Negative curvature fibers

presented by
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with
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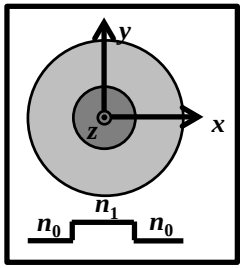
Outline

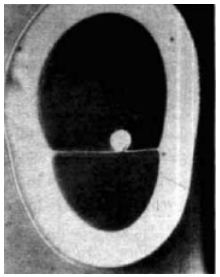
- ✓ Background
- ✓ Guiding mechanism
- ✓ Recent advances
- ✓ Applications
- ✓ Future prospects
- ✓ Summary

History of hollow-core optical fiber

Step-index fiber:
Total internal reflection

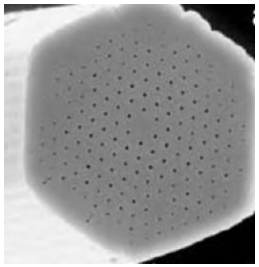


First photonic crystal fiber:
Total internal reflection



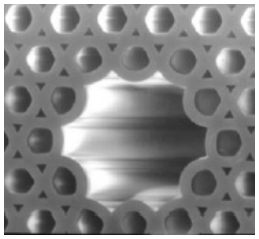
TP. V. Kaiser *et al.*, Bell Syst. Tech. J. **53**, 1021 (1974).

Solid core photonic crystal fiber:
Total internal reflection



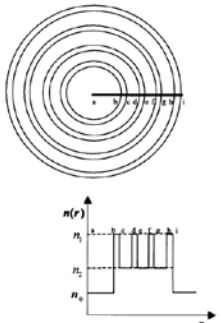
T. A. Birks *et al.*, Opt. Lett. **22**, 961 (1997).

Hollow core photonic bandgap fiber: Bandgap



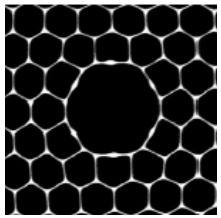
R. F. Cregan *et al.*, Science **285**, 1537 (1999).

Bragg fiber: Bandgap

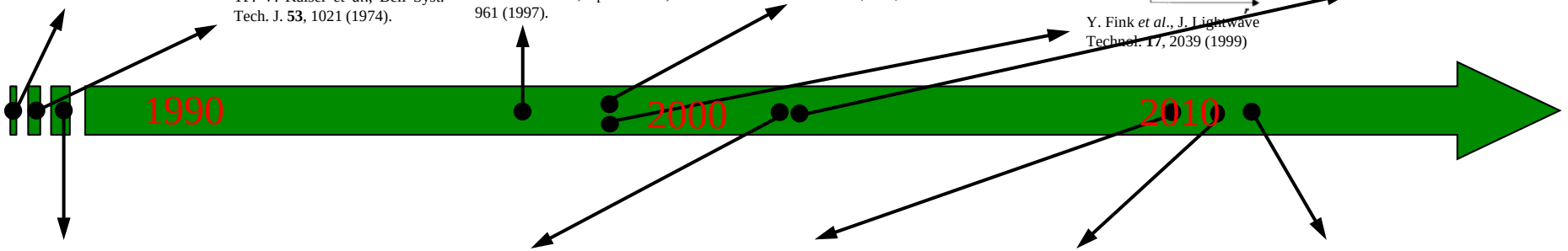


Y. Fink *et al.*, J. Lightwave Technol. **17**, 2039 (1999)

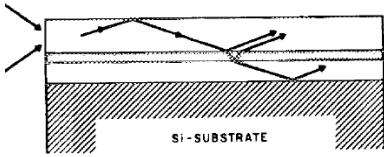
Low loss Hollow core photonic bandgap fiber: Bandgap



C. M. Smith *et al.*, Nature **424**, 657 (2003).

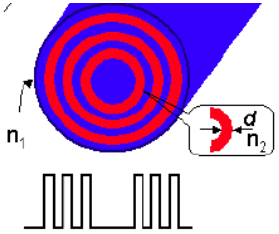


1-D antiresonant slab waveguide: Antiresonance



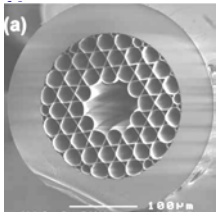
M. A. Duguay *et al.*, Appl. Phys. Lett. **49**, 13 (1986).

2-D antiresonant waveguide: Antiresonance



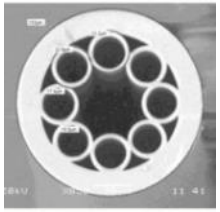
N. M. Litchinitser *et al.*, Opt. Express **11**, 1243 (2003).

Hypocycloid-shaped Kagome hollow core



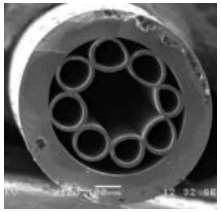
Y. Y. Wang *et al.*, CLEO 2010, paper CPDB4.
Y. Y. Wang *et al.*, Opt. Lett. **36**, 669 (2011).

Negative curvature hollow core fiber: Antiresonance



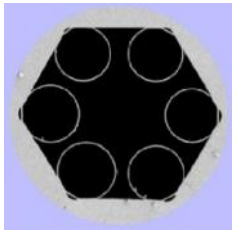
A. D. Pryamikov *et al.*, Opt. Express **19**, 1441 (2011).

Chalcogenide negative curvature fiber: Antiresonance

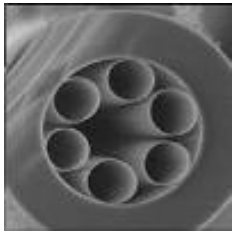


A. F. Kosolapov *et al.*, Opt. Express **19**, 25723 (2011).

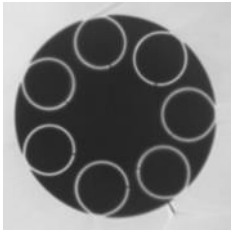
Negative curvature hollow core PCF



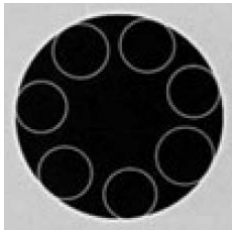
P. Uebel *et al*., Opt. Lett. **41**, 1961 (2016).



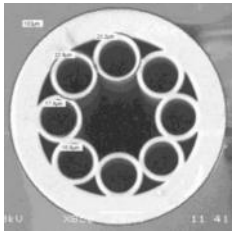
X. Liu *et al*., Opt. Lett. **42**, 863(2017).



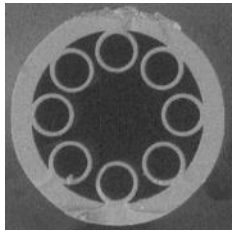
M. Michieletto *et al*., Opt. Express **24,** 7103 (2016)



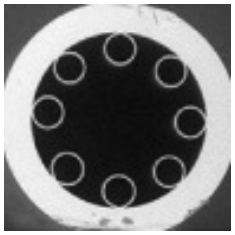
J. R. Hayes *et al*., J. Lightwave Technol. **35**, 437 (2017)



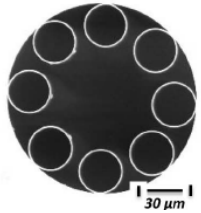
A. D. Pryamikov *et al*., Opt. Express **19**, 1441 (2011).



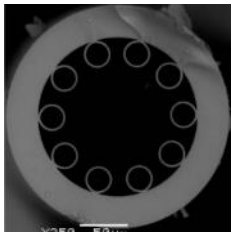
A. N. Kolyadin *et al*., Opt. Express **21,** 9514 (2013).



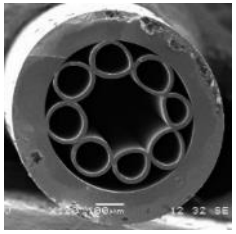
A. V. Newkirk *et al*., Opt. Lett. **41**, 3277 (2016)



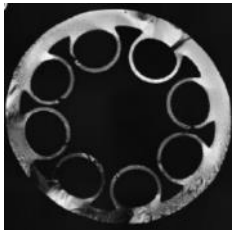
B. Debord *et al*., Optica **4**, 209 (2017)



W. Belardi *et al*., Opt. Express **22**, 10091 (2014).

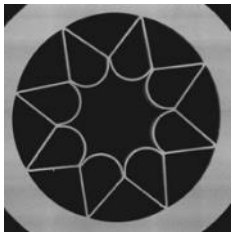


A. F. Kosolapov *et al*., Opt. Express **19**, 25723 (2011).

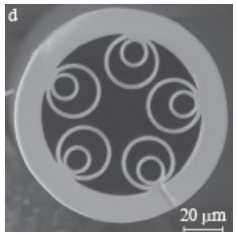


R. R. Gattass *et al*., Opt. Express **24**, 25697 (2016).

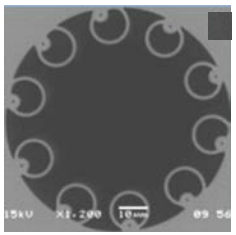
V. Setti *et al*., Opt. Express **21**, 3388 (2013).



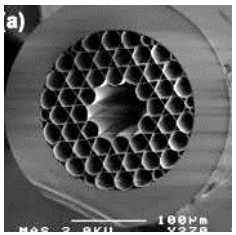
F. Yu *et al*., Opt. Express **20**, 11153 (2012).



A. F. Kosolapov *et al*., Quantum Electronics **46**, 267 (2016).

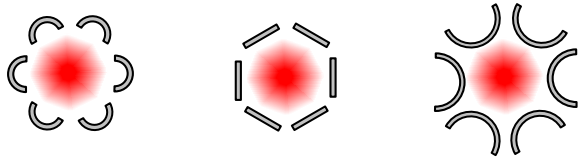


W. Belardi *et al*., J. Lightw. Technol **33**, 4497 (2015).



Y. Y. Wang *et al*., Opt. Lett. **37**, 3111 (2012).

Positive curvature | Flat | Negative curvature



Properties

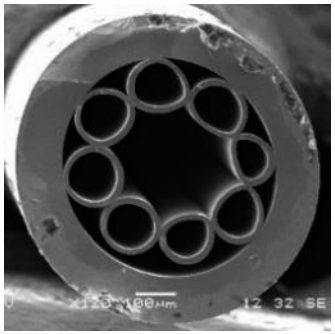
- Simple structure
- Broad bandwidth
- Low loss transmission
- High power delivery

Applications

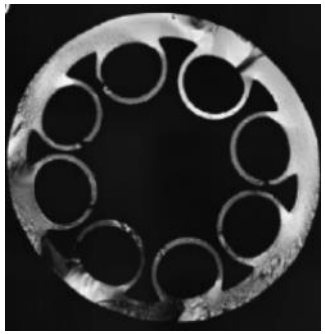
- Fiber laser
- Micromachining
- Surgical procedures
- ...

Importance of negative curvature fibers in mid-IR applications

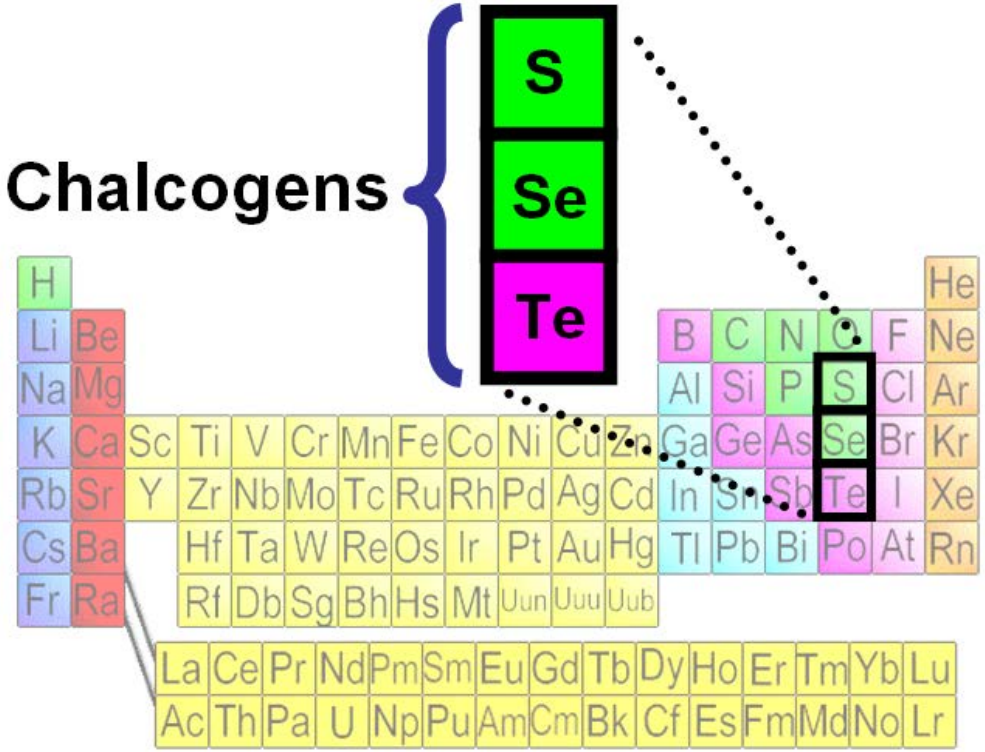
Chalcogenide glass: Transmission wavelength extended to mid-IR



