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Fiber loop ring-down spectroscopy with a long-period grating cavity

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FIBER LOOP RING-DOWN SPECTROSCOPY WITH A LONG-PERIOD GRATING CAVITY

by

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B.Sc. Chang Chun Optical and Fine Mechanic Institution, P.R.China, 1995

A thesis

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Master of Applied Science

in the Program of

Electrical and Computer Engineering

Toronto, Ontario, Canada, 2009

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Abstract

FIBER LOOP RING-DOWN SPECTROSCOPY WITH A LONG-PERIOD GRATING CAVITY

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Master of Applied Science

Electrical and Computer Engineering

Ryerson University

Cavity Ring-down spectroscopy is an absorption detection technique that makes the use of an optical cavity to realize a long effective optical path length through a sample and to render the measurement independent of intensity. These two features give the ring-down spectroscopy many advantages over traditional absorption techniques and allow it to measure chemicals present in trace amount.

This thesis presents my study of fiber loop ring-down spectroscopy with a long-period grating (LPG) cavity as the sensing section. There are several advantages in this design: 1) It provides a relatively larger sensing area for the evanescent wave to interact with the environment when compared with a fiber taper and a D-shaped fiber; 2) The LPG cavity has a much lower insertion loss than the micro-cell; and 3) The tensile strength of the fiber is well preserved.

Many issues such as the LPG mode order, LPG cavity loss, sample cell design, ring-down pulse detection and analysis have been studied. As an example, the technique was applied to measure the spectral absorption of 1-octyne in decane solution and a detection limit of 0.62% 1-octyne was determined with the exist experimental setup, which is a fact or 2 better than the result using fiber taper.

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Chapter 1 Introduction

1.1 Absorption and Fluorescent Spectroscopy

Absorption and fluorescent spectroscopy in the UV, visible and IR range of the electromagnetic spectrum are basic techniques in chemical analysis. They are almost universally applicable to both liquid and the gaseous phases. Whereas for example, in fluorescence spectroscopy [1], a type of electromagnetic spectroscopy or REMPI (resonantly enhanced multi-photo ionization) the molecule should be fluorescent or ionizable. However, fluorescence sensing generally requires the analytes to be tagged with a fluorescent dye. This labeling step can require both considerable time and effort and if not performed with care may result in errors being introduced in quantitative measurements. A lot of effort has been and still is being spent on developing alternative detection modes. While not as sensitive, optical absorption detection is a general method applicable to almost all analytes and requires less sample preparation. CRDS (cavity ring-down spectroscopy) is an example of such an approach. While it has become a fast developing implementation in gas-phase and liquid-phase analytic method, the goal of this thesis is to improve and expand the scope of a specific CRDS sensor with a higher sensitivity. This work involves the design, characterization and optimization of such a sensor.

Conventional absorption spectroscopy measures the intensity of light transmitted through a sample, $I(d, \lambda)$ and compares it to the incident intensity, I_0 . The light absorbed by the sample is thus

$$\Delta I = I_0 - I(d, \lambda) \quad (1.1)$$

The transmitted light intensity is described by the Beer-Lambert law

$$I(d, \lambda) = I_0 e^{-\varepsilon(\lambda)Cd} \quad (1.2)$$

where $\varepsilon(\lambda)$ is the wavelength dependent absorption coefficient. C is the concentration of the absorbing species. And d is the optic path length

through the sample. Equation (1.2) demonstrates the fundamental limitation in the conventional means of performing absorption spectroscopy. For low concentrations, weak absorbers, or short path length, both I_0 and $I(d, \lambda)$ are very close, so by taking the difference ΔI one is measuring a small intensity change over a large background. Thus conventional absorption measurements are highly dependent on the intensity stability of the light source and detector used. We now compare this with ring-down spectroscopy.

1.2 Ring-down Sensing and Spectroscopy

CRDS is based on the measurement of the decay rate of light behind a high-finesse cavity (see Fig.1.1). The cavity consists of a pair of high- quality mirrors with reflectivity being on the order of 99.9% or 99.99%. This means that only 0.1 to 0.01% of the excitation light will enter the cavity,

Figure 1.1 Schematics of the principle of CRDS. After abrupt termination of the excitation, the light stored in the cavity will decay exponentially as it bounces back and forth between the mirrors, losing a small portion at each reflection. The decay rate of this light can be measured behind the cavity

and the leakage from the cavity is also 0.1 to 0.01% per round-trip. After abrupt termination of the excitation, the rate of decay of the light is measured behind the cavity and fitted to an exponential:

$$I_t = I_0 e^{-t/\tau} \quad (1.3)$$

where I_t is the measured intensity and t is the time. The ring-down time τ of this exponential is directly related to the reflectivity R of the mirrors, scattering loss β_{scatt} and the absorption coefficient α of the absorber between the mirrors:

$$\tau = \frac{(n_{\text{avg}} L) / c}{[(1 - R) + \alpha l] + \beta_{\text{scatt}}} \quad (1.4)$$

where L is the cavity length and l the effective path length through the sample (in many cases, $L=l$) while c is the speed of light and n_{avg} is the weighted refractive index of the cavity if it contains more than a single medium. Absorbance units (ϵCl) can be derived from the ring-down time via: [2]

$$\epsilon Cl = \frac{\alpha l}{2.303} = \frac{n_{\text{avg}} L}{2.303 c} \left[\frac{1}{\tau} - \frac{1}{\tau_0} \right] \quad (1.5)$$

where τ and τ_0 are the ring-down times in presence or absence of analyte respectively, and ϵ is the molar extinction coefficient and C is the concentration. 2.303 is the constant to convert from natural log to log base 10. Subtraction of the baseline loss τ_0 is necessary to account for the background (reflection and scatter) losses, as well as impurities in the blank solvent.

The main advantages of ring-down spectroscopy is its multi-pass nature, which results in a long effective optic path length through the sample, and its insensitivity to the fluctuations in the light source intensity, making the accurate measurement of the concentration of analyte possible. The state-of-art CRDS development will be described in 1.3.2 and 1.3.3.

