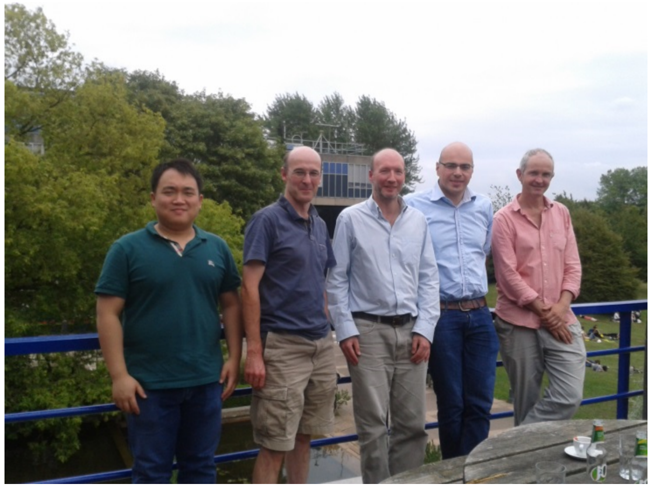
Thank you…




SHETLAND ISLANDS
Lerwick
Kirkwall
Scrabster
Stornoway
Isle of Skye
Invergordon
Peterhead
Portree
Atlantic Ocean
Fort William
Tobermory
Dundee
Staffa
Iona
Oban
Rosyth
Greenock
Leith
Edinburgh
Glasgow
S Queensferry
North Sea
SCOTLAND
Newcastle-upon-Tyne
Londonderry
NORTHERN IRELAND
Belfast
Barrow-in-Furness
Douglas
Liverpool
Dublin
Holyhead
IRELAND
ENGLAND
Waterford
Dunmore East
Cork
Cobh
Harwich
WALES
Milford Haven
Newport
London
Tilbury
Tower Bridge
Greenwich
Dover
Lundy Island
Southampton
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Portsmouth
Plymouth
Portland
English Channel
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CHANNEL ISLANDS
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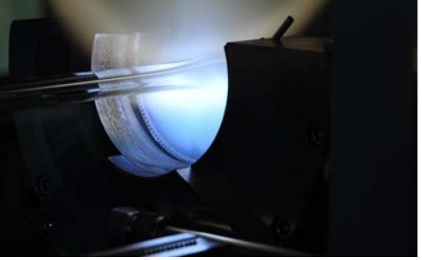


Hollow core Optical Fibers: a brief history and future perspectives

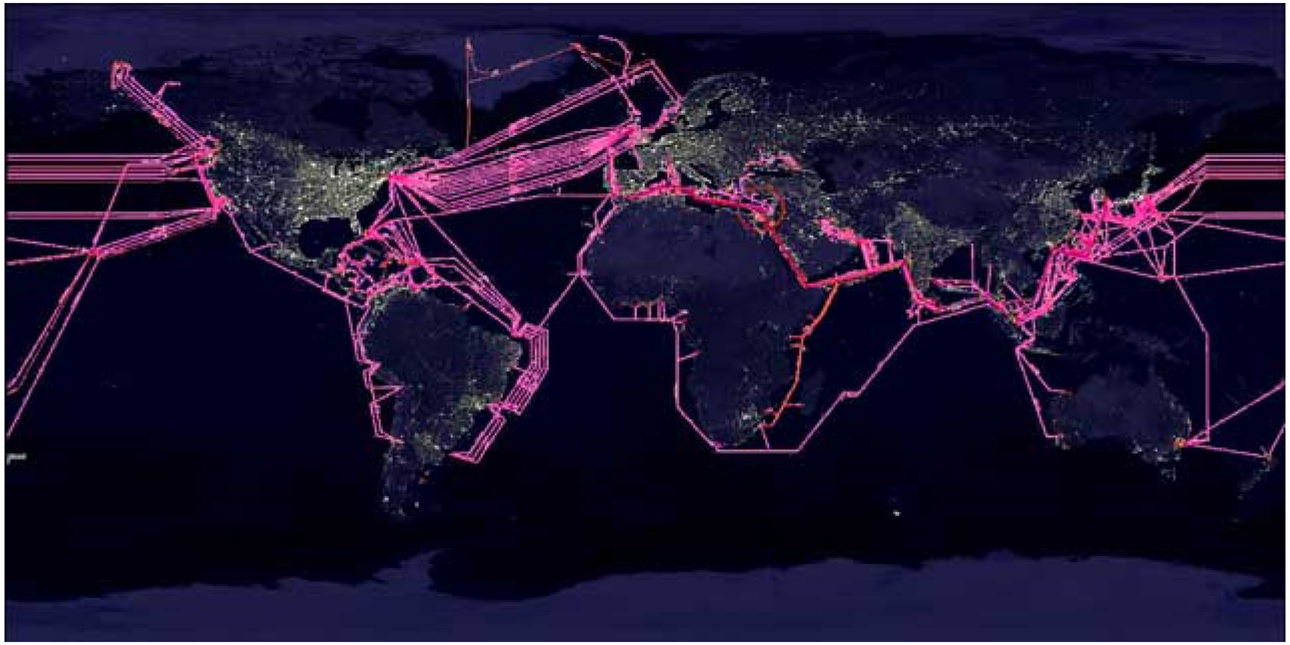
Walter Belardi

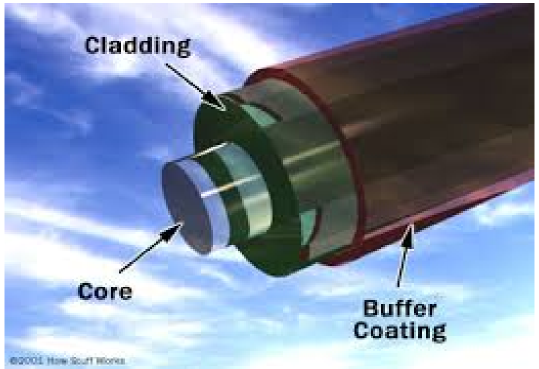
Optoelectronics Research Centre
University of Southampton, UK

University, of Pavia 10th March 2016, Pavia

University
of Southampton

Global optical fibre network





200 million km
produced every year

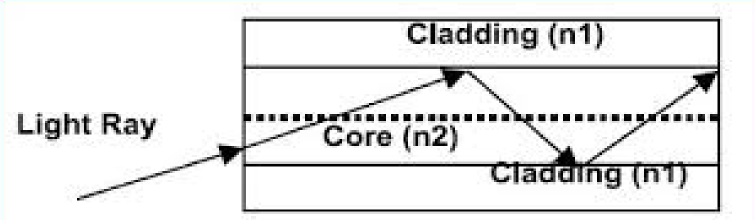
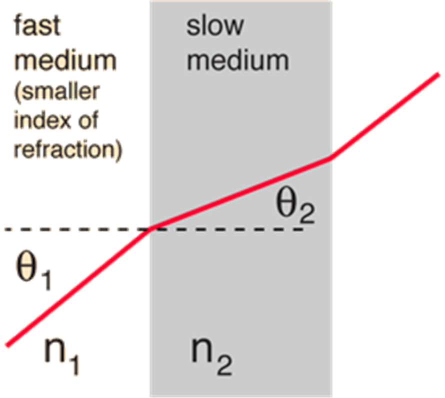
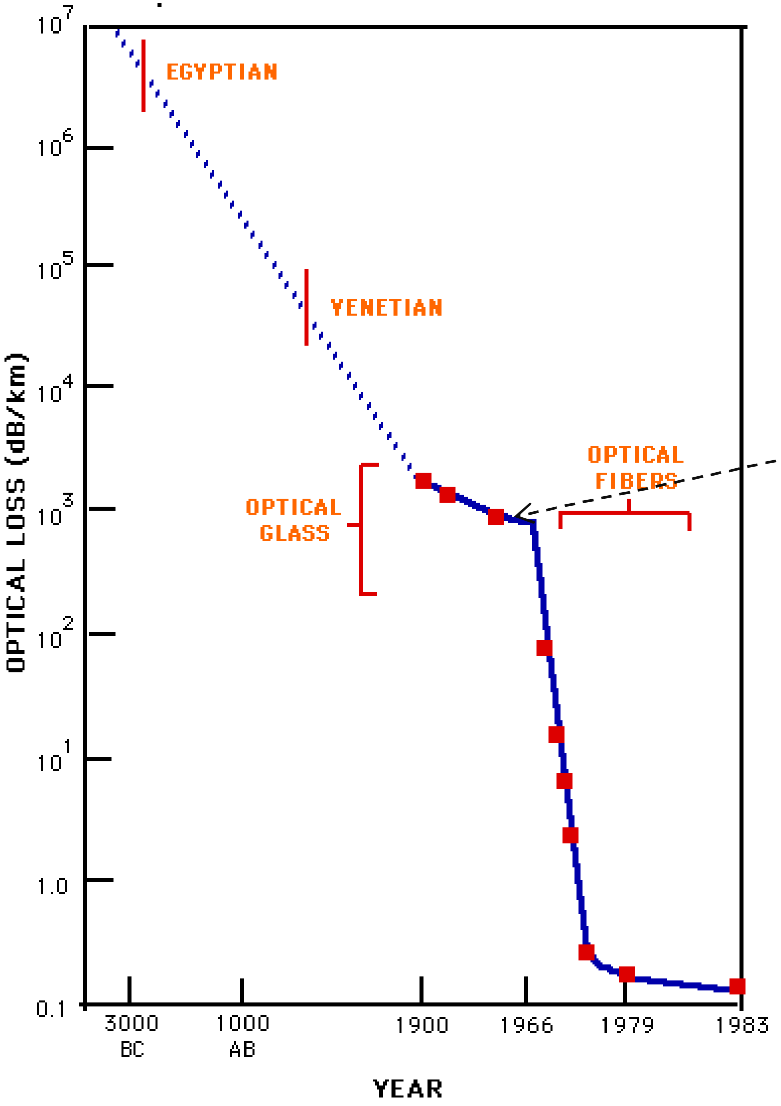


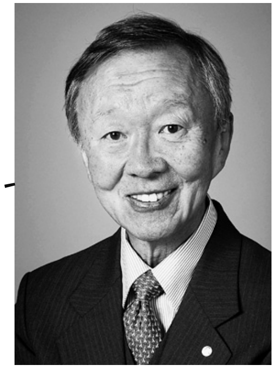
Figure 1: Light launched into the fiber core