A. F. Kosolapov *et al.*, Opt. Express **19**, 25723 (2011).



R. R. Gattass *et al.*, Opt. Express **24**, 25697 (2016).



Mid-IR applications

- ✓ Military
- ✓ Medical
- ✓ Sensing

C. Wei *et al.*, Front. Phys. **4**, 30 (2016).

Outline

- ✓ Background
- ✓ Guiding mechanism
- ✓ Recent advances
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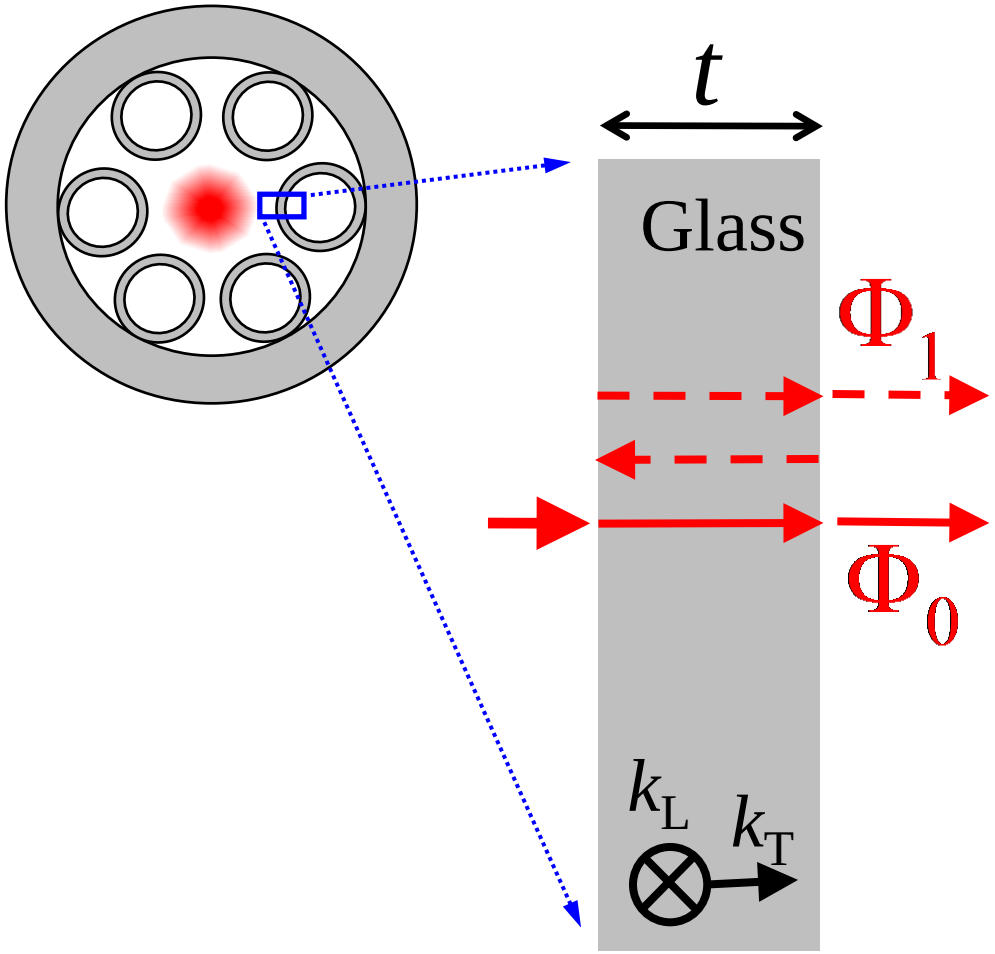
- ✓ Future prospects
- ✓ Summary

Antiresonance condition



Resonance condition:

$$\Delta\Phi = \Phi_1 - \Phi_0 = 2m\pi$$

$$t = m\lambda / [2(n_{\text{glass}}^2 - n_{\text{air}}^2)^{1/2}]$$

Antiresonance condition:

$$\Delta\Phi = \Phi_1 - \Phi_0 = (2m+1)\pi$$

$$t = (m+0.5)\lambda / [2(n_{\text{glass}}^2 - n_{\text{air}}^2)^{1/2}]$$

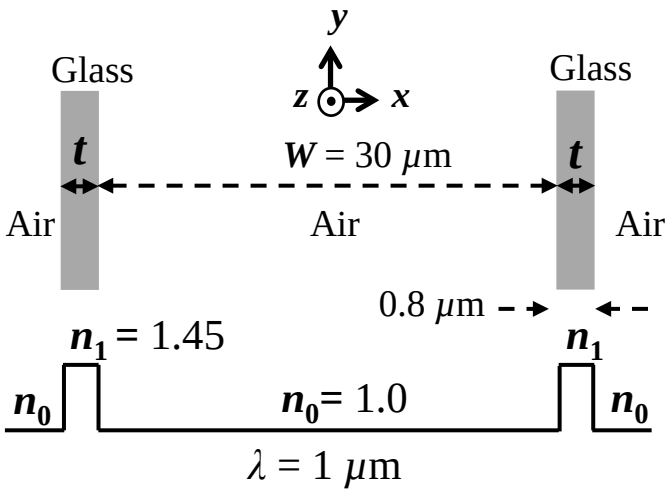
k_T: Transverse wave vector

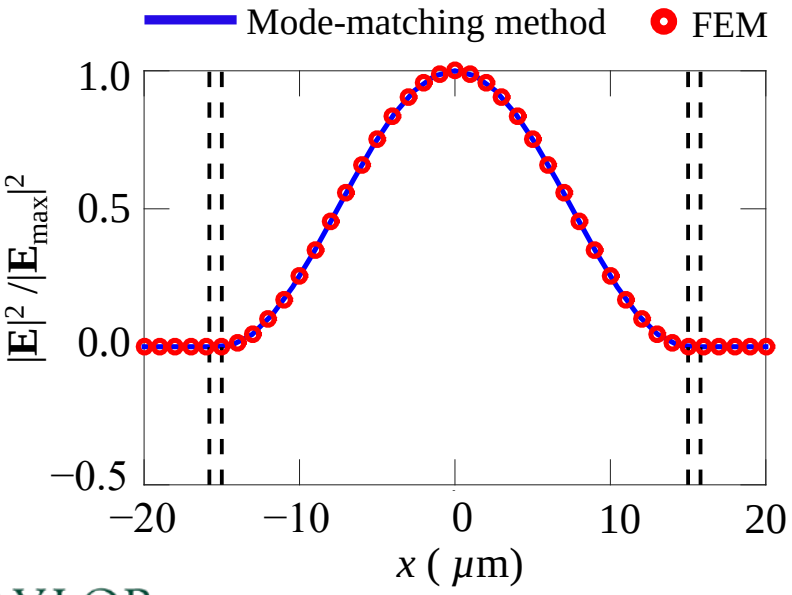
k_L: Longitudinal wave vector

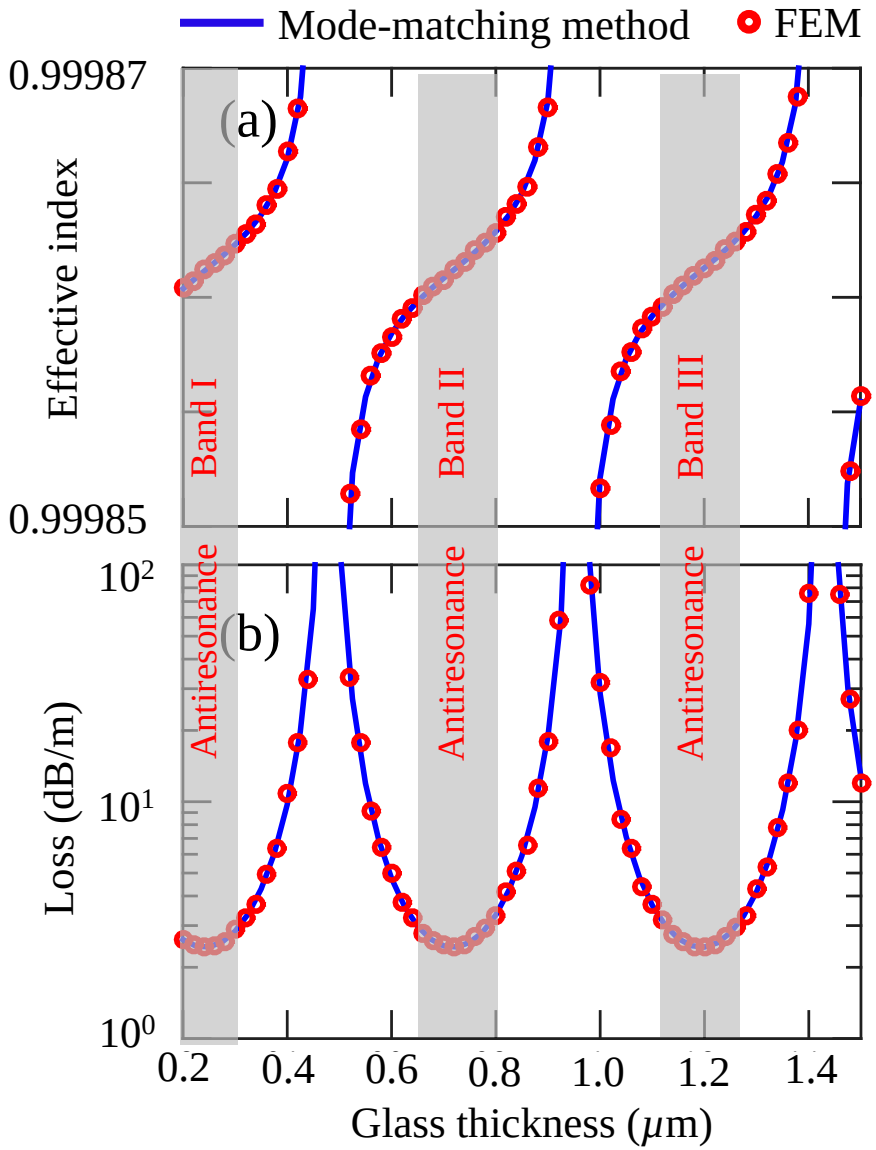
N. M. Litchinitser *et al.*, Opt. Lett. **27**, 1592–1594 (2002)

C. Wei *et al.*, Adv. Opt. Photon. **9**, 504 (2017)

Slab Waveguide







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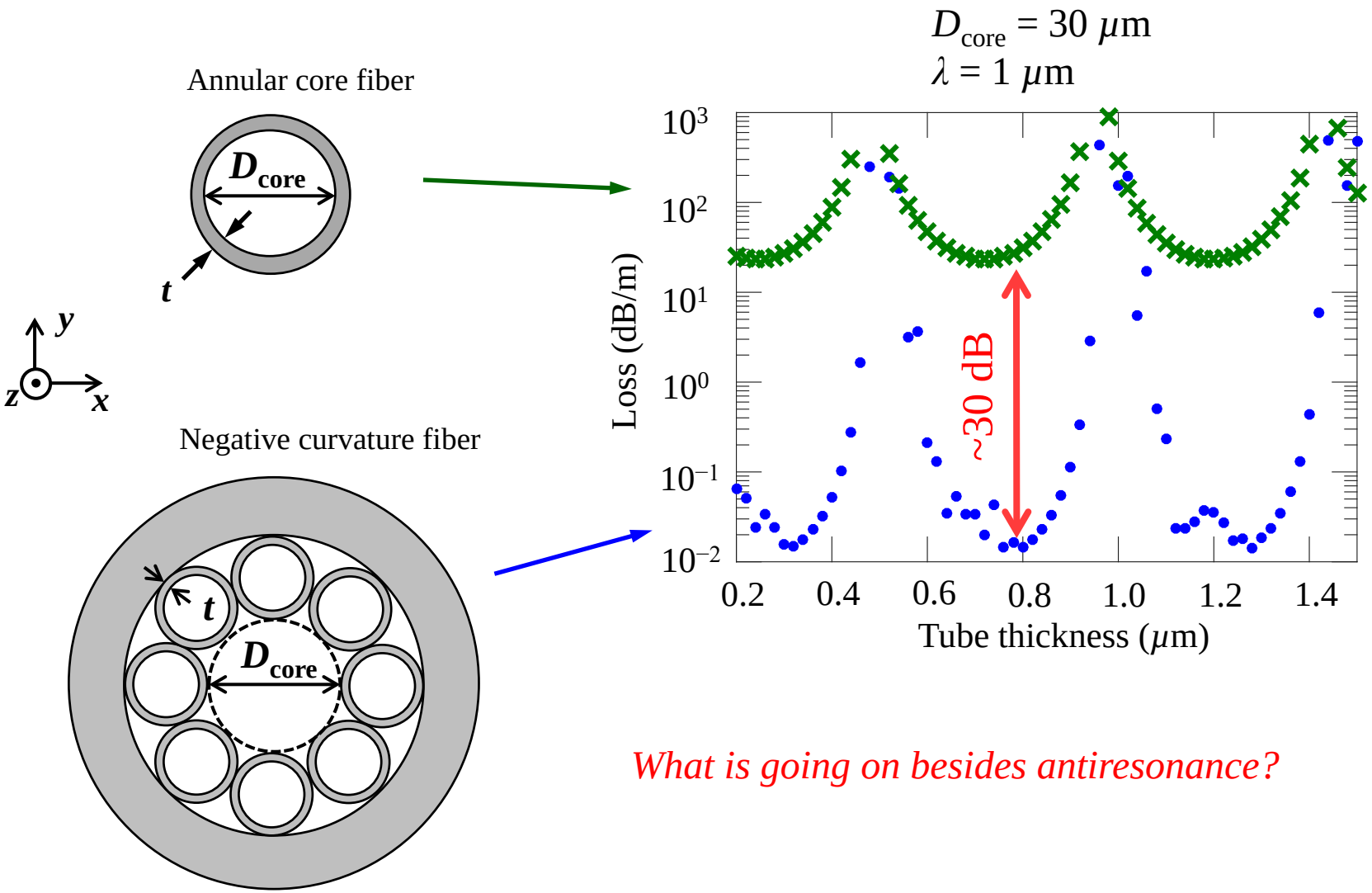
Annular core fiber and negative curvature fiber



What is going on besides antiresonance?