1.3 Literature Review

1.3.1 Review of In-fiber Grating Sensors

The past decade has witnessed intensive research in the development of a new class of fiber optic component — the UV-inscribed in-fiber Bragg gratings [3][4]. While the major driving force has come from the needs of new, high-performance fiber grating devices for applications such as wavelength division multiplexing (WDM) filters, gain equalizer for erbium doped fiber amplifier (EDFA), and dispersion compensators to expand the bandwidth for high-speed telecommunication, the development of fiber grating technology in the optical sensing has also increased pace[5] . In-fiber grating-based sensors have many advantages over conventional electrical and other type of fiber optic sensor configurations. They are inexpensive to produce, immune to electromagnetic (EM) interference, lightweight, small in size and self-referencing with a linear response. Most significantly, their wavelength multiplexing capability allows tens of gratings in a single piece of fiber to form an optical sensor array. The combination of their multiplexing capability and inherent compatibility with fiber-reinforced composite materials permits in-fiber gratings to be embedded in a number of important structural materials for smart structure applications. Indeed, the development of structurally integrated fiber optics sensors, using fiber Bragg gratings, leads to improvements in safety in many engineering fields, including major civil engineering works, such as road and rail bridges, tunnels, dams, maritime structures, airframe sections, oil/gas prospecting and numerous medical applications.

1) Fiber Bragg Grating Sensors

The elementary fiber Bragg grating comprises a short section of single-mode optical fiber in which the core refractive index is modulated periodically.

As depicted in Fig. 1.2, this structure acts as a highly wavelength-selective reflection filter with the wavelength of the peak reflectivity λ_B , determined by the phase matching condition

$$\lambda_B = 2n_{\text{eff}}\Lambda \quad [1.6]$$

where Λ is the grating period, and n_{eff} is the effective refractive index of the fiber core.

Figure 1.2 Fiber Bragg Grating work mechanism

The most common fiber Bragg grating is the Bragg reflector, which has a constant pitch. Regularly, it has been used in strain and temperature sensing which are wavelength encoded. Also, it employs many other interrogation techniques. For example, 1) Wavelength — amplitude conversion: edge filter that provides a wavelength-dependent transmittance, offering a linear relationship between the wavelength shift and the output intensity change of the filter. 2) Wavelength — frequency conversion: an acoustic-optic tunable filter (AOTF) shows wavelength-dependent light transmittance,

which is controlled by the radio frequency (RF) applied. 3) Wavelength — phase conversion: an unbalanced optical fiber Mach-Zehnder interferometer is used as a wavelength discriminator to detect the wavelength shift of an FBG sensor. In many applications a large number of Fiber Bragg Grating sensors are multiplexed to achieve a distributed measurement, including applications in wavelength-division-multiplexing (WDM), spatial-division-multiplexing (SDM), time-division-multiplexing (TDM).

Tilting (or blazing) the Bragg grating planes at angles to the fiber axis will result in light, that is otherwise guided in the fiber, to be coupled out of the fiber core into loosely bound guided cladding modes or into radiation modes outside the fiber. It is used in the gain-flattening of erbium-doped fiber amplifier, also it can be used as coupling a forward propagating core mode to a backward propagating cladding mode.

A chirped Bragg grating is a grating that has a monotonically varying grating period. This type of grating has a broader reflection spectrum with each wavelength reflecting at a different position resulting in a time delay difference for each wavelength. Chirped gratings, therefore, can be used as a distributed sensor for strain and temperature measurements.

2) Long Period Grating sensors

Long period grating (LPG) has a transmission spectrum as shown in Fig. 1.3. Typical spectral profiles of the LPG is determined by the period (hundred of μm) and grating lengths (20 to 50 mm).

Any modulation of the core and cladding guiding properties will modify the spectral response of LPG, which is essential for sensing purposes. LPG optical sensors are capable of measuring temperature/strain as well as external refractive index. The unique sensitivity to the external refractive index of an LPG structure has invoked great discussions on using LPG for chemical/biochemical sensing. For instance, Patrick et al. demonstrated that

Figure1.3 Long Period Grating work mechanism

LPG could be used to effectively measure the concentration of ethylene, a principal compound, in the antifreezer [6]. Comparably, in this thesis, a novel LPG cavity based chemical sensor will be demonstrated.

1.3.2 The Development of Cavity Ring-down Spectroscopy

CRDS had its origins in technology developed by the aerospace industry for characterizing high reflectivity mirrors. Its application to molecular absorption measurements was first described by O'Keefe and Deacon in 1988, and over the past ten years or so it has become established as the ultra-sensitive spectroscopic detection technique of choice for a wide variety of applications, ranging from fundamental studies of molecular spectroscopy, kinetics and dynamics through to atmospheric and environmental sensing. A literature search using a popular citation database reveals an almost linear growth in publications in the field over the past decade, from around 10 per year in 1994 to over 100 in 2004. An extensive

historical review of CRDS methods was published by Paldus et al. in 2005 [7] and this section will therefore focus mainly on CRDS methods that are relevant to the this work.

The origin of CRDS lies in the attempts to measure the reflectivity, R , of very high quality mirrors (e.g. $R > 0.99$). The first instance of this is the cavity-attenuated phase-shift method (a method now referred to as phase shift CRDS) reported by Herbelin et al. [8]. There, a cw laser was intensity modulated and the phase shift of the cavity output was detected using a lock-in amplifier. The phase shift was related to the total optical loss of the cavity $1-R$. Anderson et al. later developed a method (now termed cw-CRDS) for a similar purpose that measured the ring-down time of the cavity directly [9]. A cw laser of constant intensity was coupled into the cavity and the cavity output was allowed to build up to a threshold value before the input was switched off using a Pockels cell. A ring-down trace could then be directly recorded. Both of these techniques, however, suffered from the problem of coupling the laser light to a resonant cavity mode. If the laser cavity and optical cavity were not vibrationally well isolated, coupling of a laser mode to a cavity mode would occur at random. This could produce intensity fluctuations, differing delays between successive signals, and even non-exponential decays.

Though it had been proposed by Herbelin et al. Deacon and O'Keefe reported the first use of the CRDS performing spectroscopy. They avoided the problem of coupling cw laser into a single cavity mode by using a laser pulse shorter than the round-trip time of the cavity, which inherently was observed in the time domain (termed pulsed CRDS) [10]. They used this pulse CRD spectroscopy method to record very weak forbidden transition ($b^1\Sigma_g^- \leftarrow X^3\Sigma_g^-$) of $O_2(g)$ near 690 and 630 nm.

Since the example of Deacon and O'Keefe numerous variations of CRDS have been explored, in terms of both methods and sample types. Other

methods include cavity enhanced [11], phase shift [12], broadband [13], evanescent wave [14] CRDS as well as CRD polarimetry to study solid, liquid, gas and plasma phases.

In this thesis, a pulsed signal is adopted due to the reason that the ring-down pulses are easily visualized and controlled compared with a continuous-wave (CW) sources.

