

Daytime observation technology of a lidar using an atomic filter

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Abstract Based on the dual-wavelength high altitude detecting lidar we developed, daytime observation capability was realized in its sodium fluorescence channel by employing a Na (sodium) atomic filter and other relevant technologies. Because of the very narrow passband and very high out-of-band suppression of the Na atomic filter, the lidar echo at an 80–110 km altitude can be obtained even at noontime when background light from the sun is very strong. The capability for a 24-h continuous observation of the lidar system has been demonstrated by the preliminary observation result. This development makes the constant detection and investigation of high altitude atmosphere over the country possible.

Keywords lidar, daytime observation, Na (sodium) fluorescence, atomic filter, atomic frequency stabilization

1 Introduction

The dual-wavelength, high altitude detection lidar has been developed by Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences. It can detect at altitudes of 30–80 km and 80–110 km simultaneously [1]. However, the lidar can only be operated at night, lacking 24-h continuous observation capability. The reason is that the intensity of the lidar echo is quite weak that counting individual photons to get the lidar echo is indispensable. Sunlight during the daytime is a serious problem, which makes most of the high altitude detection lidars able to work only during nighttime (usually, local time 19:00–5:00). This is unfavorable for continuous observation and investigation of high altitude atmosphere. At present, the atomic filter, whose passband is the narrowest and out-of-band suppression is the highest, is the best choice to suppress noise from strong background light. The wavelength on the Na (sodium) fluo-

rescence channel of the dual-wavelength high altitude lidar we reported [1] is 589 nm. Since it matches the wavelength of the Na atomic filter, it could be suitable to realize daytime observation of Na layer fluorescence. Currently, only a few countries such as the USA and Germany realize daytime observation of fluorescence lidar by using an atomic filter [2,3]. We have also developed daytime observation capability by using a simpler configuration at a lower latitude, which is more economical and offers higher system stability. This means that the background light noise to be suppressed is stronger in our case.

2 Technical scheme of daytime observation of lidar

The schematic diagram of the daytime Na fluorescence lidar is shown in Fig. 1. In this figure, only the Na fluorescence channel of our dual-wavelength lidar is shown. As general Na fluorescence lidar, the Na fluorescence lidar for the daytime observation also contains three main parts: the laser emitter, the echo receiver and the signal processor [4,5]. However, to realize daytime observation ability, it is important to adopt a strict optical filter technology. In our experiment, a Na atomic filter (FADOF) is used as the main filter, and a narrow bandwidth interference filter is used as an assistant filter. At the same time, bandwidth and center wavelength of the laser also match those of the FADOF. Therefore, etalon technology inside the dye laser cavity is adopted to compress the line width of the multimode pulse dye laser, while atomic frequency stabilization is used to lock laser wavelength automatically on the Na atomic transition for a long-term period.

3 Principle and technology of FADOF

The schematic of the FADOF is shown in Fig. 2 [6]. It consists of a Na atomic cell and a pair of orthogonal polarized prisms. The Na atomic cell is in a constant temperature oven and a longitudinal magnetic field. Incident

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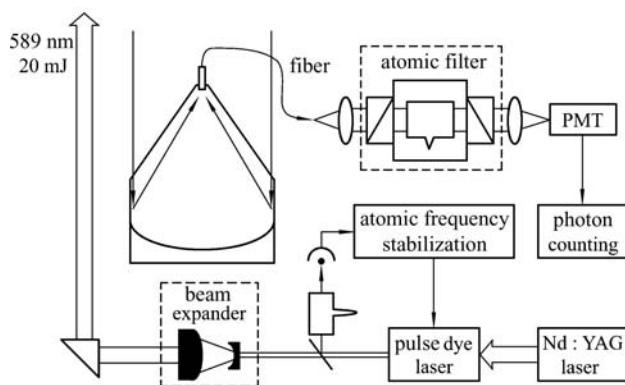


Fig. 1 Schematic diagram of daytime detection lidar

light coming from left of the filter will be blocked by the orthogonal polarized prism pair, unless the light could excite the specific transition in the Na vapor cell. Only light with some specified wavelength, for example the D_2 resonance of Na at wavelength of 588.995 nm, can excite the transition of Na. If the temperature and magnetic field of the atomic filter are set correctly, the polarization of the specified light can rotate by odd times of 90° . The specified light can then pass through the filter. Because of the strict wavelength selectivity of the atoms in the cell and the high optical blocking ability of the polarization prism pair, the atomic filter has a very narrow passband and a very high out-of-band blockage. Therefore, it is suitable for suppressing noise from strong sunlight in many applications such as lidar and free space laser communication [7,8].

