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Towards Direct Detection Lidar Velocimetry Measurements using Spectral Hole Burning

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Abstract: Weather modelling, detection of clean air turbulence, detection of wind shear, and other applications benefit from precise wind speed measurements. This work reports on progress towards a direct detection lidar velocimetry method utilizing an adaptable vapor filter. The method uses spectral hole burning, in which a pump beam excites atoms in a vapor cell moving them from the ground state to a trapping state, creating deep “holes” in the inhomogenously transmission profile. A three-level atomic model was created and experimentally validated to characterize the position and magnitude of the hole in the transmission profile, as well as the time required to reach equilibrium, under different pump frequencies and powers. Work towards using the technique for tabletop velocimetry measurements of an under-expanded jet is described.

1. Introduction

Detection of small changes in wind speed is important in a variety of weather forecasting applications, from improvements in forecast models to detection of clean air turbulence near aircraft and wind shear near ground structures. To date, multiple lidar systems have been implemented for large scale monitoring of the Earth’s winds from ground, air, and space-based platforms. For example, the Atmospheric Laser Doppler Instrument (ALADIN) on the European Space Agency’s Aeolus satellite utilizes a Fizeau and a dual filter Fabry-Perot interferometer to measure the Doppler frequency shift of the backscattered signal, allowing estimates of the wind speed. This system has a sensitivity of 1.8 m/s and a vertical resolution from 500 m to 2 km [1]. Atomic filters are also commonly used in lidar applications to filter molecular and particulate returns, particularly in High Spectral Resolution Lidar (HSRL) systems. Although iodine filters with absorption lines are commonly used [2, 3], other atomic vapors can also be used including ones that take advantage of excited state transitions [4]. These filters however, with some exceptions [5], only operate at specific wavelengths.

Here the use of a tunable atomic filter is suggested for frequency, and as a result velocity, discrimination. This work investigates using a concept known as spectral hole burning to produce an adaptive atomic vapor filter, which may be modified in real time and used as an edge filter for direct detection Doppler lidar. Spectral hole burning has been shown to be capable of altering the susceptibility of an atomic vapor and was used to achieve slow light among other applications [6-8]. Work has also shown how arbitrary shapes and positions of the transmission profile may be created [7], as well as much narrower slopes compared to the inhomogenously broadened linewidths produced without pumping the medium. These narrow spectral slopes, combined with the tunability of the system, can allow for a precise direct detection lidar method to estimate wind speeds.

The basic process of spectral hole burning is outlined in part (a) of figure 1. A pump beam that is near resonance with an atomic transmission of an inhomogenously broadened medium pumps a velocity subset of the atoms from one of the ground hyperfine states (i) to an excited state (j). Since the pump beam is continuously applied, atoms decay into the second hyperfine ground state (d), identified as the trapping state, until few atoms remain in the original ground state. The absence of these atoms creates a narrow rise in transmission along the frequency spectrum, called the spectral hole. As seen in part (b) of figure 1, the change in frequency of a narrow signal beam can be determined by finding the change in intensity of the signal as it shifts along the edge of the spectral hole. The slope of this hole can be several times steeper than the slope of the transmission without pumping, allowing for more precise frequency discrimination.

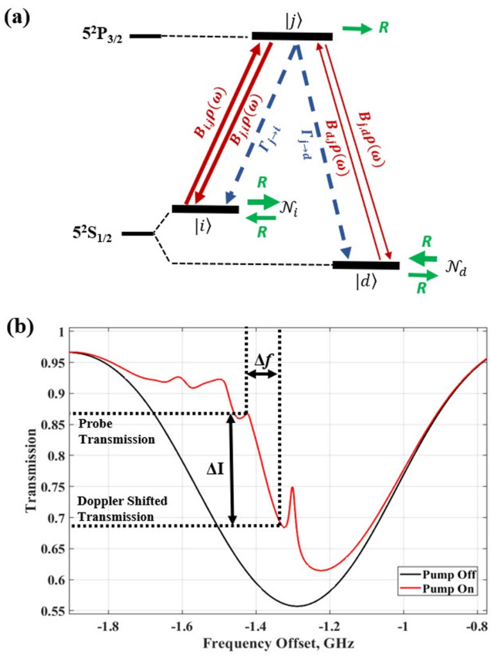

Figure 1. (a) Model of the 3 level system. (b) Frequency shift corresponding to change in transmission intensity.

2. Spectral Hole Characterization

This work characterizes the D2 transition of rubidium vapors, which occurs at approximately 780 nm, due to its strong absorption line and the availability of narrowband, tunable lasers at this frequency. To understand how to shape the spectral hole for velocimetry measurements, the position and shape of the hole was characterized at various pump frequencies and powers. A three level model determined transmission profile by first finding the number density of atoms in each energy state through solving ordinary differential equations. This model is explained elsewhere [9-11] and considers spontaneous emission, stimulated absorption, stimulated emission, and movement of atoms into and out of the pump beam, as seen in part (a) of figure 1. Experiments to measure the transmission spectra using a counterpropagating pump and probe then validated the model. Figure 2 part (a) shows the percent of transmission (measured from 0 to 1) modelled at various pump and probe frequencies offset from the center of the rubidium D2 absorption line (780.261 nm). This part of the figure shows simulated transmission in a 70 mm cell at 21° C with an 8 mW pump beam, corresponding to the selected experimental conditions. An increase in transmission occurs at velocity subsets within the transmission line corresponding to the hyperfine ground state, or the state nearest to resonance with the pump beam. Note that, since the pump and probe counterpropagate, the position of the hole in the probe spectrum varies inversely with the pump frequency. Meanwhile, a decrease in transmission occurs at the transmission line corresponding to the trapping hyperfine state. Parts (b) and (c) of the figure show a comparison of the modelled and experimentally obtained spectra at a far detuned frequency (b) and tuned near one of the peaks (c) given by the dotted red line. The location of part (c) is indicated by the white dotted line in part (a). Again, an increase in transmission occurs when the probe is near resonance with the original ground state, but decreases when near resonance with the trapping state.