Another method of producing high finesse cavities in optic fiber is to employ fiber Bragg gratings (FBGs). FBGs are produced by irradiating a photosensitive fiber with a UV laser beam to change the refractive index of the fiber core in a periodic pattern. The grating is permanently imprinted on the fiber core, and is designed to reflect a predetermined range of incident wavelengths. FBGs have several advantages over high reflection mirror at the coated fiber ends, namely that they are insensitive to the fiber mirror quality and the reflection is always normal to the fiber. Gupta et al [15] were able to produce a fiber cavity of this type (Fig.1.4) using

Figure 1.4 A linear fiber cavity resonator of Gupta et al.[15]

different production techniques, with losses ranging from 0.2% to 2.3%, largely attributable to the absorption produced within the fiber during the grating fabrication process. Spectroscopic measurements of glycerin in water were made by immersing a section of fiber from which the cladding had been partially stripped to expose the evanescent wave of the fiber core to the surrounding medium.

1.3.3 Fiber-Loop Ring-down Spectroscopy

One of the most recent and promising developments in CRDS is the fiber-loop ring-down spectroscopy, based on circulation of light within a closed loop of optical fiber. In contrast to CRDS experiments involving dielectric mirrors or fiber Bragg gratings, the range of wavelengths that may be utilized in a fiber-loop spectroscopy is limited only by the transmission characteristics of the fiber and fiber couplers that may cover several hundred of nanometers.

The first reported use of fiber loop employed as an optical cavity for CRDS came in 2001 from Stewart et al. where the technique was used for stand-off sensing of methane in landfills using a optic gas cell of length 5 cm. To counteract the high loss associated with the gas cell, an erbium doped fiber amplifier (EDFA) was included in the loop. This resulted in a long ring-down time (2.6 μ s) but with the consequence of the ring-down time, τ being dependent on the stability of the amplifier.

Soon after Stewart et al.'s initial report, a passive fiber loop for performing CRDS was published [16]. A 12m long loop of multimode fiber exhibited a bi-exponential decay with time constants of 900 and 235ns, corresponding to the decay of light in the core and cladding respectively. A 3.8 μ m gap in the loop allowed for introduction of a liquid sample while maintaining relatively high optical coupling. The absorption spectrum of the dye DDCI was recorded and a detection limit of $\epsilon C = 2 \text{ cm}^{-1}$ was determined [17].

Lehmann et al. had used a tapered section of fiber in a fiber loop to expose the evanescent field of a single core mode to an external medium (Figure 1.5). They recorded the absorption spectrum of the first vibrational overtone of 1-octyne between 1525 and 1550nm, with an estimated detection limit of 1.05% 1-octyne in a non-interacting solvent. They later showed that single-cell detection was possible with a tapered fiber coated with poly-D-lysine to absorb the cells on the surface of the taper [18]. This method had succeeded in the detection of chemical absorption, its wavelength sensing region was broader. However, its sensing area was rather limited, and the fiber became fragile owing to the drastic modification of its geometry. In order to overcome these limitations, in this thesis, CRDS using a LPG pair will be described.

Figure1.5 Passive fiber loop for liquid phase spectroscopy via the evanescent wave of Lehmann et al.

1.4 Conclusion

The need for sensitive absorption measurements has prompted the development of cavity ring-down spectroscopy. There are a number of examples of optical cavities and loops being applied to spectroscopy of the liquid phase. This chapter presents some examples, improvements and new means for performing ring-down spectroscopy intended to find applications in analyte detection.

However, in order to overcome the constraint of the limited sensing area and large insertion loss reported by many previous reports, a new CRDS method with a long-period grating pair design is proposed in this thesis.

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Chapter 2 Theoretical Background of Fiber Grating Sensor and its Fabrication

2.1 Long Period Grating Parameters

Long period gratings couples light from a guided core mode into forward propagating cladding modes where it is lost due to absorption and scattering in the buffer. This coupling is wavelength dependent so we can obtain a spectrally selective loss. The period of such long period gratings is in the order of a few hundred micrometers. In contrast to the fiber Bragg gratings, LPGs couple co-propagating modes with close propagation constants, therefore, the period of such a grating can considerably exceed the wavelength of the light propagating in the fiber. Because the period of an LPG is much larger than the wavelength, LPGs can be fabricated relative easily and inexpensively, their resonances can only be observed in transmission spectra.

An example of a long period grating is shown in Figure 2.1

Figure 2.1 A example of the long period grating spectrum with $\Lambda = 404\mu\text{m}$

2.2 Coupled-Mode Solution for Long-period Fiber Gratings

2.2.1 Coupled-Mode Equations

Coupled-mode theory is one approach to obtaining an approximate solution for the light propagation in a periodic layered medium. As such, it is a useful tool for modeling how grating refractive index fringes affect a light propagation in an optical fiber.

The coupled-mode equations for co-directional coupling of a long-period fiber gratings is as follows

$$\begin{aligned}\frac{dA_{01}^{co}(z)}{dz} &= j\kappa_{lp}^{cl} e^{-j2\delta_{lp}^{cl}z} B_{lp}^{cl}(z) \\ \frac{dB_{lp}^{cl}(z)}{dz} &= j\kappa_{lp}^{cl} e^{-j2\delta_{lp}^{cl}z} A_{01}^{co}(z)\end{aligned}\quad (2.2)$$

where $-L/2 \leq z \leq L/2$, z indicates the locations of the grating, L is grating length. $A_{01}^{co}(z)$ and $B_{lp}^{cl}(z)$ are the amplitudes of the forward core mode and coupled cladding modes. κ_{lp}^{cl} is the coupling coefficient given by

$$\kappa_{lp}^{cl} = \frac{\pi \Delta n_0 C_{lp}^{cl}}{\lambda_{lp}} \frac{2}{\pi} \quad (2.3)$$

Where C_{lp}^{cl} is the overlap factors between LP_{01}^{co} core and LP_{lp}^{cl} cladding modes. $\kappa_{lp}^{cl} L$ is the coupling strength δ_{lp}^{cl} is the detuning parameter from the resonance of a long-period fiber grating, given by

$$\delta_{lp}^{cl} = \frac{1}{2} [\beta_{01}^{co} - \beta_{lp}^{cl} - \frac{2\pi}{\Lambda}] = (n_{01}^{co} - n_{lp}^{cl}) (\frac{1}{\lambda_0} - \frac{1}{\lambda(z)}) \quad (2.4)$$

where β_{01}^{co} and β_{lp}^{cl} are propagation constants of the core mode and cladding mode respectively. Λ is the grating period. n_{01}^{co} and n_{lp}^{cl} are the indexes of the core LP_{01}^{co} mode and cladding modes LP_{lp}^{cl} respectively. λ_{lp} is the resonance wavelength given by $\delta_{lp}^{cl} = 0$ as

$$\lambda_{lp} = (n_{01}^{co} - n_{lp}^{cl}) \Lambda \quad (2.5)$$

where $l = 0, 1, 2, \dots$ and $p = 1, 2, 3, \dots$ indicate the order of the LP_{lp}^{cl} cladding modes.