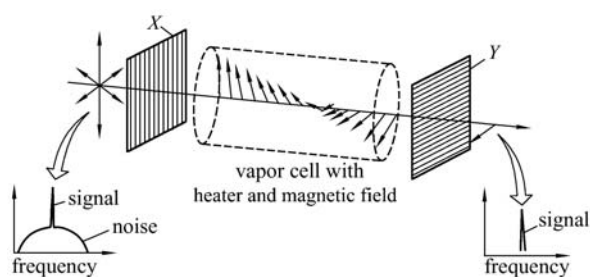


Fig. 2 Principle of an atomic optical filter

Figure 3 shows the picture of an FADOF. A permanent magnet offers a longitudinal magnetic field with an intensity of 0.2 T. The length of the vapor cell is 2 cm. A Glan-Thompson prism with the extinction ratio of 10^{-5} is used. The temperature of the Na vapor cell is controlled over a selected range of 100°C – 200°C . The temperature control precision is better than 0.5%. In the experiment, one could change the transmission spectrum of the filter to obtain ideal bandwidth and transmission by changing the temperature. The main characteristic of the atomic filter is determined by the property of the atoms, and the line-width of the laser and atomic filter is about 2–3 GHz. Thus, the

small variation of temperature, magnetic field or the Doppler frequency shift introduced by thermal motions would not generate an obvious effect [9]. For example, the experiment of our wide bandwidth lidar system indicates that if the variation of temperature is lower than 0.5°C , there is no observable influence due to the change of transmission and the bandwidth of atomic filter.

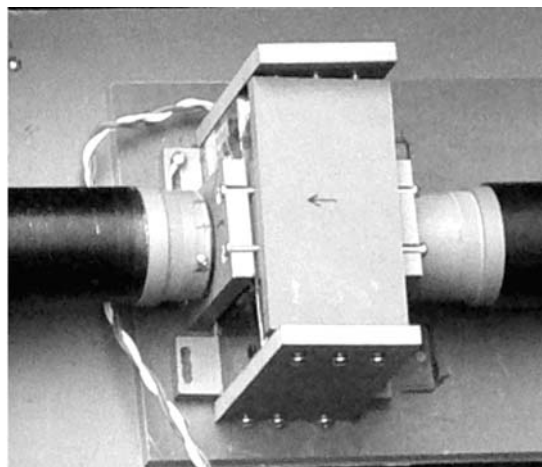


Fig. 3 Photograph of Na atom optical filter

We have used the pulse dye laser of the lidar to measure the transmission characteristics of the atomic filter to ensure that the selected parameter of the atomic filter is suitable. Figure 4 shows some typical measurement results. As the pulse dye laser was used, the transmission spectra of the filter seem slightly noisy. However, the results can still be used for selecting the proper working parameters of the filter. In the figure, the photon current spectra of a Na atomic hollow-cathode lamp (the lower intensity curves in the figure) are also shown with the filter spectra (the higher intensity curves in the figure). The former was used for calibrating the Na resonance wavelength, while the latter was the representation of the filter transmission. Figure 4(a) indicates that the filter spectra have a single transmission peak in the resonance wavelength, but as the temperature of the filter was too low, the transmittance of the filter was low. Shown in Fig. 4(b) is the proper result: the transmittance of the filter is high, and the main peak of the filter transmission matches the resonance wavelength because the right temperature of the filter was used. Figure 4(c) indicates that the temperature is too high, so the transmission peaks do not match the resonance wavelength, but are located on both sides of the resonance peak. According to Fig. 4(b), the experiment parameters are determined as follows: the temperature of the Na cell is 165°C , and the intensity of the magnetic field is 0.21 T. Under these conditions, the transmission peak value of the atomic filter is about 50% for polarization light, while the bandwidth is about 2–3 GHz. Because of the convolution superposition of the atomic filter bandwidth and the laser bandwidth, the

transmission bandwidth in Fig. 4(b) is slightly more than 2–3 GHz. The parameters of the atomic filter mentioned above are similar to the result that has been internationally reported [2]. However, the length of the cell is longer and the intensity of the magnetic field is stronger in our case. Therefore, the working temperature is lower (5°C – 10°C), which is beneficial for extending the lifetime of the filter.

