Rlationship between the aerosol scattering ratio and temperature of atmosphere and the sensitivity of a Doppler wind lidar with iodine filter

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The sensitivity of Doppler wind lidar is an important parameter which affects the performance of Doppler wind lidar. Aerosol scattering ratio, atmospheric temperature, and wind speed obviously affect the measurement of Doppler wind lidar with iodine filter. We discuss about the relationship between the measurement sensitivity and the above atmospheric parameters. The numerical relationship between them is given through the theoretical simulation and calculation.

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Ocean University of China constructed a mobile ground-based incoherent Dopper wind lider[1−4] (MIDWiL) using 532-nm Nd:YAG laser[5] and iodine filters[6] based on single-edge technique[7−10]. It can measure wind field from 100 m to 15 km altitude at night and to 12 km during daytime[11,12]. Two iodine filters are used in this system, one is used to lock the laser frequency of the transmitter and the other is used to discriminate the Doppler frequency shift[13]. The backscattering signal is collected by a Cassegrain telescope with a 30-cm aperture. A narrow-band interference filter (bandwidth = 0.11 nm) is used to get rid of the background light. The signal after the filter is split into two channels by a beam splitter: signal of one channel is detected by a photomultiplier tube (PMT) directly as reference channel $N_{\rm R}$; the remaining light is sent into an iodine filter which acts as a frequency discriminator, then it is detected by a PMT as measurement channel $N_{\rm M}$.

For the iodine filter, No. 1109 iodine absorption line is selected in this lidar system to match the 532-nm laser wavelength. To keep the temperature and the pressure of iodine filter stable, a temperature control system is constructed, which controls the temperature of the iodine cell and the cell finger, according to our test, it has long term stability. For wind speed measurement, the laser frequency is tuned and locked to the midpoint of one edge of iodine absorption line. For aerosol measurement, the laser frequency is locked at the center of the absorption cell[11,12].

As shown in Fig. 1. The maximum transmission of the iodine absorption line is normalized as 0.8, mainly due to the continuum absorption of iodine under the operational conditions[14]. The laser frequency is locked at the midpoint of right edge of absorption line, where the transmission ratio is about 0.4.

In troposphere, the backscattering signal contains aerosol (Mie) scattering and molecular (Cabannes) scattering. We define backscattered aerosol scattering ratio $R_{\rm b}$ as the ratio of aerosol volume backscatter coefficient $\beta_{\rm a}$ to molecular volume backscatter coefficient $\beta_{\rm m}$.

The detected photons at a range r in the total scattering reference channel $N_{\rm R}$, and in the measurement channel $N_{\rm M}$ are given in

$$N_{\rm R} = k_{\rm R}\left(\frac{\Delta r}{r^2}\right)[\beta_{\rm a}+\beta_{\rm m}] \times \exp\left(-2\int {\rm d}r\left[\alpha_{\rm a}(r')+\alpha_{\rm m}(r')\right]\right), \quad (1a)$$

$$N_{\rm M} = k_{\rm M}\left(\frac{\Delta r}{r^2}\right)[f_{\rm a}\beta_{\rm a}+f_{\rm m}\beta_{\rm m}] \times \exp\left(-2\int {\rm d}r\left[\alpha_{\rm a}(r')+\alpha_{\rm m}(r')\right]\right), \quad (1b)$$

where Δr is the range resolution, $\beta_{\rm a}$ and $\beta_{\rm m}$ ($\alpha_{\rm a}$ and $\alpha_{\rm m}$) are aerosol and molecular volume backscatter (extinction) coefficients respectively, and $k_{\rm R}$ and $k_{\rm M}$ are the system constants for reference and measurement channel respectively, which depend on total laser emission energy and the efficiency of each optical and electronic component[11].