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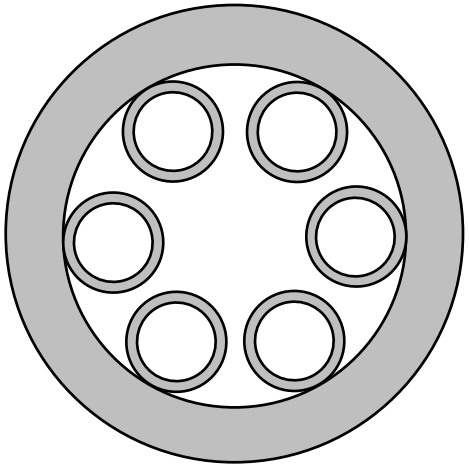
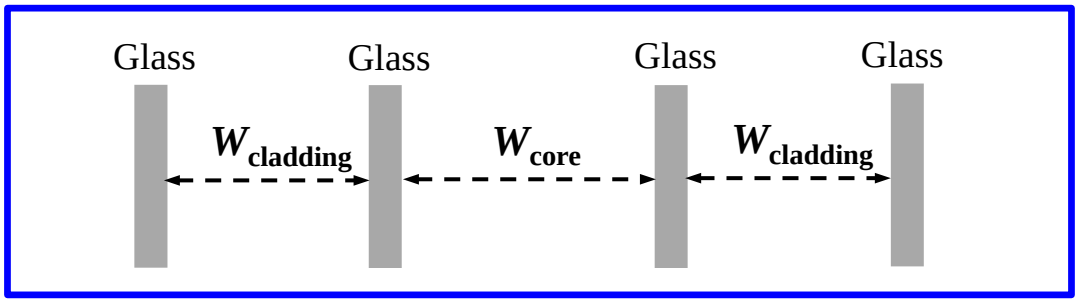
What is going on besides antiresonance?



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



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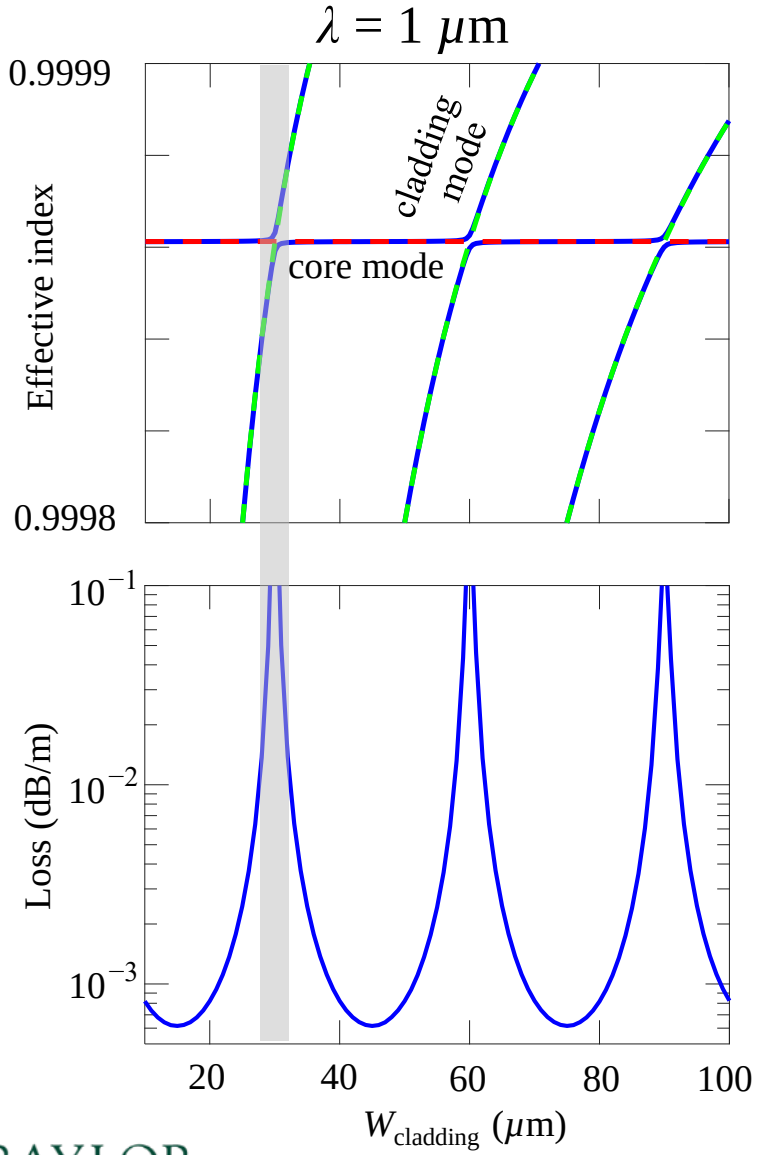
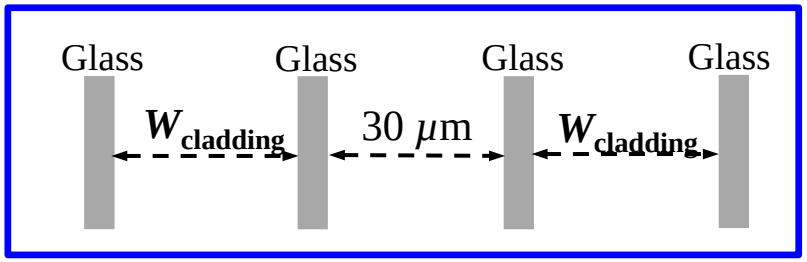
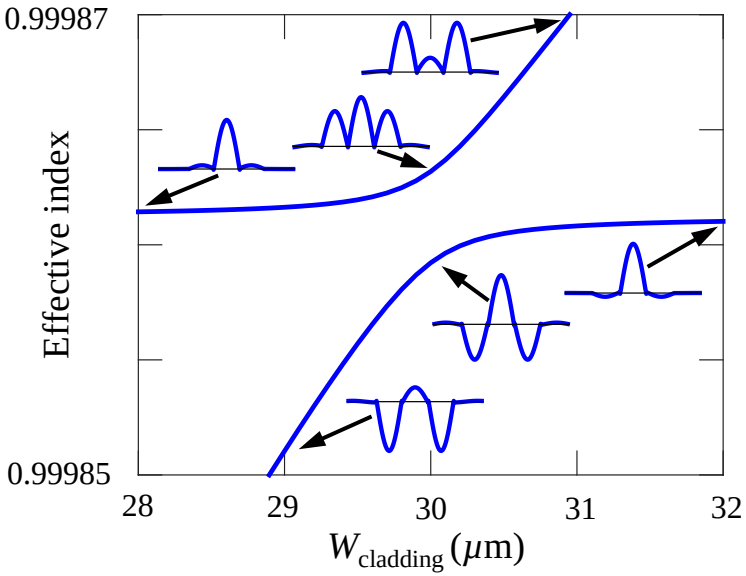
Inhibited coupling in slab waveguides





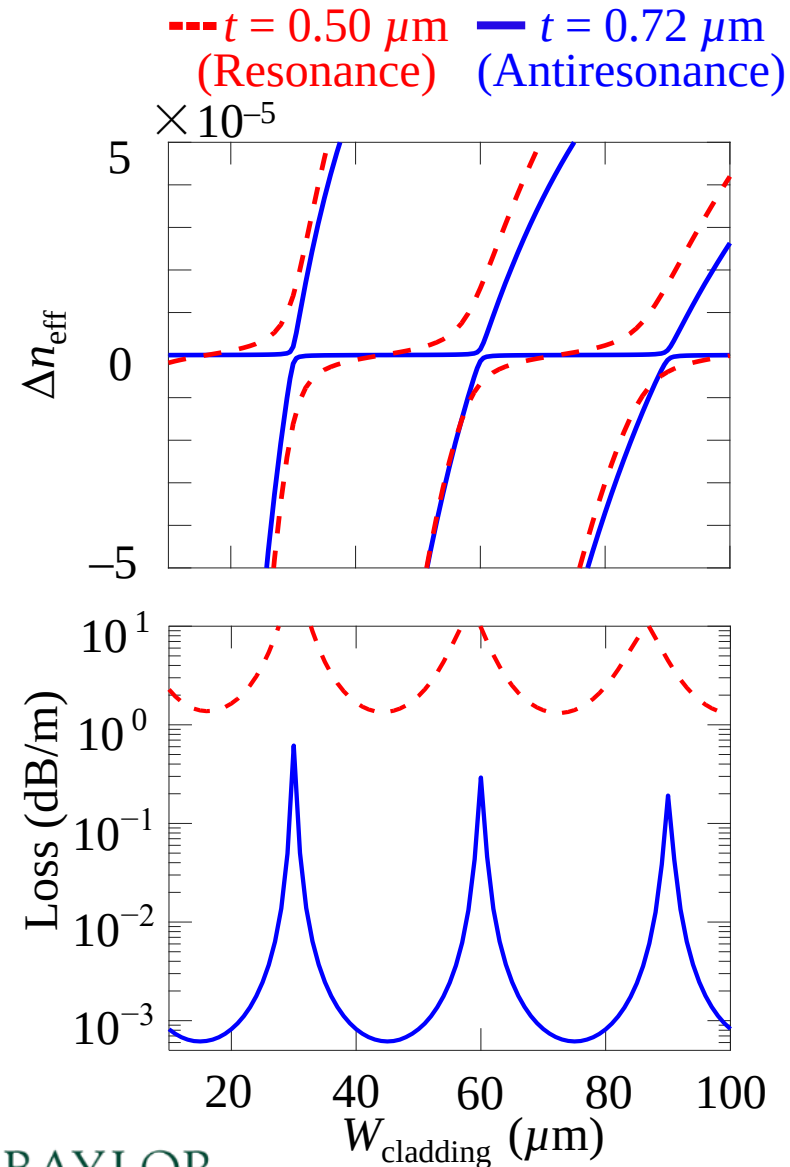


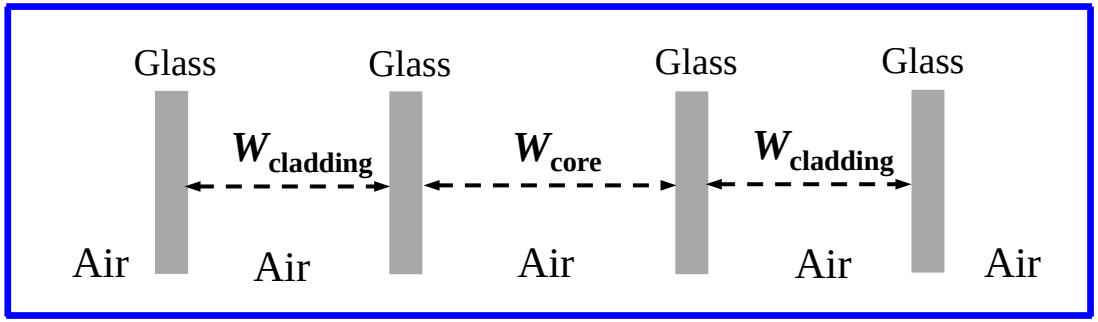
To inhibit coupling,

- ✓ *minimize the overlap between the core and cladding modes (antiresonance)*
- ✓ *ensure the wavenumbers do not match*

C. Wei *et al.*, Adv. Opt. Photon. **9**, 504 (2017)

Inhibited coupling in slab waveguides





$\Delta n_{\text{eff}} = |n_{\text{eff}} - n_{\text{eff0}}|$

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

Antiresonance plays a critical role in inhibiting coupling between these modes.

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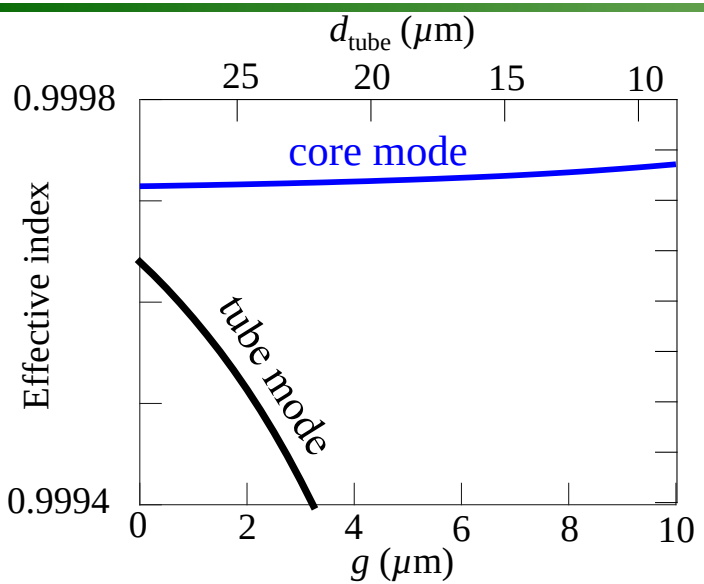
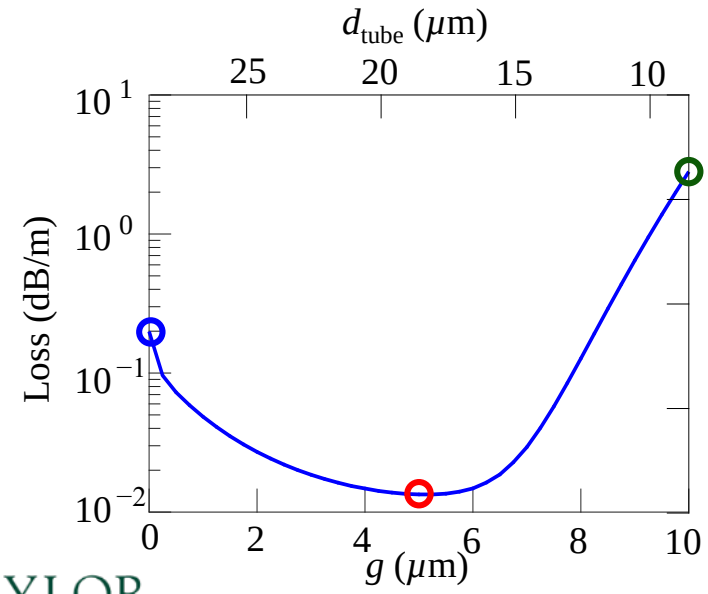
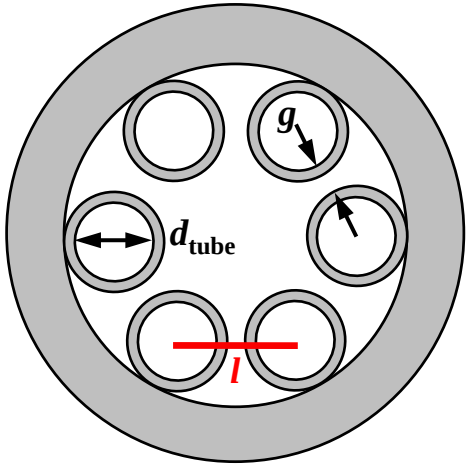
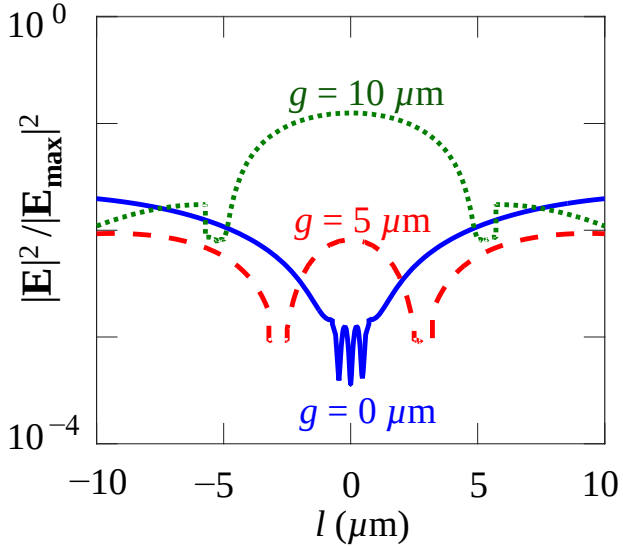
Inhibited coupling in negative curvature fibers









