

Cavity-Enhanced Spectroscopy in Optical Fibers

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Cavity-Enhanced methods have been extended to fiber optics by using Fiber Bragg Gratings (FBGs) as reflectors. High-finesse fiber cavities were fabricated from FBGs made in both germanium/boron co-doped photosensitive fiber and hydrogen-loaded Corning SMF-28. Optical losses in these cavities were determined from the measured Fabry-Perot transmission spectra and Cavity Ring Down Spectroscopy (CRDS). For a 10-m long single-mode fiber cavity, ringdown times in excess of 2 microseconds were observed at 1563.6 nm and individual laser pulses were resolved. An evanescent wave access block was produced within a fiber cavity and an enhanced sensitivity to optical loss was observed as the external medium's refractive index was altered. © 2002 Optical Society of America

OCIS codes: 060.2370, 050.2230, 300.1030

Intrinsic fiber optic sensors are widely utilized in a variety of fields including biosensing, industrial monitoring, and civil engineering¹. A large class of these sensors relies on evanescent wave absorption, where a small fraction of light propagating through the fiber extends outside the fiber core and is absorbed by the detected species. The sensitivity of these devices is often limited by the small losses induced by the sparse sample and weak evanescent wave. Several attempts have been made to improve these systems. Most of these attempts have involved replacing the fiber cladding with a chemically specific polymer layer that can preconcentrate the species of interest² or using specialized dyes to change the absorption signal into fluorescence³. Despite these enhancements, evanescent sensors are still unable to measure trace quantities of pollutants required in many environmental monitoring applications, and further improvements are still needed.

In this Letter, we describe a method of increasing the sensitivity of intrinsic fiber optic sensors by enclosing the sensing region within a high-finesse optical cavity. Within the last 10 years, high-finesse optical cavities have been extensively used to increase the absorption sensitivity of gas-phase measurements yielding over 300 publications worldwide⁴. Very small absorptions have been determined by measuring a decrease in the rate at which light leaks out of the cavity (Cavity Ring Down Spectroscopy^{4,5}) or by measuring the absolute intensity at the cavity's output (Integrated Cavity Output Spectroscopy⁶).

It is well known that high-finesse optical cavities enhance absorption losses. For very small

absorptions, the change in absorption due to the presence of the species can be approximated by⁷

$$\frac{\Delta I}{I} = GA \quad (1)$$

where $G = R/(1 - R)$ and $A = (1 - e^{-\alpha L})$. Note that, in order to determine the loss due to absorption, the mirror reflectivity, R , must be known. For a Fabry-Perot cavity, the finesse can be used to determine total cavity loss, and the peak transmission can be used to determine the losses in absence of the cavity.

Alternatively, in (CRDS), light is coupled into the cavity, rapidly switched off, and the resultant exponential decay is measured. The decay time, τ , gives an absolute measure of all losses within the cavity and, for very small absorptions ($A \ll R$), can be approximated as⁸

$$\tau = \frac{nL}{c(1 - R + A)} \quad (2)$$

where c is the speed of light, n is the refractive index of the medium, L is the cavity length, R is the reflectivity, and A is losses due to absorption. This technique provides an absolute measure of loss without the need for calibration and, because it is relatively insensitive to the input energy, is especially useful if the light source is unstable (i.e. pulsed lasers). Extending this technique to fiber optics is not straightforward, because of the complexities

associated with producing high-finesse fiber optic cavities.

Fiber optic cavities have been produced by a variety of methods. Initially, two high-reflectivity mirrors were placed adjacent to the polished fiber ends and index-matching fluid was used to help reduce coupling losses. Although this technique yielded cavities with finesse approaching 500⁹, it proved to be very sensitive to mirror tilt, distance, and polishing¹⁰.

Within the last few years, high-finesse fiber optic cavities have been produced by directly depositing a highly reflective dielectric coating on the polished fiber ends. Losses in these cavities have been determined by using CRDS and cavity-enhancement of bending and etching losses have been observed¹¹. Though this technique has shown preliminary success, it remains expensive and limited due to the need to have the fibers specially coated. Moreover, the authors of the previous study observed an unexplained 0.42% loss per pass. They have suggested that this loss is due to imperfect coupling between the mirror coating and the fiber core. This coupling loss maybe due to surface roughness, a slightly angled cleave, or light reflecting off the fiber endface into the cladding and still remains unaccounted for.

In this paper, we present another method of producing high-finesse fiber cavities by employing Fiber Bragg Gratings (FBGs)¹². Since the FBG is within the fiber core, it is not affected by fiber polishing and is always normal to the fiber axis. Due to their widespread utility in the telecommunications industry, including applications requiring wavelength separation, dispersion compensation, and gain flattening FBGs have become increasingly popular, cost-effective, and commercially available. Fiber cavities made from FBGs have also been employed in the telecommunications industry for wavelength filtering, but they have not been used in conjunction with CRDS or chemical sensing¹².