2.2.2 Characteristics of Uniform Long-Period Fiber Gratings

Basically, no analytical solution can be solved from the coupled-mode equations for a long-period fiber grating except the simplest case of a uniform structure. For a uniform long-period grating, the dominant coupling is between LP_{01}^{co} core and LP_{0p}^{cl} radially-symmetric cladding modes. The power transmission is given by

$$T_{0p}(\lambda) = 1 - \frac{\sin^2[\kappa_{0p}^{cl} L \sqrt{1 + (\delta_{0p}^{cl} / \kappa_{0p}^{cl})^2}]}{1 + (\delta_{0p}^{cl} / \kappa_{0p}^{cl})^2} \quad (2.6)$$

For the wavelength at the resonance. $\delta_{0p}^{cl} = 0$, the power transmission becomes

$$T_{0p}(\lambda_{0p}) = 1 - \sin^2(\kappa_{0p}^{cl} L) \quad (2.7)$$

One example of long period gratings simulation was plotted using Matlab in Figure 2.2. The long-period grating is 41mm long with a 404 μm period, inscribed on SMF-28 single mode fiber. $\Delta n = 0.88 \times 10^{-4}$ for the simulation (solid line), dash line is the measurement spectrum as shown in Fig. 1.3

Figure 2.2 A typical transmission spectrum of a long-period fiber grating

2.2.3 Fiber Material Index and Mode Overlap Index

For a pure silica glass, when the light wavelength is far from the material resonance, the refractive index $n(\lambda)$ can be approximated by the Sellmerier equation as

$$n_{cl}(\lambda) = \sqrt{1 + \sum_{j=1}^M \frac{B_j \lambda_j^2}{\lambda_j^2 - \lambda^2}} \quad (2.8)$$

where λ_j is the resonance frequency and B_j is the oscillator strength, listed in Table 2.1 [1]

	B_1	B_2	B_3	$\lambda_1(\mu\text{m})$	λ_2	λ_3
SiO ₂	0.6961663	0.4079426	0.8974794	0.0684043	0.1162414	9.896161
3.1m/o GeO ₂ , 96.9% SiO ₂	0.7028554	0.4146307	0.8974540	0.0726751	0.1151435	10.00239
3.5m/o GeO ₂ , 96.5% SiO ₂	0.7042038	0.4160032	0.9074049	0.0727723	0.1143085	9.896161
4.1m/o GeO ₂ , 95.9% SiO ₂	0.6867174	0.4348151	0.8965658	0.0726752	0.1151435	10.00239
5.8m/o GeO ₂ , 94.2% SiO ₂	0.7088876	0.4266803	0.8956557	0.0609053	0.1254514	9.896162
7.0m/o GeO ₂ , 93.0% SiO ₂	0.6869829	0.4447951	0.7907351	0.7808758	0.1155184	10.43663

Table 2.1 Coefficient value of different Ge doping percentage silica fiber

The index of the fiber core and cladding are given by equation (2.8) with slightly different coefficients and resonance.

Figure 2.3 Refractive indices of a fiber core (up) and cladding (low) versus wavelength

The plot of refractive indexes of a fiber core and cladding as a function of wavelength is shown in Figure2.3

For LP_{lp}^i cladding mode, when the eigenvalues u_{lp}^i ($i=co, cl$) is derived from the mode eigenvalue equation (2.10), the mode index is then given by equation (2.11)

$$\frac{J_l(u^i)}{u^i J_{l+1}(u^i)} - \frac{K_l(w^i)}{w^i K_{l+1}(w^i)} = 0 \quad (2.10)$$

mode index is then given

$$n_{lp}^i(\lambda) = \sqrt{n_i^2 - \left(\frac{u_{lp}^i}{2\pi r_i / \lambda}\right)^2} \quad (2.11)$$

where $i=co, cl$ indicates the core and cladding modes respectively, $l = 0, 1, 2, \dots, p = 1, 2, 3, \dots, l$ depicts the order of LP_{lp}^i modes.

The overlap factors between LP_{01}^{co} core and LP_{0p}^{cl} cladding modes is given by equation (2.12) [2]

$$C_{0p}^{cl} = \frac{\int_0^{r_{co}} J_0(u_{01}^{co} r / r_{co}) J_0(u_{0p}^{cl} r / r_{cl}) r dr}{\frac{r_{co} r_{cl}}{2} \frac{V^{co} V^{cl}}{w_{01}^{co} w_{0p}^{cl}} J_1(u_{01}^{co}) J_1(u_{0p}^{cl})} \quad (2.12)$$

For a fiber with $NA=0.12$, $r_{co}=4\mu m$ and $r_{cl}=62.5\mu m$ at wavelength 1500nm, the overlap factors of the cladding mode of the different order is listed in Table2.2.

Order	1	2	3	4	5	6	7	8
Overlap	0.1253	0.1895	0.2333	0.2653	0.2879	0.3019	0.3073	0.3071

Table 2.1 Overlap factors between LP_{01}^{co} core mode and LP_{0p}^{cl} cladding modes

From the table 2.1. it can be understood that the higher the mode order, the more overlap between core mode and cladding mode. Hence in this CRDS with a long period grating cavity, the optimization value is to select one of $LP_{06} - LP_{08}$ modes for the highest core and cladding mode coupling.

2.3 Fiber Grating Fabrication Techniques

Gratings were initially fabricated by the internal writing [3] and holographic method [4]. The usual experimental arrangement for writing uniform fiber Bragg gratings into optical fibers is by combining two-beam UV (Excimer laser is adopted in our lab used for UV laser radiation) interferometric exposure. In order to concentrate the UV intensity, the beams are focused onto the fiber core in one dimension by a cylindrical lens.

Another approach for grating fabrication is the point-by-point technique [5] developed at CRC. In this method each index perturbations of the grating are written point-by-point. For gratings with many index perturbations, the method is not very efficient.

2.3.1 Two-beam Holographic Fabrication technique

The major breakthrough for FBG fabrication came with the report on holographic writing of gratings by Gerry Meltz et al. [6] They demonstrated the fabrication of reflection gratings in the visible region using two interfering beams external to the fiber. The scheme provided the much-needed degree of freedom to shift the Bragg condition to longer and more useful wavelengths, by changing the angle between two interfering beams. This principle was extended to fabricate reflection grating in 1525-1565nm region, the wavelength of interest in telecommunications.

