Development of an All-Solid-State Iron Resonance Temperature Lidar

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Abstract: The coupling between the neutral and ionized atmosphere is important to improve our understanding of the dynamics of the upper atmosphere and thus improving the prediction of space weather. The Arctic atmosphere is a natural laboratory for understanding these processes. The High-frequency Active Auroral Research Program (HAARP) facility located in Gakona Alaska hosts many scientific instruments that can be used for active experiments. An all-solid state Iron Resonance Temperature Lidar system is under development to be deployed at HAARP to enrich the capability of the HAARP facility. We present recent developments of this lidar system. Progress has been made on the development of the transmitter, and the etalon-based laser frequency monitoring system. We are modifying a commercial Nd:YAG laser to operate at 1116 nm. We have achieved broadband lasing at 1116 nm with 1mJ at 100 Hz in long-pulse mode. The 1116 nm laser will be Q-switched and injection seeded to yield narrowband high power emission. The light will then be tripled to 372 nm and serve as the lidar transmitter. Using a frequency-lock Rb laser, we demonstrate accurate monitoring of the laser's frequency differences when locked to different Doppler free features with errors <1MHz. This will support the measurement of temperature with this lidar.

1. Introduction

An all-solid-state Iron Resonance Temperature Lidar (IRTL) is under development to be deployed at the HAARP (High-Frequency Active Auroral Research Program) facility [1]. This system will provide measurements of the neutral iron atoms in the mesosphere-lower-thermosphere region in support of the controlled scientific investigations of the ionosphere. We present the developments of the HAARP IRTL system over the last year, specifically the lidar transmitter and the etalon-based laser frequency monitoring system, showing that we are making good progress in the development of the lidar system.

This work is conducted under an NDA (Non-Disclosure Agreement) with Quantel USA.

2. Developments of the lidar system

A schematic diagram of the IRTL is shown in Figure 1. This system is based on a prototype established by Kaifler [2]. The lidar system is composed of three major components, the transmitter, the receiver, and the laser spectroscopy system.

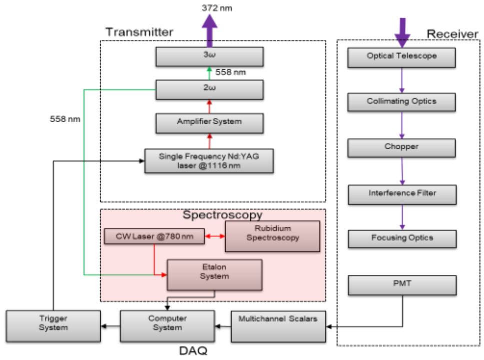

Figure 1. A schematic diagram of the iron resonance wind temperature lidar at HAARP.

2.1 Developments of the transmitter

The transmitter is based on a compact, high power diode-pumped Nd:YAG laser which is commercially available (MERION C, Quantel USA, Bozeman, MT, USA, Figure 2), which is modified to operate at 1116 nm. The modifications are: one of the end mirrors and the folding mirrors are replaced with mirrors coated for high reflectivity at 1116 nm and low reflectivity at 1064 nm and 1319 nm; the 40% 1064 nm output coupler is replaced by an 80% 1116 nm output coupler. These modifications allow us to yield 10 mJ/pulse of 1116 nm lasing with TEM00 transverse mode. In Figure 3, a spectrum of the laser output. It's clear that the 1064 nm lasing is perfectly suppressed in the modified laser cavity, and the 1116 nm lasing dominates the radiation. Another feature that's present is the 1123 nm radiation. This, along with the 1116 nm and 1112 nm, are the three minor lines that's present in the spectroscopy of Nd:YAG crystal. We will insert an etalon in the cavity to suppress the 1123 nm lasing next.

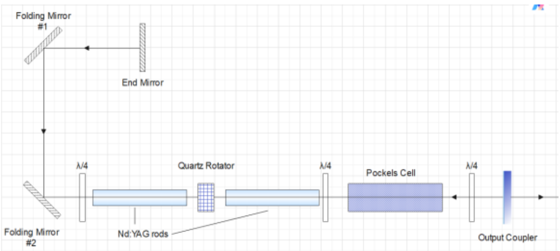

Figure 2. A diagram of the MERION-C laser by Quantel USA.

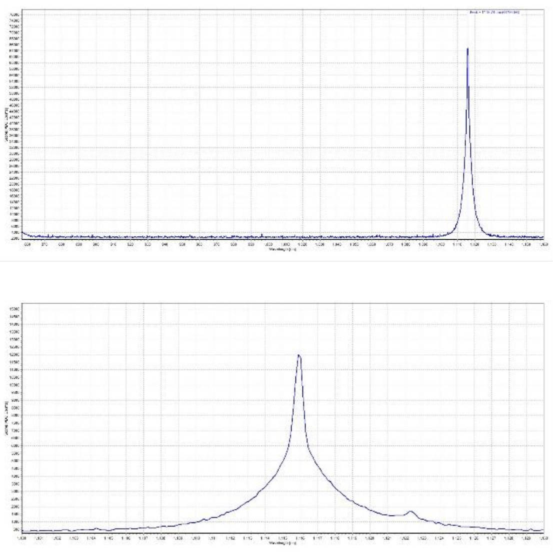

Figure 3. Spectrum of the 1116nm-modified MERION-C laser. The top panel shows the spectrum over 800-1150 nm. The bottom panel shows a zoomed in version.

