Power modulation based optical fiber loop-sensor for structural health monitoring in composite materials

Nikhil Gupta and Kevin Chen
Mechanical and Aerospace Engineering Department
New York University, Polytechnic School of Engineering
Brooklyn, NY 11201

SysInt 2014, Bremen, Germany
List of Publications and Patents

- **The technologies covered in this work are presented in the following**
  - **Patents:**
  - **Papers:**
Introduction

• Structural Health Monitoring (SHM)
  A process of identifying one or more of
  – Load applied or displacement obtained on the structure
  – Extent of damage
  – Growth rate of damage
  – Performance of the structure as damage accumulates

• SHM can help in moving from *predictive maintenance* to *need-based maintenance*
  – Increase in safety
  – Cost saving
Whispering Gallery Mode Sensors

- Tunable laser is used
- Evanescent field of the stripped off section of fiber interacts with that of the resonator (particle)
- Coupling back of the evanescent field in the fiber gives resonance peaks, which can be tracked
Whispering Gallery Mode Sensors

- Very high sensitivity
  - Detection of single chemical molecules
  - Detection of a single HIV virus
  - Measurement of sub-nanometer displacement

For \( r \gg \lambda \), resonance condition:

\[
2\pi r n \approx \ell \lambda \quad (\ell = \text{integer})
\]

\[
\frac{\Delta n}{n} + \frac{\Delta r}{r} \approx \frac{\Delta \lambda}{\lambda}
\]

\( n \) = refractive index of the microsphere
\( \lambda \) = wavelength
\( r \) = micro-sphere radius
WGM Sensors: Effect of Refractive Index

\[ n_1 = n_0 + C_1 \sigma_1 + C_2 (\sigma_2 + \sigma_3) \]
\[ n_2 = n_0 + C_1 \sigma_2 + C_2 (\sigma_1 + \sigma_3) \]
\[ n_3 = n_0 + C_1 \sigma_3 + C_2 (\sigma_1 + \sigma_2) \]

Where
- \( n_0 \) undeformed index of refraction
- \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) are principal stresses
- \( C_1 \) and \( C_2 \) are elasto-optic coefficients of the material of the sphere.

- Sensitivity comes at a price!
  - Signal to noise ratio can be low
  - Keeping the particle in resonance can be difficult

<table>
<thead>
<tr>
<th></th>
<th>Silica (Yves Belouard et al. 2006)</th>
<th>PMMA (Feridun et al. 2004)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_1 (m^2/N) )</td>
<td>-4.22 \times 10^{-12}</td>
<td>-12 \times 10^{-12}</td>
</tr>
<tr>
<td>( C_2 (m^2/N) )</td>
<td>-0.65 \times 10^{-12}</td>
<td>-12 \times 10^{-12}</td>
</tr>
<tr>
<td>( n_0 )</td>
<td>1.467</td>
<td>1.4876</td>
</tr>
</tbody>
</table>
**Introduction**

- **Microbend sensors**
  - Use multi-mode fiber
  - Require high power light source
  - Normally used under compression
  - Large size
Results and Discussion

- **Power attenuation**
- **Critical radius** (Jeunhomme, 1983)

\[
R_c = 20 \frac{\lambda}{(\Delta n)^{3/2}} \left( 2.748 - 0.996 \frac{\lambda}{\lambda_c} \right)^{-3}
\]

where

- \( \lambda \) is the operating wavelength
- \( \lambda_c \) is cut-off wavelength
- \( \Delta n \): core-cladding index of refraction difference

- For present single-mode optical fiber

\( \lambda = 1.31 \, \mu m, \lambda_c = 1.26 \, \mu m, \Delta n = 0.0058 \)

\( R_c = 11.8 \, mm \)
Fiber-loop sensors

- Power transmission due to curvature

\[ P_R = \frac{P_{\text{out}}}{P_{\text{in}}} \]

- \( P_{\text{out}} \) is transmitted power through the loop
- \( P_{\text{in}} \) is power incoming to the loop

- Compressing loop creates more losses, relative transmitted power

\[ \bar{P} = \frac{P'_{\text{out}}}{P_{\text{out}}} \]

- \( P'_{\text{out}} \) is transmitted power with the applied force
- \( P_{\text{out}} \) is power with no load applied
Fiber-loop sensors

• Compression of loop $R_B=7$ mm

• Resonances occur between leaky mode reflected from cladding/coating interface and fundamental mode
Fiber-loop sensors

• Pure bend loss-Marcuse model

Assumption: infinite cladding, large bend radius, weakly guided index fiber

\[
\bar{P}_R = \exp\left(-2\alpha_B l_B^e\right)
\]

where

\[
\kappa = \frac{2\pi}{\lambda}
\]

\[
V = ak\left(n_{co}^2 - n_{cl}^2\right)^{1/2}
\]

\[
\kappa = \left(k^2 n_{co}^2 - \beta_0^2\right)^{1/2}
\]

\[
\gamma = \left(\beta_0 - k^2 n_{cl}^2\right)^{1/2}
\]

\[
2\alpha_B = \frac{1}{2}\left(\frac{\pi}{\gamma R_B^e}\right)^{1/2} \frac{k^2}{V^2 K_1^2(\gamma a)} \exp\left(-\frac{2\gamma^3 R_B^e}{3\beta_0^2}\right)
\]

\[
l_B^e = 2\pi R_B^e
\]