Snell's Law

$$\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1}$$

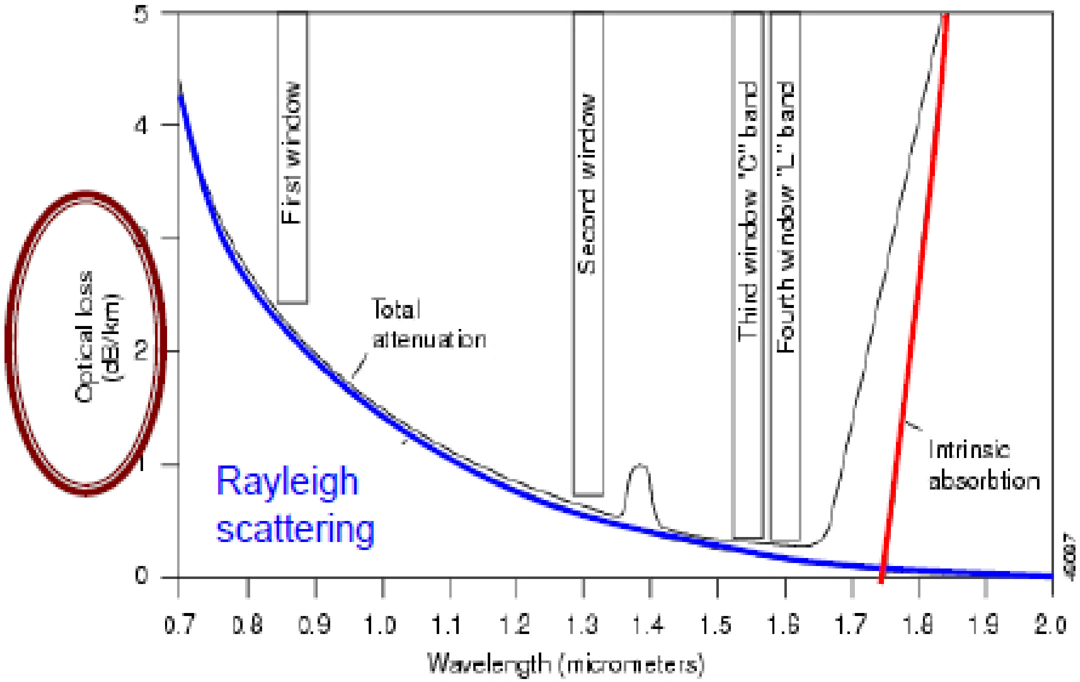


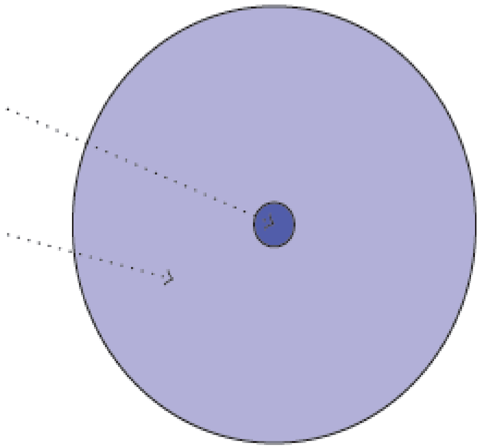


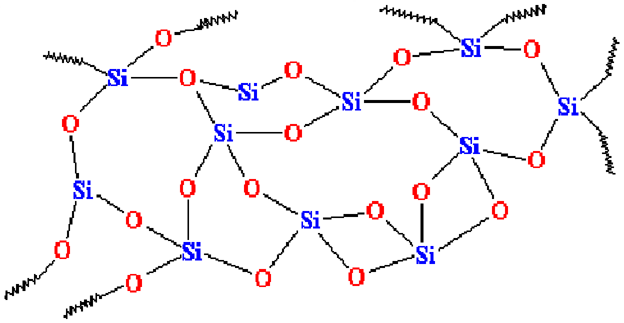


Charles KAO
Nobel Prize in Physics
2009

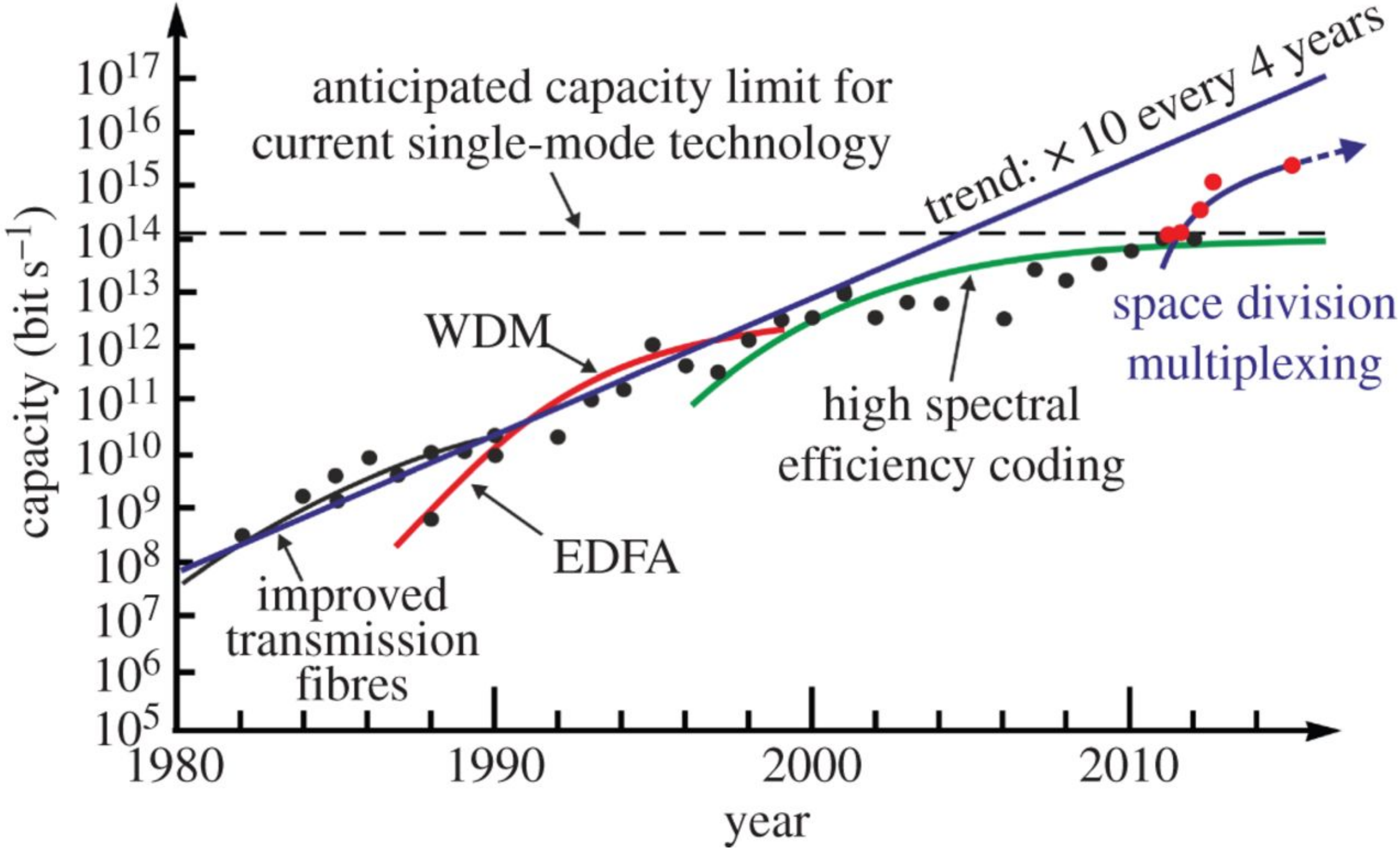
Transparency of fused silica





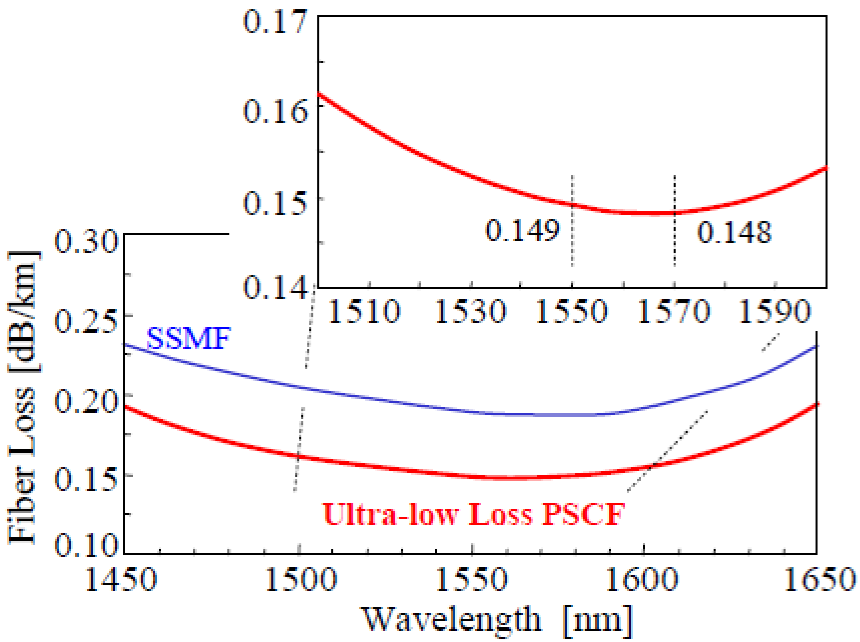


Capacity Crunch

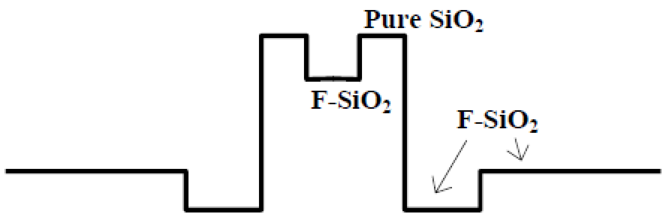


The dream of beating telecom fibres !!

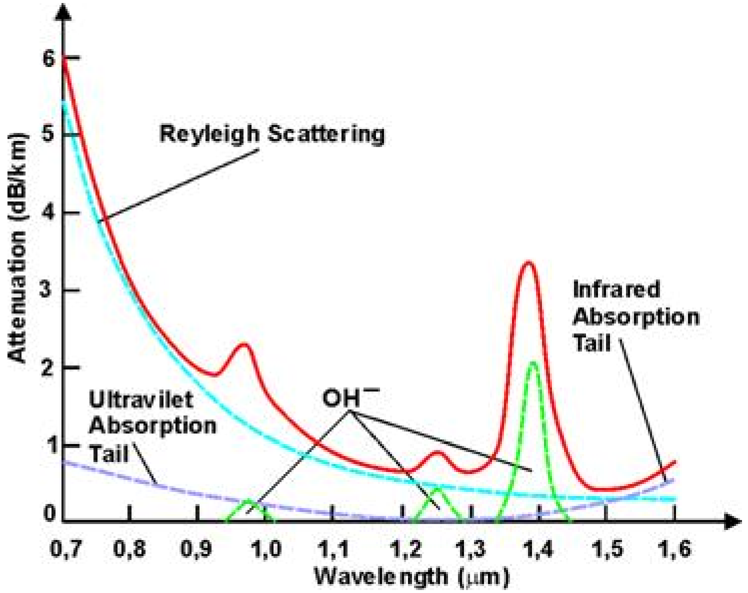
Telecom Fibres today



	Aeff [µm^2]	Fiber Loss [dB/km]	Dispersion [ps/nm/km]	Disp. Slope [ps/nm^2/km]
PSCF	135	0.149	21.0	0.061

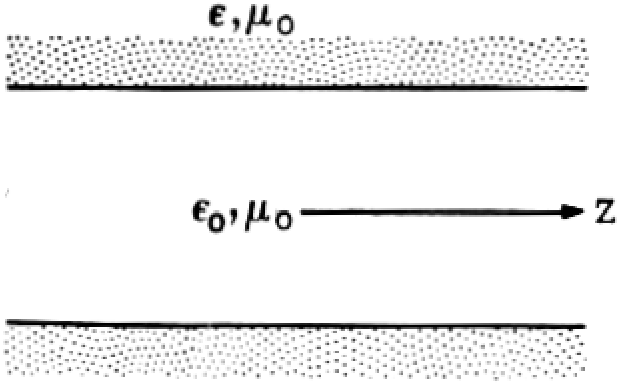


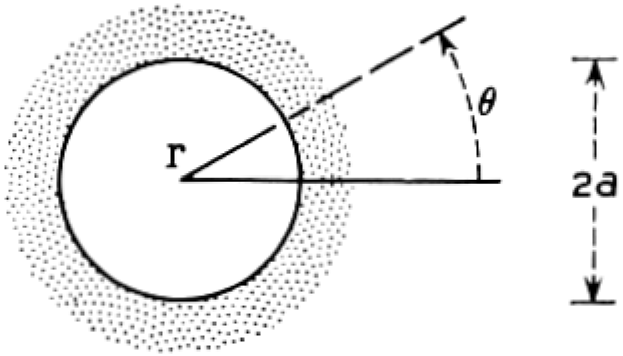
Limit of attenuation of silica glass

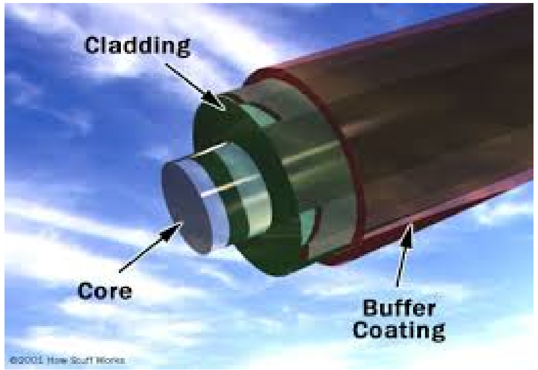


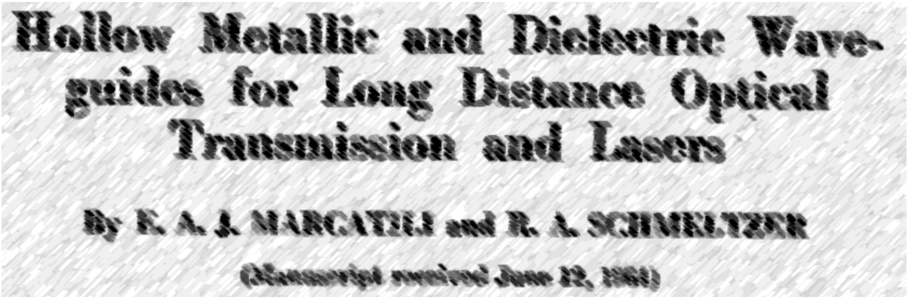
M. Hirano et al.,"Record Low Loss, Record High FOM Optical Fiber with Manufacturable Process", OFC 2013 postdeadline

