

## Progress in the development of Fe resonance fluorescence Doppler lidar

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Temperature and wind profiling in the middle and upper atmosphere with high accuracy precision and resolution is crucial in the validation and improvement of global atmosphere models. Resonance fluorescence Doppler lidar is a powerful tool for temperature and wind measurements with high-resolution in the mesopause region. Because of the state-of-the-art laser technology and high Fe abundance, Fe resonance fluorescence Doppler lidar is considered to be an ideal candidate for the next-generation lidar<sup>[1]</sup>. As the complexity of the Fe lidar, only few Fe lidars have been operated in few locations. Therefore, considering the importance of temperature and wind measurement and the superiority of Fe lidar, it is very meaningful to make some contributions to the development of high-performance Fe lidar.

The generation of pulsed laser at 372 nm wavelength and frequency stabilization of pulsed laser are key technologies for the development of high-performance Fe lidar. For the generation of pulsed laser at 372 nm wavelength, the method we use is directly through the third harmonic generation of a Nd:YAG laser operating at 1116nm wavelength<sup>[2]</sup>. The Nd:YAG crystal have an emission line with a linewidth of about 1.3 nm near 1116 nm wavelength, which is within a few GHz of the tripled wavelength of the iron absorption line at 372 nm wavelength. A specific laser frequency can be obtained by injection-seeded technique in combination with an active cavity control technique. For the frequency stabilization of pulsed laser, the saturation absorption spectrum of iodine near 558 nm wavelength is carried out, and the frequency difference between the lock point and the needed frequency (the tripled wavelength of the iron absorption line at 372 nm wavelength) is corrected by the beat and lock frequency modules.

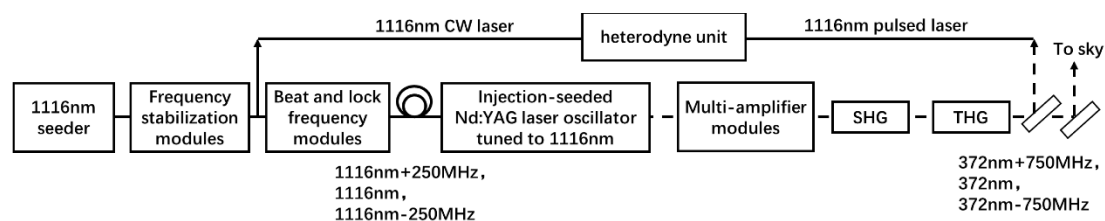


Fig. 1. Schematics of the injection-seeded Nd:YAG laser system.

The overall layout of the laser system is shown in Fig. 1. A fiber laser is used to generate single-longitudinal mode seeder laser at 1116 nm wavelength. The beat and lock frequency modules are used to replace the acousto-optical modulator (AOM) which is commonly used in Na lidar to realize the output of seeder laser with three

different frequencies<sup>[3]</sup>. In the Nd:YAG laser, injection-seeded technique combined with an active cavity control technique is applied to maintain resonance with the seeder laser, so as to ensure that all three frequencies match a longitudinal mode of the oscillator<sup>[4]</sup>, and then, master oscillator power amplifier (MOPA) configuration and two nonlinear frequency conversions are applied to yield sufficient power of pulsed laser at 372 nm wavelength.

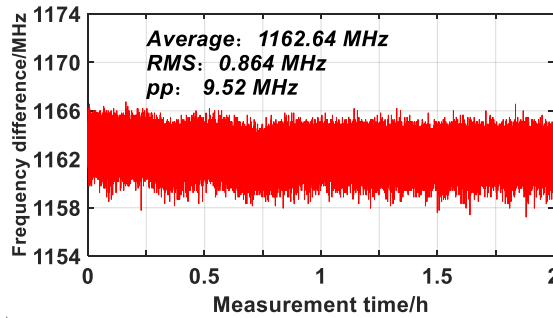


Fig. 2. Measurement results of frequency stability.