The generic experimental arrangement of two-beam holographic fabrication is shown in Figure 2.4. The UV beam is split into two with equivalent power (50%) at the beam splitter. The two beams are then reflected by highly reflective mirrors to intercept to produce the interfering fringes on a piece of photosensitive fiber. A disadvantage of this technique is that the total length of each grating fabricated is limited by the size of the two interfering beams. Also, inherent with this system is the ‘self-chirping’ of

the grating which occurs due to the beam profile producing a non-uniform exposure over the length of the grating.

Figure 2.4 Two-beam holographic gratings fabrication

2.3.2 Phase Mask Fabrication Technique

A major step forward for inscribing fiber gratings was made by the application of the phase mask as a component of the interferometer. The phase mask technique has the advantage of greatly simplifying the manufacturing process, yet still yielding gratings with a high performance. In comparison with the holographic technique, the phase mask technique offers easier alignment of the fiber for photo-imprinting, reduced stability requirements on the photoimprinting apparatus and lower coherence requirements on ultraviolet laser beam, thereby permitting the use of a low-coherent length excimer laser source. The capability to manufacture high-performance gratings at a low cost is critical for the economic viability of using gratings in some applications. A drawback of the phase mask technique is that a separate phase mask is required for each different Bragg wavelength. However, some wavelength tuning is possible by applying tension to the fiber during the photo-imprinting process: the Bragg wavelength of the relaxed fiber will shift by as much as $\sim 2.0\text{nm}$.

The arrangement of phase mask fabrication is shown as Figure 2.5. The optical fiber is placed almost in contact with the phase mask corrugations. Laser light, incident normally onto the phase mask, passes through it and is diffracted by the periodic corrugation structures. Normally, most of the diffracted light is contained in the 0, +1, and -1 diffracted orders. However, the phase mask is designed to suppress the diffraction into the zero-order by controlling the depth of the corrugations. In practice the amount of light in zero-order can be reduced to less than 3% with approximately 40% of the total light intensity diffracted in the +1 and -1 orders equally. The two ± 1 diffracted order beams interfere to produce a periodic pattern that photoimprints a corresponding grating in the optical fiber. If the period of the phase mask grating is Λ_{mask} , the period of the photoimprinted index grating is $\Lambda_{\text{mask}}/2$. Note that this period is independent of the wavelength of ultraviolet light irradiating the phase mask. However, the corrugation depth required to obtain reduced zero-order light is a function of the wavelength and the optical dispersion of the silica.

Figure 2.5 Phase mask gratings fabrication

It is well known that in addition to the central reflection peak, a uniform fiber Bragg gratings exhibits a series of sidelobes on either side of the main peak. These sidelobes are inherent in Bragg gratings and are highly undesirable for most of the grating applications. In wavelength division multiplexing (WDM) systems these sidelobes induce cross talk between adjacent channels and in dispersion compensating system they induce ripples in the dispersion characteristic of a chirped Bragg grating, degrading the system performance. To suppress the sidelobes, the FBG needs to be apodized.

A couple of methods are developed to apodise the grating. For instance,

- 1) Dithering phase mask during UV writing;
- 2) The use of phase mask with non-uniform diffraction efficiency;
- 3) Using two non-uniform UV light beams.

Figure 2.6 Reflection spectrum of an unapodized FBG and an apodized FBG

In our lab , apodisation is achieved by varying the intensity of the UV beam along the grating length, which is achieved by varying the exposure time along the full length of the grating. In this method, an amplitude mask with a Gaussian or SINC profile is applied for varying UV intensity . The spectrum of an apodised FBG is compared with an unapodized FBG in Figure 2.6.

2.4 Conclusion

This chapter has given a brief description on the theory for long-period fiber gratings and grating fabrication techniques. Starting from the coupled mode equation, the fabrication technique and the reported grating structures. The discussion is focused on the case of co-directional coupling in the long-period gratings. The mode overlap factor for describing possible mode coupling has been introduced analytically as well .

2.5 Reference

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Chapter 3 Experiment Work of Fiber Loop Ring-down Spectroscopy with a Long-Period Gratings Cavity

3.1 Apparatus and experiment

In this chapter, the design, fabrication and the measurement of the LPG cavity will be presented. The effect of wavelength shift due to refractive index and temperature will be discussed. The schematic diagram of pulse-CRDS experimental setup will be described in detail and 1-octyne has been selected as the near-infrared chemical absorber for this CRDS experiment.

3.1.1 Long-Period Gratings Cavity

1) Fabrication of LPGs

Each LPGs was fabricated by irradiating a fiber core with 248nm KrF laser light through a mask, which induces a periodic refractive-index modulation along the fiber axis in hydrogen-loaded germanosilicate fibers. The LPG has a total length of 41mm with a period of 404 μ m and a duty cycle of 50%. The irradiation exposure time was controlled so that the high loss dip was achieved after anneal. The LPG inscription process was monitored by an optical spectrum analyzer. The laser pulses has the energy density of $\sim 150 \text{ mJ/cm}^2/\text{pulse}$ and operate at a frequency of 20Hz. The transmission spectrum of LPG – LP06 mode after anneal is shown in Figure3.1. The parameters of two LPGs were: LPG1, central wavelength = 1542.3nm, depth = 40.53dB and LPG2, central wavelength = 1542.4nm, depth = 32.6dB, bandwidth = 13.3nm

Figure 3.1 LPG – LP06 transmission spectrum

2) Construction of An LPG Cavity

Long-Period Gratings Cavity consists of two almost identical LPGs separated at a pre-selected optimal distance, of which the first LPG couples more than 99% of the light from core to cladding, the light interacts with the surrounding environment; then the unabsorbed light is coupled back into the single mode core by the second LPG and part of it is directed to a photo-detector. Since the distance between two LPGs can be $\sim 20\text{cm}$, it provides a relatively larger surface area (62.8mm^2) for the evanescent wave to interact with the environment.

The spectrum of Long-Period Gratings cavity is shown as Figure 3.2. The flat spectral window we are interested in has a insertion loss as low as 0.2dB, which is suitable for CRDS experiment.

To explain the other sharp interference fringes, the two identical LPGs function as a Mach-Zehnder interferometer. The first LPG couples part of the core mode intensity into a cladding mode, then the second LPG couples the unabsorbed cladding mode back into the core and combines two modes together. In the other word, two LPGs behave as a beam splitter, where the two optical paths are the traveling core mode and the cladding mode respectively. At -3dB wavelength, the amount of light coupled out is $\sim 50\%$, that leads to the high contrast of the interference fringe observed in Fig. 3.2.