Hollow fibres (1964)







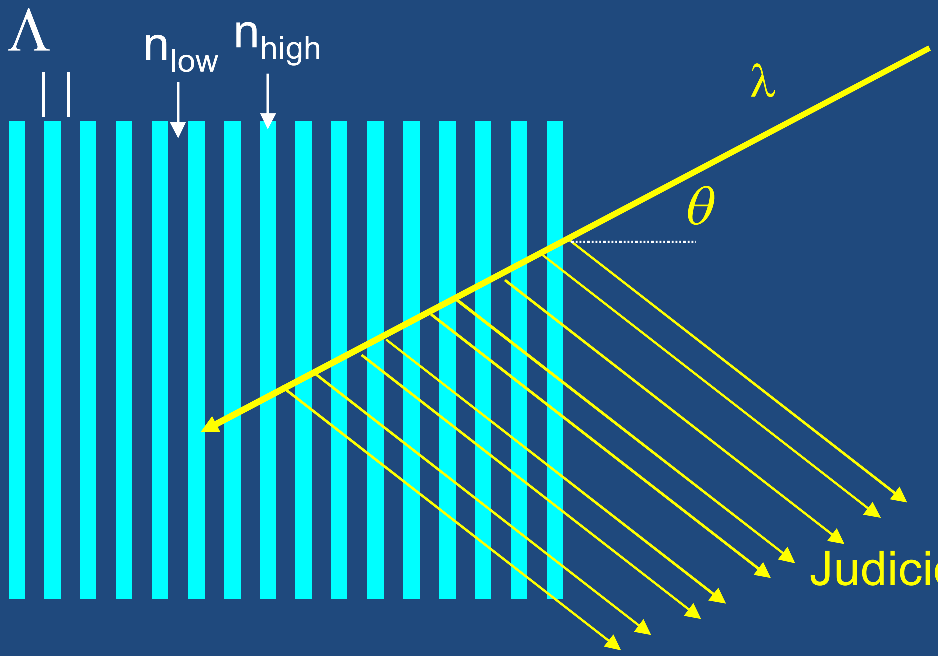

Hollow Metallic and Dielectric Waveguides for Long Distance Optical Transmission and Lasers

By E. A. J. MARCATILI and R. A. SCHMELTZER

(Manuscript received June 12, 1963)


THE BELL SYSTEM TECHNICAL JOURNAL, JULY 1964

Bragg Law



Bragg law

(1st order)

$$\lambda = 2\Lambda \sin\theta$$

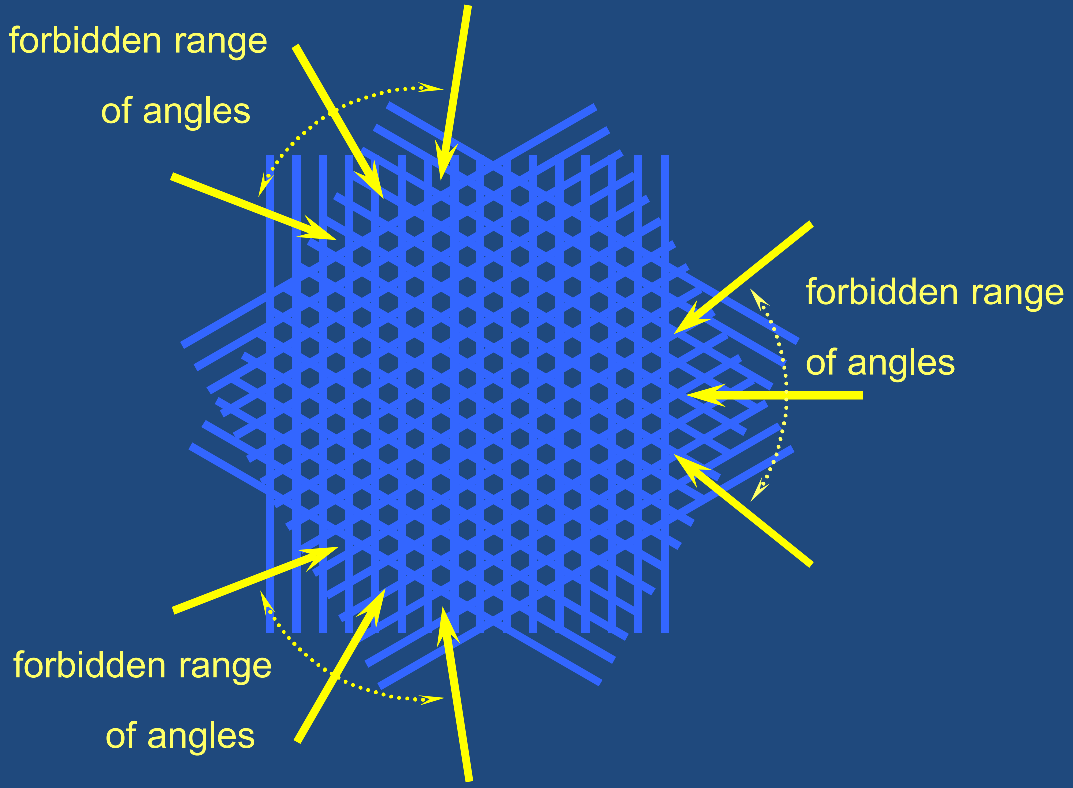
Judicious choice of n_{low}, n_{high} and Λ

Constructive interference

$\Downarrow$

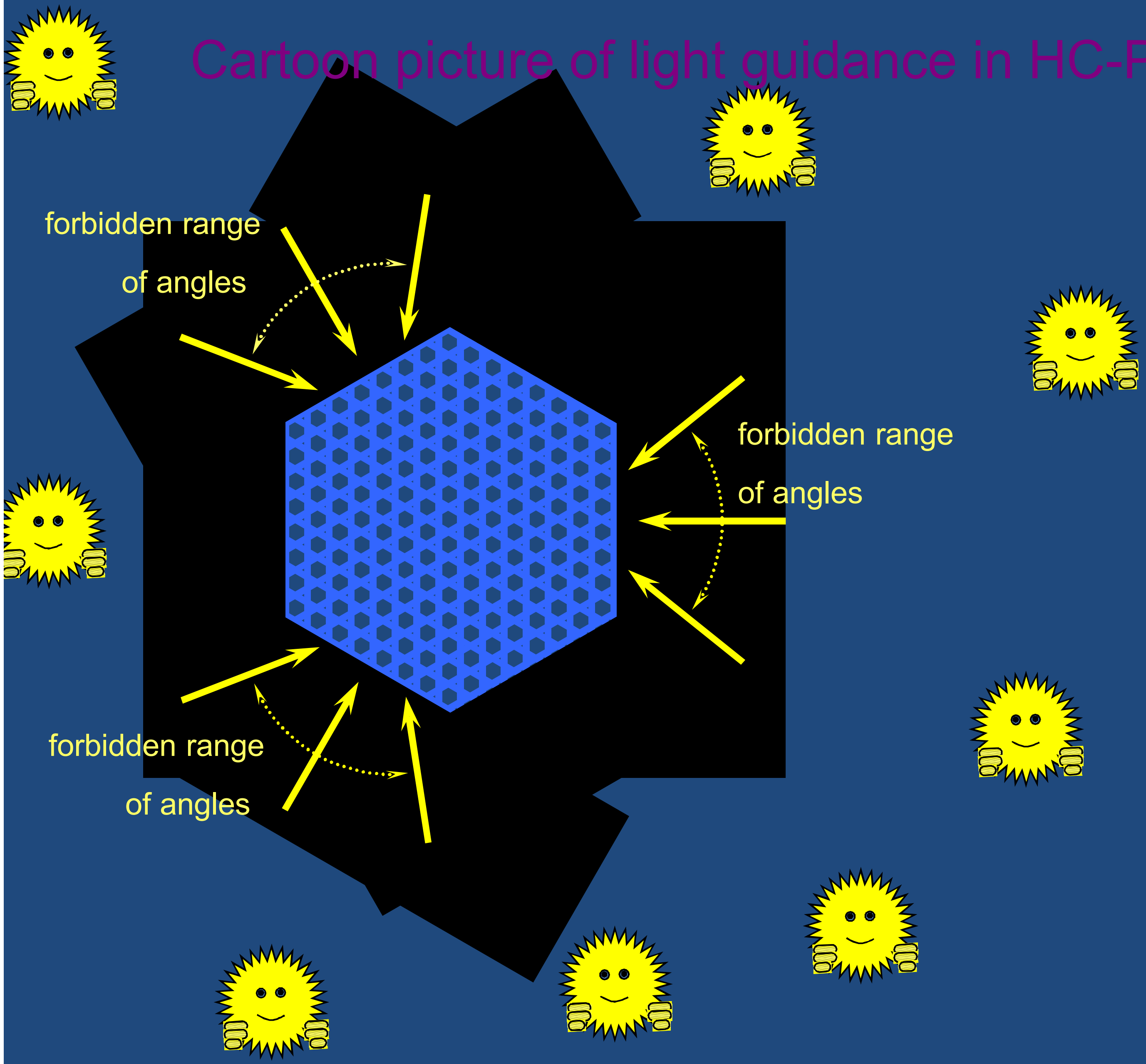
Total reflection for $\Delta\lambda$ centred around λ