Experiments were performed using fiber cavities fabricated from FBGs made in both germanium/boron co-doped photosensitive fiber (Newport Corporation, F-SBG-15) and hydrogen-loaded standard single-mode silica fiber. The former were manufactured in-house by using a long-coherence KrF excimer laser (TuiLaser Braggstar S-200) operating in conjunction with an ion-etched phase mask (O/E Land Inc.). The resultant FBGs were probed by a widely-tunable external cavity diode laser and found to be >99% reflective.

Due to the hazards of working with high pressures of hydrogen at elevated temperatures, hydrogen-loaded FBGs were purchased from Advanced Optics Solutions GmbH (Dresden,

Germany). The FBGs were produced in standard SMF-28 telecommunications fiber using a chirped phase mask and were >99.9% reflective with a bandwidth of >2 nm. This wider bandwidth provides a larger spectral overlap between the two FBGs and increases the fiber cavity finesse.

Shorter fiber cavities (3 - 100 cm) were probed by coupling a widely-tunable external cavity diode laser (New Focus 6330) into the cavity and scanning across the Fabry-Perot transmission spectrum. Longer fiber cavities (2 - 10 m) were probed with CRDS by using a Raman-shifted pulsed laser system to generate 10 ns pulses tunable around 1550 nm.

Figure 1 shows the measured Fabry-Perot transmission spectrum of 2.9 cm long fiber cavity made in germanium/boron co-doped fiber. Due to the birefringence of silica, the two polarizations of light have slightly different refractive indices and the constructive interference peaks will be shifted in wavelength relative to one another. The finesse of the cavity is measured to be 1276 and the losses due to absorption are 0.2% as determined from the 2.5% peak transmission. These losses are due to the presence of boron and account for the specified 100 dB/km loss in the fiber. Several cavity lengths were fabricated (3, 4.5, 100 cm) and the losses in the cavity could all be accounted for by this specified absorption loss. Since the cavity finesse is limited by absorption in the photosensitive fiber, long fiber cavities have a very high loss and CRDS cannot be used to probe them due to their very short ringdown times.

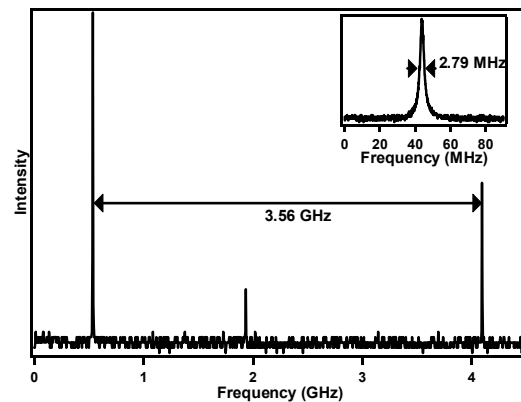


Figure 1: Fabry-Perot transmission spectrum centered at 1590.5 nm of a fiber cavity fabricated in germanium/boron co-doped photosensitive fiber. The cavity is 2.9 cm long and has a finesse of 1276. The inset shows an expanded view of a single transmission peak used to determine the cavity finesse.

This problem can be circumvented by using hydrogen-loaded FBGs, because they can be made in ordinary silica fiber whose losses are very low. Figure 2 shows the CRDS of a 10-m long fiber cavity fabricated from hydrogen-loaded FBGs. The ringdown time is a function of wavelength and is longest where the two gratings are most reflective. Since the roundtrip time (97 ns) is almost 10 times longer than the pulse width (10-20 ns), the individual pulses are fully resolved. The loss in this cavity, as determined directly from the ringdown time, is 2.3%, which is much higher than that expected from scattering in SMF-28 (0.07% in a 10-m length) and the grating transmission (0.1%). The additional loss is due to absorption within the hydrogen-loaded FBG and is a result of the UV light used to fabricate the grating. This absorption has been attributed to a weak, broad overtone absorption of Ge-OH at 1.41 microns that extends to 1.55 microns. Previous studies have found that this absorption loss is about 0.1-0.2 dB/cm within the FBG¹³. Assuming that only 1/2 of the 2 cm long FBG absorbs, the loss is expected to be approximately 0.1 (2.2%), which is consistent with the measured value. In future experiments, this loss can be circumvented by using deuterium-loaded FBGs. The by-product of ultraviolet exposure in these FBGs is Ge-OD that absorbs at 1.9 microns, giving rise to a much smaller absorption at 1550 nm¹².