Figure 3.2 Long-Period Gratings Cavity spectrum in the air

In CRDS experiment, the minimum insertion loss in the cavity is crucial for reducing ring-down pulse decay. The insertion loss in the spectral window as a function of the long-period gratings cavity length was measured and compared in Figure 3.3 that gave a cavity length of 22.5cm as the optimal.

Figure 3.3 Insertion loss plot with respect to different LPG cavity length optimum value for long-period gratings cavity combination.

3) Refractive Index Shift and temperature Effects Discussion

Long-Period Gratings, as intrinsic optical sensing elements, its core to cladding-mode coupling properties are highly dependent on its refractive index of the medium in contact with the cladding. Particularly, for chemical sensors, the sensitivity of LPGs to the surrounding refractive index is important for CRDS experiments. The liquid solution of 99% decane (refractive index equals to 1.4123) from Sigma-Aldrich, was used. In the experiment, it was observed that the wavelength of the LPG cavity was shifted to lower by $\sim 10\text{nm}$ in the solution of higher refractive index than in the air, as shown in Figure3.4

Similarly, a temperature change also causes a shift of the LPG spectrum at $\sim 0.046\text{ nm}/^\circ\text{C}$ for SMF-28 fiber [1] but not its spectral shape. For a moderate temperature variation of approximate $\pm 10^\circ\text{C}$, the shift in the spectral window will be $\pm 0.46\text{nm}$, which should not affect the ring-down measurement since the spectral window of the LPG cavity is $\sim 2\text{nm}$ wide. Moreover, in the laboratory environment with a central air condition, temperature variation will be kept much less than $\pm 10^\circ\text{C}$.

Figure3.4 Transmission spectra of the LPG cavity in air and in decane

3.1.2 Pulse Laser Fiber Loop Ring-down Spectroscopy Measurement

Ideally, since a mode-locked pulse laser has a higher signal noise ratio (SNR) and very short pulse width, it was the first candidate for this experiment. However, the laser has a high repetition rate of 10MHz, that would only allow a fiber ring of a few meters. In this experiment, a lithium niobate intensity modulator was used herein to modulate a cw laser to generate laser pulses.

1) Fiber-ring Using Standard Telecom Components

The schematic diagram of the experimental setup of the CRDS is illustrated in Figure 3.5 and a photograph of the experimental apparatus is shown in Figure 3.6. Explicitly, the resonator was excited by a train of laser pulses obtained by amplitude modulation of a cw tunable laser source (Model 3642-PYCL, Photonics) at 100kHz by a LiNbO₃ modulator (Model OC-192, JDS Uniphase Corp.).

Figure 3.5 Schematic diagram of experimental setup for fiber loop cavity ring-down spectroscopy with a pair of LPGs

Fiber loop cavity consisted of two 1×2 optical couplers with a coupling ratios of 1% and 99%, connecting with a long-period grating cavity of 0.2~0.25dB insertion loss and a 27.2m SMF-28 single mode fiber . When a

laser pulse was launched from the 1% pigtail of the left coupler into the fiber loop, it could be detected from the other 1% pigtail when it reached the right coupler. The pulse transmits through the 99% pigtail of the right coupler, after a round trip, it could be detected again by the photodetector and thus formed a sequential pulse train, with the pulse separation determined by the fiber loop round-trip time. The intensity reduction of the subsequent pulses was determined by the total loss of the fiber ring

Figure 3.6 fiber loop cavity ring-down spectroscopy experimental setup in the lab

A pulse-function generator (Model 8116A, Hewlett-Packard) supplied 20ns square-shaped electric pulses to the modulator. The laser pulses were further amplified by a home-made erbium-doped fiber amplifier(EDFA) with a gain of 21.75dB.

A bandpass filter was used to eliminate the amplified spontaneous emission of the EDFA before the laser pulses being launched into the fiber loop. At the output of fiber loop resonator, the ring-down pulse train was detected by an InGaAs photodiode (Model 1819, New Focus) with a bandwidth of 80MHz

2) Ring-down pulse train measurement

In this experiment, a digital oscilloscope (Model TDS3054B, Tektronix) was used to measure the ring-down pulse train. The oscilloscope has a bandwidth of 500MHz and a sample rate up to 5GSa/sec.

The pulse trains from the photo-detector was sampled by the digital oscilloscope and was averaged 512 times to improve the signal noise ratio.

3) Liquid Sample Cell

Liquid sample cell was the key component in this experiment. It was made of a 5mm inner diameter circular glass tube, which was sealed at two ends with two rubber plugs. A 1.7mm wide slot was cut along the top of glass tube, therefore, liquid solution was able to injected into the glass tube using a pipette. The long-period grating cavity was laid inside the glass tube and kept straight, and its two pigtails were spliced into the fiber loop.

The glass tube was mounted onto a wooden board by the rubber cement to keep the tube horizontal. The diagram is shown in Figure 3.7

Figure 3.7 A top-view of the liquid sample cell picture

4) Erbium Doped Optical Amplifier and FBG Optical Bandpass Filter

When the Er^{3+} ion is implanted in the host glass material it has the energy levels indicated in Figure 3.8 where E_1 corresponds to the lowest energy possible for the Er^{3+} ion. Once the Er^{3+} ions are optically pumped by a 980nm laser diode to E_3 level, the Er^{3+} ions decay rapidly from E_3 to E_2 which has a long lifetime of about $\sim 10\text{ms}$. Thus more and more Er^{3+} ions accumulate at E_2 which is 0.8eV above the ground energy. The accumulation of Er^{3+} ions at E_2 leads to a population inversion between E_2 and E_1 . Signal photons at 1550nm have an energy of 0.8eV, or $E_2 - E_1$, and give rise to stimulated transitions of Er^{3+} ions from E_2 to E_1 .

Figure 3.8 Energy diagram for the Er^{3+} ion in the glass fiber medium and light amplification by stimulated emission from E_2 to E_1

In this experiment, a home-made EDFA was used which was schematically illustrated in Figure 3.9. Where, a 980nm laser diode was used to forward pump 30 meters of erbium doped fiber. An optical isolator was inserted at the input end to prevent any back-reflected signal.