From F. Benabid



From F. Benabid

Cartoon picture of light guidance in HC-PCF



forbidden range

of angles

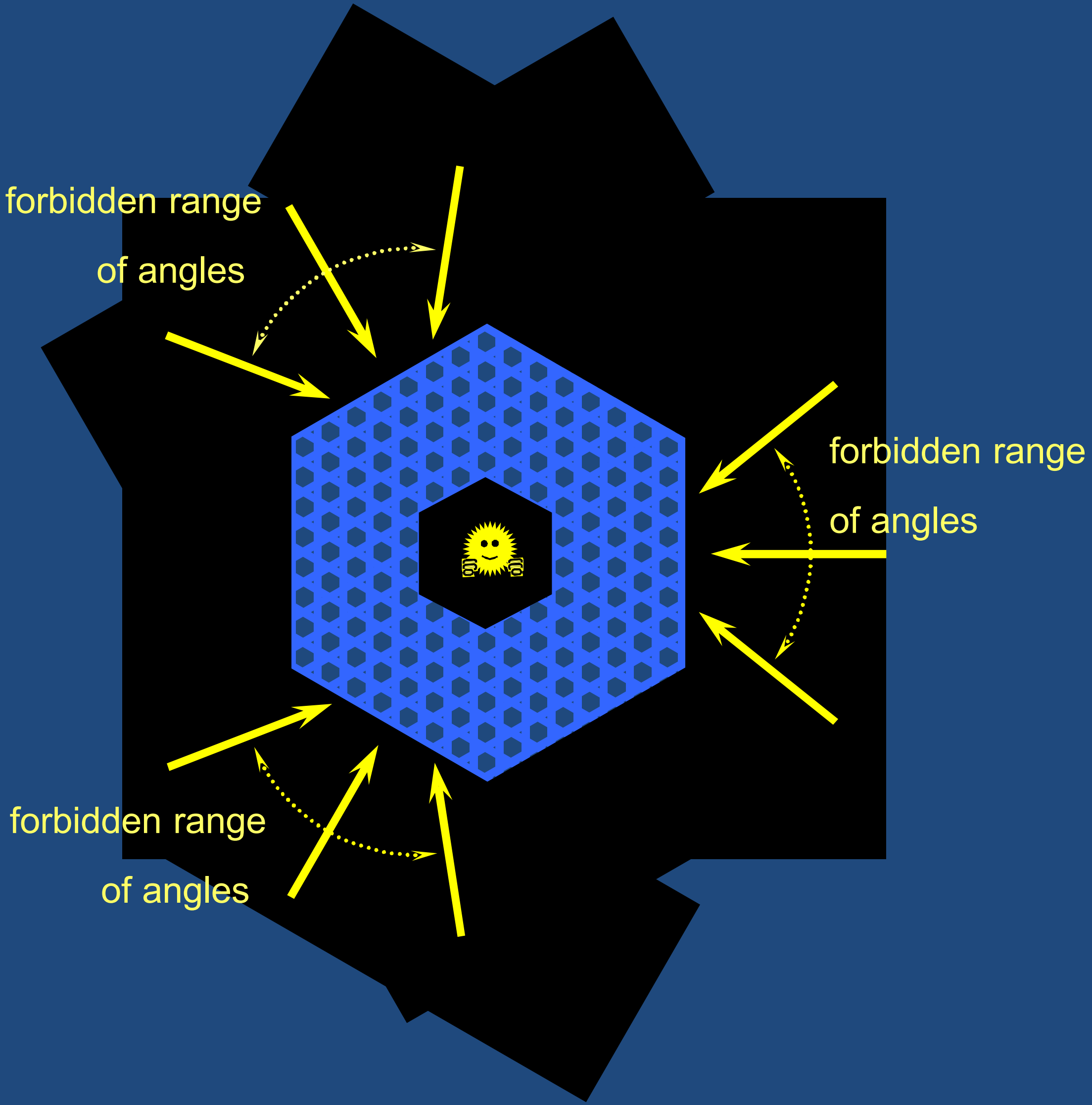
forbidden range

of angles

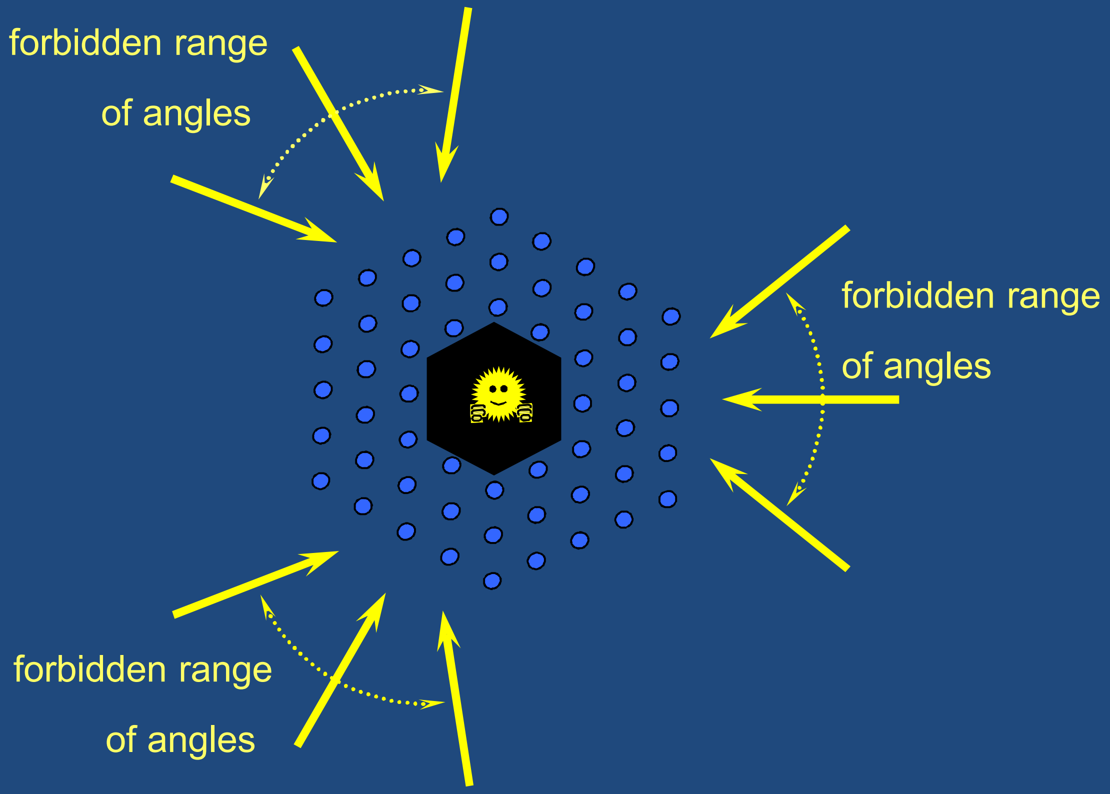
forbidden range

of angles

From F. Benabid



From F. Benabid

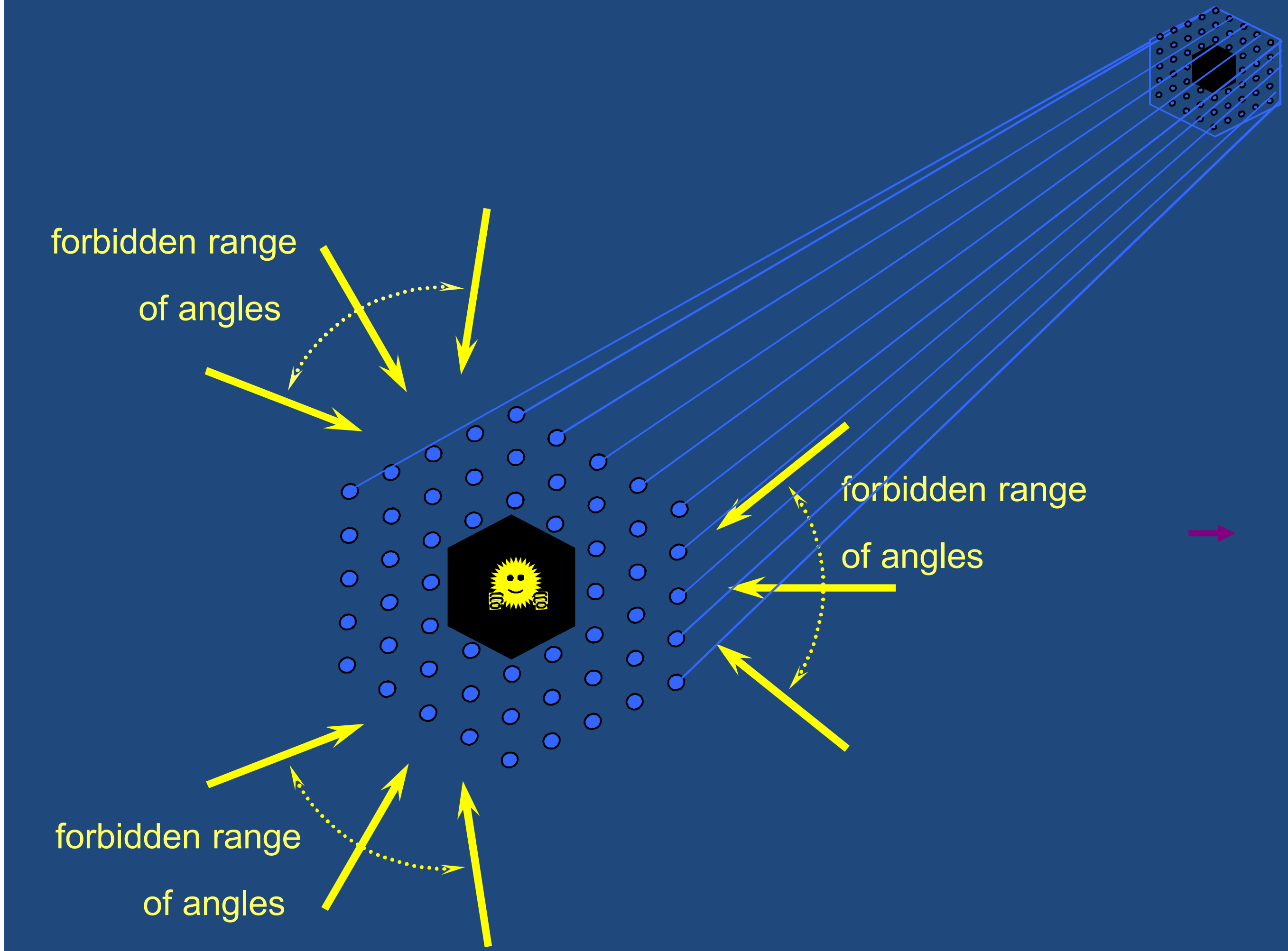


forbidden range
of angles

forbidden range
of angles

forbidden range
of angles

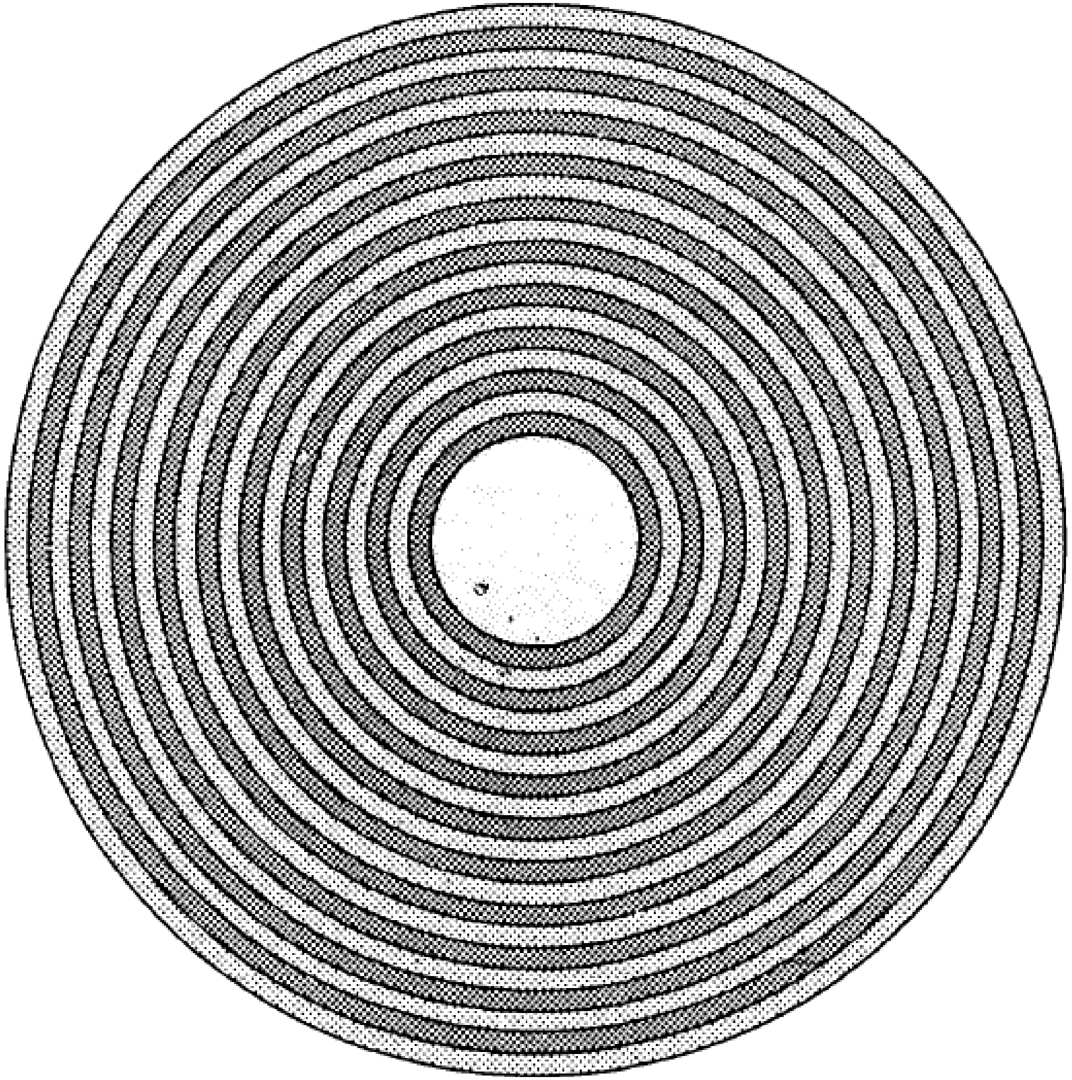
From F. Benabid



From F. Benabid

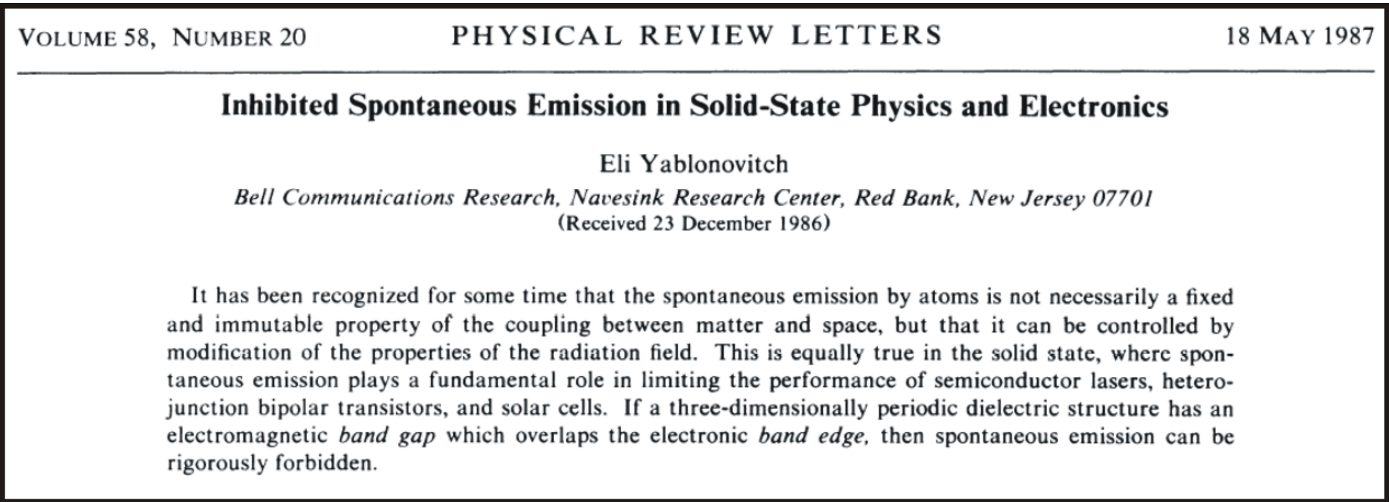
The concept of Bragg Fiber (1978)

$$n(r) = \begin{cases} n_g, & 0 \le r < r_1 \\ n_2, & r_1 \le r < r_2 \\ n_1, & r_2 \le r < r_3 \\ n_2, & r_3 \le r < r_4 \\ n_1, & r_4 \le r < r_5 \\ \vdots & \vdots \\ & \text{etc.} \end{cases}$$