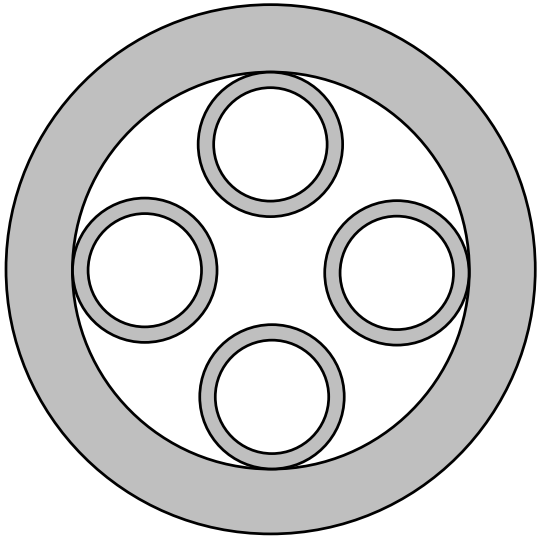
The mode intensity increases inside the gap when the gap increases from 0 to 10 μm.

B. Debord *et al.*, Optica 4, 209–217 (2017).

C. Wei *et al.*, Adv. Opt. Photon. **9**, 504 (2017)

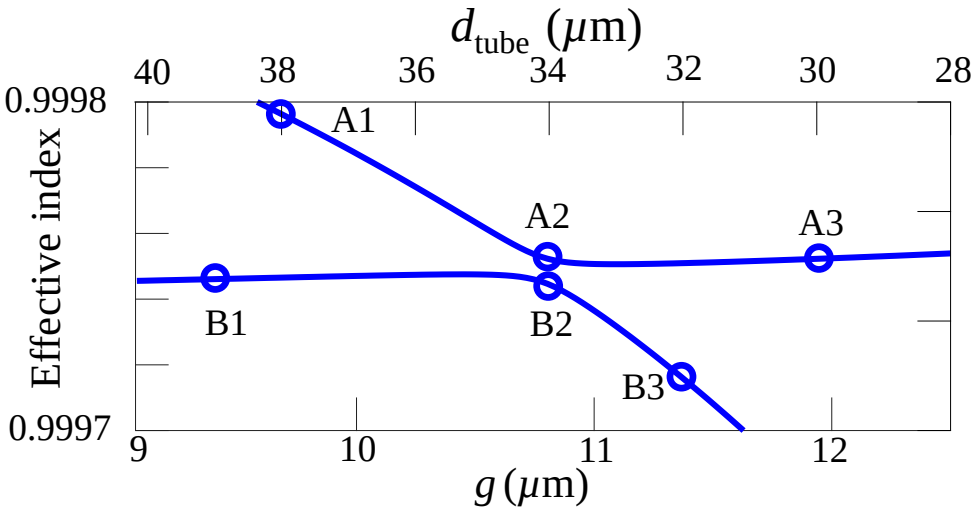
Inhibited coupling in negative curvature fibers

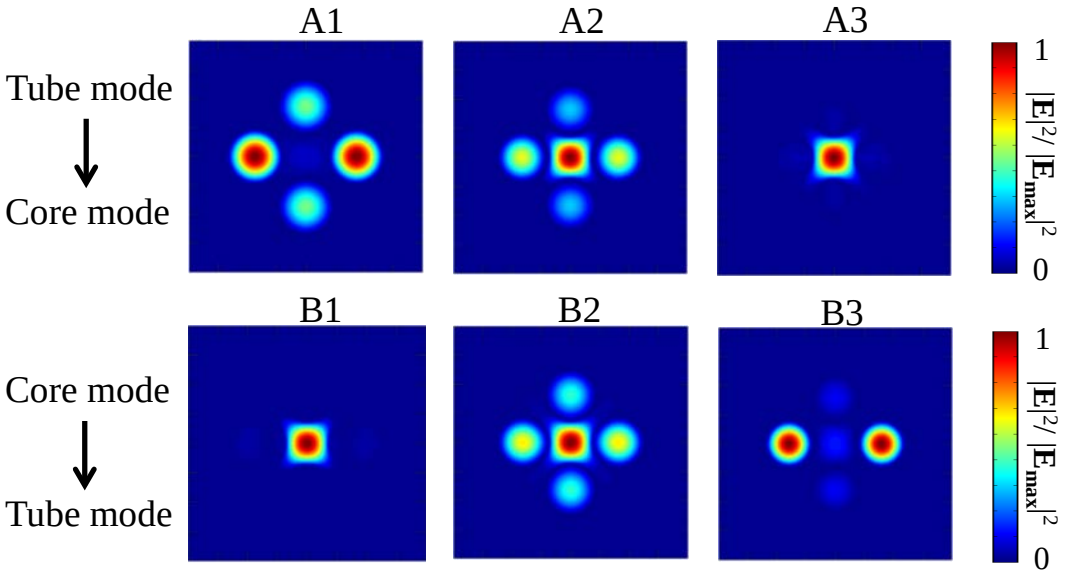
Negative curvature fibers with four cladding tubes show the avoided crossing



D_{core} = 30 μm

t = 0.72 μm





C. Wei *et al*., Adv. Opt. Photon. **9**, 504 (2017)

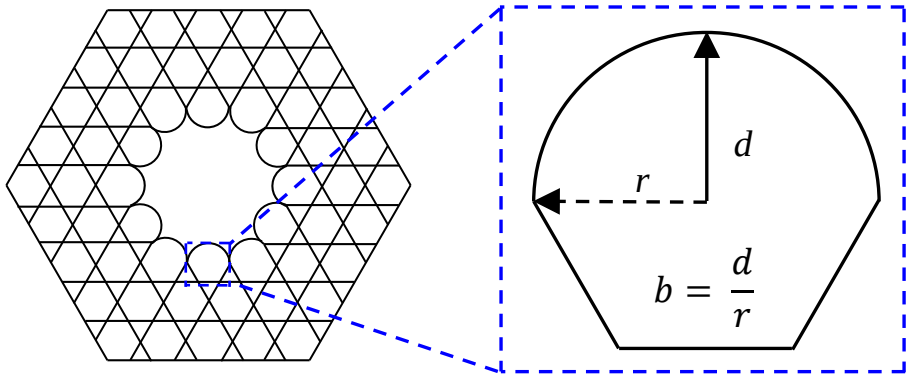
Outline

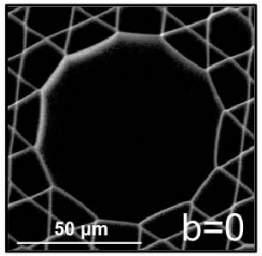
- ✓ Background
- ✓ Guiding mechanism
- ✓ Recent advances
- ✓ Applications
- ✓ Future prospects
- ✓ Summary

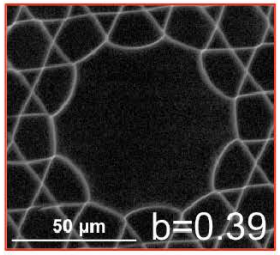
Negative curvature that decrease loss

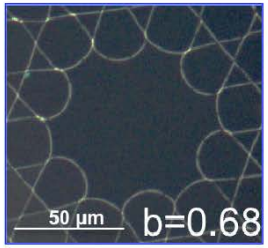
Scanning electronic microscope (SEM) image of the fiber

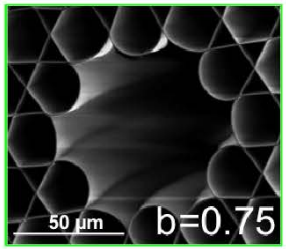
Schematic of the hypocycloid-shaped hollow-core fiber

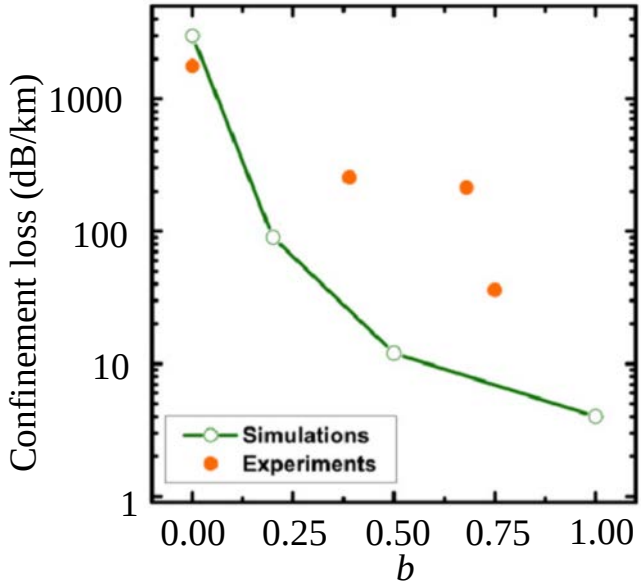








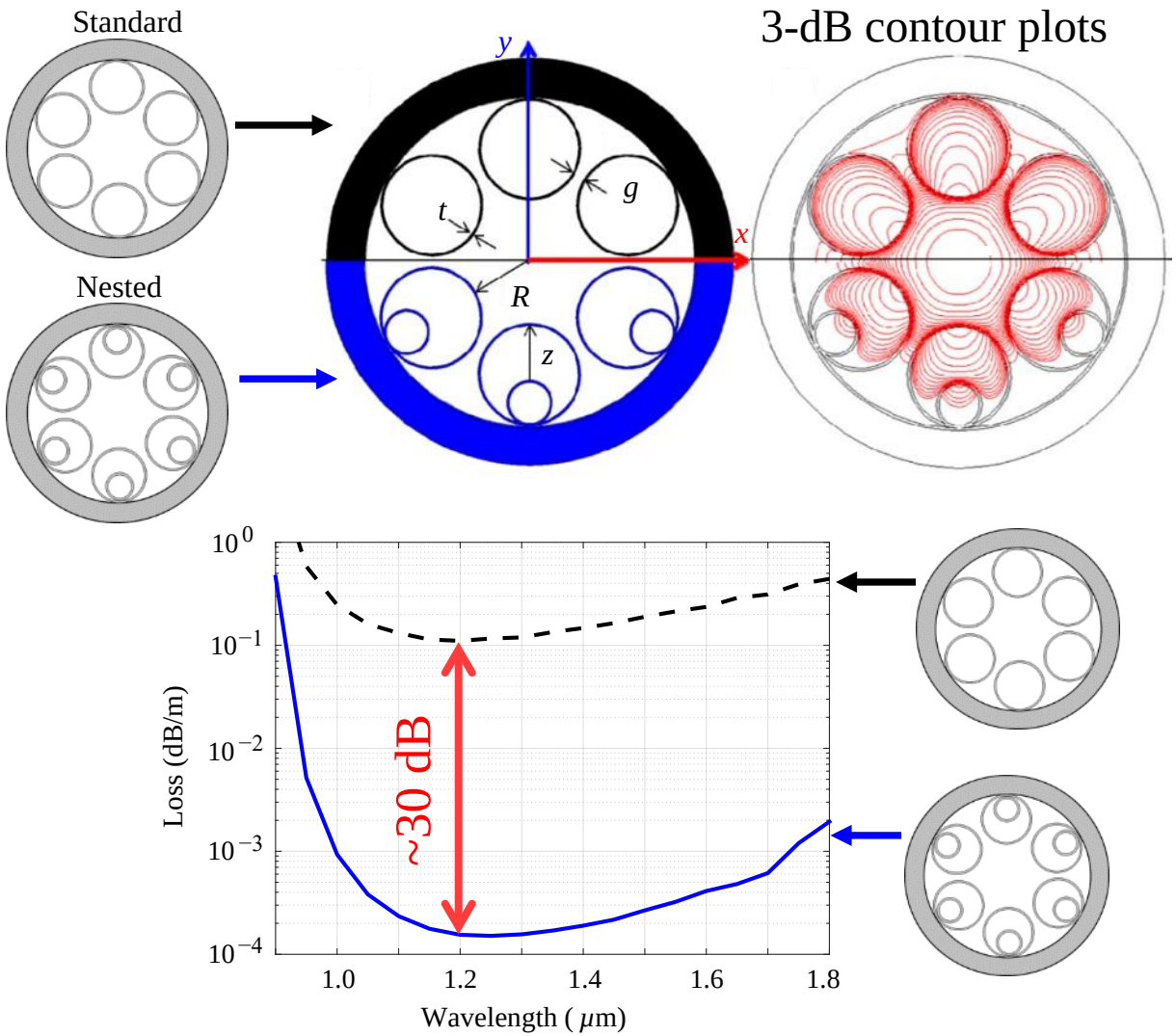




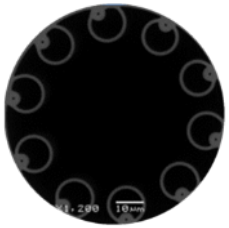
Leakage loss decreases as the curvature increases.

