Spectral Hole Burning of Acetylene Gas inside a Photonic Bandgap Optical Fiber

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Abstract: We have observed saturated-absorption spectra of acetylene gas inside a photonic bandgap fiber. Significant signal sizes observed at low pump powers (< 20 mW) indicate the utility of this technology for portable optical frequency references.

Acetylene has been extensively investigated as an optical frequency reference in the near-infrared region of the spectrum. It offers many well-separated transitions, and lacks a permanent dipole moment, which makes it relatively immune to external fields and shifts. Furthermore, the overtone transition corresponding to a symmetric C-H stretch ($\nu_3$) and an antisymmetric C-H stretch ($\nu_2$) gives rise to about 60 lines from 1512 nm – 1544 nm in $^{12}$C$_2$H$_2$ and another 60 from 1522 nm -1552 nm in $^{13}$C$_2$H$_2$ [1]. Precise realizations of these lines have so far relied on sub-Doppler saturated absorption spectroscopy [2] performed within a power build-up cavity. In 2001, based on measurements by Nakagawa et al.[3], the International Committee for Weights and Measures (CIPM) established 53 of these features as optical frequency references with an uncertainty of 200 kHz, and one of them, P(16), with a provisional uncertainty of 100 kHz [4]. Since then, three groups have reduced the uncertainty in the measurement of the P(16) line, as realized in a cavity, by up to 2 orders of magnitude by comparing a laser stabilized to the acetylene transition with a stabilized, Ti:sapphire-based optical frequency comb [5-7].

One of the primary applications of these improved standards is to support the optical telecommunications industry and especially dense wavelength division multiplexing (DWDM). Indeed, many commercially available wavelength measurement devices, such as optical spectrum analyzers, contain acetylene-filled vapor cells certified by the National Institute of Standards and Technology (NIST) to have absorption lines known to 130 MHz, or is some cases 13 MHz [1, 8]. Some applications of DWDM call for increased accuracy in portable frequency references, and some proposed applications will require increasingly accurate references. The vapor cells provided by NIST are limited by Doppler and pressure broadening to their existing levels of accuracy, and cavity-based references are not readily portable. Therefore, new technology is needed to combine the portability of the vapor cells with accuracies approaching that of the gas-filled build-up cavity.

Photonic bandgap fiber [9] offers an excellent medium in which to perform spectroscopy on weak molecular transitions. Due to its low losses (as compared with capillary tubing), light can propagate through a molecular vapor at high intensity over long distances. These features are already being exploited in applications such as gas sensing [10], high-energy soliton propagation [11], and wavelength conversion via rotational Raman scattering [12]. Considerations for signal strength and linewidth are similar in photonic bandgap fiber and in power build-up cavities. Shifts in the cavity-based standards have been observed to contribute on the kHz level to uncertainties [13], and sub-MHz transitions have readily been observed. The two most significant differences between a fiber-based standard as compared to a build-up cavity are the proximity of the fiber surface to the molecules being probed, and the small beam size (~11 μm in the fiber vs. ~500 μm in the cavities). The former is not expected to be observable under the conditions described here. The small beam size results in short interaction times between the molecules and the laser field, giving rise to a transit-time broadening [2] at room temperature in a 10 μm core fiber, of ~50 MHz. Further reduction of the line width in acetylene will require a reduction in this transit time, either by increasing the fiber core size or by preserving coherence between the molecules and the laser field as the molecules bounce off the walls, for example with a wall coating.

We report the observation of sub-Doppler absorption features in molecular gases contained in photonic bandgap fiber. The experimental set-up is shown in Fig. 1. A 56 cm length of commercially-available photonic bandgap fiber (Blaze Photonics HC-1550-02) is attached on each end via a Torr Seal to a metal tube, which is in turn sealed to two separated vacuum chambers by a compression fitting. It is evacuated to ~1 mTorr using a roughing pump, and can then be filled to arbitrary pressures with $^{12}$C$_2$H$_2$, as measured with a thermocouple gauge. Light is coupled into and out of each fiber through an AR-coated, wedged window on each chamber using mirrors and a lens mounted to a translation stage. The counter-propagating beams required for saturation spectroscopy are created from a tunable diode laser (~4 mW) at ~1531 nm that is split into two beams. One passes through an acousto-optic
modulator and is used as the probe, while the second is amplified by an erbium-doped fiber amplifier (EDFA) to up to 500 mW. The probe and pump are separated by polarizing beamsplitters, and the probe beam is detected on a photodiode and read out on an oscilloscope. The resulting signals are shown in Fig. 2.

Fig. 1: Schematic drawing of vacuum system and optical beam path for the observation of saturated absorption features in acetylene or other reference gases. The presence of the acousto-optic modulator (AOM) minimizes interference between the probe light and pump light that reflects off the end of the fiber and then strikes the photodetector. The erbium-doped fiber amplifier (EDFA) amplifies the diode laser powers as high as 500 mW, and typically 40% coupling efficiency is achieved into the photonic bandgap fiber.

Fig. 2: Saturated absorption spectra of the P(11) feature as a function of pump power. Each signal represents an average of 16 sweeps of ~1s duration across the transition. At higher pump powers, the curves are offset from zero for clarity by the amount indicated in the key. The frequency axis is calibrated using the theoretical Doppler width at room temperature, and the resulting offset of the saturation feature is precisely consistent with half of the AOM frequency, as expected. The increase in noise with pump power is attributed to a residual interference effect between the probe beam and stray pump light. The widths of the features are ~40 MHz, consistent with the expected transit-time broadening.

Saturated absorption spectra over a range of pump powers are shown in Fig. 2, at pressures of ~1.6 Torr. The features have a width of about 40 MHz, consistent with the expected transit-time broadening. The signal size clearly depends on the pump power, consistent with the expected saturation power for this fiber and this transition of ~300 mW. Notably, a significant signal is observed at pump powers as low as 10-20 mW. Thus these signals will be observable with off-the-shelf diode lasers, without an EDFA.
Recently, the signal-to-noise ratio on these transitions was significantly improved by increasing the probe power, which diminished the interference effects between the reflected pump power and the probe beam (these effects are seen in Fig. 2 off-resonance as large ripples in the fractional absorption at high pump power). Efforts are ongoing to further narrow the transition by using larger-core fibers, and to investigate the dependence of signal quality on vapor pressure. We intend to seal the fibers on both ends, eliminating the need for the vacuum system. Finally, we plan to measure the optical frequency of these transitions using a frequency comb, looking for possible shifts in optical frequency due to surface interactions or other systematic effects.

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