Pochi Yeh, Amnon Yariv, and Emanuel Marom, "Theory of Bragg fiber," J. Opt. Soc. Am. **68**, 1196-1201 (1978)

The photonic crystal concept (1987)



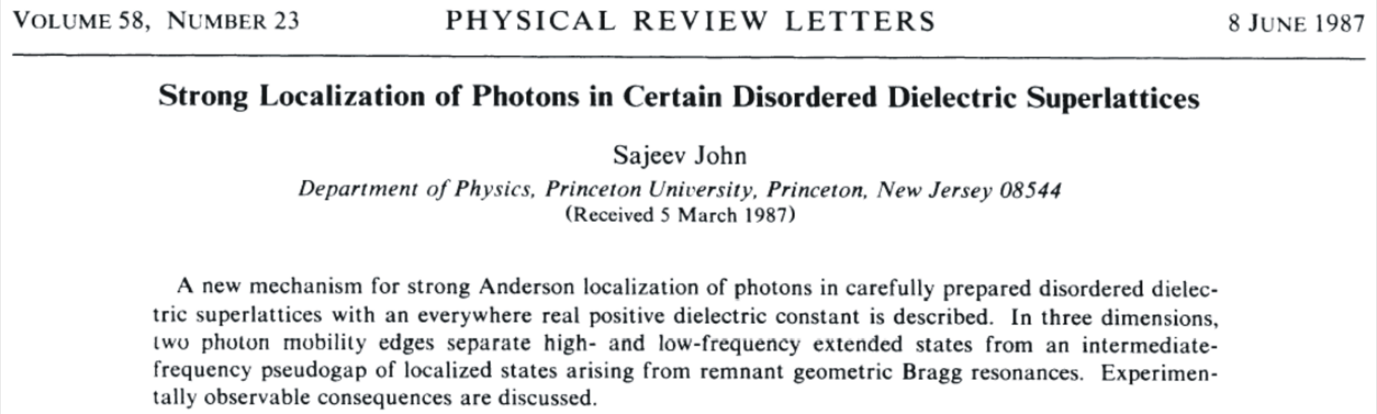
VOLUME 58, NUMBER 20 PHYSICAL REVIEW LETTERS 18 MAY 1987

Inhibited Spontaneous Emission in Solid-State Physics and Electronics

Eli Yablonovitch
Bell Communications Research, Navesink Research Center, Red Bank, New Jersey 07701

(Received 23 December 1986)

It has been recognized for some time that the spontaneous emission by atoms is not necessarily a fixed and immutable property of the coupling between matter and space, but that it can be controlled by modification of the properties of the radiation field. This is equally true in the solid state, where spontaneous emission plays a fundamental role in limiting the performance of semiconductor lasers, heterojunction bipolar transistors, and solar cells. If a three-dimensionally periodic dielectric structure has an electromagnetic *band gap* which overlaps the electronic *band edge*, then spontaneous emission can be rigorously forbidden.



VOLUME 58, NUMBER 23 PHYSICAL REVIEW LETTERS 8 JUNE 1987

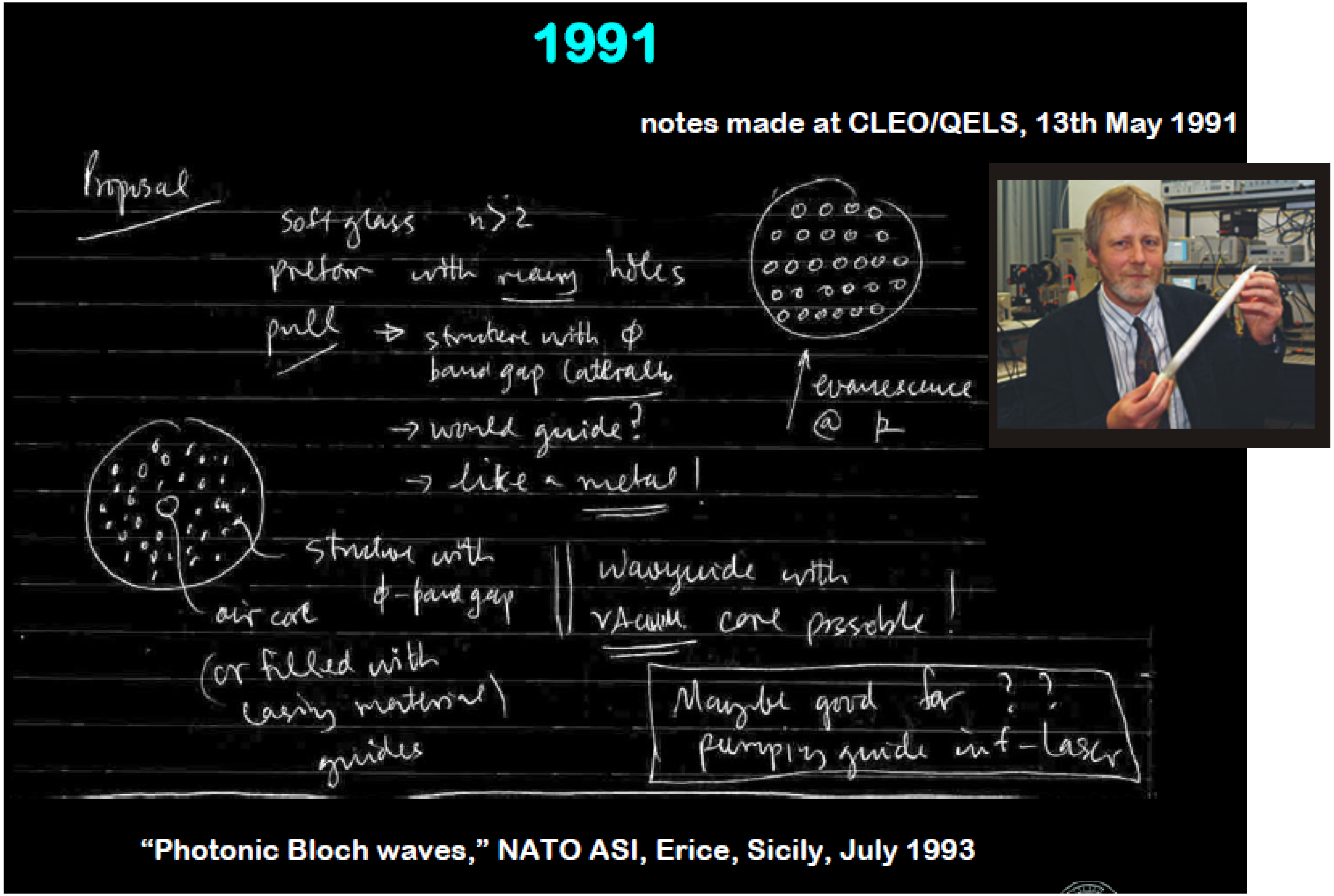
Strong Localization of Photons in Certain Disordered Dielectric Superlattices

Sajeev John
Department of Physics, Princeton University, Princeton, New Jersey 08544

(Received 5 March 1987)

A new mechanism for strong Anderson localization of photons in carefully prepared disordered dielectric superlattices with an everywhere real positive dielectric constant is described. In three dimensions, two photon mobility edges separate high- and low-frequency extended states from an intermediate-frequency pseudogap of localized states arising from remnant geometric Bragg resonances. Experimentally observable consequences are discussed.

The photonic crystal FIBRE concept



1991

notes made at CLEO/QELS, 13th May 1991

Proposal

soft glass $n>2$
preform with many holes
pull → structure with ϕ band gap laterally
→ would guide?
→ like a metal!

evanescence @ p

structure with ϕ-band gap

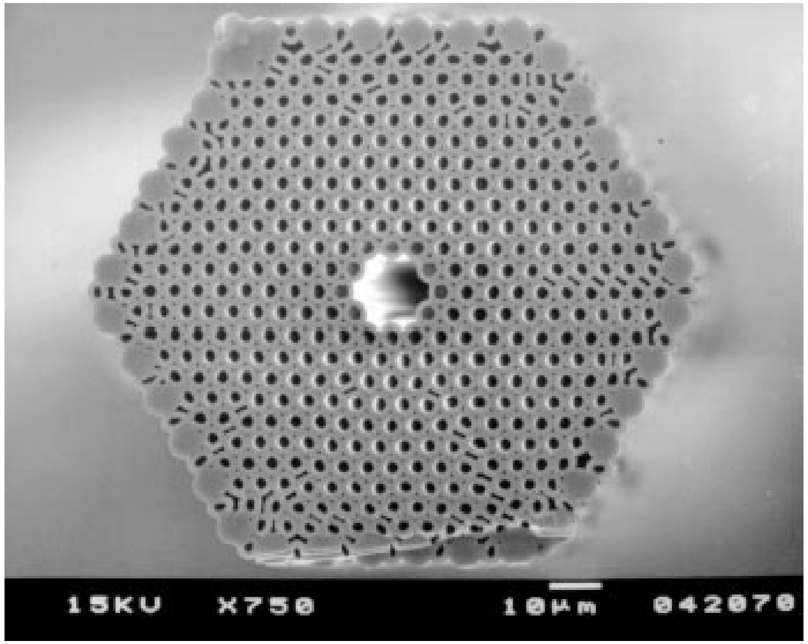
air core
(or filled with lasing material)
guides

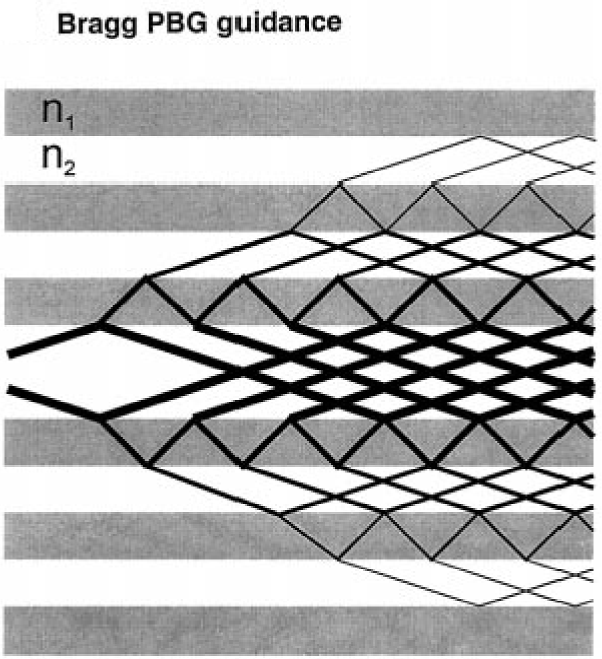
waveguide with vacuum core possible!