The frequency stability and linewidth of pulsed laser at 1116 nm wavelength can be measured in the heterodyne unit. To record the beat frequency signal accurately, an indium gallium arsenic (InGaAs) detector is used for photoelectric conversion, and the interference waveform is acquired by a high-speed data capture card. A fast Fourier transform algorithm applied to the digitized beat frequency signal to obtain the spectrum information. The data of full width at half maximum (FWHM) of laser linewidth can be got as about 33.1 MHz. Fig. 2 shows the measurement results of frequency stability over 2 hours. The average value is 1162.64 MHz, characterized the frequency difference between pulsed laser and CW laser. The frequency peak-to-peak (PP) value is 9.52 MHz. The frequency stability of 864.26 kHz root mean square (RMS) is converted to a frequency stability of 2.59 MHz RMS at 372 nm wavelength. It causes a systematic error of wind measurement estimated to be 0.83 m/s, according to the derivation results of frequency RMS jitter in Table 9 of [5].

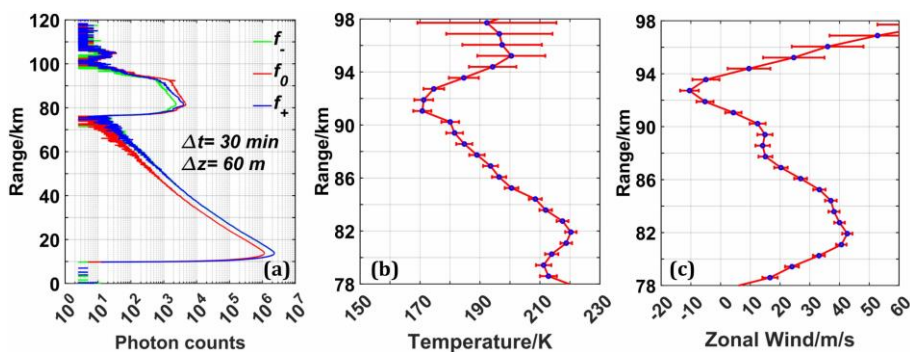


Fig. 3. The preliminary observational result using novel laser system as Fe lidar transmitter. (a). backscattered signals were acquired from central frequency ( $f_0$ ) and two wing frequencies( $f_{\pm}$ ) of iron absorption line; (b). Temperature profile with error bar; (c). Zonal wind profile with error bar.

The first lidar observation using the injection-seeded Nd:YAG laser system as transmitter is carried out at the Anhui institute of optics and fine mechanics site in Hefei, China (31.91N, 117.17E), on the night of February 26 2023. The laser beam points 30 off-zenith to the east, coaxial to the 1000 mm diameter receiving telescope.

Fig. 3a shows backscattered signals with 60 m distance resolution integrated between 12:00 and 12:30 UT. The Rayleigh scattering signals are dominant below 70 km altitude, and the iron resonance fluorescence scattering signals are visible at the range of 75 km to 96 km and 102 km to 105 km. The useful signals are drowned in background noise above 105 km altitude. At the peak altitude of iron atomic density (e.g., 82 km), the intensity of resonance fluorescence scattering signal at central frequency of iron absorption line is equivalent to that of Rayleigh scattering signal at 38 km altitude. After data preprocessing of noise deduction, distance averaging, signal calibration and signal filtering, the three-frequency ratio doppler technology is conducted to measure temperature and radial wind simultaneously. The temperature-wind calibration curve is acquired with the dwell time of central frequency of 0.2 and the central frequency shift of 750 MHz. Moreover, the influence of laser linewidth and iron atom isotope is also considered, more details can be found in [6]. As the laser beam is pointed to east during the lidar observation, the zonal wind (u-wind) can be synthesized from radial wind. According to the principle of doppler beam swinging technique (DBS), the magnitude of the zonal wind is twice as large as the radial wind when the vertical wind is not considered. Fig.3b and 3c are the measurement results of temperature and zonal wind. Assuming that the random measurement error is mainly caused by photon noise, the temperature-wind uncertainties can be obtained by using the same error propagation method introduced in [6]. They are estimated to be  $\pm 1.9$  K and  $\pm 1.8$  m/s, respectively, with 960 m spatial and 30 min temporal resolutions under the clear sky condition at 82 km altitude, and 8.3 K and 7.5 m/s at both iron layer edges (e.g., 78 km and 96 km).

At present, we are working on daytime observations of Fe lidar, and there are two points should be focused on. One, a single-channel Fabry-Perot etalon is developed to achieve narrow-band filtering with an integrated bandwidth of less than 5 pm. Two, the performance of oscillator is optimized to increase laser energy. The laser pulse duration is about 80 ns and the divergence is above 0.2 mrad after beam expander, saturation effects of iron resonance scattering are negligible.

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