The utility of high-finesse fiber cavities in intrinsic fiber optic sensing lies in their ability to enhance optical losses. In order to demonstrate this ability, we have fabricated a 6.9 cm long evanescent wave access block within a fiber cavity. The block is produced by mounting a single-mode fiber onto glass and then asymmetrically grinding the fiber to remove the cladding to within a micron of the core, exposing the core's evanescent wave. Loss can then be induced within the fiber by varying the external medium's refractive index. This was accomplished by immersing the access block in a glycerin/water mixture and measuring the fiber's transmission as a function of the mixture's composition. The mixture was constantly stirred to assure a homogenous medium and its refractive index could be varied from 1.4746 (pure glycerin) to 1.330 (pure water). Figure 3 shows how the fiber's transmission varies as a function of the medium's index of refraction both with and without a fiber cavity. The fiber cavity's transmission was determined at the peak of the Fabry-Perot transmission. The data accumulated without a fiber cavity was empirically fit and the loss as a function of refractive index was determined. The measured intensity and this loss was then inserted into equation 1 to determine a cavity gain factor of ~100 for small absorptions.

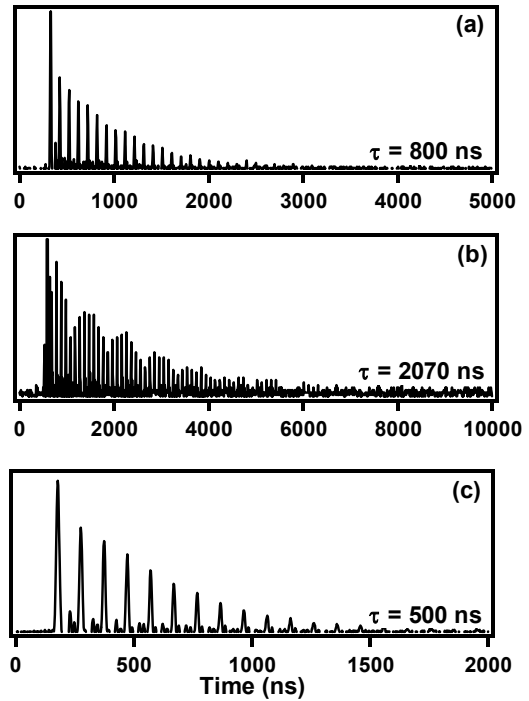


Figure 2: Cavity Ring Down Spectra of a 10-m long fiber cavity fabricated using hydrogen-loaded FBGs in SMF-28 telecommunications fiber. The ringdown time changes as the laser is tuned through 1563.6 nm, the grating's resonance (a-c). Since the cavity roundtrip time exceeds the laser's pulse width, the individual laser pulses are clearly resolved. The slow modulation in (b) is a finite data sampling artifact.

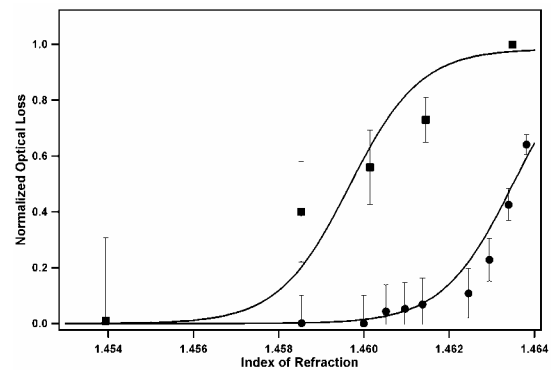


Figure 3: Optical loss through an exposed core fiber as a function of the external medium's index of refraction. The black circles represent a regular evanescent wave access block and the black squares are a cavity-enhanced block. The fit to the regular block data is empirical and the fit to the cavity-enhanced data gives an enhancement factor of ~100 for small absorptions.

We have demonstrated the ability to enhance the sensitivity of intrinsic fiber optic sensor by using a high-finesse optical cavity consisting of highly reflective Fiber Bragg Gratings. The gratings were manufactured in both germanium/boron co-doped photosensitive fiber and hydrogen-loaded SMF-28 telecommunications fiber, and the losses in the resultant fiber cavities were measured using both the Fabry-Perot transmission spectra and Cavity Ring Down Spectroscopy. These losses were attributed to known absorptions within the cavity. Finally, enhanced sensitivity was demonstrated by fabricating an evanescent wave access block within a fiber cavity and inducing loss by altering the external medium's refractive index. Future improvements will include manufacturing fiber cavities from deuterium-loaded FBGs to decrease absorptive losses, demonstrating chemical sensitivity, and thermally and physically stabilizing the fiber cavities.

We gratefully acknowledge the National Science Foundation (grants DMI-9860853 and DMI-0078367) for their funding support. M. Gupta's email address is mglgr@mindspring.com.

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