Study of Bending Losses in Optical Fibers using COMSOL

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COMSOL CONFERENCE
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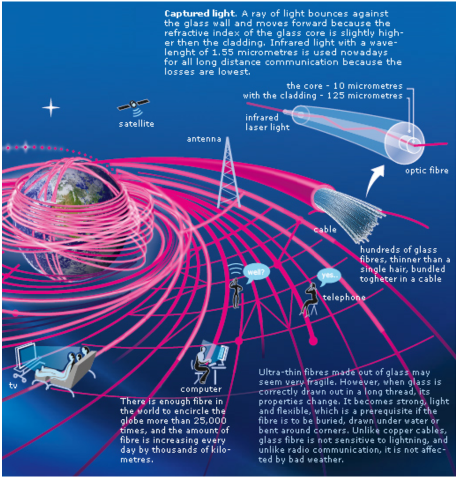
Overview

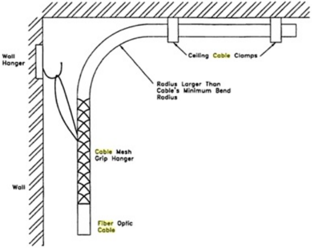
- Material: Silica glass
- Dimensions: In microns
- Advantages:
  - Small size, easily installed
  - Low power loss
  - High transmission rate over very long distances
- Circulatory system that nourishes our information system

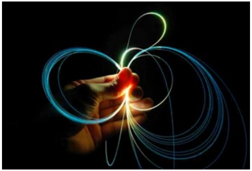


Overview

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



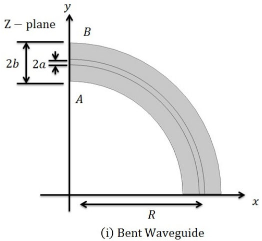


[0] Picture Reference: (a) https://www.rp-photonics.com/fibers.html
(b) https://www.fiberoptics4sale.com/blogs/archive-posts/95053062-fiber-optic-cable-installation-overview

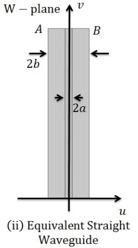
Geometric Effect: Conformal Mapping

- 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]

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



(i) Bent Waveguide

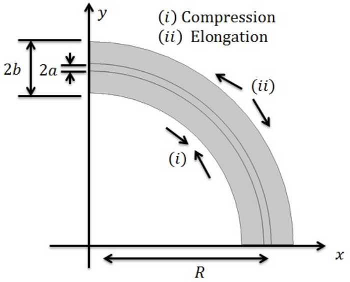


(ii) Equivalent Straight Waveguide

[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) $\uparrow$, @ point (ii) $\downarrow$
- Stress effect counters geometric effect
- Conventional approach: Elasto-optic factor in conformal mapping $R_{eff} = 1.28 - 1.31R$ [1] [2]



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

[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).

[2] Renner, Hagen, Bending losses of coated single-mode fibers: a simple approach, JLT, 10.5 (1992).

Overview

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

$$n_S(x,y) = n(x,y)\left[1 - \frac{n^2}{2}\left(P_{11}\overbrace{\epsilon_1 + P_{12}(\epsilon_2 + \epsilon_3}^{\text{GEBT}})\right)\right]$$

$P_{11} = 0.113$ and $P_{12} = 0.252$ are stress optic coefficients
ϵ_1, ϵ_2, ϵ_3 are the principle strains obtained from GEBT

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

$$n_{G+S} = n_S\left(1 + \frac{x}{R}\right)$$

[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)

Overview

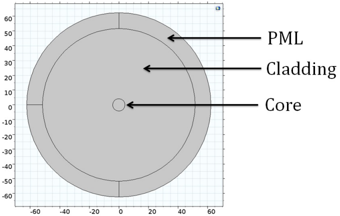
Geometry and Material Properties

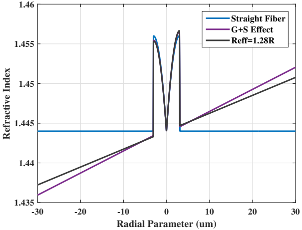
- Geometry: 2D cross section of optical fiber (G652)
- Core radius $a = 3.05\,\mu m$
- Cladding radius $b = 62.5\,\mu m$
- PML thickness $= 7\lambda$
- Refractive index profile[4]

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

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

n_{max}=1.456, $n_{clad} = 1.444$





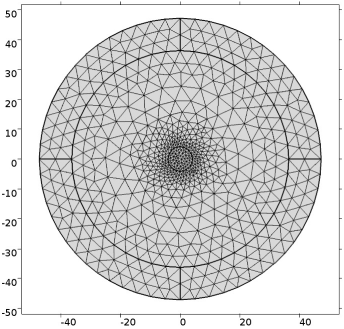
[4]Watekar, Pramod R., Seongmin Ju, and Won-Taek Han, Design and development of a trenched optical fiber with ultra-low bending loss, Op Exp 17.12 (2009)