The molecular (Cabannes) and aerosol transmission factors are, respectively,

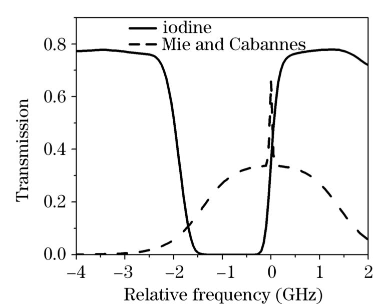

Fig. 1. Transmission function of No. 1109 iodine absorption line with a 10-cm-long vapor cell. The cell body and finger temperature are 55 and 50 °C, respectively.

$$f_{\rm a}(\nu_{\rm D}) = \int G(\nu - \nu_{\rm D})F(\nu){\rm d}\nu, \quad (2a)$$

$$f_{\rm m}(\nu_{\rm D}, T, P) = \int \Re(\nu - \nu_{\rm D}, T, P)F(\nu){\rm d}\nu, \quad (2b)$$

where $\nu_{\rm D}$ is the Doppler-shift caused by the non-zero Line-of-Sight (LOS) wind (which is positive when moving in the direction of laser beam propagation), $G(\nu - \nu_{\rm D})$ is the normalized laser lineshape function, $F(\nu)$ is the iodine filter transmittance function, $\Re(\nu - \nu_{\rm D}, T, P)$ is the normalized Cabannes function, and also,

$$\int G(\nu - \nu_{\rm D}){\rm d}\nu = 1; \quad \int \Re(\nu - \nu_{\rm D}, T, P){\rm d}\nu = 1.$$

The wind ratio may be given as

$$\begin{aligned} R_{\rm W}(\nu_{\rm D}, R_{\rm b}, T, P) &= \frac{N_{\rm M}(\nu_{\rm D}, R_{\rm b})}{N_{\rm R}(\nu_{\rm D}, R_{\rm b})} \\ &= \frac{k_{\rm M}}{k_{\rm R}} \frac{f_{\rm a}(\nu_{\rm D})\beta_{\rm a} + f_{\rm m}(\nu_{\rm D}, T, P)\beta_{\rm m}}{\beta_{\rm a} + \beta_{\rm m}} \\ &= \frac{k_{\rm M}}{k_{\rm R}} \frac{f_{\rm a}(\nu_{\rm D})R_{\rm b} + f_{\rm m}(\nu_{\rm D}, T, P)}{R_{\rm b} + 1} \\ &= \frac{k_{\rm M}}{k_{\rm R}} f(\nu_{\rm D}, R_{\rm b}, T, P), \quad (3) \end{aligned}$$

where,

$$f(\nu_{\rm D}, R_{\rm b}, T, P) = \frac{f_{\rm a}(\nu_{\rm D})R_{\rm b} + f_{\rm m}(\nu_{\rm D}, T, P)}{R_{\rm b} + 1}. \quad (4)$$

The measurement sensitivity per unit wind speed $S_{V_{\rm LOS}}$ is defined as the fractional change in the wind ratio per unit change in wind speed $V_{\rm LOS}$. Following the common practice, for this letter, the sensitivity is evaluated at zero wind speed as[14]

$$\begin{aligned} S_{\nu_{\rm D}} &= \frac{R_{\rm W}(\nu_{\rm D}, R_{\rm b}) - R_{\rm W}(0, R_{\rm b})}{R_{\rm W}(0, R_{\rm b})V_{\rm LOS}} \\ &= \frac{f(\nu_{\rm D}, R_{\rm b}, T, P) - f(0, R_{\rm b}, T, P)}{f(0, R_{\rm b}, T, P)V_{\rm LOS}} \\ &= \frac{1}{V_{\rm LOS}}[R_{\rm b}\frac{f_{\rm a}(\nu_{\rm D}) - f_{\rm a}(0)}{f_{\rm a}(0)R_{\rm b} + f_{\rm m}(0, T, P)} \\ &\quad + \frac{f_{\rm m}(\nu_{\rm D}, T, P) - f_{\rm m}(0, T, P)}{f_{\rm a}(0)R_{\rm b} + f_{\rm m}(0, T, P)}]. \quad (5) \end{aligned}$$

According to Eq. (4), four factors will affect the sensitivity of wind speed measurement. They are aerosol scattering ratio $R_{\rm b}$, atmospheric temperature T, atmospheric pressure P, and wind speed $V_{\rm LOS}$.

As for the iodine transmittance data is obtained by experiment, and the molecular scattering line is obtained by the Rayleigh-Brillouin S6 model. These cannot be expressed in formulas. Pan *et al.*[15] has a clear research about the molecular scattering. Analysis below is based on numerical calculation. The analysis approaches of effect factors to the sensitivity are as follows.

