Negative curvature fibers

presented by

Jonathan Hu

with

Chengli Wei, R. Joseph Weiblen, * and Curtis R. Menyuk

1Baylor University, Waco, Texas 76798, USA
2University of Maryland Baltimore County, Baltimore, Maryland 21227, USA
*Now with the Naval Research laboratory, Washington, DC 20375, USA
Outline

- Background
  - Guiding mechanism
  - Recent advances
  - Applications
  - Future prospects
- Summary
History of hollow-core optical fiber

Step-index fiber: Total internal reflection

First photonic crystal fiber: Total internal reflection

Solid core photonic crystal fiber: Total internal reflection

Hollow core photonic bandgap fiber: Bandgap

Bragg fiber: Bandgap

Low loss Hollow core photonic bandgap fiber: Bandgap

1990

1-D antiresonant slab waveguide: Antiresonance


2-D antiresonant waveguide: Antiresonance


Hypocycloid-shaped Kagome hollow core fiber: Antiresonance

Y. Y. Wang et al., CLEO 2010, paper CPDB4.

Negative curvature hollow core fiber: Antiresonance


Chalcogenide negative curvature fiber: Antiresonance


2000

2010
Negative curvature hollow core PCF

Properties
- Simple structure
- Broad bandwidth
- Low loss transmission
- High power delivery

Applications
- Fiber laser
- Micromachining
- Surgical procedures
- ...

Chalcogenide glass: Transmission wavelength extended to mid-IR

Importance of negative curvature fibers in mid-IR applications


Mid-IR applications

✓ Military
✓ Medical
✓ Sensing

C. Wei et al., Front. Phys. 4, 30 (2016).
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Resonance condition:
\[ \Delta \Phi = \Phi_1 - \Phi_0 = 2m\pi \]
\[ t = m\lambda / \left[ 2(n_{\text{glass}}^2 - n_{\text{air}}^2)^{1/2} \right] \]

Antiresonance condition:
\[ \Delta \Phi = \Phi_1 - \Phi_0 = (2m + 1)\pi \]
\[ t = (m + 0.5)\lambda / \left[ 2(n_{\text{glass}}^2 - n_{\text{air}}^2)^{1/2} \right] \]

\( k_T \): Transverse wave vector
\( k_L \): Longitudinal wave vector

Slab Waveguide

Glass

Air

W = 30 µm

Air

Glass

$\lambda = 1 \mu m$

$n_0 = 1.0$

$n_1 = 1.45$

0.8 µm

Effective index

0.99987

Mode-matching method

FEM

(b)

Antiresonance

Antiresonance

Antiresonance

(a)

0.99985

Loss (dB/m)

(b)

Glass thickness (µm)

0.2

0.4

0.6

0.8

1.0

1.2

1.4

0.0

0.5

1.0

0.0

0.5

1.0

|E|^2 / |E_{max}|^2

x (µm)

0

10

20

0

101

10^2

0

0.5

1.0

0

0.5

1.0

0

0.5

1.0

0

0.5

1.0

0

0.5

1.0

0

0.5

1.0

0

0.5

1.0

Annular core fiber and negative curvature fiber

What is going on besides antiresonance?

What is going on besides antiresonance?

Can we use simple slab waveguides to study the mode coupling between the fundamental core mode and tube mode in negative curvature fibers?

Inhibited coupling in slab waveguides

To inhibit coupling,
- minimize the overlap between the core and cladding modes (antiresonance)
- ensure the wavenumbers do not match

Inhibited coupling in slab waveguides

\[ \Delta n_{\text{eff}} = |n_{\text{eff}} - n_{\text{eff0}}| \]

\( n_{\text{eff0}} \) is the effective index of waveguide with the middle two glass layers.

Antiresonance plays a critical role in inhibiting coupling between these modes.
Inhibited coupling in negative curvature fibers

The mode intensity increases inside the gap when the gap increases from 0 to 10 \( \mu m \).
Inhibited coupling in negative curvature fibers

Negative curvature fibers with four cladding tubes show the avoided crossing

\[ D_{\text{core}} = 30 \, \mu m \]
\[ t = 0.72 \, \mu m \]

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Negative curvature that decrease loss

Leakage loss decreases as the curvature increases.

Nested tubes can increase antiresonance guidance.
Fiber with 6, 8, and 10 cladding tubes

The optimal gap in a fiber with 6 cladding tubes is 3 times as large as the optimal gap in fibers with 8 or 10 cladding tubes.
Comparison between fibers with 6 and 8 cladding tubes

A larger gap is required to remove the weak coupling between the core mode and tube modes in a fiber with 6 cladding tubes.

Higher-order mode suppression

Use coupling to suppress higher-order core modes!
Higher-order mode suppression

High loss peaks in bend fibers

\[ t = 1.8 \, \mu m \]

- Effective index
- Parallel-polarized
- Perpendicular-polarized

Bend loss peaks are induced by mode coupling

- Fibers with small tubes have lower bend loss

Parallel

Perpendicular

\[ R = 9.4 \, \text{cm} \]

\[ R = 5.7 \, \text{cm} \]


Different bend directions

The bend loss changes by a maximum factor of 10 as the bend direction changes when coupling happens.

This negative curvature fiber could be used to make bending sensors.

Bend radius = $R$

Bend radius = $2R$

http://coolshitindustries.com/2011/10/data
glove-with-ghetto-flex-sensors-circa-2000/


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Mid-IR gas fiber lasers

Energy level diagram in acetylene

Measured output spectrum


Micromachining

Micro-milled pattern in a fused silica

Cutting of aluminum sheet

Marking on a titanium


Surgical procedures

A fiber mounted with the end tip using a heat shrinking tube

Ablation of ovine bone in air

Sapphire tube

- Negative curvature fiber
- Sapphire window

Dimensions:
- 0.5 mm
- 1.2 mm
- 1.4 mm

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✔ Antiresonant reflection and inhibited coupling
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Future prospects

Data communications
Power delivery
Nonlinear optics
Chemical sensing
Bend sensing
Ultraviolet, mid-IR, and THz transmission

F. Poletti et al., Nat. Photonics 7, 279 (2013).
Future prospects

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Future prospects

Data communications

High electron mobility
Data communications

High transparency in visible and IR
High electrical conductivity
High mechanical stiffness and flexibility
Diamagnetism
Nonlinear optics
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Number of journal publications related to hollow-core fibers that use a negative curvature inner core boundary.
Summary

✓ Inhibited coupling guides the light negative curvature fibers.
✓ Recent advances have increased their performance of the negative curvature fibers.
✓ Negative curvature fibers enable a large range of applications.
✓ Negative curvature fibers will be the best choice for a wide range of different applications due to their combined advantages of low loss, broad bandwidth, and a low power ratio in the glass.

The content of this talk has been adapted from the review paper,

Thank you!