Maybe good for ? ?
pumping guide in f-laser

"Photonic Bloch waves," NATO ASI, Erice, Sicily, July 1993

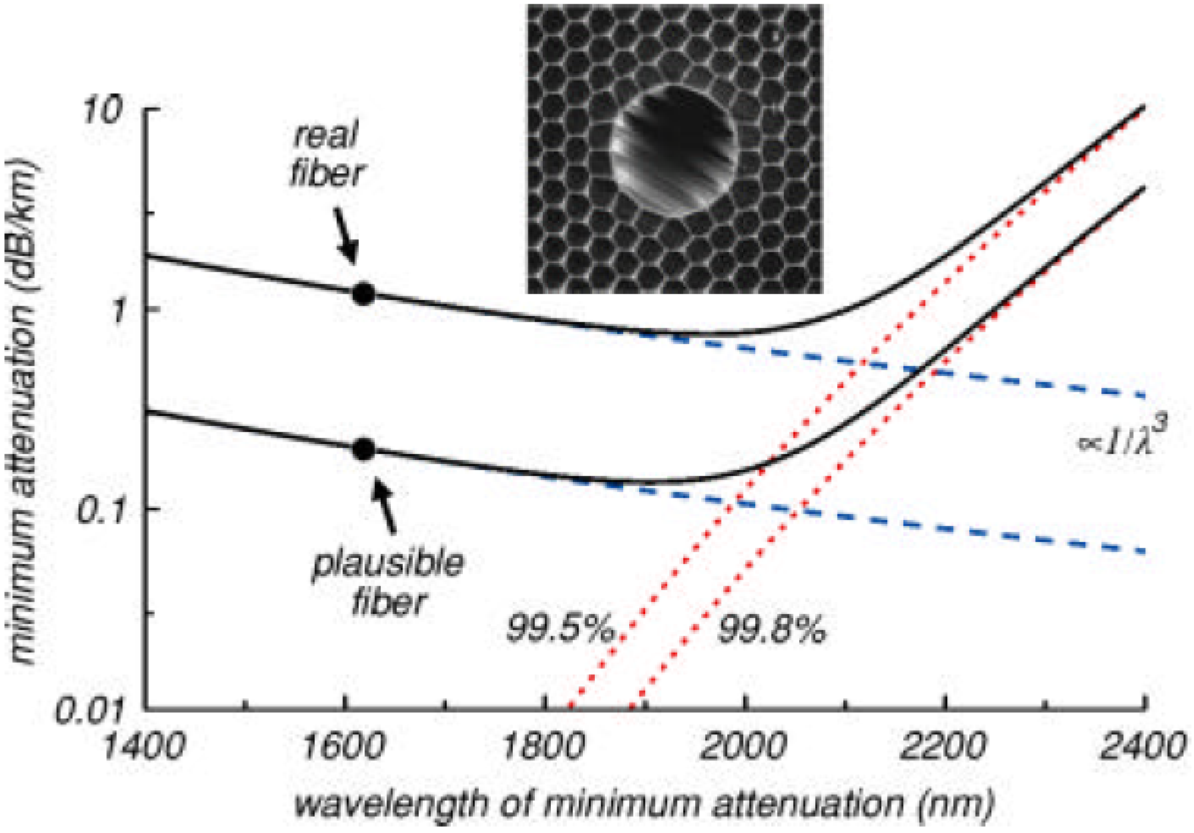
Photonic bandgap fibre (1999)





R. F. Cregan et al.," Single-Mode Photonic Band Gap Guidance of Light in Air"
Science 285, 1537 (1999)

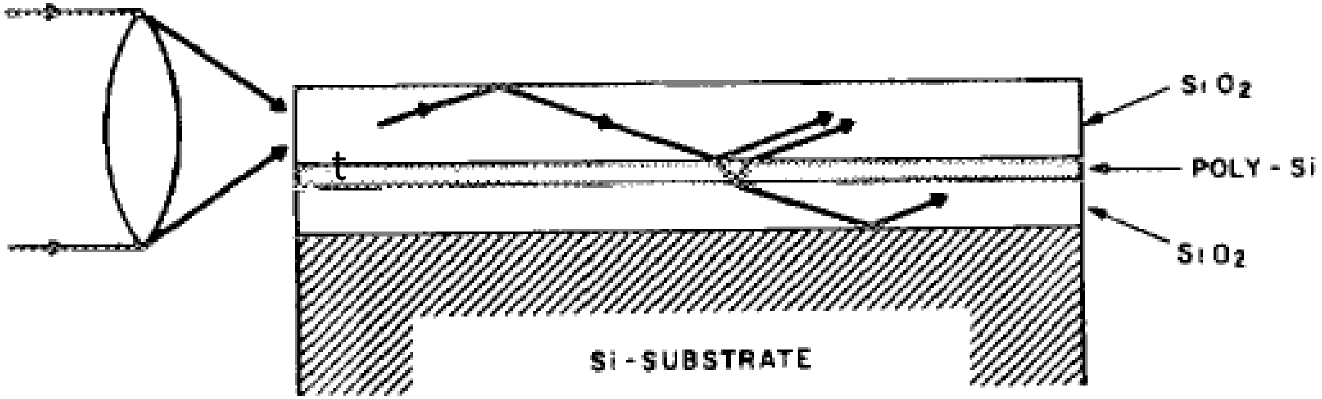
Ultimate Loss of Photonic Crystal Fibre (2005)



P. J. Roberts et al., "Ultimate low loss of hollow-core photonic crystal fibres,"
Opt. Express **13**, 236-244 (2005)

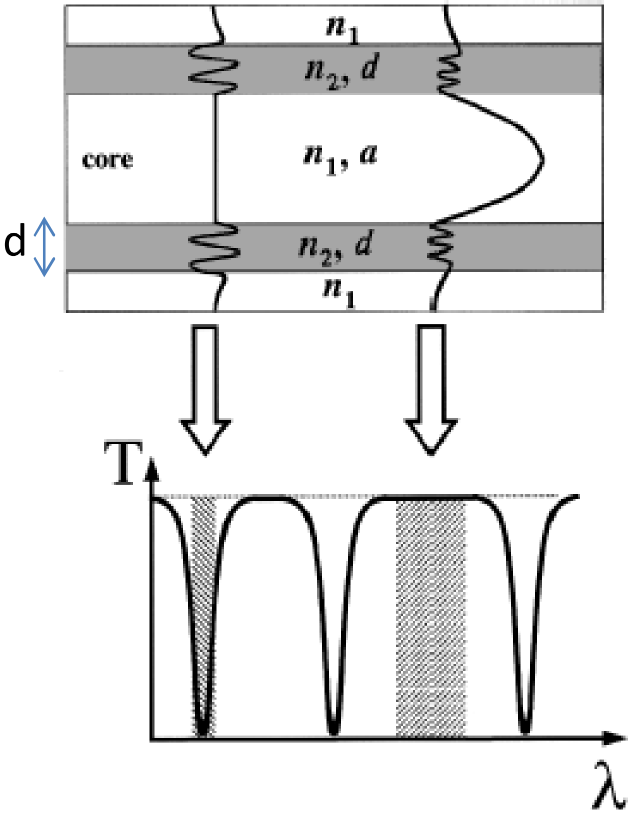
The antiresonance concept (1986)

$$t \simeq \frac{\lambda}{4n_2}(2N+1)\left(1-\frac{n_1^2}{n_2^2}+\frac{\lambda^2}{4n_2^2\, d_1^2}\right)^{-1/2} \quad N=0,1,2,\ldots$$



M. A. Duguay et al, “Antiresonant reflecting optical waveguides in Si02-Si multilayer structures”, Appl. Phys. Lett. 49, 13 (**1986**)

Antiresonance



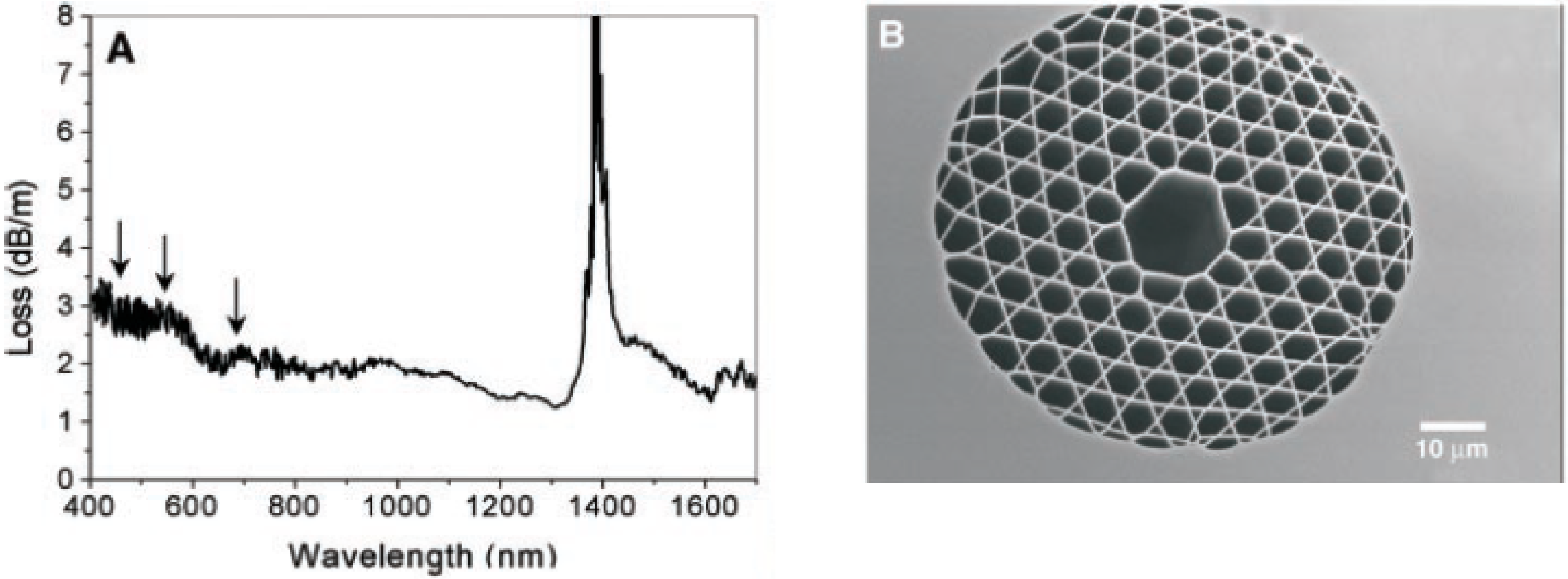
- Light guidance in a hollow core fiber can be achieved through an antiresonance phenomenon

- The wavelengths that are not in resonance with the core wall are reflected back into the core and propagate with low loss as a result of destructive interference in the Fabry-Perot resonator.

$$\lambda_l = \frac{4n_1 d}{(2l + 1)}[(n_2/n_1)^2 - 1]^{1/2}, \quad l = 0, 1, 2, \ldots .$$

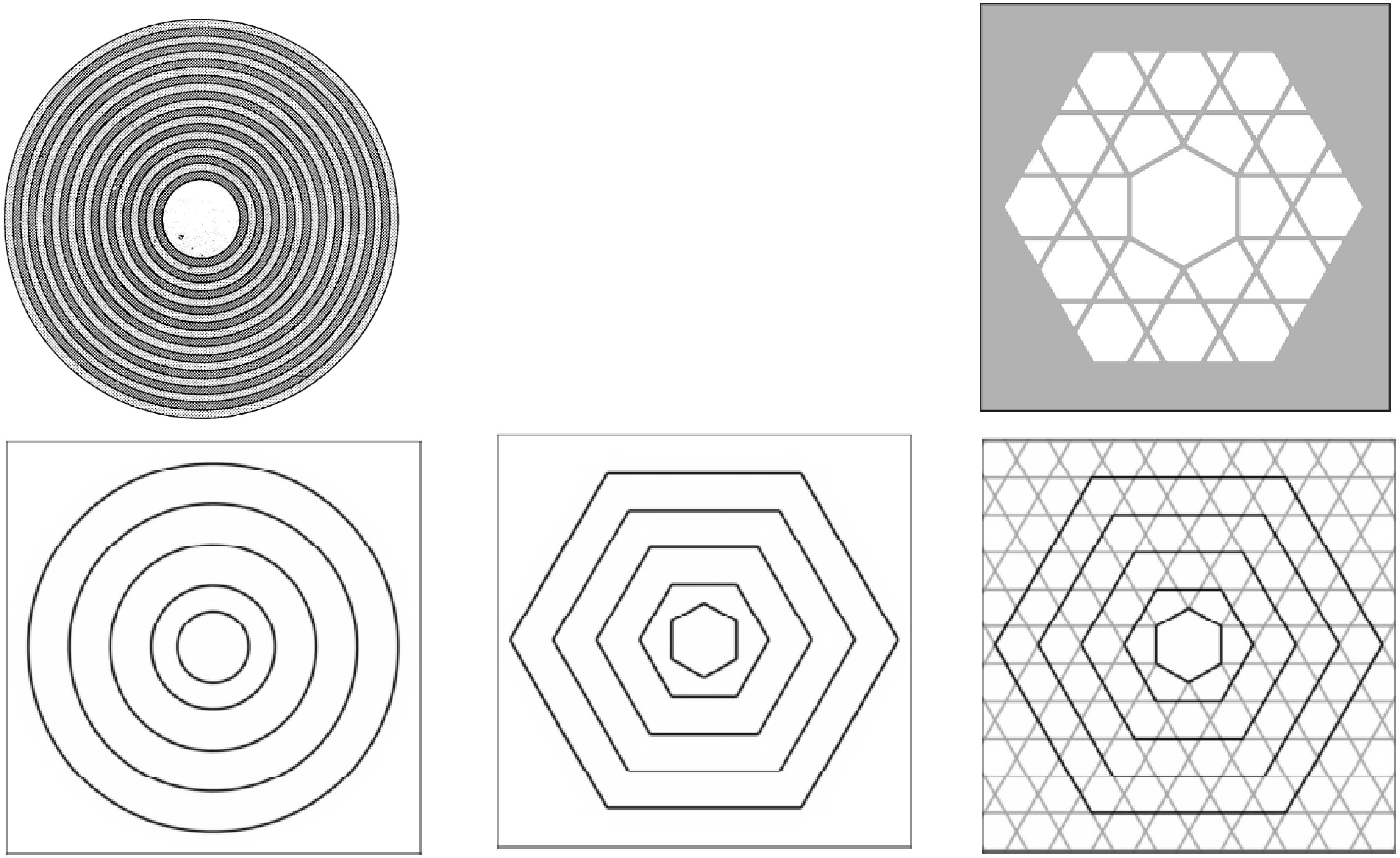
“Antiresonant reflecting photonic crystal fiber”, Litchinitser et al., Opt. Lett. 27, 1592 (2002)