In general the EDFA had a high gain peak centered close to 1532nm and a broad gain peak near 1550nm. One example of EDFA amplified signal is shown in Fig. 3.10

Figure 3.9 A simplified schematic illustration of a forward-pumped EDFA

Figure 3.10 An example of EDFA amplified signal

A fiber bandpass filter had been constructed by the combination of a fiber Bragg grating and an optical circulator. This bandpass filter was implemented to reduce the amplified spontaneous emission from the EDFA, its work mechanism is shown in Figure 3.11.

Figure 3.11 Fiber Bragg Grating optical bandpass filter work mechanism

To obtain the high reflectivity, a fiber Bragg gratings was fabricated with the reflectivity as high as 99.99%, the pass band extended from 1534.04nm to 1534.575nm

3.2 Relationship Between Pulse Decay Time and Fiber Ring Loss

Supposing we have a pulse ring-down time of $0.783\mu\text{s}$ from the measurement, the corresponding round trip time t_R is $0.14\mu\text{s}$, since the output intensity of the pulse $I(t)$ is related to the ring-down time, τ , by

$$I(t) = I_0 \exp (t_R / \tau) \quad (3.1)$$

Then the round-trip loss, $[I(t)- I_0]/ I_0$ is 16.4%.

The total loss of the fiber ring comes from the losses of four splices, two couplers and one LPG cavity (neglecting the grating scattering loss). If a typical splice loss of the SMF-28 fiber is $\sim 0.05\text{dB}$ and the LPG cavity loss is $\sim 0.25\text{dB}$, the remaining loss of 0.33dB can be attributed to the insertion loss and coupling loss of the two couplers used.

3.3 Near-infrared Chemical Solution Selection

Near infrared spectroscopy (NIR) is a spectroscopic method that studies the molecular overtone and combination vibration bands (from about 800nm to 2500nm). Such transitions are forbidden by the selection rules of quantum mechanics. One advantage is that NIR can typically penetrate much farther into a sample than mid infrared radiation. It can be very useful in probing bulk material with less sample preparation.

In this cavity ring-down spectroscopy experiment, a chemical analyte 1-octyne in a non-absorption solution of decane are selected for ring-down time measurement since 1-octyne has a suitable absorption spectrum within c-band. In addition, 1-octyne and decane do not react with each other. The absorption spectrum of 1-octyne in NIR is shown in Figure 3.11 [2].

Figure 3.12 Absorption spectrum of 1-octyne in the evanescent sensing region measured by an CRDS system [2]

3.4 Conclusion

The experimental setup for the pulse laser fiber loop CRDS set up was described in details in this chapter. The main components used were described and their characteristics were analyzed. The glass tube liquid sample cell was fabricated at glass tube workshop in University of Toronto. A 22.5cm long long-period gratings cavity with an insertion loss of 0.2dB was mounted inside the glass tube and kept tightly. The long-period gratings cavity spectrum and the following refractive index and temperature effect were also examined carefully. A cw tunable laser was modulated by lithium-niobate RF modulator to produce a laser pulse train. The laser pulses were further amplified by a home-made Er-doped fiber amplifier and the amplified spontaneous emission was mostly filtered out by a fiber Bragg grating filter. The laser pulse train was injected into fiber loop cavity and the ring-down train was detected by a high speed photodetector and recoded with a digital oscilloscope.

This fiber loop ring-down spectral system has a spectral window of 2.0nm , the passband of the LPG cavity. The quality of the cavity ring-down spectroscopy was mainly determined by the insertion loss in the fiber loop cavity and signal noise ratio of the ring-down pulse.

3.5 References

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Chapter 4 Results and Data Analysis

4.1 Introduction

In this chapter, the experimental results of the long-period gratings CRDS chemical sensor will be presented. The ring-down spectra of the LPG cavity in the air, in a pure solvent and at different concentration of the analytes were measured and analyzed. The improvement and potential for this LPG based CRDS will also be discussed.

4.2 Cavity Ring-down Spectrum of a Dry Cavity

The key to this fiber loop ring-down spectroscopy was to design a low-loss LPG cavity that couples as much light as possible from core to cladding. The spectrum of LPG cavity was plotted in the Figure 3.4. It showed an insertion loss as low as 0.2~0.25dB within the transmission window centered at the LPG loss peaks. The cavity ring-down spectrum from a 27.2m SMF-28 fiber loop without long-period gratings cavity was shown in Figure 4.1. The pulse repetition rate was set at 100Hz, and the pulse width of 20 ns. The ring down pulses were separated at 140ns since there was 27.2m length SMF-28 fiber in the fiber ring. Since the output intensity of the pulse $I(t)$ is related to the ring-down time, τ , by $I(t) = I_0 \exp(t/\tau)$, the ring-down time τ can be found from the inverse slope of the line $\ln(I/I_0)$ versus t . From the data analysis, the ring-down time of 2.31 μ s was obtained. The noise fluctuation resulted from the ASE since the bandpass filter was not used at that time. Before testing the pulse decay time at different chemical solutions, a dry LPG cavity (the fiber between two LPGs was exposed in air) was tested for its ring-down pulse decay as shown in Figure 4.2. The wavelength was selected at

27.2m SMF-28 Cavity Ring down

Figure 4.1 27.2m SMF-28 without LPG cavity ring down spectrum

Figure 4.2 dry LPG cavity ring-down spectrum

1542.6nm (considering a 10nm lower wavelength shift when the LPG cavity was immersed in decane). The ring-down time was 0.845 μ s

4.3 Cavity Ring-down Spectrum of 1-Octyne at Different Concentrations

When the medium surrounding an LPG was changed from air to liquid, the loss peak of the LPG was shifted to a short wavelength. However, the spectral shape of the loss peak remains the same. This was illustrated in Figure 3.4, when the LPG cavity was immersed into decane (n=1.412), its transmission spectral was shifted to the lower wavelength by 10nm. Noting that there was very little change of insertion loss in the spectral window, indicating a well-confined cladding mode though the refractive index changed from 1 to 1.412. The analyte, 1-octyne, used in this test causes a negligible spectral shift due to its similar refractive index of 1.417. The spectral window between 1533.2 and 1535.4nm was where the evanescent wave absorption was tested for 1-octyne in decane solution.

The ring-down pulses of the LPG cavity in a 100% decane solution was measured and shown in Figure 4.3. About 27 ring-down pulses could clearly be observed

Figure 4.3 Ring-down pulse train of the fiber loop with the LPG cavity immersed in 100% decane

within $4\mu\text{s}$ with a round-trip time of $0.14\mu\text{s}$, corresponding well to the fiber loop length of 28m, the ring-down time of 782ns was obtained from fitting. The LPG cavity was then submerged into a solution of 10%, 20%, 30% and 40% 1-octyne in decane and the ring-down pulse trains were measured respectively. It was observed that the ring-down time was reduced with the increase of the analyte concentration. The ring-down time was reduced to 709ns for the 10% 1-octyne concentration as shown in Figure 4.4; 661ns for the 20% 1-octyne concentration as shown in Figure 4.5; 617ns for the 30% 1-octyne concentration as shown in Figure 4.6; and 571ns for the 40% 1-octyne concentration as shown in Figure 4.7. The ring-down pulse amplitudes fit well with exponential decay with a standard error of 0.58%, 0.66%, 0.45% and 0.41% in their corresponding ring-down time.

