Highly Nonlinear Fibers and Their Applications

Masaaki HIRANO

Optical Communications R&D Laboratories, Sumitomo Electric Industries, Ltd.

NMIJ-BIPM Joint Workshop 2007  Optical Frequency Comb - Comb, Fiber and Metrology - Tsukuba, 2007.05.18
Outline

1. Silica Fiber Technology and Highly Nonlinear Fiber

2. Supercontinuum Generation in Fiber

3. Comparison of Highly Nonlinear Fiber to Photonic Crystal Fiber

4. Summary
Optical Fiber and its Application

Major Application: Optical Signal Transmission

Profile of Single Mode Fiber (SMF)

- Core
  - GeO₂ – SiO₂
- Cladding
  - pure SiO₂
- Coating
- Refractive Index: \( n \)
- Dimensions:
  - Core: 10μm
  - Cladding: 125μm
  - Overall: 250μm
Optical Fiber as Functional Devices

- Optical Amplifier (Er-Doped Fiber)
- Optical Filter (Fiber Bragg Grating)
- Dispersion Compensating Fiber
- Image Guiding Fiber
- Fiber Laser (Yb-doped Fiber, Er-doped Fiber)
- Highly Nonlinear Fiber (HNLF)
Efficiency of Nonlinearity Generation in Fiber

SiO₂ Glass: Low Nonlinearity

BUT...

Fiber shows High Nonlinearity

- Tight Confinement of Optical Power into Small Core Area
- Ultimately Low Attenuation (<1dB/km) Long Interaction Length
- Chromatic Dispersion Control Phase Matching, Small Walk-off

Make it Very Important as Nonlinear Medium
Parameters for Optical Nonlinearity

Kerr Effect: Change in the Refractive Index in response to Electric Field (3rd-order Nonlinear Effect)

- Change in Refractive Index : $\Delta n$
  
  $= n_2 |E|^2 \quad \Rightarrow \quad$ Nonlinear Refractive Index

  $= n_2 P / (A_{eff}) \quad \Rightarrow \quad$ Effective Area

  (Cross Section of Mode Field)

- Change in Propagation Coefficient : $\Delta \beta$
  
  $= 2\pi /\lambda \times \Delta n \quad \Rightarrow \quad$ Nonlinear Coefficient, $\gamma$

  $= 2\pi /\lambda \times n_2 /A_{eff} \times P$

- Phase Shift: $\Delta \phi$ # in case for Self-Phase Modulation
  
  $= \int_0^L \Delta \beta dz \quad = \gamma \int_0^L P(z)dz \quad = \gamma \int_0^L P_{in} \exp(-\alpha z)dz \quad \Rightarrow \quad$ Effective Length, $L_{eff}$

  (Lower Attenuation $\alpha$, Longer $L_{eff}$)

  $= \gamma \times \frac{1 - \exp(-\alpha L)}{\alpha} \times P_{in}$

Large $\gamma$ and Low $\alpha$ (Long $L_{eff}$) $\Rightarrow$ Efficient Nonlinear Generation
Chromatic Dispersion

“Chromatic Dispersion” Wavelength Dependence of Group Delay = \( \frac{\Delta (G.D.)}{\Delta \lambda} \)

- Material Dispersion
  - SiO₂ Glass, Fixed Value
- Waveguide Dispersion
- Total Controllable
- Zero-Dispersion Wavelength \( (\lambda_0) \)
- Controllable
- Four Wave Mixing (FWM)
- Self Phase Modulation (SPM)
- Cross Phase Modulation (XPM)
## Highly Nonlinear Fiber, HNLF

<table>
<thead>
<tr>
<th></th>
<th>HNLF</th>
<th>SMF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Profile</strong></td>
<td><img src="image" alt="Profile Diagram" /></td>
<td><img src="image" alt="Profile Diagram" /></td>
</tr>
<tr>
<td><strong>Nonlinear Refractive Index</strong> (n_2)</td>
<td>(4 \sim 6 \times 10^{-20} \text{ m}^2/\text{W})</td>
<td>(3 \times 10^{-20} \text{ m}^2/\text{W})</td>
</tr>
<tr>
<td><strong>Effective Area (of Mode Field)</strong> (A_{\text{eff}})</td>
<td>(9 \sim 20 \text{ [\mu m}^2)</td>
<td>(80 \text{ [\mu m}^2)</td>
</tr>
<tr>
<td><strong>Nonlinear Coefficient</strong> (\gamma = n_2/A_{\text{eff}} \times 2\pi/\lambda)</td>
<td>(10 \sim 30 \text{ [W/km]})</td>
<td>(1.5 \text{ [W/km]})</td>
</tr>
<tr>
<td><strong>Attenuation at 1550nm</strong></td>
<td>(0.5 \sim 1 \text{ [dB/km]})</td>
<td>(0.2 \text{ [dB/km]})</td>
</tr>
<tr>
<td><strong>Zero Dispersion Wavelength</strong></td>
<td>(&gt; 1350 \text{ [nm]})</td>
<td>(1310 \text{ [nm]})</td>
</tr>
</tbody>
</table>
HNLF Application for Future Photonic Network

Wavelength Conversion

- Pump
- Signal
- Idler (Newly Generated)

Raman Amplifier

- Pump
- Stimulated Raman Scattering (SRS)

Supercontinuum Generation (SC Generation)

- Cross Phase Modulation (XPM), Self Phase Modulation (SPM), SRS, FWM...

