2k}{mT_0}}A(T - T_0)P, \quad (4)$$

where A is the radiating area.

Considering the effects of radiation, heat conduction and environmental pressure, we may describe the essential features of the complex emission behavior as follows:

$$(1 - R)I_{\mathrm{ex}} = \kappa(T - T_0)\chi + \sigma A(T^4 - T_0^4) + \frac{3}{4}\sqrt{\frac{2k}{mT_0}}A(T - T_0)P. \quad (5)$$

The term on the left-hand side is the input intensity I_{ex} (corrected for reflectivity R at the input). The first term on the right-hand side (RHS) is the thermal conduction loss through the host, which is proportional to the difference between the sample temperature T and environmental temperature T_0, and is determined by the thermal conductivity κ, and a geometric factor χ. The second term on the RHS describes the radiation loss from blackbody emission, where σ is the Stefan–Boltzmann constant [6]. The third term on the RHS is the energy loss caused by the collisions of gas molecules.

We have measured the fluorescence spectra under different air pressures from 200 to 350 Pa. The integrated intensity ratio I_{em}/I_0 of the emission versus air pressure is plotted in Fig. 4. The corresponding color temperatures fitted by the Planck's law are listed in Table 1. In order to reflect the relative variation, I_{em}/I_0 was plotted as the ordinate, where I_0 is the integrated intensity under atmospheric pressure. As shown in the figure, with only a slight decrease of the pressure from 350 Pa down to 200 Pa, the radiation intensity increased linearly with a relative increasing rate of 1.63% per pascal. The observed phenomenon may be interpreted as follows: (1) The measured radiative intensity, I_{em}, is proportional to the whole radiative energy, i.e., $I_{\mathrm{em}} \propto \sigma AT^4$; (2) Because of the very small change of $(T - T_0)$ compared to its relatively large value (see Table 1), the $(T - T_0) = \Delta T$ term is almost a constant, then, Eq. (5) may be rearranged to give

$$I_{\mathrm{em}} \propto \sigma AT^4 = (1 - R)I_{\mathrm{ex}} + \sigma AT_0^4 - \kappa(\Delta T)\chi - \frac{3}{4}\sqrt{\frac{2k}{mT_0}}A(\Delta T)P. \quad (6)$$

Equation (6) shows that the emission intensity is basically a linear function of pressure with a negative slope as the experimental results revealed in Fig. 4.

We found that the photoinduced blackbody radiation behavior could be observed in any rare-earth oxide powders with high Yb^{3+} doping, such as Yb^{3+}:Gd_2O_3, Yb^{3+}:Er_2O_3, Yb^{3+}:Pr_6O_{11}, Yb^{3+}:CeO_2, and Yb^{3+}:Tb_4O_7, etc. In addition, Er_2O_3 induced by a 980 nm diode laser and Tm_2O_3 excited by a 808 nm diode laser could also radiate such broadband emissions. However, due to the ample levels in high excited states of Er^{3+} and Tm^{3+}, the broadband continuous emissions were absorbed and reradiated to become a characteristic broadband luminescence.

In order to understand the essential physics of the photoinduced blackbody radiation behavior, raw pure Yb_2O_3 powders were employed in our study. The effect of environmental air pressure on the radiation intensity was studied and a linear relationship between them could be well interpreted by the ideal gas model. As demonstrated in our study, the radiation intensity is extremely sensitive to the pressure variation, which provides a possibility to develop a sensitive noncontact type pressure sensor. In order to achieve such practical applications, one must quantify the intensities in absolute values, which is still a challenge to be resolved in the near future.

This work was supported by the Natural Science Foundation of Heilongjiang Province, China under grant A200503 and the Key Scientific and Technology Project of Harbin City Bureau of Science and Technology under grant 2009AA3BS131.

References

1. R. Kapoor, C. S. Friend, A. Biswas, and P. N. Prasad, Opt. Lett. **25**, 338 (2000).
2. A. Bhattacharya, R. S. Rao, and M. G. Krishna, Sens. Actuators A. Phys. **134**, 348 (2007).
3. H. Rhee and T. Joo, Opt. Lett. **30**, 96 (2005).
4. M.-F. Joubert, Opt. Mater. **11**, 181 (1999).
5. R. H. Page, K. I. Schaffers, P. A. Waide, J. B. Tassano, S. A. Payne, W. F. Krupke, and W. K. Bischel, J. Opt. Soc. Am. B **15**, 996 (1998).
6. S. M. Redmond, S. C. Rand, and S. L. Oliveira, Appl. Phys. Lett. **85**, 5517 (2004).
7. J. W. Wang and P. A. Tanner, J. Am. Chem. Soc. **132**, 947 (2010).