Hollow antiresonant fibres:
Kagomé Fibres



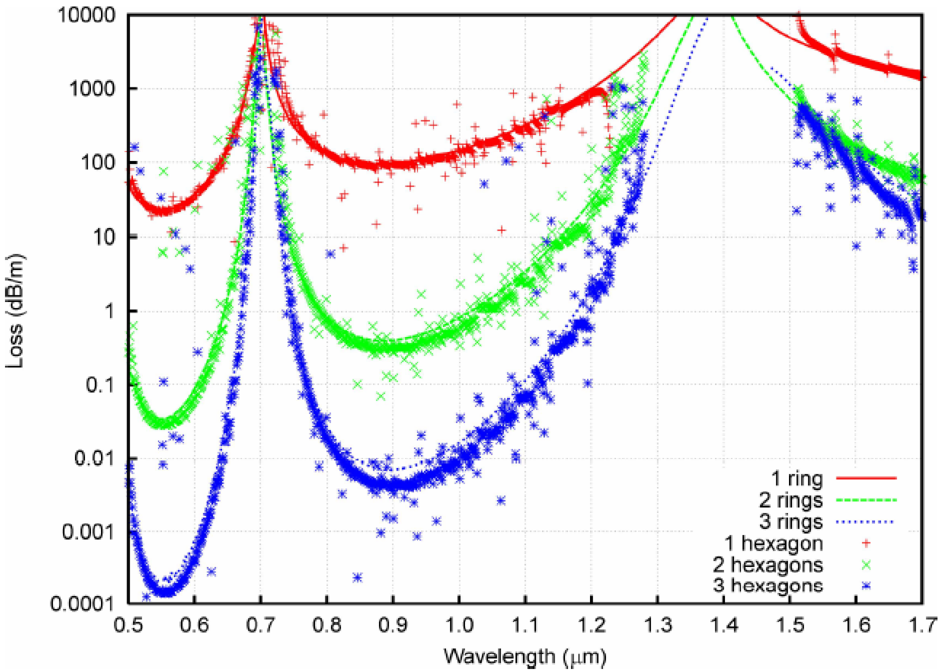
“Stimulated Raman scattering in hydrogen-filled hollow core photonic crystal fiber”, **F. Benabid** et al., Science 298, 399 (2002)

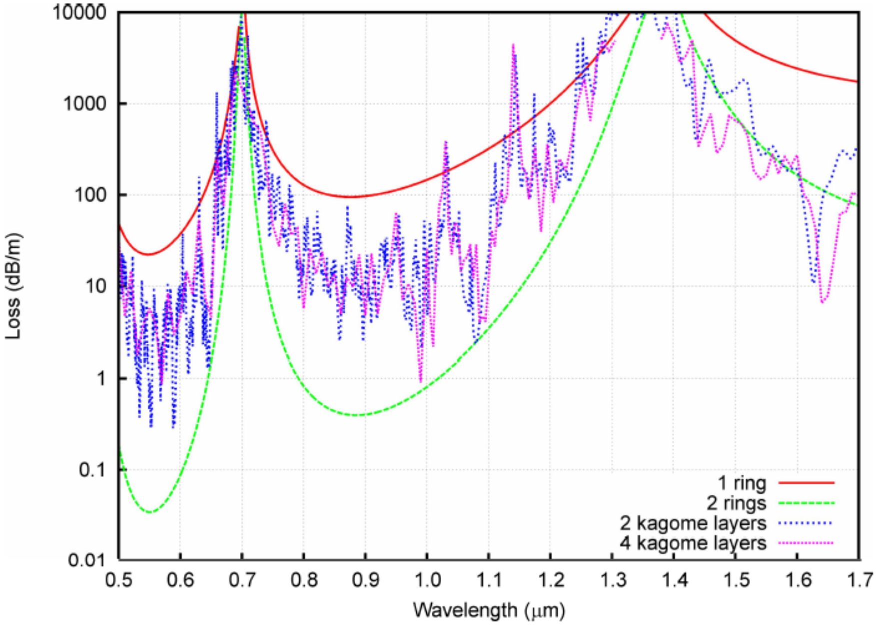
Bragg to Kagomé

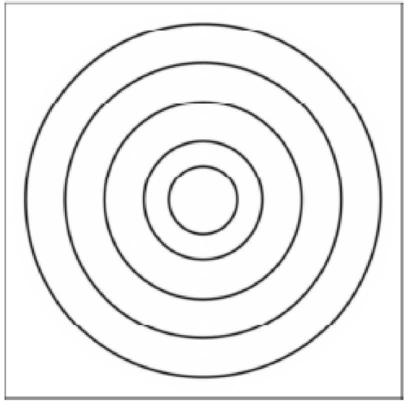


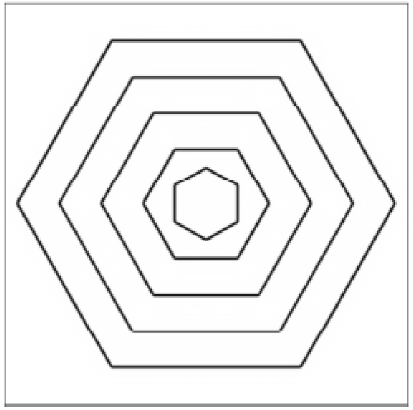
<u>G. J. Pearce</u> et al., "Models for guidance in kagome-structured hollow-core photonic crystal fibres,"
Opt. Express **15**, 12680-12685 (2007)

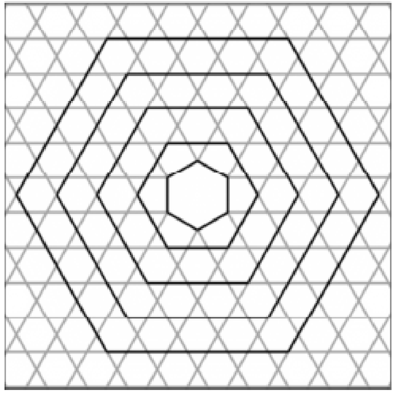
Comparison





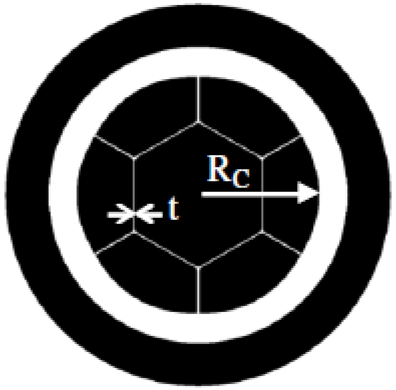


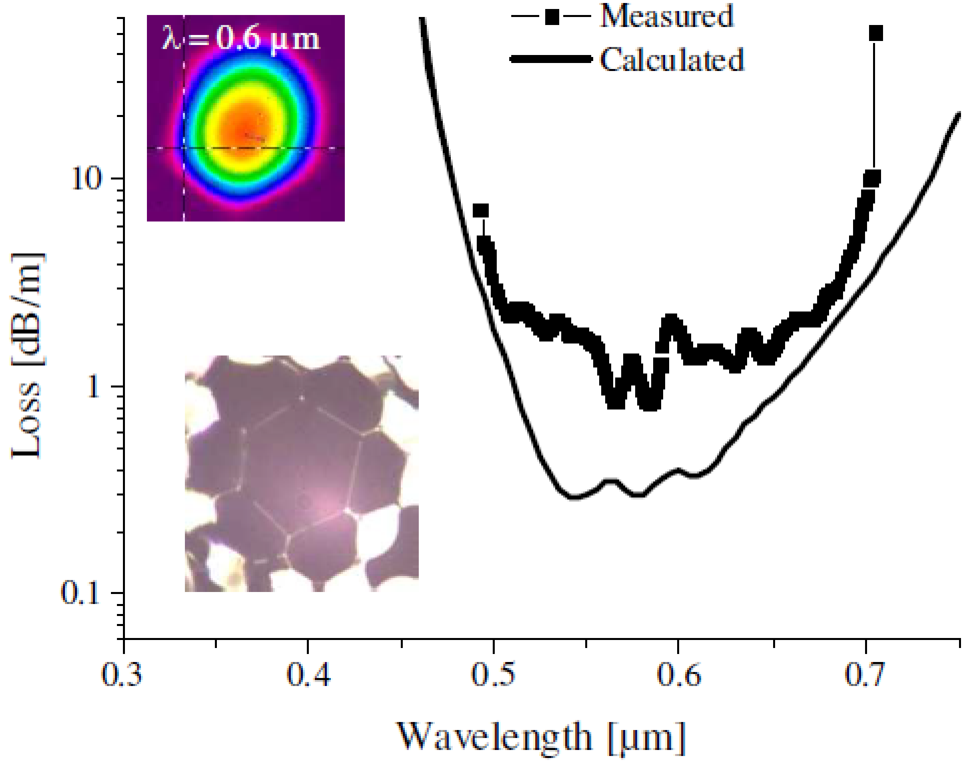




G. J. Pearce et al., "Models for guidance in kagome-structured hollow-core photonic crystal fibres," Opt. Express **15**, 12680-12685 (**2007**)

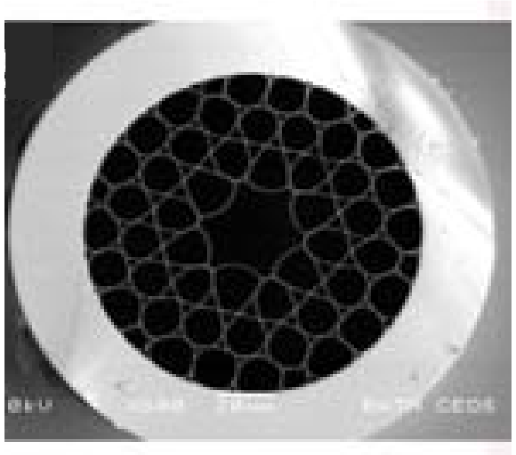
Structure simplification



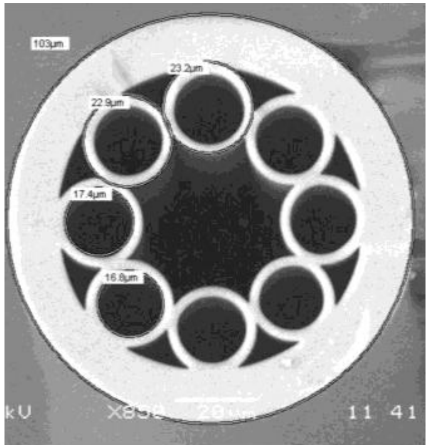


S. Février et al., "Understanding origin of loss in large pitch hollow-core photonic crystal fibers and their design simplification",
Opt. Express **18**, 5142-5150 (2010)