1) Calculate the molecular scattering spectrum and the laser line shape spectrum. Using the Rayleigh-Brillouin S6 model to obtain the molecular scattering spectrum. While the laser line shape spectrum is a Gauss shape line with a full-width at half-maximum (FWHM) of 100 MHz.

2) Obtain the iodine transmittance line by experiment using a laser scanning technique.

3) Calculate the terms $f_{\rm m}(\nu_{\rm D}, T, P)$ and $f_{\rm a}(0)$. $f_{\rm m}(\nu_{\rm D}, T, P)$ is the convolution of the iodine line and molecular spectrum, atmospheric temperature T, and atmospheric pressure P, while $f_{\rm a}(0)$ is the convolution of the iodine line and laser spectrum.

4) Combine the terms $f_{\rm m}(\nu_{\rm D}, T, P)$ and $f_{\rm a}(0)$ together according to different $R_{\rm b}$ to obtain the total return signal from the atmosphere to the lidar. It is the received signal by PMT. Using the two channel signals to get the wind speed ratio $R_{\rm W}$.

5) Calculate the sensitivity according to Eq. (4).

6) Calculate the sensitivity uncertainty using the result from step 5.

In the atmosphere below 15 km, molecular scattering and aerosol scattering both exist. The term $f_{\rm m}(\nu_{\rm D}, T, P)$ in Eq. (5) is the molecular scattering function of atmospheric temperature T and pressure P. The term $f_{\rm a}(0)$ in Eq. (5) is the aerosol scattering function which does not vary with T and P. Aerosol scattering ratio $R_{\rm b}$ can account for the aerosol scattering intensity in the total scattering.

As for aerosol scattering ratio $R_{\rm b}$, the method to obtain it is well introduced in Ref. [11]. If the lidar system is able to reject aerosol backscatter, $R_{\rm b}$ can be measured. The reference channel and measuring channel signals in receiving system are expressed respectively as Eqs. (1a) and (1b).

In MIDWiL system, when the frequency of injection YAG pulse laser is locked at the valley of iodine 1109 absorption line of I_2 filter, aerosol backscattering signal will be rejected (35 dB), i.e. $f_{\rm a} = 0$ in Eq. (1b). Then $R_{\rm b}$ can be expressed as

$$R_{\rm b}(r) = \frac{\beta_{\rm a}(r) + \beta_{\rm m}(r)}{\beta_{\rm m}(r)} = \frac{f_{\rm m}N_{\rm R}(r)}{N_{\rm M}(r)}.$$

She *et al.*[16] analyzed the influence of aerosol variation to wind uncertainty. The simulation (Fig. 2) shows that the uncertainty of wind speed of LOS is less than 0.2 m/s when $R_{\rm b}$ is measured with the accuracy better than 10% and is in range of 1 to 20 (corresponding to altitude 0 to 3 km). And when R_b is in range of 0.1 to 0.4 (corresponding altitude 3 to 10 km) and is also measured with the accuracy better than 10%, then the uncertainty of wind speed of LOS is less than 0.8 m/s.

Figure 2 shows the relationship of $f(\nu_{\rm D}, R_{\rm b}, T, P)$ and $R_{\rm b}$ when T = 275 K, P = 0.79 atm. Here, $f(\nu_{\rm D}, R_{\rm b}, T, P)$ is a function of $f_{\rm m}(\nu_{\rm D}, T, P)$ and $f_{\rm a}(0)$ at different aerosol scattering ratio according to Eq. (4).

Figure 3(a) shows the relationship between the measurement sensitivity and the aerosol scattering ratio when T = 275 K, P = 0.79 atm. Figure 3(b) is the corresponding uncertainty of the sensitivity. From these two figures, we can find that when the aerosol scattering ratio increase from 0 to 10, the corresponding measurement

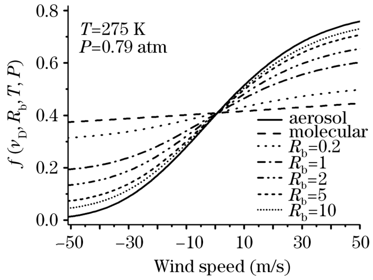

Fig. 2. Transmission factor versus wind speed under different aerosol scattering ratio conditions.