Figure 4.4 Ring-down pulse train measured when the LPG cavity was immersed in the solution of 10% 1-octyne in decane. The ring-down time was reduced to $0.71\mu\text{s}$

Figure 4.5 Ring-down pulse train measured when the LPG cavity was immersed in the solution of 20% 1-octyne in decane. The ring-down time was reduced to 0.66 μs

Figure 4.6 Ring-down pulse train measured when the LPG cavity was immersed in the solution of 30% 1-octyne in decane. The ring-down time was reduced to 0.62 μs

Figure 4.7 Ring-down pulse train measured when the LPG cavity was immersed in the solution of 40% 1-octyne in decane. The ring-down time was reduced to $0.57 \mu s$

4.4 Data Analysis and Discussion

The ratio of round-trip time t_R which was 0.14 in this test to the ring-down time τ is proportional to the concentration of the analyte, c , the minimum detectable concentration of 1-octyne can be calculated from the following equations:

$$\tau = \frac{t_R}{L_t + cL} \quad (4.2)$$

$$\Delta c = \alpha \frac{t_R}{\tau^2} \Delta \tau \quad (4.3)$$

where L_t is the total fiber ring loss without analyte and L is the LPG cavity length. $L_t=0.179$ was obtained from Figure 4.3 when the concentration of 1-octyne was zero and cL is the loss due to evanescent wave absorption. The relationship between t_R/τ versus concentration was plotted in Figure 4.8, therefore $\alpha = 6.1$ was obtained. If we chose the ring-down time of $782 ns$ and

its measurement error, $\Delta\tau/\tau = 0.57\%$, for the low concentration measurement, the minimal detectable concentration, $\Delta c = 0.62\%$, could be calculated from equation 4.3.

Figure 4.8 Absorption of 1-octyne measured as the reduction of ring-down pulse ring-down time in a fiber loop with an LPG cavity

The data clearly demonstrated the feasibility of an LPG cavity as an effective chemical sensor. The sensitivity of the detectable concentration can be further improved in several ways. One is to select the cladding modes with high field amplitude near the perimeter of the fiber cladding. Another is to use a mode locked pulsed laser as the light source to improve the optical signal-to noise ratio so that more ring-down pulses can be detected. The evanescent wave absorption can also be increased significantly, as reported by Barnes et al. [1], by coating the fiber with a polymer layer with the refractive index lower than that of the fiber cladding so that the penetration depth of the cladding mode can be increased.

4.5 Conclusion

We have successfully demonstrated fiber loop ring-down spectroscopy with an LPG cavity serves as a chemical sensor. The relatively long LPG cavity provides a much large area for evanescent wave to interact with the surrounding medium that compensates for the short penetration depth of the cladding mode in the medium. In addition, absorption is enhanced by the multiple passes of each photon launch into the fiber loop. All components used in fiber ring are standard, low-cost ones readily available in the telecommunication industry. Our preliminary results on the measurement of 1-octyne showed that a concentration of 0.62% can be obtained. In addition to chemical sensing, the LPG cavity may also be used for biochemical sensing, since cell or other biomaterial can be adsorbed on the fiber cladding.

4.6 References

- [1] J. Barnes, M.Dreher, K.Plett, R.S.Brown, C.M.Crudden, and H.-P.Looock, Analyst (London) 133, 1541 (2008)

CHAPTER5 Conclusions and Future Work

5.1 Conclusions

Fiber loop ring-down spectroscopy with a LPG cavity provides a new means for performing absorption spectroscopy for liquid phase samples. This method opens new avenues for using fiber optic sensors for chemical liquids or even gases. Using long-period grating cavity for this type of application has several advantages over the conventional fiber loop or fiber mirror resonators: an optical fiber components are inexpensive and readily available; the ring-down time at a fixed wavelength is independent of the laser pulse fluctuation; long-period grating pair has a relatively larger effective sensing area, lower insertion loss and high mechanical strength.

My contribution in this work is that I have successfully demonstrated a fiber loop ring down spectroscopic method with a novel long-period grating cavity sensor. Experimentally, the long period gratings which have more than 30dB loss and have LP_{06} or higher mode were fabricated and a low insertion loss of 0.2~0.25dB was achieved at an optimized separation of 22.5cm. The ring-down pulse decay of the LPG cavity was measured in the different media. The data analyzed showed a linear relationship between the ratio of the pulse round-trip time to the pulse ring-down time and the 1-octyne concentration.

From the experiment results, It was determined that 1-octyne concentration as low as 0.62% can be measured accurately by this method, which is a factor of 2 better than report by Lehmann et al. [1]

In addition to the chemical sensing as described in this experiment, the LPG cavity may also be used for biochemical sensing, since cell or other biomaterial can be adsorbed on the fiber cladding.

5.2 Suggested Future Work

An obvious direction for the future experiments is to refine the design to achieve a lower insertion loss. This may be accomplished by a number of routes, for example by using a pair of highly reflective fiber Bragg gratings to replace the optical ring since it will eliminate the losses from two 1%/99% fiber couplers. When a linear FBG cavity is used, the ring-down time is expected to increase substantially. For example, a pair of FBGs (one at central wavelength 1541.85nm with a reflectivity of 99.84%, the other central wavelength at 1541.775nm with a reflectivity of 99.83%) was used to build a fiber cavity and tested for its pulse decay. The ring-down time of 4.79 μ s was achieved as shown in Figure 5.1. This is a significant improvement when compared to the ring-down time of 2.31 μ s for the fiber ring. With the reduced loss of the linear FBG cavity, an LPG cavity can be inserted inside the FBG cavity to form a sensing section.

Figure 5.1 27.2m SMF-28 FBG pair (without LPG cavity) ring down spectrum

The other avenue of long-period cavity chemical sensor is to extend its applications to gas phase absorption. For example, the acetylene C_2H_2 [2] [3] is a good candidate since its molecular absorption is in 1530nm wavelength region. However it is necessary to build a gas tube that can accommodate fiber sensor and with appropriate pressure regulators.

5.3 Reference

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