4 System technology of daytime observation

To obtain the daytime operation ability of a high altitude lidar, the atomic filter has to be used. Some relevant technologies in the receiving and emitting system of the lidar also need to be applied.

First, the atomic filter is not able to completely overcome the background disturbance of the sunlight, making it necessary to compress the receiving view field of lidar. The fiber ($\Phi 1.5$ – 2 mm) in the focal plane of the telescope is used as the optical collector in the lidar receiver, which limits the view field to about 0.75 – 1 mrad. Correspondingly, the divergence of a 589 nm laser beam is also set lower than 0.5 mrad by beam collimating technology. An effective alignment technology of the lidar is needed for this set of emitting and receiving parameters to ensure a good transmitter/receiver match. In addition, to make the echo overpass the atomic filter with a certain length, a strict optical collimation technology has to be used for the receiving optical fiber to improve the transmission efficiency of the optical echo and avoid background light scattering in the atomic filter. Since magnetic flux leakage of the atomic filter and sensitivity of the photomultiplier to the magnetic field, adequate magnetic shielding and proper separation between the filter and the PMT are required. The whole receiving channel has to be strictly light shaded to avoid background light leakage.

At the same time, the bandwidth of the emitting laser must match the narrow bandwidth of the atomic filter to improve the efficiency of laser energy utilization. The bandwidth is compressed from 10 to 2 GHz by using an etalon inside the cavity of a general multimode pulse dye

laser. The bandwidth of pulse dye laser thus matches the atomic absorption line width of the filter. Compared with the single pulse laser used internationally, our technology has a lower cost and higher stability. In addition, the atomic frequency stabilization technology is utilized to reduce wavelength shifting of the dye laser and lock the wavelength of the dye laser to that of the atomic filter [10]. The D_2 transition in a Na atomic hollow cathode lamp offers the wavelength standard for the stabilization. Intelligent digital control is utilized to keep the frequency of laser on the frequency of Na D_2 transition. Similar to the atomic frequency stabilization in a semiconductor laser [11], the intelligent digital control is used to control the dye laser wavelength by maximizing the photocurrent signal through real time detection of light signal from the Na atomic hollow cathode lamp. The experimental result indicates that the frequency stabilization technology mentioned above is efficient for reducing wavelength shifting of the dye laser. In 24-h continuous observation, the photocurrent variation is under 5% . Accordingly, the frequency stability of the dye laser is better than ± 250 MHz.

The fiber coupling in the atomic filter receiver makes the installation and the optical alignment of the system easier, but the reduction of polarization by the fiber reduces the transition rate of the atomic filter by 50% . Thus, the next step is to use two atomic filters in the receiving channel to receive two kinds of polarization components.

Photos for the emitting and receiving system of the daytime observation lidar are shown in Figs. 5(a) and 5(b), respectively.

5 Testing detection performance

To check the practical rejection ability of the atomic filter, 24-h continuous comparison using the atomic filter and interference filter (absorber) were conducted respectively. The measurements were carried out in the receiver system of the lidar, and the result is shown in Fig. 6. When the interference was used in the receiving channel, the back-

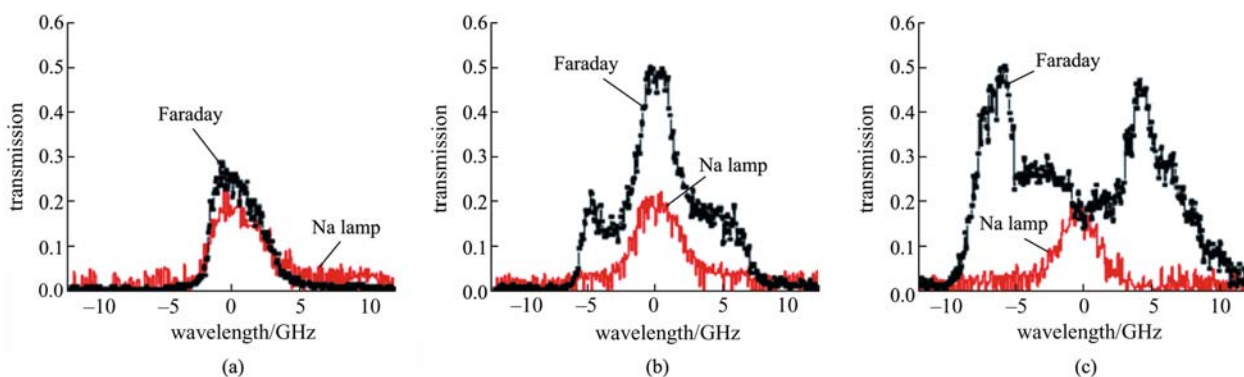


Fig. 4 Some typical transmission curves of a Na atomic optical filter. (a) 150°C ; (b) 170°C ; (c) 190°C