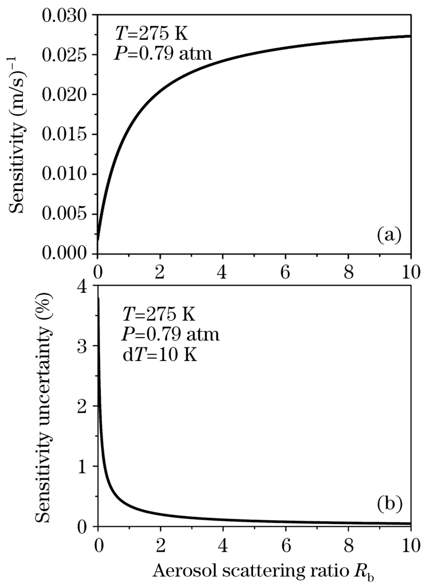

Fig. 3. (a) Measurement sensitivity and (b) measurement sensitivity uncertainty as a function of different aerosol scattering ratios.

sensitivity increase from about 0.002 to 0.026 $(\mathrm{m/s})^{-1}$, the corresponding sensitivity uncertainty decreases, and the aerosol scattering ratio higher, the uncertainty lower. More analysis can be found in Ref. [4].

According to the analysis above we can draw that R_b has an evident effect to the wind speed measurement, higher R_b will obviously improve the measurement sensitivity.

As for atmospheric temperature T and atmospheric pressure P, they are parameters of the molecular (Cabannes) scattering function $f_\mathrm{m}(\nu_\mathrm{D}, T, P)$. The standard air model and Rayleigh-Brillouin S6 model are used to calculate $f_\mathrm{m}(\nu_\mathrm{D}, T, P)$.

According to the standard atmosphere model, as shown in Figs. 4 and 5, T varies from about 290 to 220 K, when the altitude from about lower 0 km to higher 10 km. The temperature difference can be about 70 K. From the ground to 15-km altitude, P reduces from 1 to 0.1 atm.

Using the Rayleigh-Brillouin S6 model, Fig. 6 is the calculated result at different atmospheric pressures when temperature is 275 K, and Fig. 7 is the result of different atmospheric temperatures when the pressure is 0.79 atm. According to these two figures, the atmospheric temperature and the pressure will both affect the molecular scattering. As the influence of pressure can be converted

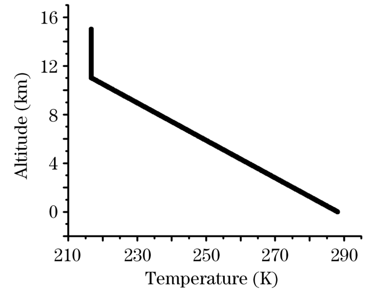

Fig. 4. Temperature profile of standard atmosphere.

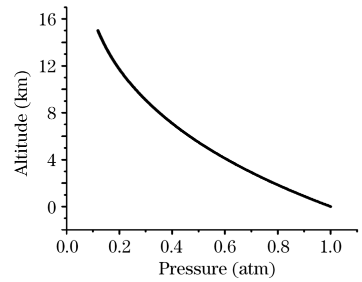

Fig. 5. Pressure profile of standard atmosphere.

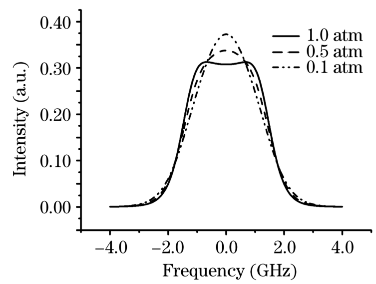

Fig. 6. Molecular scattering spectrum at different atmospheric pressures.

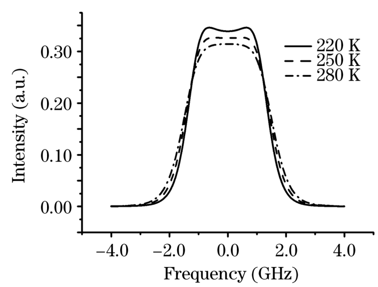

Fig. 7. Molecular scattering spectrum at different atmospheric temperatures.

to the influence of temperature according to the ideal gas equation, only the effect of temperature on the measurement sensitivity is discussed below.