2.2 Development of the laser spectroscopy system

The laser spectroscopy system (LSS) is an etalon-based system. A photo of the LSS is shown in Figure 4. The 1116 nm pulsed laser from the transmitter will be frequency doubled to yield 558 nm light, which will be directed into the etalon. The 780 nm light from a frequency-locked Rb laser will be sent into the etalon as well. The ring structures of the 558 nm and 780 nm lights will be captured by a camera. By monitoring the relative changes of the ring structures of the 558 nm light and the Rb 780 nm light in the etalon, we will be able to monitor the frequency shift of the lidar transmitter.

The key component of the system is an air-spaced etalon. This etalon is an 150 mm air-spaced etalon, with an free-spectral-range of 1GHz, and an finesse of 31.

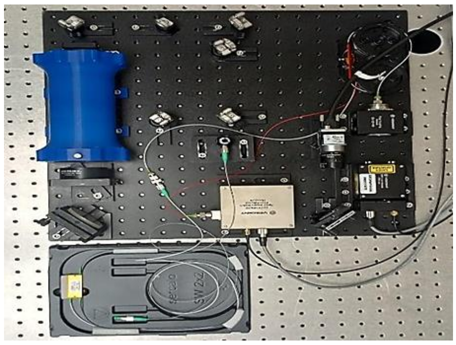

Figure 4. A photo of the laser frequency monitoring system.

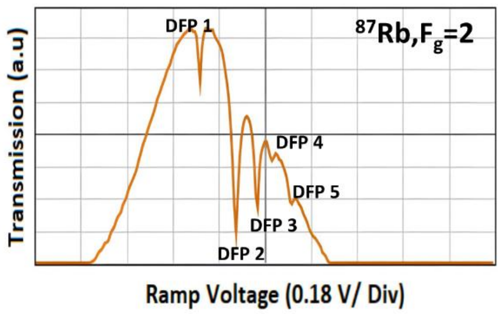

Figure 5. The five Doppler-free dips resolved by the Rb laser (from left to right: Fg = 2 →Fe = 3, cross-over Fe = 2&3, cross-over Fe = 3&1, Fe = 2, and cross-over Fe = 2&1).

To demonstrate the capability of this LSS, we locked the Rb laser to five different doppler-free peaks (DFPs, Figure 5 [3]). The ring structures are then integrated to yield a distribution of intensity at different radial distances (Figure 6). From the intensity distribution, we were able to measure the frequency shifts of the laser when locked to these DFPs. The theoretical values and observed values of the frequency shifts between different DFPs are summarized in Table 1. Based on these results, we confirm that the etalon-based LSS is able to accurately monitor laser frequency shifts to <1MHz.

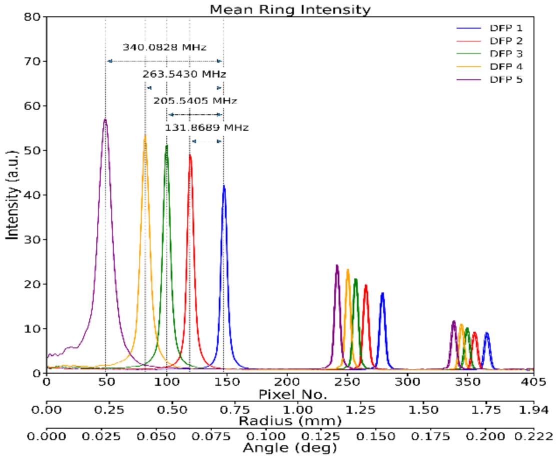

Figure 6. Intensity distribution as function of pixel number, radial distance and angle, achieved from the ring structures formed in the etalon using frequency-locked Rb 780 nm laser when locked to five DFPs.

Table 1. Accuracy of the etalon-based LFMS to monitor the frequency shift of the Rb laser

Peaks	Theoretical frequency shift (MHz)	Observed frequency shift(MHz)	Absolute Difference (MHz)
DFP1-2	133.3	133.4	<0.1
DFP1-3	211.8	211.7	<0.1
DFP1-4	266.7	267.6	0.9
DFP1-5	345.1	345.0	0.1

3. Summary and conclusion

In this work, we presented the recent progress in the development of an all-solid-state iron resonance wind temperature lidar. We reported the progress we made in the development of the transmitter and laser frequency monitoring system. We yielded broad band 1116 nm lasing operating in long pulse mode, with 1 mJ/pulse at 100 rep rates. This proves the capability of the current laser configuration to yield 1116 nm lasing. We also demonstrated that the laser frequency monitoring system is able to monitor the frequency differences when the Rb laser is locked to different Doppler free features to <1MHz accuracy, which allows us to use this system to make temperature measurements.

4. References

[1]. Collins, R., et al. All-Solid State Iron Resonance Lidar for Measurement of Temperature and Winds in the Upper Mesosphere and Lower Thermosphere. in Proceedings of the 30th International Laser Radar Conference. 2023. Cham: Springer International Publishing.189-195.

[2]. Kaifler, B., et al., Demonstration of an iron fluorescence lidar operating at 372 nm wavelength using a newly-developed Nd:YAG laser. Optics Letters, 2017. 42(15): p. 2858-2861.

[3].Kraft, S., et al., Rubidium spectroscopy at 778–780 nm with a distributed feedback laser diode. Laser Physics Letters, 2005. 2(2): p. 71.