\(n_{co}\) and \(n_{cl}\) are indices of refraction of the core and cladding

\(\beta_0\) is the propagation constant in straight fiber, solved by the eigenvalue equation

\[
\kappa J_1(\kappa a) = i\gamma H_1^1(i\gamma a) \frac{H_0^1(i\gamma a)}{H_0(i\gamma a)}
\]

\(R_B^e\) is effective bend radius, differing from \(R_B\) by a stress correction factor, taken 1.28 for SMF28e fiber

---

<table>
<thead>
<tr>
<th>Fiber layer</th>
<th>Radius (μm)</th>
<th>Index of refraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>4.1</td>
<td>1.4517</td>
</tr>
<tr>
<td>Cladding</td>
<td>62.5</td>
<td>1.447</td>
</tr>
<tr>
<td>Coating</td>
<td>125</td>
<td>1.4786</td>
</tr>
</tbody>
</table>

SMF28e from Corning, NY
Fiber-loop sensors

- Renner model - finite, coating and cladding thickness

\[ P_R = \exp\left(-2\alpha_{BC}l_B^e\right) \]

where

\[ 2\alpha_{BC} = 2\alpha_B \frac{2\left(Z_{ct}Z_{cl}\right)^{1/2}}{(Z_{ct} + Z_{cl}) - (Z_{ct} - Z_{cl})\cos\left(2\Theta_0\right)} \]

\[ Z_{cl} = k^2n_{cl}^2\left(1 + 2b / R_B^e\right) - \beta_0^2 \]

\[ Z_{ct} = k^2n_{ct}^2\left(1 + 2b / R_B^e\right) - \beta_0^2 \]

\[ \Theta_0 = \frac{\gamma^3R_B^e}{3k^2n_{cl}^2} \left( \frac{R_c}{R_B^e} - 1 \right)^{3/2} \]

\[ R_c = \frac{2k^2n_{cl}^2b}{\gamma^2} \]

\[ \frac{4b\gamma R_B^e}{3\pi R_c} \left( \frac{R_c}{R_B^e} - 1 \right)^{3/2} = \begin{cases} 2m - 1/2 & \text{for maximum} \\ 2m - 3/2 & \text{for minimum} \end{cases} \]

where \( m \) is an integer.

\[ l_B^e = 2\pi R_B^e \] is the effective length of the loop

- Experimental data are obtained by changing the radius of fiber-loop
Loop sensor calibration setup

- Square wave signal is sent to the loop
- Photodetector tracks the transmitted power
- Relative transmitted power and force are monitored with respect to increment in displacement
Loop sensor calibration

- Calibration of different loop radii

- Smaller loops have higher sensitivity but lower measurement range
- Loop-sensors allow large deformation without losing its elasticity and repeatability
Loop sensor calibration

- In high sensitivity domain

- Resolution
  - Force: $10^{-4}$ N
  - Displacement: $10^{-5}$ m
Cyclic loading tests

• Pear-shaped loop and experimental setup

Optical fiber

Hollow tube

$2R_o$
Cyclic loading tests

• Results in 10,000 cyclic loading

- Loop radius: 5 mm
- Displacement: 6 mm
- Displacement rate: 0.4 mm/s
- 30 s per loading/unloading cycle

• Total testing time: 4 days
• The sensors survived after 10,000 cycles
• Results show repeatability and consistency for $10^4$ loading/unloading cycles
Cyclic loading tests

- Different displacement rate

$v=0.01 \text{ mm/s}$

$v=0.05 \text{ mm/s}$

$v=0.2 \text{ mm/s}$

$v=0.4 \text{ mm/s}$

- Loop radius: 6 mm
- Displacement: 6 mm
SHM of laminated composites

- Loop sensors bonded to laminated composites under flexural loading
SHM of laminated composites

- Quasi-static loading on loop of radius 6 mm

$R_B = 4.9 \text{ mm}$

$R_B = 5.9 \text{ mm}$

$R_B = 6.2 \text{ mm}$

$R_B = 6.5 \text{ mm}$
Optical fiber loop sensor setup for calibration of vibration measurement

The setup used for measuring the free vibration characteristics of a composite material.
Vibration Measurement

- The Vibration measurements are accurate and match with the frequency of the shaker.
- No fatigue or hysteresis is observed for over 10,000 cycles.
The system is tested with and without optical fiber sensor using only a PSD. Then the output of the sensor is related to the PSD measurements.
Conclusions

• A low-cost, high sensitivity loop-sensor has been developed for stress or strain measurement
• The sensor can be used in dual measurement ranges for displacement
• The sensor shows survivability in large number of loading cycles
• Use of loop-sensor for vibration measurement is possible
• Potential applications in chemical sensing
Acknowledgements

• National Science Foundation grant # CBET 0809240/ 0619193
• Environmental Protection Agency: Smart Fellowship to Kevin Chen for chemical sensing
• Zachary Nishino, Dr. Nguyen Q. Nguyen
• Dr. Volkan Otugen’s group at Southern Methodist University, Dallas