The term $f_\mathrm{m}(\nu_\mathrm{D}, T, P)$ is a factor of the measurement sensitivity which will affect the measurement sensitivity. To estimate its variation with different temperatures, we calculated the $f_\mathrm{m}(\nu_\mathrm{D}, T, P)$ at three different atmospheric temperatures. Figure 8 shows the relationship between the atmospheric temperature and $f_\mathrm{m}(\nu_\mathrm{D}, T, P)$. When the wind speed is -50 m/s, $f_\mathrm{m}(\nu_\mathrm{D}, T, P)$ is 0.292, 0.299, and 0.306 for T = 265, 275, and 285 K respectively. It changes around 2.4% when temperature varies 10 K at 265 K.

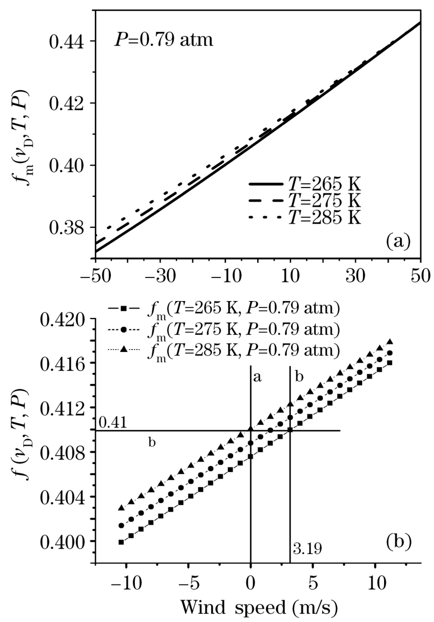

Fig. 8. Molecular transmission factor versus wind speed under different temperature conditions.

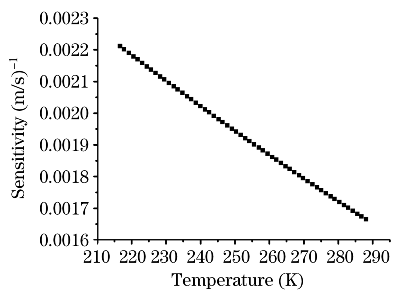

Fig. 9. Sensitivity measurement as a function of temperature.

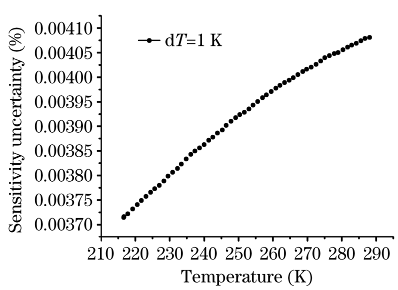

Fig. 10. Sensitivity uncertainty as a function of temperature.

Figure 9 shows the relationship between the measurement sensitivity and the atmospheric temperature. Figure 10 is the corresponding uncertainty of the sensitivity. According to Figs. 9 and 10, when the temperature is at the range of 220 − 280 K, the sensitivity reduces from 0.00218 to 0.00172 $(\mathrm{m/s})^{-1}$, and the relative error is 21.1% at 220 K. The corresponding sensitivity uncertainty increases from 0.00373% to 0.00406%, and the relative error is also 21.1% at 220 K.

To estimate the effect of atmospheric temperature to the wind speed, Fig. 8(b) is extracted from Fig. 8(a). When the temperature is 285 K, the wind speed is 0, the $f_{\mathrm{m}}(\nu_{\mathrm{D}}, T, P)$ is 0.41, while when the temperature is 265 K, the wind speed is 3.19 m/s at this $f_{\mathrm{m}}(\nu_{\mathrm{D}}, T, P)$. This means when the temperature reduces from 285 to 265 K, the corresponding wind speed varies from 0 to 3.19 m/s. So at zero wind speed, 10-K temperature variation will cause the absolute error of 1.60 m/s.

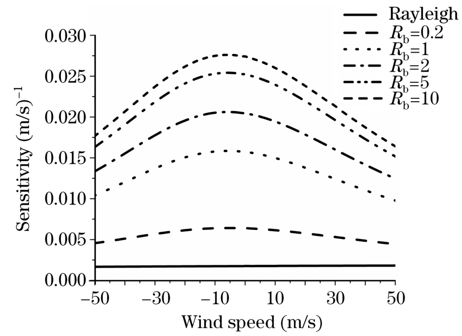

Fig. 11. Sensitivity measurement as a function of wind speed for different aerosol scattering ratios.