B. Debord *et al*., Opt. Express **21**, 28597 (2013).

Nested tubes that increase antiresonance guidance



Fabricated fibers with nested tubes



W. Belardi *et al*., J. Lightw. Technol **33**, 4497 (2015).

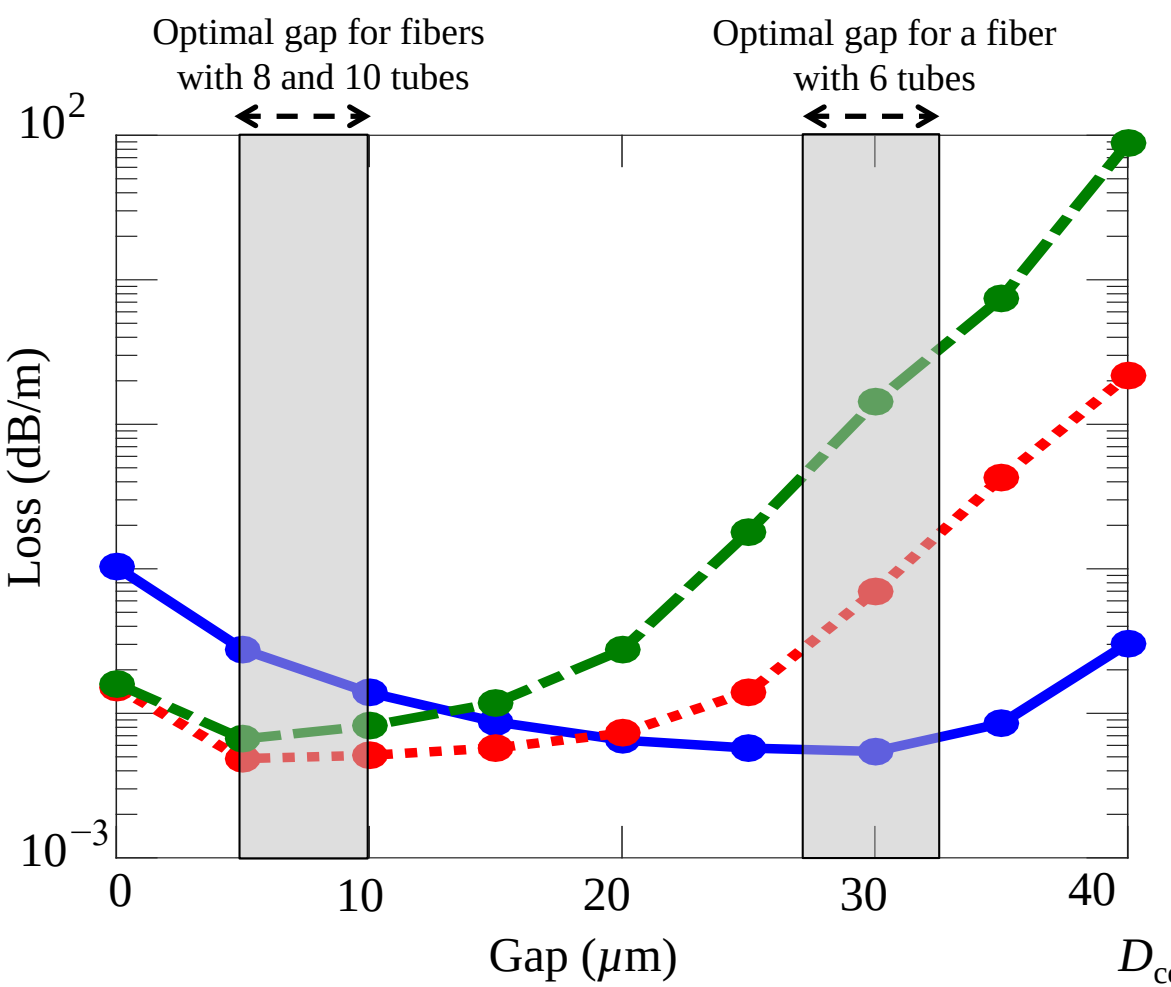
A. F. Kosolapov *et al*., Quantum Electronics **46**, 267 (2016).

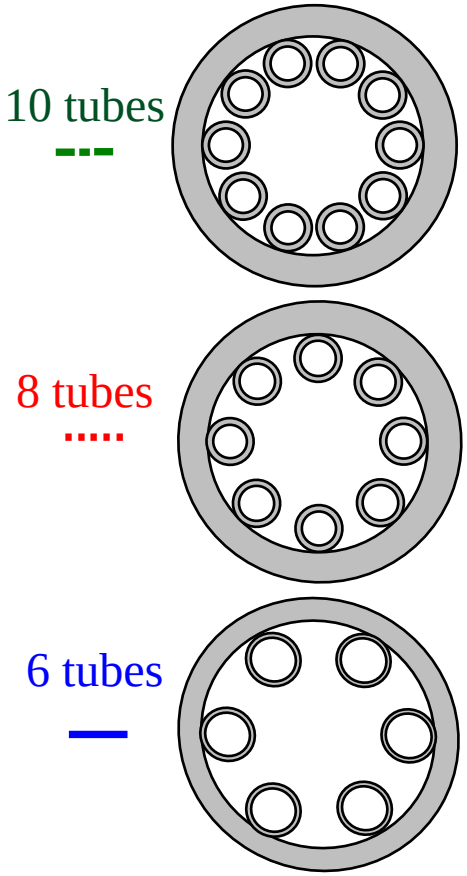
J. E. Antonip-Lopez, *et al*., , in IEEE Photonics Conference (IPC), pp. 402-403, 2016.

Nested tubes can increase antiresonance guidance.

F. Poletti *et al*., Opt. Express **22**, 23807 (2014).

Fiber with 6, 8, and 10 cladding tubes



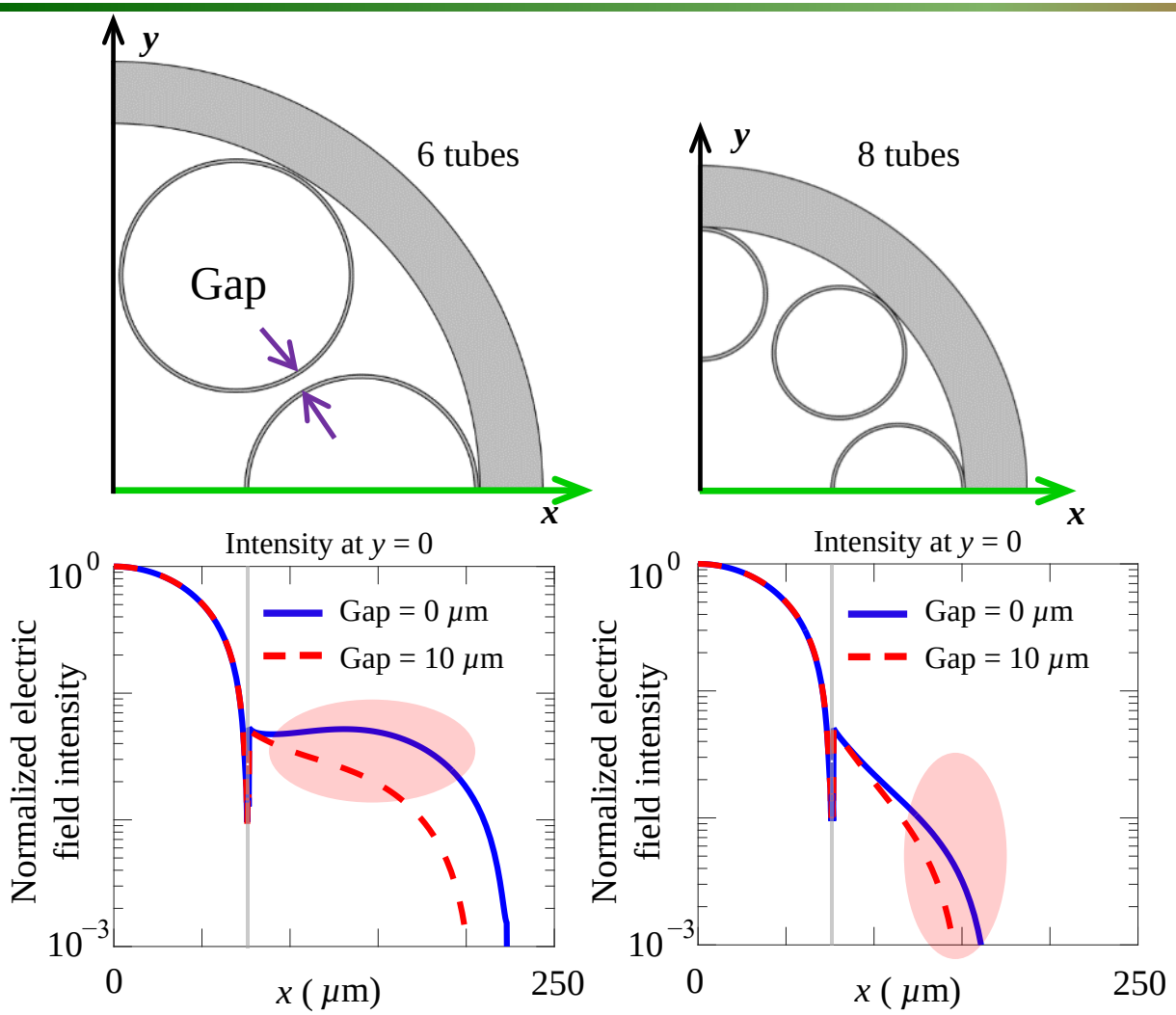


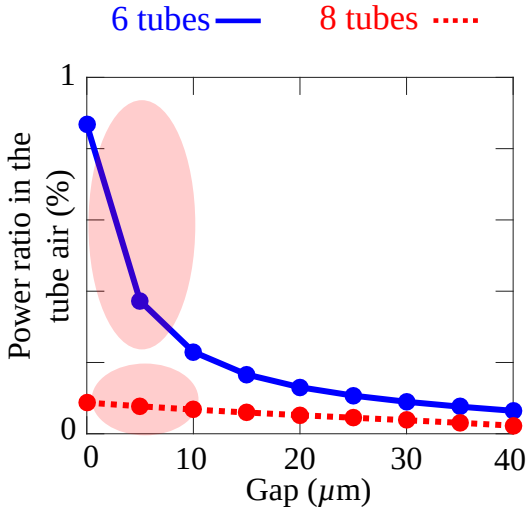
D_{core} =150 μm t =1.8 μm λ =5 μm

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.

C. Wei *et al.*, IEEE Photon. J. **8**, 2200509 (2016).

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.

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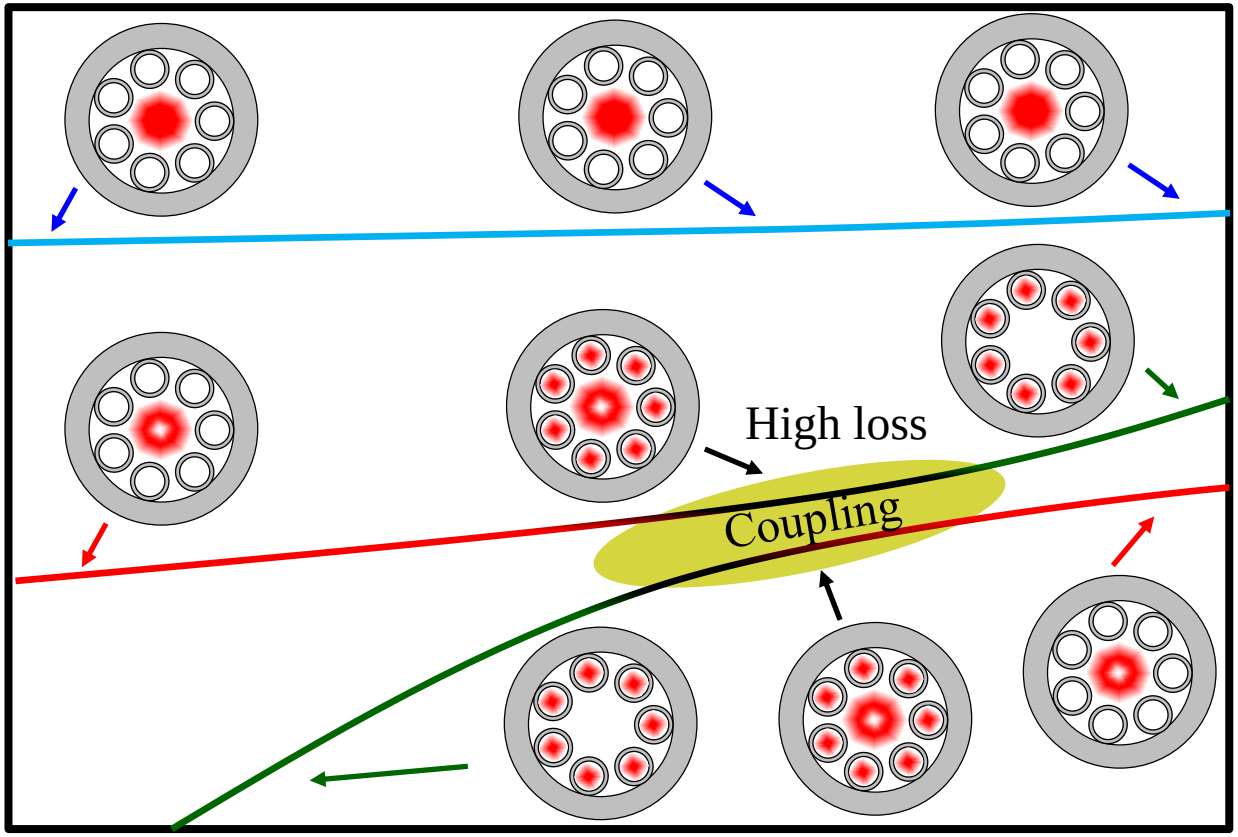
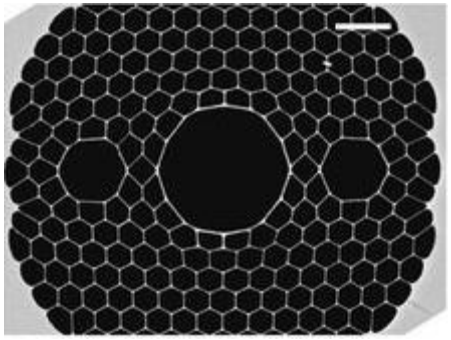
C. Wei *et al.*, IEEE Photon. J. **8**, 2200509 (2016).