Four Wave Mixing (FWM)
SC Generation for Telecomm Light Source

Ps Pulsed Laser with Watts Peak Power

HNLF \rightarrow SC Generation

"Telecomm" Multiwavelength Light Source
Proposed by NTT in 1993

7.6ps, 100W (Peak)

Fig. 1 Experimental setup of multiwavelength optical pulse generator

1224 – 1394nm (Δλ = 170nm)

Fig. 2 Supercontinuum spectra generated by 7.6 ps, 100 W optical pulse, and multiwavelength spectra filtered by all-fibre birefringent filter (spectral resolution = 0.1 nm)

Highly Efficient SC Generation in “DFDF”

Dispersion Flattened and Decreasing Fiber (DFDF)

Evaluated Broadband SC Spectrum

Input Pulse:
- 10GHz, 3ps
- Peak=3W

ML-EDFL: Mode-locked EDF ring laser

OSA

Octave Spanning SC generation

fs Pulsed Laser with kilo-Watts Peak Power

HNLF

Ultrabroad SC Generation

Input Pulse:
75MHz, 210fs
Ave. = 89mW, Peak=2kW

HNLF (10m)

1140 – 2400 nm
(Δλ = 1260nm)

Output [a.u., dB]
Possible Applications

- Metrology

- Spectroscopy

- OCT (Optical Coherence Tomography)

...
Spectral Modification by Fiber Characteristics?

Relation between Dispersion Characteristics and SC-Spectra Shape?

- **HNLF-1**: Pump peak ∼1377 nm
- **HNLF-2**: Peak wavelength λ₀ = 1535 nm, measured +0.3 ps/km/nm, calculated +0.14 ps/km/nm
- **HNLF-3**: Peak wavelength λ₀ = 1535 nm, measured +6.7 ps/km/nm

Measured range: (1520-1640) nm
SC-Spectra with Different Dispersion

SC-Spectra Shape (Wavelength Range, Ripple, etc.) : Controlled by HNLF Dispersion Characteristics
SC Generation in Photonic Crystal Fiber

Photonic Crystal Fiber (PCF)

Photograph of supercontinuum generation in PCF

University of Bath, http://www.bath.ac.uk/physics/groups/cppmpcf_supercontinuum.php
<table>
<thead>
<tr>
<th></th>
<th>HNL F</th>
<th>PCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ [/W/km]</td>
<td>10~30</td>
<td>10~100</td>
</tr>
<tr>
<td>Zero-Disp. Wavelength [nm]</td>
<td>&gt;1350</td>
<td>&gt;700</td>
</tr>
<tr>
<td>SC Spectral Range</td>
<td>800~2500nm</td>
<td>400~2000nm</td>
</tr>
<tr>
<td>Dispersion Controllability</td>
<td>High</td>
<td>Difficult</td>
</tr>
<tr>
<td>Coupling Loss [dB]</td>
<td>~0.1dB/end</td>
<td>~1dB/end</td>
</tr>
<tr>
<td>Polarized Mode Coupling</td>
<td>Low PMD (~0.1ps/ km) or PMF</td>
<td>High PMD or PMF</td>
</tr>
</tbody>
</table>
Dispersion Controllability of HNLF

**Zero-disp. Wavelength**

- **GeO$_2$-SiO$_2$**
  - $\Delta^+ = 3\%$
- **Core**
  - $\Delta^+ = 1\%$
- $\Delta\lambda_0 \sim 8\text{nm/\%}$

$\Delta\lambda_0 \sim 33\text{nm/\%}$

**Longitudinal Dispersion Uniformity**

- $\Delta\lambda_0 < +/- 1.0\text{nm}$

PCF… ?

*Sumitomo Fabricated*
Longitudinal Uniformity for SC Spectrum

Five 1-m-long Samples from one Spool

1m 1m 1m 1m 1m
A B C D E

Intensity [dBm/nm]

Wavelength [nm]

966 ~ 974nm
$\Delta\lambda=8$nm
Conclusion

Highly Nonlinear Fibers
- Promising Optical Devices for Future Photonic Network

SC generation in Silica-Based HNLF
- SC Spectrum Shape Control
  by Dispersion Characteristics of HNLF

SC Generation in PCF or HNLF?
- PCF: VIS – NIR SC Spectral Range due to Dispersion Flexibility
  PMD and Dispersion Fluctuation → Large

- HNLF: NIR Limited SC Spectral Range
  PMD and Dispersion Fluctuation → Negligible