Study of Bending Losses in Optical Fibers using COMSOL

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Overview

1. Optical Fibers and Advantages

2. Bent Optical Fiber and Analysis
   - Geometric Effect
   - Stress Effect

3. Geometrically Exact Beam Theory (GEBT)

4. COMSOL Simulations

5. Simulation Results and Optimization

6. Bend Insensitive Fiber

7. Conclusions
Optical Fibers and Advantages

- Material: Silica glass
- Dimensions: In microns
- Advantages:
  - Small size, easily installed
  - Low power loss
  - High transmission rate over very long distances
- Circulatory system that nourishes our information system
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Bent Optical Fiber

- FTTH: Fiber to the home networks
- Bent at the tight corners of the walls
- Bending of fibers cause severe power loss
- Bending range: 3 – 10 mm bend radius
- Two possible sources to modify refractive index are considered
  - Geometric effect
  - Stress effect

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0 Picture Reference: (a) https://www.rp-photonics.com/fibers.html
(b) https://www.fiberoptics4sale.com/blogs/archive-posts/95053062-fiber-optic-cable-installation-overview
Geometric Effect: Conformal Mapping

- Equivalent straight waveguide approximation
- Bent wave guide in Z-plane is mapped to straight wave guide in W-plane
- Modified Index @ point A ↓, @ point B ↑
- Refractive index of equivalent waveguide is obtained using conformal mapping\(^1\)

\[
n_G \approx n \left(1 + \frac{x}{R}\right)
\]

\(^1\)Schermer, Ross T., and James H. Cole, Improved bend loss formula verified for optical fiber by simulation and experiment, IEEE JQE 43.10 (2007)
Stress Effect

- Compression @ point (i), Elongation @ point (ii)
- Modified Index @ point (i) ↑, @ point (ii) ↓
- Stress effect counters geometric effect
- Conventional approach: 
  Elasto-optic factor in conformal mapping 
  \[ R_{\text{eff}} = 1.28 - 1.31R^1 \] 

\[ n_{G+S} = n \left( 1 + \frac{x}{R_{\text{eff}}} \right) \]

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Geometrically Exact Beam Theory (GEBT)

- Captures bending of the fiber and calculates strain tensor corresponding to the bend radius\(^3\)
- Strain tensors are employed in to stress-optic law to obtain modified refractive index

\[
\begin{equation}
\begin{aligned}
n_S(x, y) &= n(x, y) \left[ 1 - \frac{n^2}{2} \left( P_{11} \epsilon_1 + P_{12} (\epsilon_2 + \epsilon_3) \right) \right] \\
\end{aligned}
\end{equation}
\]

\(P_{11} = 0.113\) and \(P_{12} = 0.252\) are stress optic coefficients
\(\epsilon_1, \epsilon_2, \epsilon_3\) are the principle strains obtained from GEBT

- Modified refractive index = GEBT + Stress-Optic law + Conformal mapping

\[
\begin{equation}
\begin{aligned}
n_{G+S} &= n_S \left( 1 + \frac{x}{R} \right) \\
\end{aligned}
\end{equation}
\]

\(^3\)Simo, Juan C, A finite strain beam formulation. The three-dimensional dynamic problem. Part I, Computer methods in applied mechanics and engineering 49.1 (1985)
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Geometry and Material Properties

- Geometry: 2D cross section of optical fiber (G652)
- Core radius $a = 3.05 \, \mu m$
- Cladding radius $b = 62.5 \, \mu m$
- PML thickness = $7\lambda$
- Refractive index profile

$$n(r) = n_{\text{max}} \sqrt{1 - 2\Delta \left(1 - \frac{r}{a}\right)^2}$$

$$\Delta = \frac{n_{\text{max}}^2 - n_{\text{clad}}^2}{2n_{\text{max}}^2}$$

$$n_{\text{max}} = 1.456, \quad n_{\text{clad}} = 1.444$$

Simulation Parameters

- **Module**: Wave Optics
- **Physics**: Electromagnetic wave, frequency domain (ewfd)
- **Solve the wave equation**
  \[ \nabla \times \nabla \times \vec{E} - k_0^2 \epsilon_r \vec{E} = 0 \]
- **Mesh**: Free triangular mesh with fine element size
- **Study**: Mode Analysis, solve for the effective index of the modes

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Simulation Results

- Straight Fiber $n_{\text{eff}} \approx 1.4475$
- Bent Fiber $n_{\text{eff}} \approx 1.4464 - i1.3275e - 5$

$$\text{Loss}[\text{dB/turn}] = \frac{20}{\ln(10)} \frac{2\pi}{\lambda} \times \text{Im}\{n_{\text{eff}}\} \times 2\pi R$$

- Simulation results are compared with formula given in\(^5\)

\(^5\)Marcuse, Dietrich, Curvature loss formula for optical fibers, JOSA 66.3 (1976):
Perfectly Matched Layer

- Perfectly matched layer (PML)
- Absorbs unwanted reflections from cladding boundary
- What is the thickness we need to apply?
- PML thickness varied from $1\lambda - 7\lambda$ ($\lambda$ is the operating wavelength)
- Thickness optimized to $7\lambda$

![Graph showing imaginary part of effective index vs. PML thickness]
COMSOL solves this problem using full-vectorial finite element method (FEM) mode solver.

Mesh element size along with the type of mesh applied has its influence on the end results.

Fine element size was applied in the simulations as the variation in bend loss is minimal in the region of interest.

![Mesh Element Size Graph]

- Mesh Element Size
  - Extremely Coarse
  - Extra Coarse
  - Coarser
  - Coarse
  - Normal
  - Fine
  - Finer
  - Extra Fine
  - Extremely Fine

Bend Loss (dB/turn)

- Bend Diameter = 13.5 mm
  - 2
  - 2.2
- Bend Diameter = 9.5 mm
  - 13
  - 14
  - 15
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Bend Insensitive Fiber

- Designed to reduce bend loss induced in a fiber by adding low index trench in cladding
- Trench Parameters:
  - Trench depth
    \[
    \Delta n_{trench} = n_{clad} - n_{trench}
    \]
  - Distance of trench from core \(b\)
  - Trench width \(c\)
- Optimization following standard ITU-T recommendations\(^4\)
  - \(\Delta n_{trench} = 0.002\)
  - \(b/a = 2.12\)
  - \(c/a = 2.84\)

Addition of trench has reduced the bend loss induced in the fiber.

Bend radius: 5 mm @ 1550 nm wavelength.

Experiments $^4 = 0.014 \pm 0.0023$ dB/turn.

Simulations = 0.012 dB/turn.

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Conclusions

- Proposed a new method to estimate bend losses in optical fiber with arbitrary index profiles.
- Applied GEBT and conformal mapping to obtain modified refractive index.
- Wave optics module, ewfd physics, mode analysis study and free triangular mesh of COMSOL are used in solving the wave equation.
- PML thickness and mesh element size are optimized to minimize any variations in simulation results.
- Simulation results for standard G652 fiber along with bend insensitive fiber are presented.
- Analytical approach and semi analytical formulas derived\(^1\)\(^2\)\(^5\) are applicable for simple refractive index profiles.