Higher-order mode suppression



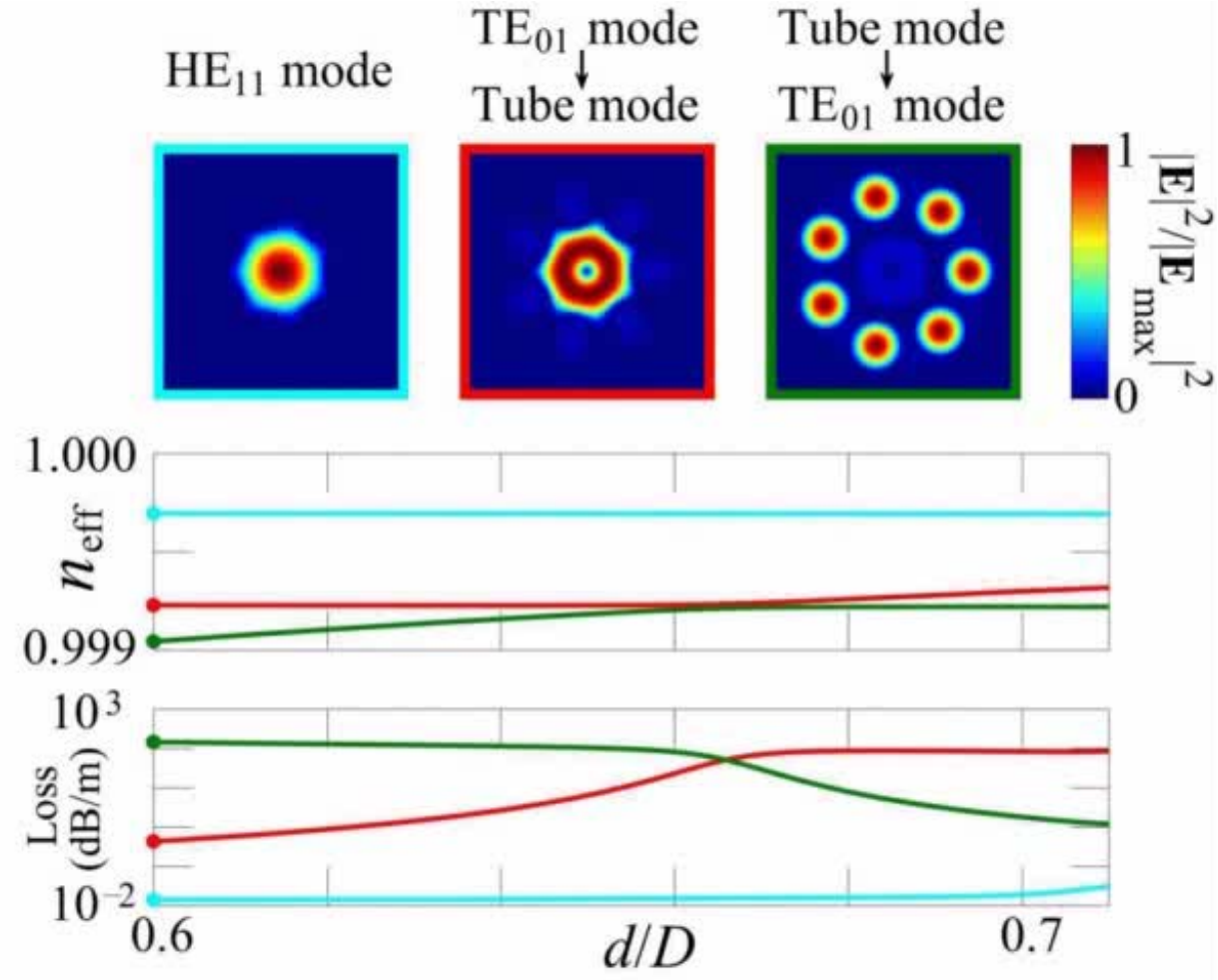


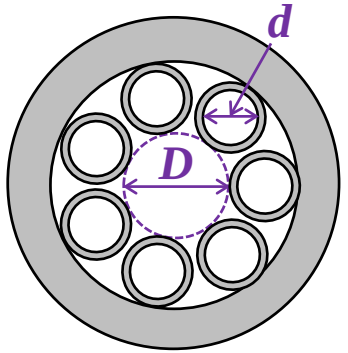
J. M. Fini *et. al*., Opt. Express **21**, 6233 (2013)
J. M. Fini *et. al*., Nat. Commun. **5**, 5085 (2014)

Use coupling to suppress higher-order core modes!

B. Debord *et al*., Opt. Express **21**, 28597 (2013).
M. S. Habib *et al*., Opt. Express **23**, 17394 (2015).
F. Poletti, Opt. Express **22**, 23807 (2014).
M. Michieletto *et al*., Opt. Express **24**, 7103 (2016).
C. Wei *et al*., Opt. Express **23**, 15824 (2015).
P. Uebel *et al*., Opt. Lett. **41**, 1961 (2016).

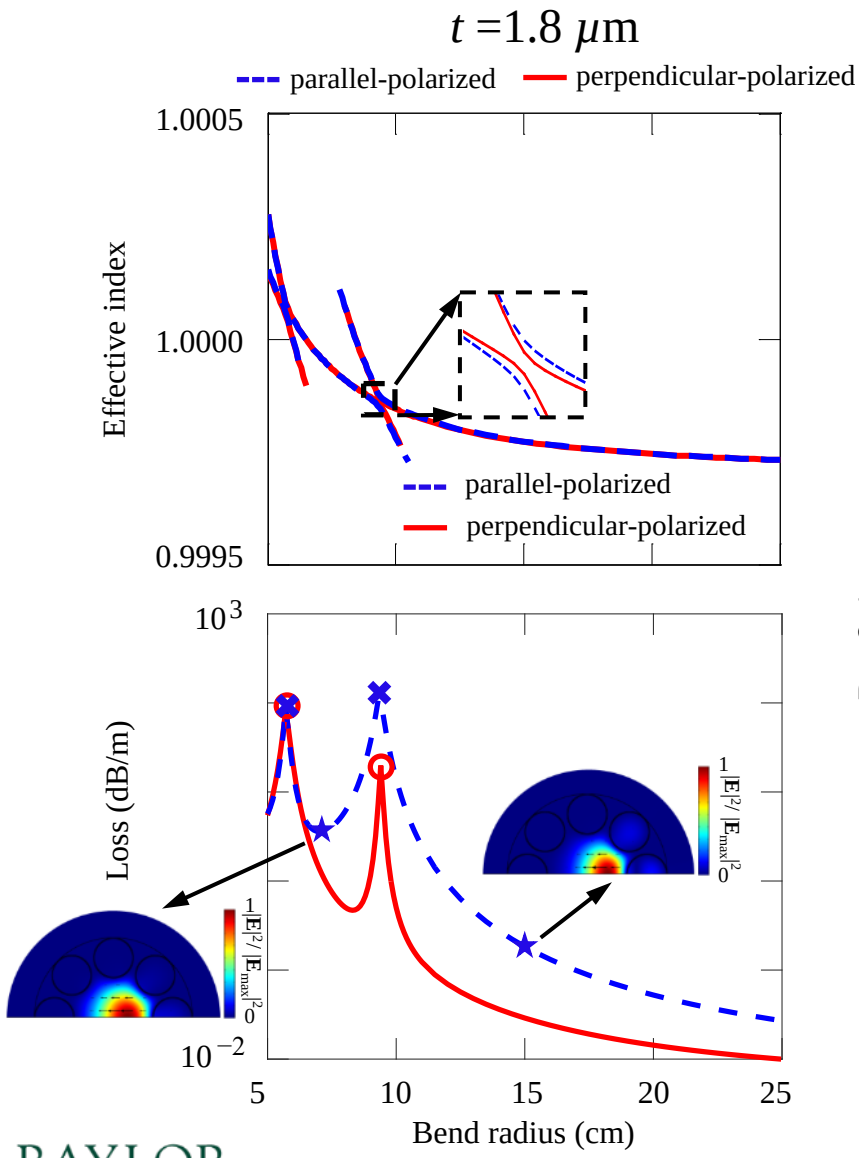
Higher-order mode suppression

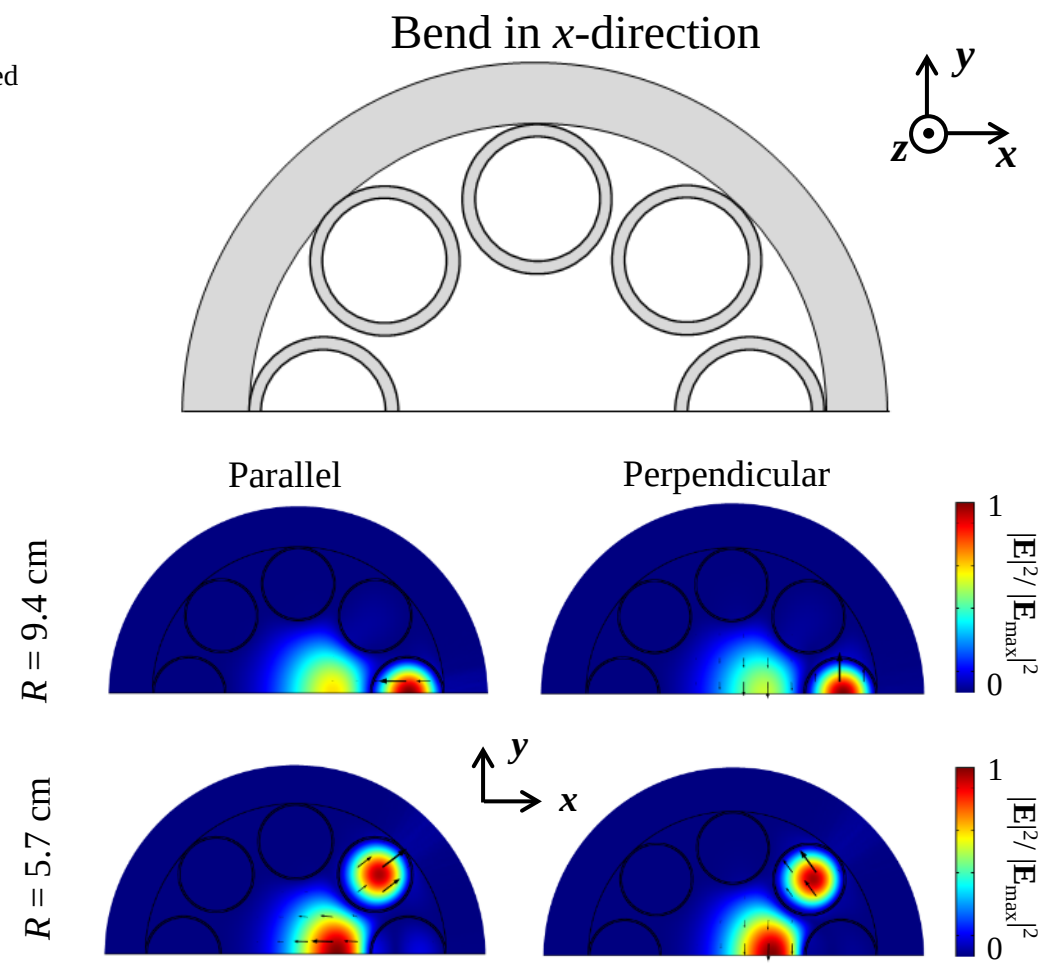




C. Wei *et al*., Opt. Express **23**, 15824 (2015).
P. Uebel *et al*., Opt. Lett. **41**, 1961 (2016).
M. Michieletto *et al*., Opt. Express **24**, 7103 (2016).
C. Wei *et al*., Adv. Opt. Photon. **9**, 504 (2017)

High loss peaks in bend fibers





- ✓ *Bend-loss peaks are induced by mode coupling*
- ✓ *Fibers with small tubes have lower bend loss*

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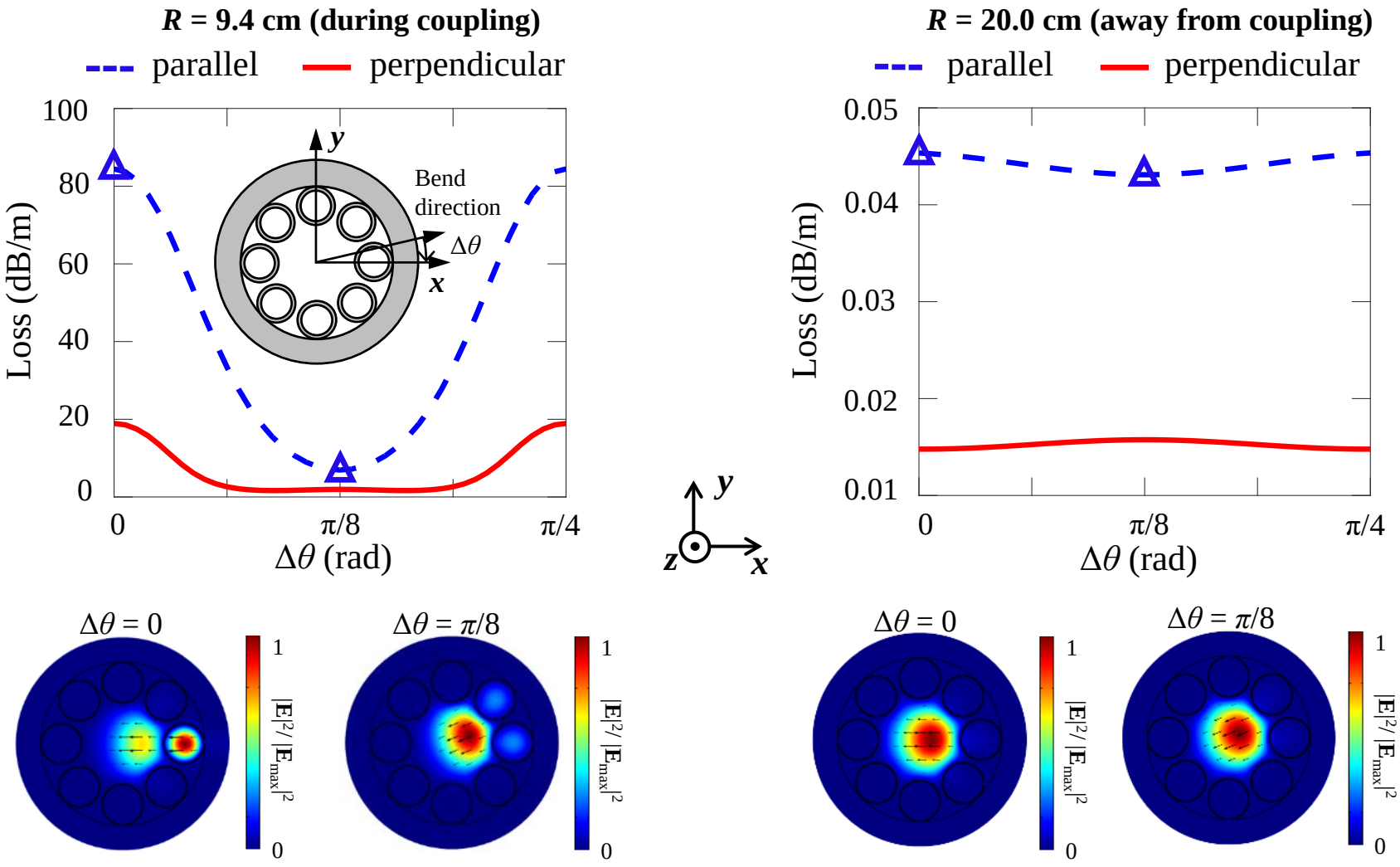
C. Wei *et al*., Opt. Express **24**, 12228 (2016).