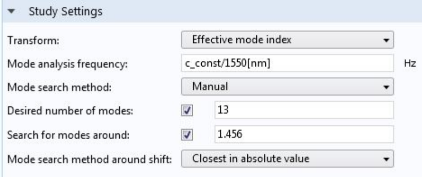
Simulation Parameters

- Module: Wave Optics
- Physics: Electromagnetic wave, frequency domain (ewfd)
- Solve the wave equation

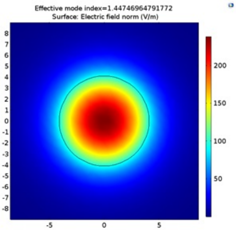
$$\nabla \times \nabla \times \vec{E} - k_0^2 \epsilon_r \vec{E} = 0$$

- Mesh: Free triangular mesh with fine element size
- Study: Mode Analysis, solve for the effective index of the modes

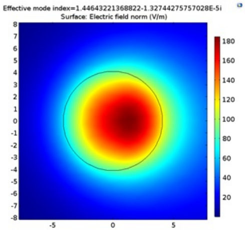




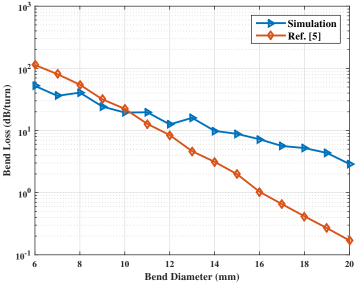
Simulation Results



(a) Straight Fiber



(b) Bend radius = 5mm



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

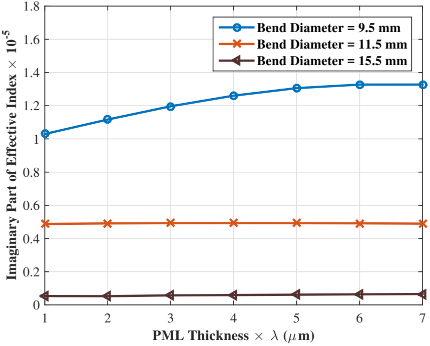
$$\text{Loss[dB/turn]} = \frac{20}{\ln(10)} \frac{2\pi}{\lambda} \times \text{Im}\{n_{\text{eff}}\} \times 2\pi R$$

- Simulation results are compared with formula given in[5]

[5] Marcuse, Dietrich, Curvature loss formula for optical fibers, JOSA 66.3 (1976).

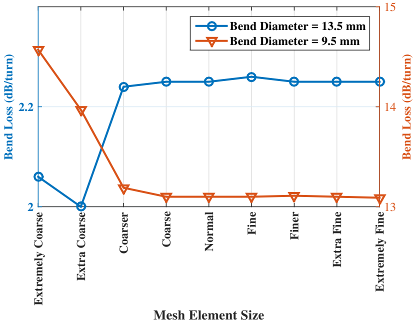
Perfectly Matched Layer

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



Mesh Element Size

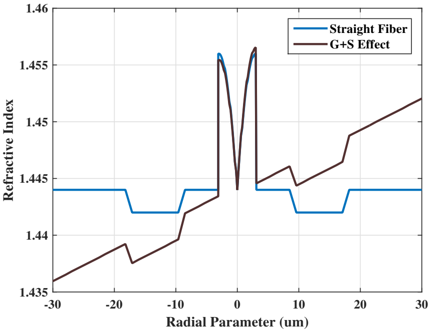
- COMSOL solves this problem using full-vectorial finite element method (FEM) mode solver
- Mesh element size along with the type of mesh applied has its influence on the end results
- Fine element size was applied in the simulations as the variation in bend loss is minimal in the region of interest



Overview

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]
  - $\Delta n_{trench} = 0.002$
  - $b/a = 2.12$
  - $c/a = 2.84$

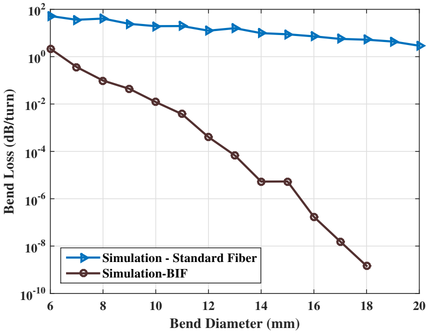


- GEBT + Conformal mapping + COMSOL Simulations to BIF

[4] Watekar, Pramod R., Seongmin Ju, and Won-Taek Han, Design and development of a trenched optical fiber with ultra-low bending loss, Op Exp 17.12 (2009)

BIF: Simulation Results

- Addition of trench has reduced the bend loss induced in the fiber
- Bend radius: 5 mm @1550 nm wavelength
- Experiments[4] = 0.014 ± 0.0023 dB/turn
- Simulations = 0.012 dB/turn



[4]Watekar, Pramod R., Seongmin Ju, and Won-Taek Han, Design and development of a trenched optical fiber with ultra-low bending loss, Op Exp 17.12 (2009)

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