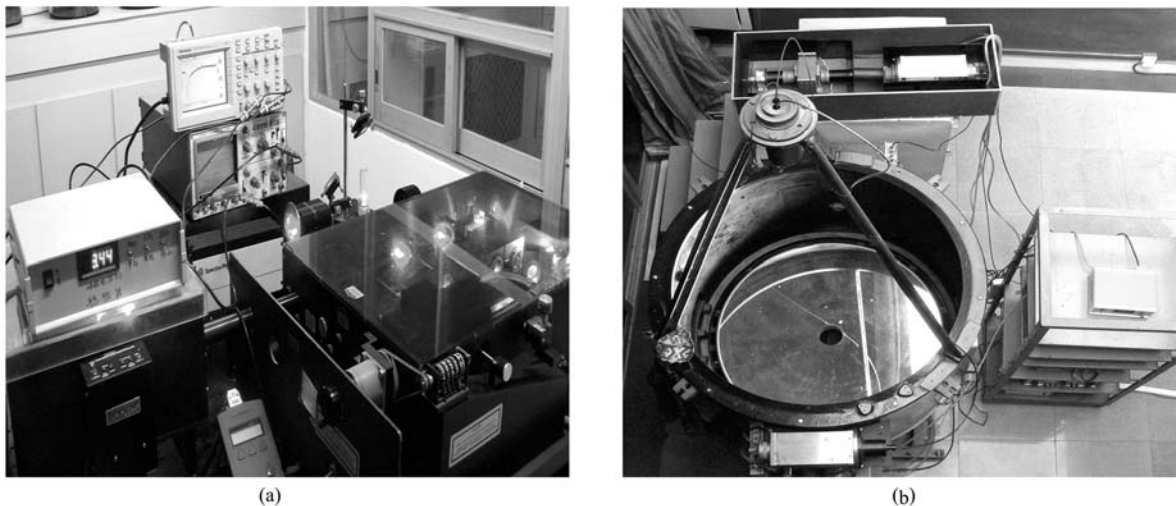


Fig. 5 Pictures of our daytime observation lidar system. (a) Emitting system; (b) receiving system

ground light increased sharply after 5:00, Na fluorescence signal is buried completely by the background noise at about 6:00, and the noise quickly saturates the photoelectric detector. However, when using the atomic filter, even at noon, the photoelectric detector is not saturated by the noise, although the background noise is quickly increased. Figure 6 indicates that the atomic filter improves the background noise rejection ability by 3 orders of magnitude compared to the interference filter. Therefore, the lidar is capable of observing a high altitude Na layer when the intensity of the sunlight is high.

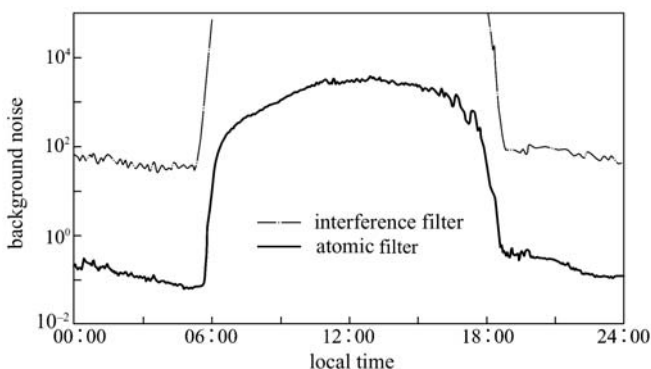


Fig. 6 Comparison of lidar background noise by using an interference filter and an atomic filter

To study whether the atomic filter influences the high altitude Na layer observation, the Na layer observation results using an atomic filter and interference filter during the nighttime are compared. The test was carried out on the same lidar system. A set of echoes is obtained by using the atomic filter in the first instance. The atomic filter is then quickly removed, and another set of echoes is obtained by using the interference filter. The result is shown in Fig. 7. It indicates that two Na layers are consistent in terms of their

shapes, distributions and other properties. Thus, the atomic filter does not influence the Na layer observation.