W. Belardi *et al*., Opt. Express **22**, 10091 (2014).

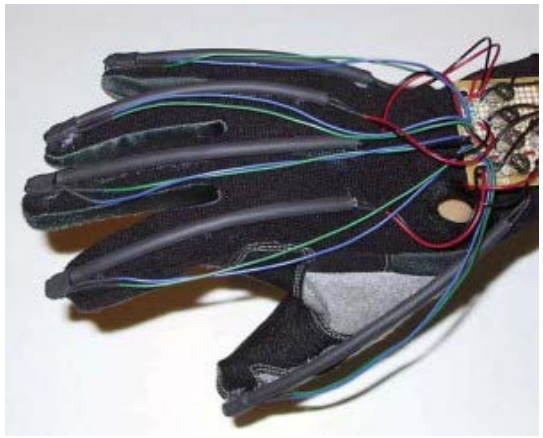
Different bend directions



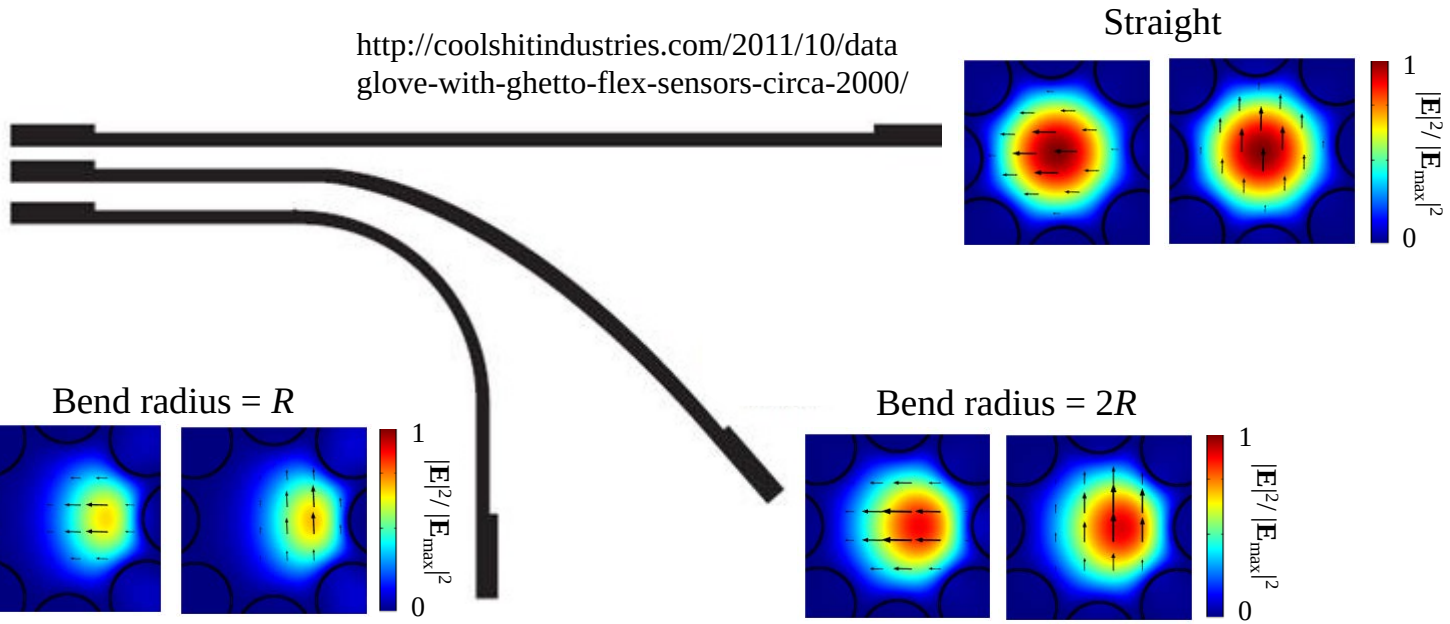
The bend loss changes by a maximum factor of 10 as the bend direction changes when coupling happens.

C. Wei *et al.*, Opt. Express **24**, 12228 (2016).

Bending sensors



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



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

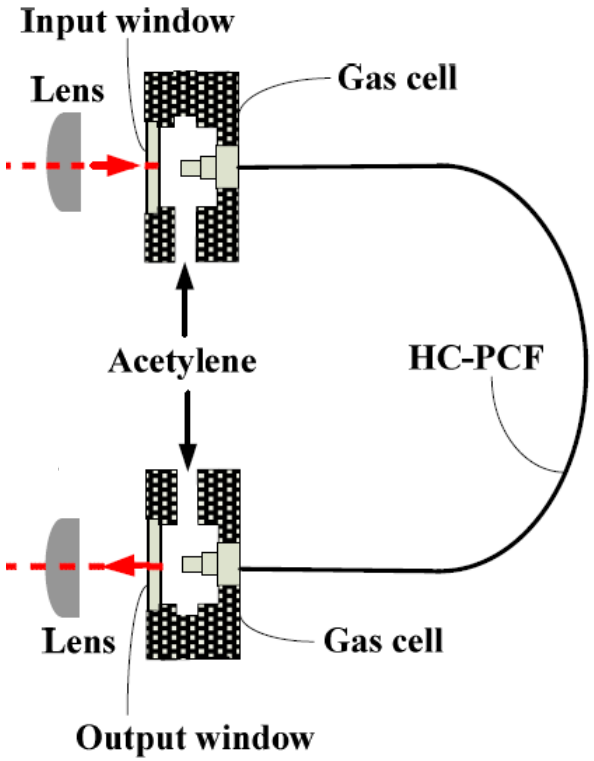
C. Wei *et al*., Opt. Express **24**, 12228 (2016).

R. Gao *et al*., Opt. Express **25**, 18081 (2017)

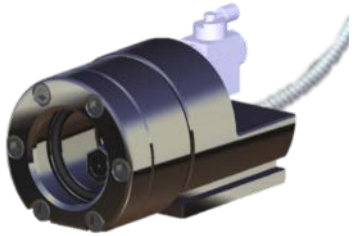
Outline

- ✓ Background
- ✓ Guiding mechanism
- ✓ Recent advances
- ✓ Applications
- ✓ Future prospects
- ✓ Summary

Mid-IR gas fiber lasers

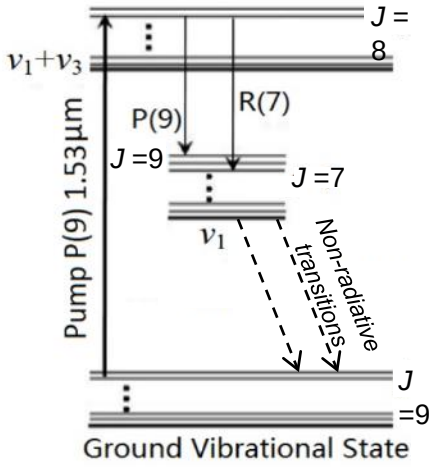


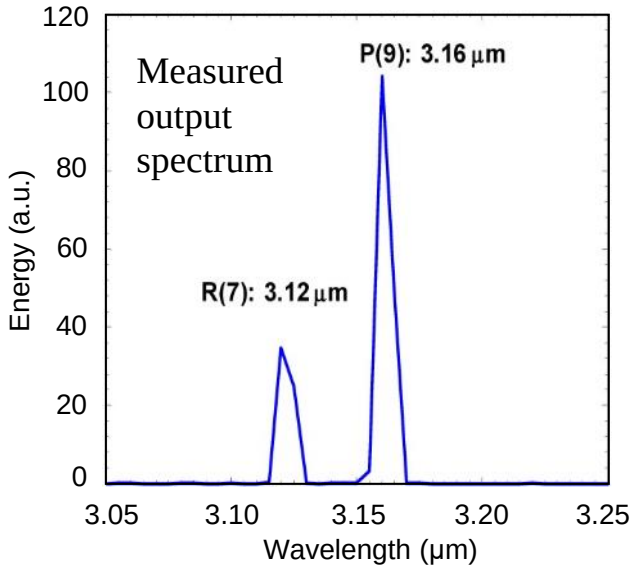
Gas cell



http://www.glophotonics.fr/index.php/product-2.html

Energy level diagram in acetylene

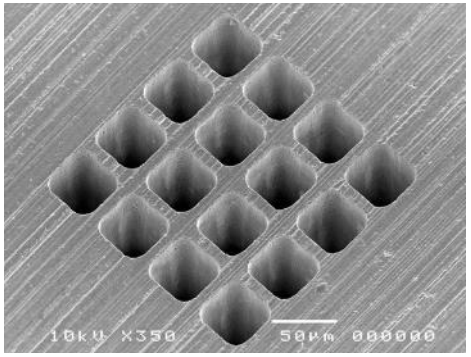




Z. Wang *et al.*, Opt. Express **22**, 21872 (2014).

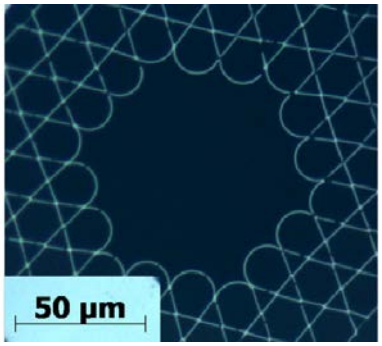
Micromaching

Micromaching



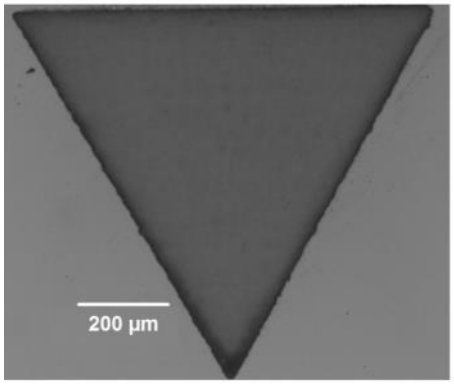
http://www.warsash.com.au/products/laser-systems/MICROMACHINING.php

Glass sheet engraving



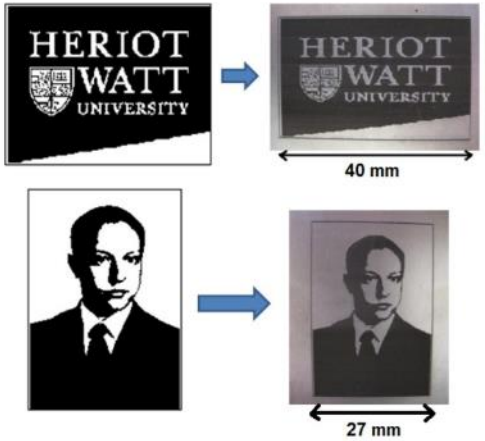
B. Debord *et al*., Opt. Express **22**, 10735 (2014).

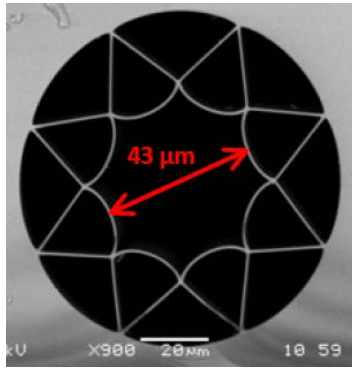
Micro-milled pattern in a fused silica



Cutting of aluminum sheet

Marking on a titanium

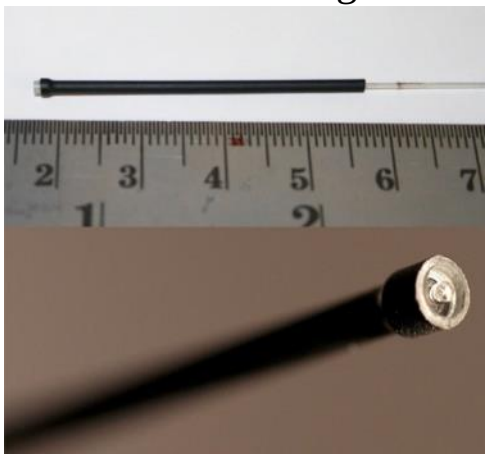




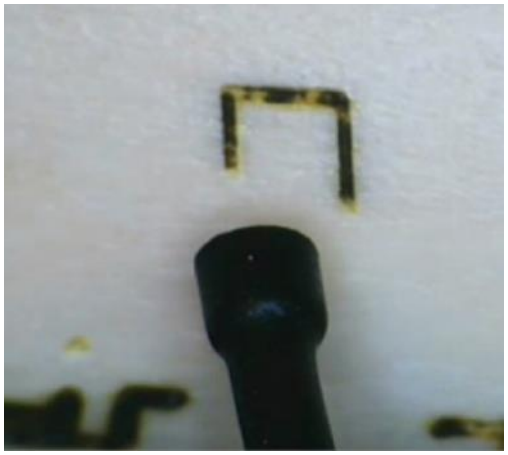
P. Jaworski *et al*., Opt. Express **21**, 22742 (2013).

