Improved Sensitivity Spontaneous Raman Scattering Multi-Gas Sensor

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Abstract: We report a backward-wave spontaneous-Raman multi-gas sensor employing a hollow-core photonic-bandgap-fiber to contain gasses and increase interaction length. Silica Raman noise and detection speed are reduced using a digital spatial filter and a cladding seal.

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1. Introduction

We demonstrate rapid (few seconds) detection of gases often monitored in industry using a novel backward wave spontaneous Raman scattering sensor system based on hollow-core photonic bandgap fiber (PBF).

Photonic bandgap fibers provide large interaction lengths between a pump beam and gasses contained in the hollow core for spontaneous Raman scattering. We show that backward wave Raman provides simple optical alignment and efficient collection, even at wavelengths outside of the bandgap of the PBF. Two key attributes of our detection system are a) a reduction of silica Raman scattering noise by spatially resolving Raman signals generated in the PBF and b) fast sensing with speeds limited by gas exchange times. Exchange times were minimized by sealing the fiber's small cladding holes, thus eliminating gas flow in the cladding.

We have previously shown that a visible wavelength hollow-core PBF can be used effectively as a gas cell and Stokes light collector gathering *forward*-wave Raman signals from gases introduced into the fiber core. Signals detected are hundreds of times larger than those obtainable using conventional optics and free space beams [1]. Herein, a 780nm-pumped, *backward*-wave Raman PBF-based multi-gas sensor is reported. The sensor is capable of detecting numerous hydrocarbons, homonuclear diatomics, and other gasses with Raman shifts less than about 2500 cm^{-1} and accuracies better than 0.1%, in as little as a few seconds.

Our previous demonstration of visible wavelength spontaneous forward-wave Raman in PBFs for gas detection was limited by noise produced by Raman scattering from the silica in the fiber's cladding [1]. The present work demonstrates that since most of the silica Raman arises outside of the fiber's core, appropriate spatial filtering can greatly reduce silica noise by only passing signals that arise from within the core.

2. Experiments

Our experimental sensor system is shown in Figure 1.

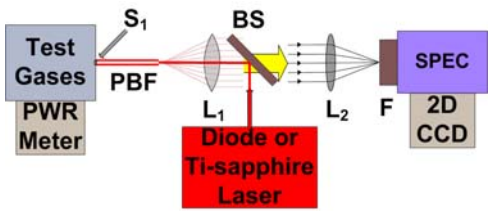

Figure 1a: L1: 11-mm aspheric singlet, L2: 6-cm efl spherical singlet, BS: dichroic long-pass beamsplitter, SPEC: 0.55-m grating spectrometer, 2D CCD: Princeton Instruments SpectruMM 250B with Hamamatsu MPP back illuminated 1024X252 element sensor array, S_1: fusion-splicer cladding seal

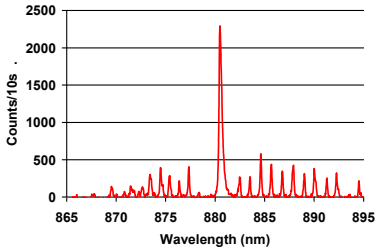

Figure 1b: Stokes spectrum of methane (1532 cm^{-1} line). Rotational-vibration substructure is clearly visible despite the low Raman cross section. HC-800-01 PCF [2], pump power ~15mW (λ = 780 nm), ten second integration time

This system was used to detect five gases (methane, ethane, propane, carbon dioxide, and oxygen) whose Stokes wavelengths lie within the bandgap of the PBF and one (nitrogen) whose Stokes wavelength lies outside the low

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attenuation region of the bandgap. A typical spectrum for an in-bandgap Stokes signal (methane, 1532 cm^{-1}) is shown in Figure 1b.

The spectrum shown was obtained using the 2-D Hamamatsu CCD detector array to record the image of the fiber's end facet produced at the input to the spectrometer. A background spectrum (containing only silica Raman and minimal Rayleigh scattering) taken with an evacuated fiber was subtracted from the recorded gas spectra. Digital spatial filtering was accomplished by summing only the central 4 rows of array pixels, which contained the image of the fiber core and gas Raman signals. This limited the silica Raman noise recorded and greatly improved the SNR in the spectrum displayed over those shown in reference 1.

The backward-wave scattering arrangement also leads to simpler optical alignment than that required for forward scattering. The backscattering arrangement uses the same optic to couple the pump-light into the fiber as is used to collect the Raman output. This means that in the absence of significant chromatic aberration in the coupling lens, alignment at the pump wavelength leads to alignment at the Stokes wavelength, and subsequent imaging of the Stokes output.

Similar results were obtained for ethane, propane, carbon dioxide, and oxygen Raman lines [1000, 870, 1286, and 1556 cm^{-1} respectively]. The magnitudes of the measured Stokes spectral peaks for these gases agree well with previously published Raman cross sections.

A vibrational Raman spectrum was also obtained for nitrogen (2231 cm^{-1}). The Stokes wavelength (~953 nm) for this line lies outside of the bandgap of the PBF and hence is significantly attenuated. However, the backward-wave Raman configuration minimizes the effect of the fiber attenuation since the Raman signal emerges from pump-input end of the fiber [3]. This results in an effective interaction length shorter than the physical length of the fiber.

Limits to the measurement time of the Raman technique were shown to be imposed by the time required for the gas to enter and exit the fiber. An impediment to rapid gas exchange times was determined to be gas trapped inside the small array of cladding holes. We have observed that without proper precautions, gas can be trapped in an atmospheric pressure fiber for many weeks. We have reduced gas exchange times to a few seconds by employing a fusion splicer arc to seal the cladding holes at one end of the fiber so that gases cannot enter these holes [4]. We show that 1/e Stokes signal rise times vary linearly with gas input pressure falling to less than 1.5 seconds at 150psi input pressure in CO2 gas. We have also noted that this sealing technique prevents dust and debris from being forced into the cladding holes during gas transfer, and subsequently prevents loss of transmission while measuring a particulate-laden gas stream.

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3. References

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