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Wavelength-agile source based on a potassium atomic vapor cell and application for absorption spectroscopy of iodine

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Abstract

Output from a mode-locked Ti:Sapphire laser was transmitted through a cell containing atomic potassium vapor. Because the group velocity dispersion near the D1 resonance varies strongly with wavelength, a chirped pulse was emitted from the cell. This chirp was treated as a wavelength-agile source and was applied for a high-resolution measurement of the $R(101)A^3\Pi_{1u}$–$X^1\Sigma_g^+(0,13)$ iodine absorption feature. The agile measurement was compared to one obtained using an external cavity diode laser. The characteristics of the potassium vapor cell and the associated effects on the transmitted chirp were examined in detail. Extensions of this general approach to practical applications are discussed.

Keywords: Time-of-flight spectroscopy; Wavelength-agile; Group velocity dispersion; Atomic vapor

1. Introduction

It is well-known that wavelength-tunable light sources are useful for spectroscopy. Recently, sources that rapidly scan through a broad range of wavelengths (known as wavelength-agile sources) have emerged [1–5]. The fast, broad scans produced by these wavelength-agile sources can be used to measure absorption features and thereby obtain pressure and temperature information in harsh environments, such as those found in internal combustion engines [6]. One way to generate wavelength-agile light is to inject a spectrally broadband pulse into a long optical fiber [2,4,7,8]. In this case, wavelength scans are created using the group-velocity dispersion (GVD) in the long fiber. In brief, because the fiber's index of refraction depends on wavelength, different wavelengths propagate through the fiber at different speeds. Thus, when a multi-wavelength pulse is

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injected into a long fiber, the different colors emerge at different times. For example, if red light travels faster than blue light through the fiber, a broadband input pulse is converted to a rapid wavelength-scan from red to blue at the fiber output.

Here, we report an alternative method for creating a wavelength-agile source. Essentially, we replaced the long fiber with an atomic vapor cell (AVC). Due to attenuation, ordinary silica fibers typically limit wavelength-agile sources to high scan rates ($\sim$1 cm^{-1}/ns or higher) and are relatively ineffective away from the communication band. Atomic vapor cells circumvent both of these shortcomings. Near an atomic resonance line, the index of refraction changes dramatically. As in the case of the fiber, this change in the index of refraction leads to a wavelength scan. In this experiment, measurements were made on the red side of a potassium absorption line, so the scan was from red to blue. Relative to a fiber, the atomic vapor cell enables higher resolution measurements over a narrower range. In a fiber, the index of refraction does not change appreciably over a narrow range of say 1 cm^{-1}, whereas in the atomic vapor cell the change can be extreme. Another advantage is that the atomic vapor cell could be used at UV wavelengths, unlike traditional fibers. It may also be possible to use excited-state atomic transitions at mid-IR wavelengths, for example using a noble-gas plasma to temporally disperse a broadband pulse.

Atomic vapor cells have been used previously for similar purposes. Yalin et al. [9] used a mercury vapor cell to measure the laser seeding efficiency of a Ti:Sapphire laser. The seeded portion of the laser was narrow-band and therefore, when tuned near a mercury absorption line, the GVD was large. The unseeded portion of the laser was broadband and therefore very little of that light was affected by the absorption line. Kash et al. [10] used a hot rubidium atomic vapor cell to slow the speed of light to 90 m/s. Phillips et al. [11] essentially slow light to a standstill, storing it in rubidium vapor until choosing to release it. Atomic vapor cells have also been used for spatial, rather than temporal, dispersion. For example, Tang et al. [12] used a rubidium vapor cell with a density gradient to create a prism. This prism is then used as a Raman spectrometer.

In this experiment we first used a diode laser to measure the $R(101)\mathrm{A}^3\Pi_{1u}$–$\mathrm{X}^1\Sigma_g^+(0,13)$ iodine absorption feature [13–15] (12985.0843 cm^{-1}) for reference. This feature was selected for its proximity to the potassium D1 absorption line (12985.17 cm^{-1}) [16]. The wavelength-agile measurement was then performed as follows. A pulsed laser (80 ps duration) was tuned to the iodine absorption frequency. The pulses were directed through an atomic vapor cell containing potassium; the result was a wavelength-agile source that scanned over the iodine absorption line. The atomic vapor cell increased the laser pulse duration from 80 ps to approximately 5 ns, allowing measurement of the iodine feature at high resolution; in contrast, a high-dispersion fiber would have increased the pulse duration by less than 10 ps. The results of the diode laser scan and the atomic vapor cell scan were in good agreement.

Although a wavelength-agile iodine sensor is probably not directly useful, there are several reasons this experiment is of interest. First, extension of this work to the ultraviolet, where relevant species could be probed using other atomic dispersion cells, is straightforward as discussed in Section 5. Second, we have designed a system for measuring Rayleigh scattering spectra using potassium vapor to temporally disperse the scattered light, and that system directly builds on this effort. Finally, this experiment helps improve the understanding of fundamental and practical limits of wavelength-agile spectroscopy.

This paper is organized as follows. Section 2 details the experimental setup. The following section explains the theory behind the measurements. The results of the diode laser and atomic vapor cell measurements are then presented. We next discuss future improvements and extensions of this work and end with a brief summary.

2. Experimental setup

The measurement setup is shown schematically in Fig. 1. In brief, short-duration pulses were emitted by a Ti:Sapphire laser and directed through an