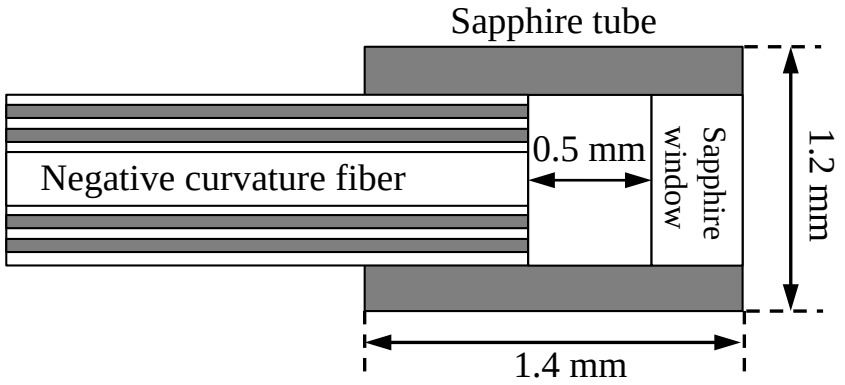
Surgical procedures

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



Ablation of ovine bone in air





A. Urich *et al.*, Biomed. Opt. Express **4**, 193–205 (2013).

Outline

- ✓ Background
- ✓ Antiresonant reflection and inhibited coupling
- ✓ Recent advances
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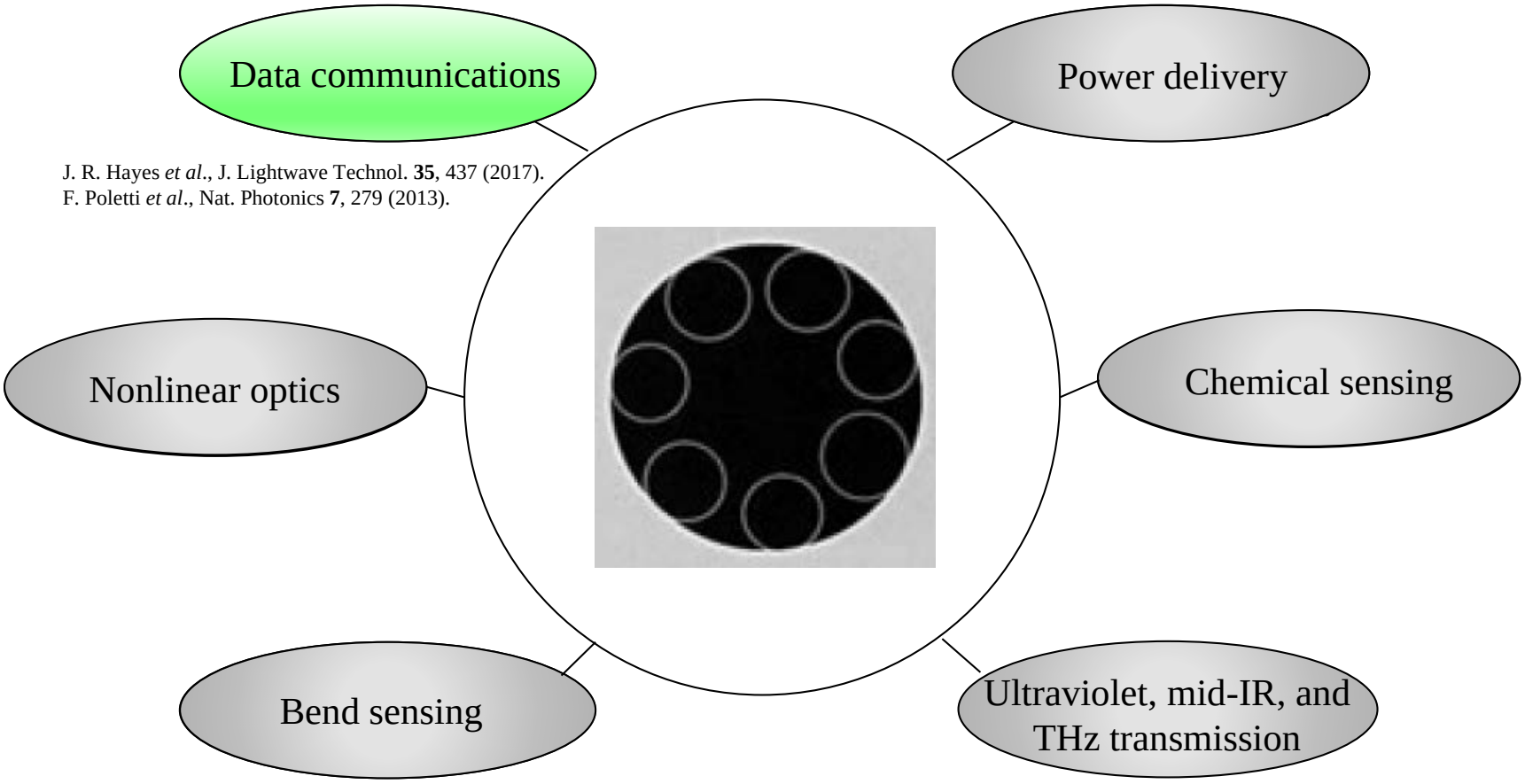
- ✓ Future prospects
- ✓ Summary

Future prospects



J. R. Hayes *et al*., J. Lightwave Technol. **35**, 437 (2017).
F. Poletti *et al*., Nat. Photonics **7**, 279 (2013).

Future prospects

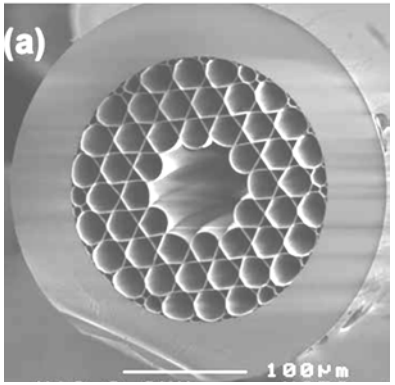
Data communications

J. R. Hayes *et al*., J. Lightwave Technol. **35**, 437 (2017).
F. Poletti *et al*., Nat. Photonics **7**, 279 (2013).

Power delivery

Y. Y. Wang *et al*., Opt. Lett. **37**, 3111 (2012).
P. Jaworski *et al*., Opt. Express **21**, 22742 (2013).
B. Debord *et al*., Opt. Express **22**, 10735 (2014).

Nonlinear optics



Chemical sensing

Bend sensing

Ultraviolet, mid-IR, and THz transmission

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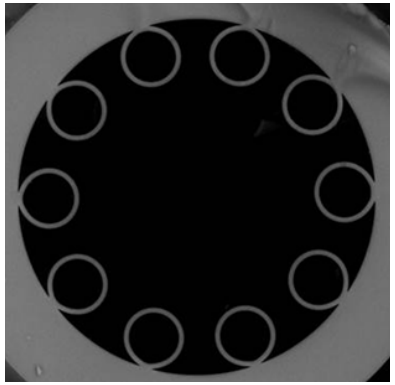
Y. Chen *et al*., Opt. Lett. **41**, 5118 (2016).



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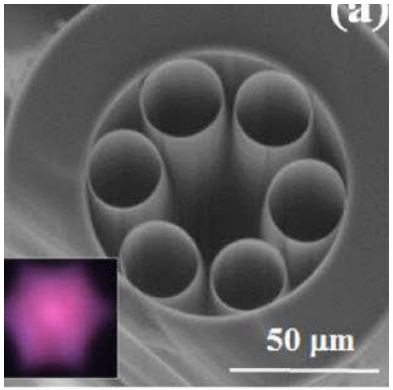

Chemical sensing

X. Liu *et al*., Opt. Lett. **42,** 863 (2017).
S. Ghosh *et al*., Phys. Rev. Lett. **94**, 093902 (2005).
N. Gayraud *et al*., Appl. Opt. **47**, 1269 (2008).

Bend sensing

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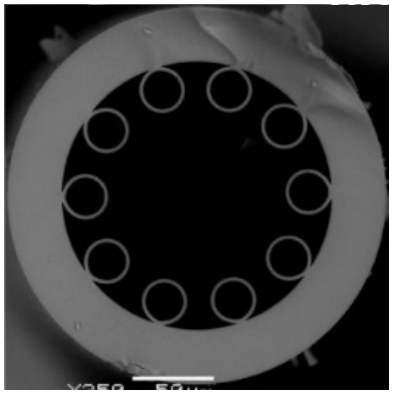

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Ultraviolet, mid-IR, and THz transmission

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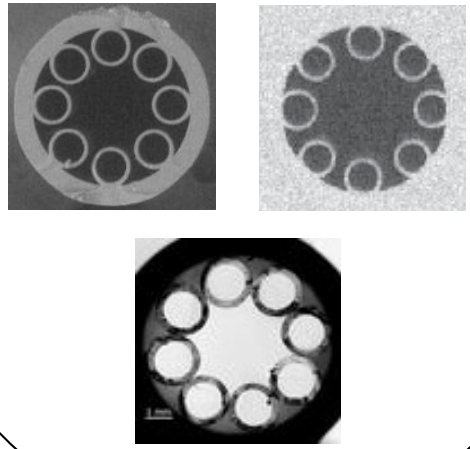

Chemical sensing

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S. Ghosh *et al*., Phys. Rev. Lett. **94**, 093902 (2005).
N. Gayraud *et al*., Appl. Opt. **47**, 1269 (2008).

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W. Belardi *et al*., Opt. Express **22**, 10091 (2014).
R. Gao *et al*., Opt. Express **25**, 18081 (2017)

Ultraviolet, mid-IR, and THz transmission

A. N. Kolyadin *et al*., Opt. Express **21,** 9514 (2013).
A. D. Pryamikov *et al*., Quantum Electron. **46**, 1129 (2016).
V. Setti *et al*., Opt. Express **21**, 3388 (2013).

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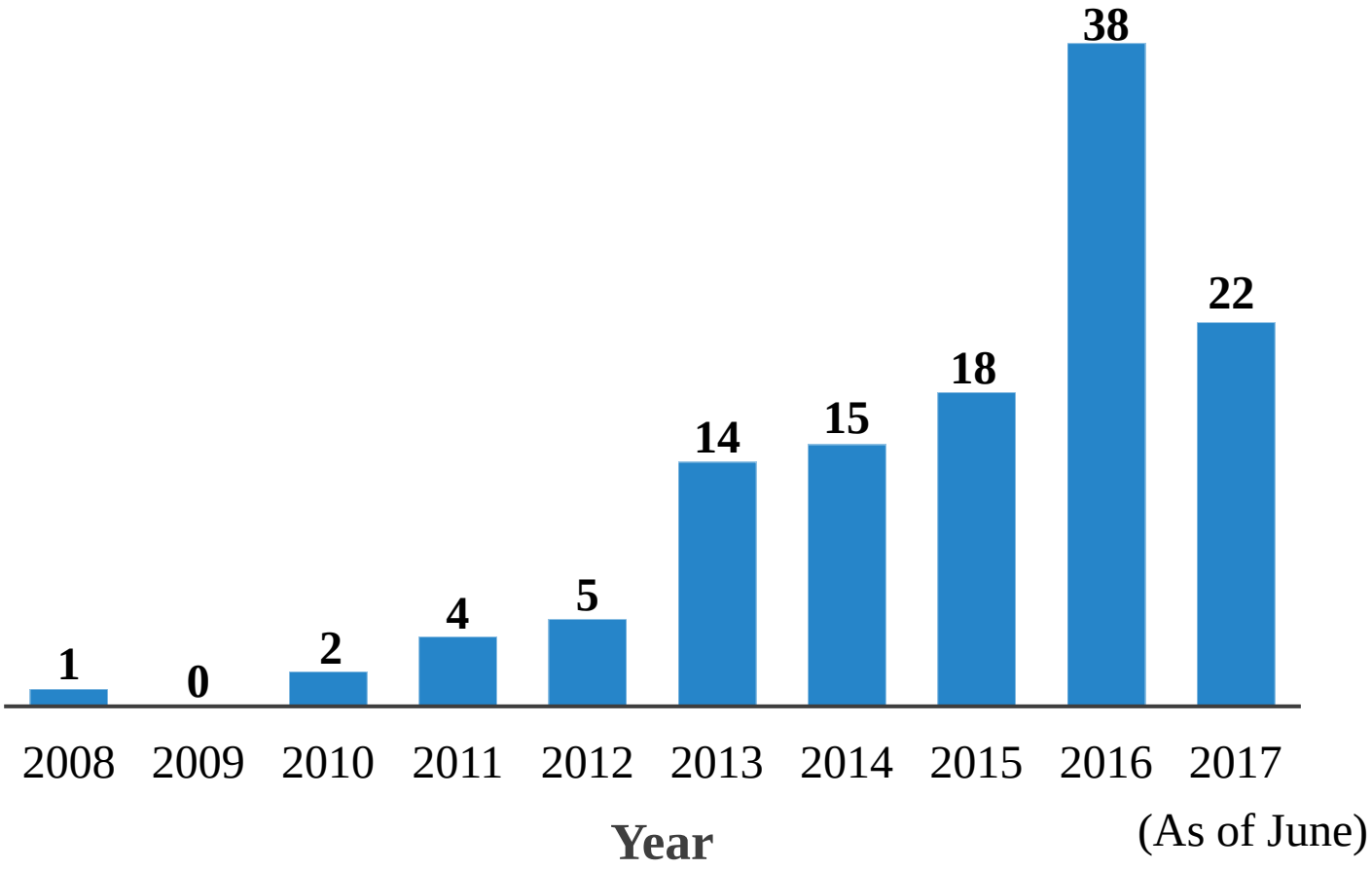
Number of journal publications



Number of journal publications related to hollow-core fibers that use a negative curvature inner core boundary.

C. Wei *et al*., Adv. Opt. Photon. **9**, 504 (2017)

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,

C. Wei *et. al*., Adv. Opt. Photon. **9**, 504–561 (2017).

Thank you!