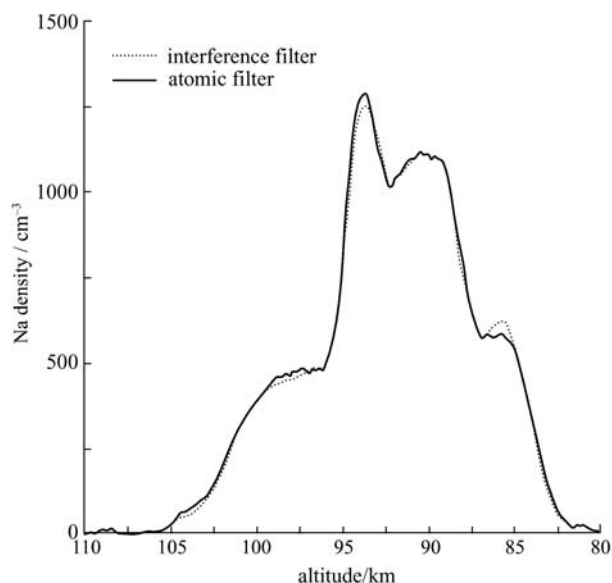


Fig. 7 Comparison of detection performance by using an interference filter and an atomic filter

Figure 8(a) shows the high altitude Na layer echo accumulating about 30 min at noon, obtained by this Na fluorescence lidar. Although the background sunlight noise is high, the profile of the Na layer is still very clear. According to the absolute value of noise, the signal-to-noise-ratio is only about 0.05. However, it is the relative signal to noise ratio that influences signal deduction. The figure shows that the relative signal to noise ratio is 5–6, therefore the profile and the detail of the Na layer can be obtained from the result in Fig. 8(a). For comparison, Fig. 8(b) shows the result obtained at night. The background is rather weak and the signal-to-noise ratio is very high (upper than 10^2) at

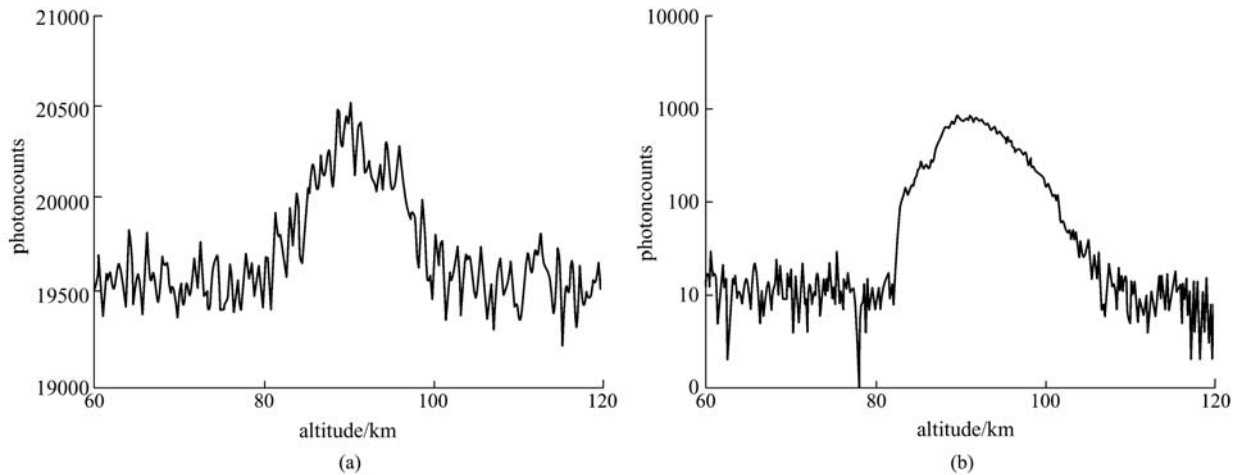


Fig. 8 Na layer profile at midday and midnight (after half an hour average). (a) Na profile at noon (11:30–12:00); (b) Na profile at night (20:00–20:30)

night, making it even easier to extract the Na layer information.

6 Conclusions

Using an atomic filter technique and some relevant laser techniques, the 24-h continuous observation ability of a high altitude Na lidar was realized. This lidar has been used for practical observation, with the longest continuous observation time of about 50 h. The technical realization of this high rejection ability of sunlight is not only beneficial for the high altitude lidar in studying the relationship between the structure and dynamics of Na layer and the solar and tidal wave activities, but can also be applied to other optoelectronic detection systems to enhance their daytime detection capabilities.

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