According to Figs. 9 − 11, we can find that the temperature higher, the sensitivity uncertainty getting higher, which means lower atmospheric temperature is beneficial to improve the performance of the wind lidar. The temperature higher, the sensitivity getting lower, which also means lower temperature is beneficial to the wind measurement. The term $f_{\mathrm{m}}(\nu_{\mathrm{D}}, T, P)$ is effective to estimate the effect of the temperature to the wind speed error.

At last, we consider the effect of wind speed to the measurement sensitivity. When $T = 275$ K, $P = 0.79$ atm, the solid line in Fig. 11 is the relationship of wind speed and sensitivity at the situation of only atmosphere molecular scattering. It shows that in aerosol free atmosphere the sensitivity does not change much when wind speed changes. For example, the sensitivity increases from 0.001744 to 0.001818 $(\mathrm{m/s})^{-1}$ when the wind speed increases from 0 to 20 m/s. The relative error is 4.2% at zero wind speed.

But when aerosol scattering exists, for example, take $R_{\mathrm{b}} = 5$, the wind speed increases from 0 to 20 m/s, the corresponding sensitivity decreases from 0.02524 to 0.02195 $(\mathrm{m/s})^{-1}$. The relative error is 13.0% at zero wind speed. This is about 3 times of 4.2%.

From Fig. 11 we can find that sensitivity varies with the wind speed, regardless of the scattering existing or not. But when aerosol scattering exists, the variation gets higher.

In summary, the measurement sensitivity for wind lidar using iodine filters under different weather conditions is discussed. Sensitivity is a function of aerosol scattering ratio R_{b}, atmospheric temperature, and wind speed. For troposphere wind speed measurement, the three factors should be considered. A solution to solve this problem is to construct a lookup table which includes these factors. With this lookup, accurate wind speed can be retrieved.

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References

1. Z. Liu, D. Wu, K. Zhang, J. Liu, J. W. Hair, and C.-Y. She, Sci. Chin. Ser. E (in Chinese) **46,** 309 (2003).

2. Z. Liu, X. Song, J. Liu, and K. Zhang, Chin. Sci. Bull. E (in Chinese) **46,** 2080 (2001).
3. F. Shen, D. Sun, Z. Zhong, M. Chen, H. Xia, B. Wang, J. Dong, and X. Zhou, Acta Opt. Sin. (in Chinese) **26,** 1761 (2006).
4. J. Liu, L. Bu, J. Zhou, T. Yu, and W. Chen, Chinese J. Lasers (in Chinese) **33,** 1339 (2006).
5. W. Chen, T. Zhang, D. Wu, and Z. Liu, Acta Opt. Sin. (in Chinese) **17,** 346 (1997).
6. S. Wu, Z. Liu, and D. Sun, Chin. Opt. Lett. **1,** 722 (2003).
7. Y. Ma, H. Lin, H. Ji, and T. Dong, Chinese J. Lasers (in Chinese) **34,** 170 (2007).
8. C. L. Korb, B. M. Gentry, and C. Y. Weng, Appl. Opt. **31,** 4202 (1992).
9. B. M. Gentry and C. L. Korb, Appl. Opt. **33,** 5770 (1994).
10. C. L. Korb, B. M. Gentry, and S. X. Li, Appl. Opt. **36,** 5976 (1997).
11. Z. S. Liu, D. Wu, J. T. Liu, K. L. Zhang, W. B. Chen, X. Q. Song, J. W. Hair, and C. Y. She, Appl. Opt. **41,** 7079 (2002).
12. Z. S. Liu, B. Y. Liu, Z. G. Li, Z. A. Yan, S. H. Wu, and Z. B. Sun, Appl. Phys. B **88,** 327 (2007).
13. H. Hu and Q. Hu, Acta Opt. Sin. (in Chinese) **21,** 720 (2001).
14. C. Y. She, J. Yue, Z. A. Yan, J. W. Hair, J. J. Guo, S. H. Wu, and Z. S. Liu, Appl. Opt. **46,** 4434 (2007).
15. X. Pan, M. N. Shneider, and R. B. Miles, Phys. Rev. Lett. **89,** 183001 (2002).
16. C. Y. She, J. Yue, Z. A. Yan, J. W. Hair, J. J. Guo, S. H. Wu, and Z. S. Liu, Appl. Opt. **46,** 4444 (2007).