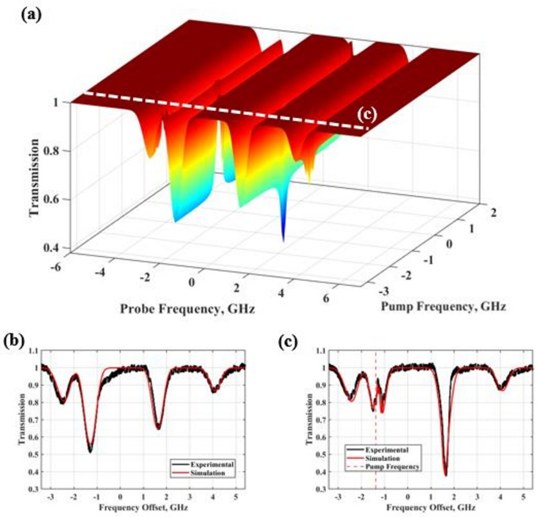

Figure 2. (a) Model of transmission at various pump and probe frequencies. (b-c) Modelled versus experimental transmission profiles at various pump frequencies [11].

Using the model, the maximum transmission slope and the centerpoints of the slopes were found for pump frequencies up to 5 GHz offset from the D2 transmission. The model was ran at different pump powers from 0 mW to 30 mW, temperatures from 20° C to 200° C, and cell lengths from 10 mm to 500 mm. Validation of the pump probe experiments was conducted for selected conditions throughout this range of parameters. Through characterization of the model, frequency differences as low as 0.685 MHz per 1% change in transmission were found. This frequency resolution corresponds to changes in velocity down to 0.27 m/s. This information will help select appropriate pump and probe frequencies when performing velocimetry measurements.

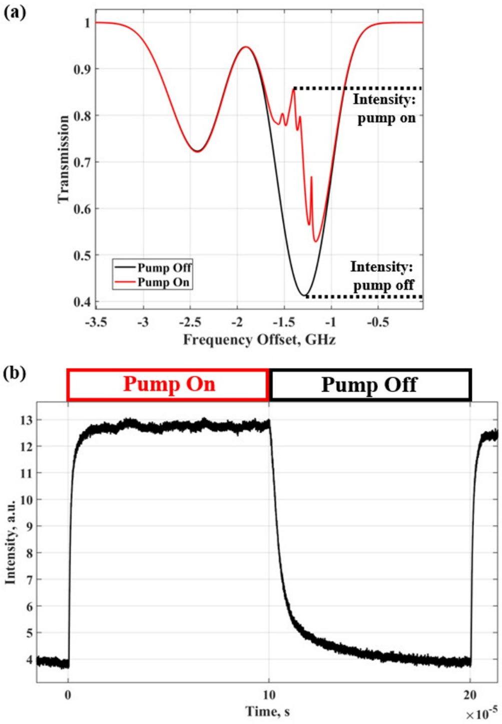

Figure 3. (a) Comparison of transmission spectra with and without probe beam. (b) Temporal response of signal when turning probe on and off.

The pump probe experiments also characterized the temporal response of the spectral hole. Using an acousto-optic modulator (AOM), the pump beam was turned on and off at a rate of up to 5 kHz to determine the time required for the spectral hole to stabilize, corresponding to how long the atoms take to reach an equilibrium state. The time required to reach equilibrium is of interest to determine how fast the spectral hole can be modulated while taking measurements. Figure 3 part (a) shows a modelled spectrum both with and without the pump beam. An increase in transmission of nearly 50% is seen when applying a 7 mW pump beam at a -1.4 GHz frequency offset. Part (b) of the figure shows the temporal response of the transmission intensity when turning on the pump then turning off. When applying the pump, the transmission stabilizes in the range of 10s of µs while requiring approximately 100 µs to stabilize back to the original spectra when removing the pump. Note that the time required for the pump to reach full intensity and the rise time of the photodiodes is several orders of magnitude faster than the timescale displayed in the figure.

3. Conclusion and Outlook

This work has spectrally and temporally characterized transmission of a probe beam through a vapor cell with a counterpropagating pump. In addition, pump frequencies and intensities are suggested that could discern sub-m/s changes in velocity. These parameters will be implemented for velocimetry measurements of an aerosol flow between 0-40 m/s performed using spectral hole burning. Current efforts focus on developing an experiment to collect Mie scattered light near 780 nm from aerosols propelled by an underexpanded jet. The Mie scattered signal passes through a pumped rubidium cell, functioning as a tunable filter, as seen in figure 4. The ratio of the signal intensity before and after the vapor cell can then be measured to estimate the drop in transmission. These tabletop measurements will provide a proof of concept for atmospheric lidar velocimetry measurements.

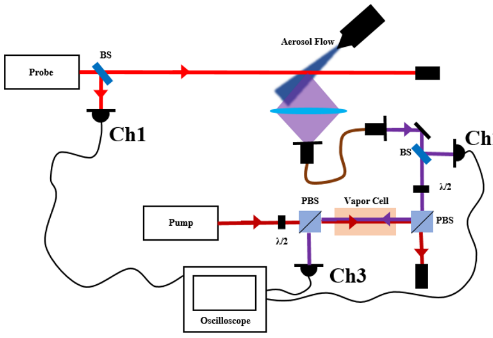

Figure 4. Outline of experimental velocimetry setup.

4. References

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