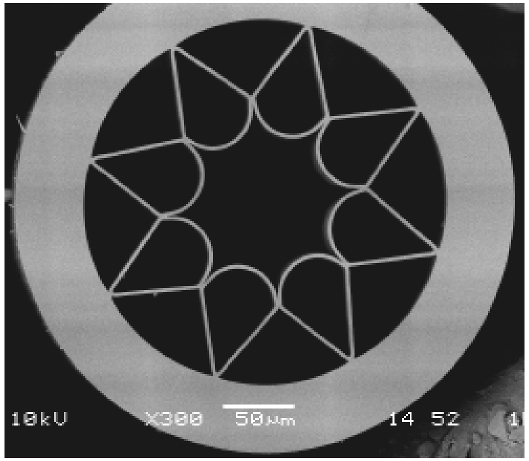
Curving the fiber core boundary



Wang et al., **CLEO 2010** Postdeadline



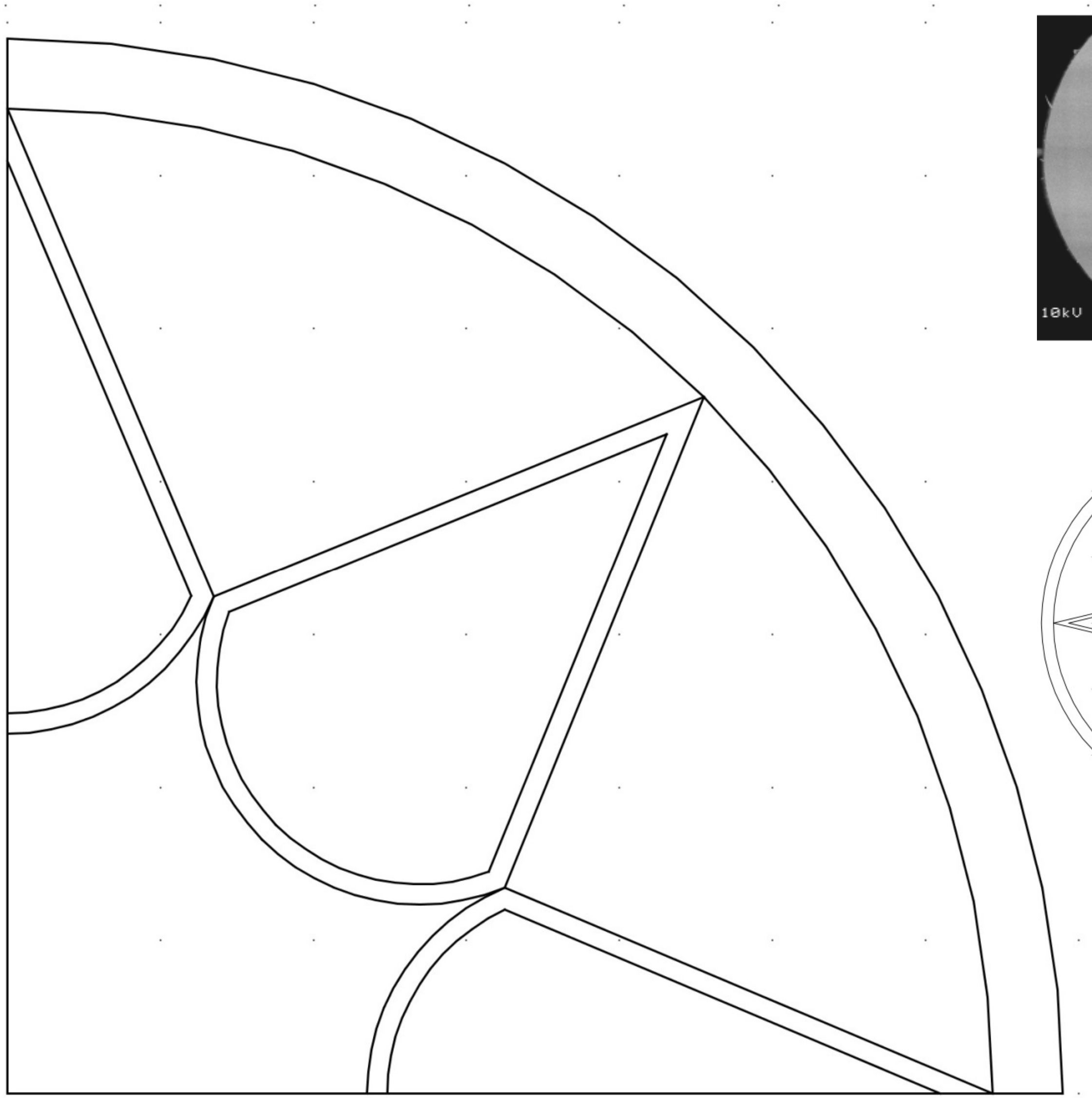
A. D. Pryamikov et al., Optics Express 19, 1441 (**2011**)

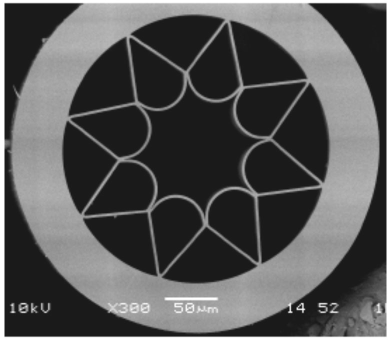


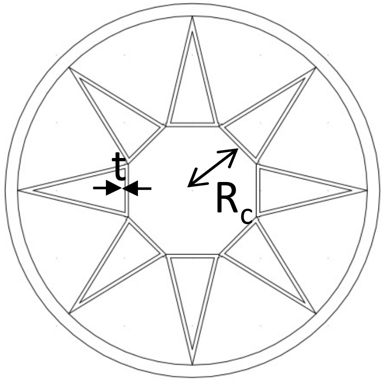
34dB/km at 3.05μm
Single mode
24dB/km at2.4μm

F. Yu et al., Optics Express 20, 11153 (**2012**)
Optics Express 21, 21466 (**2013**)

Impact of the negative curvature

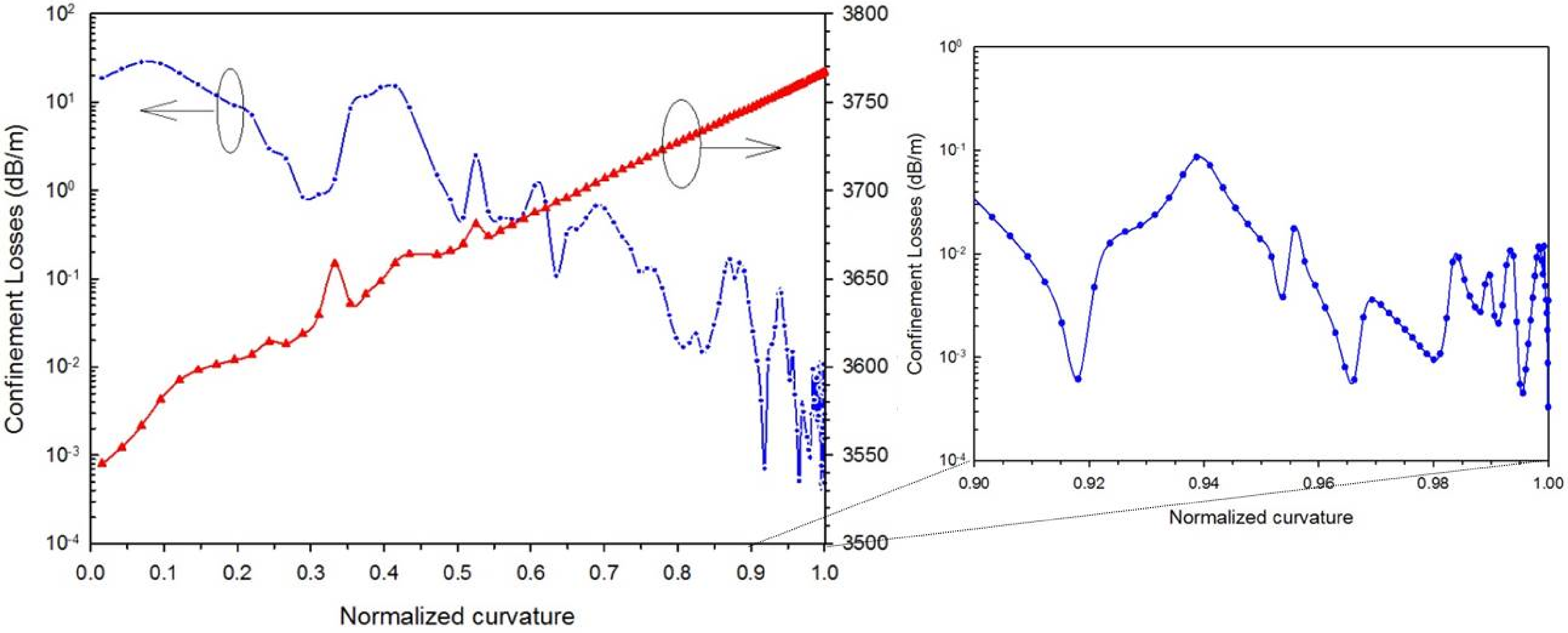






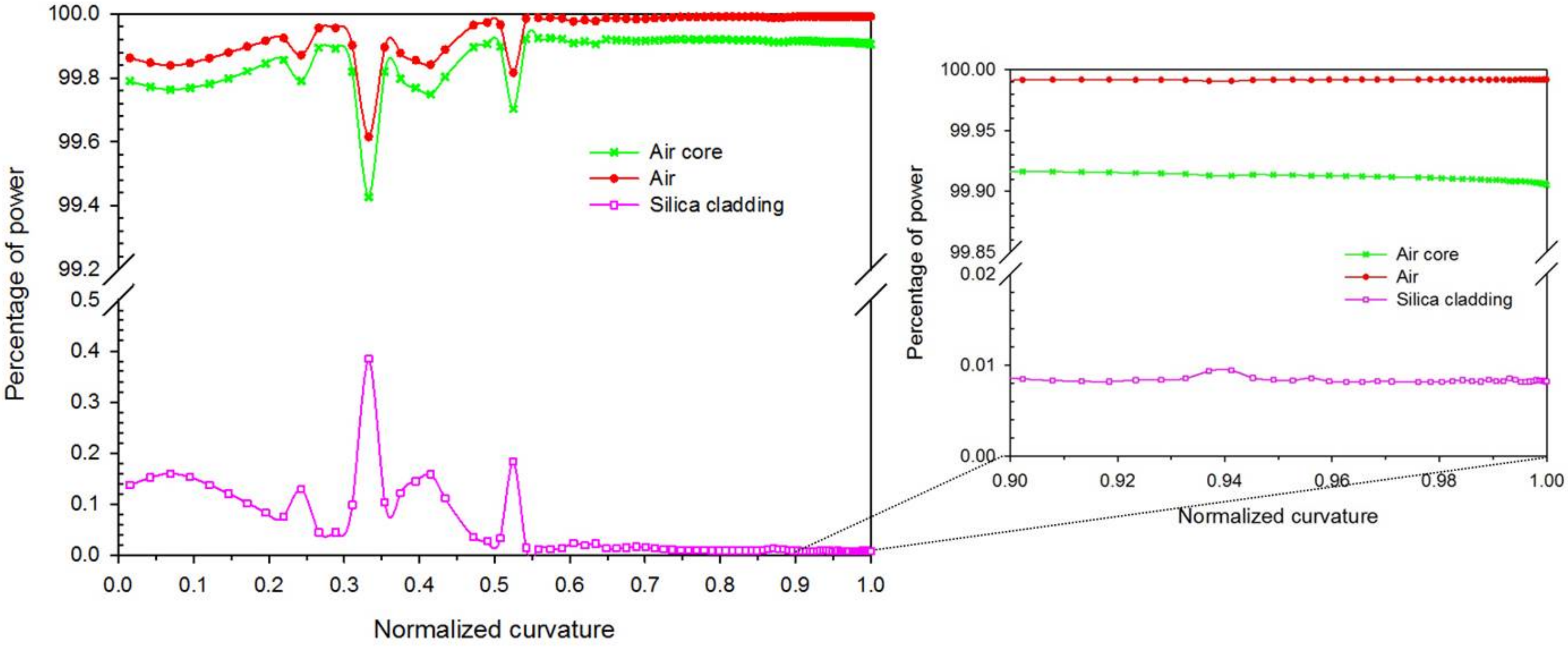
W. Belardi et al., " Effect of core boundary curvature on the confinement losses of hollow antiresonant fibers "
Optics Express **21**, 21912(2013)

Confinement losses



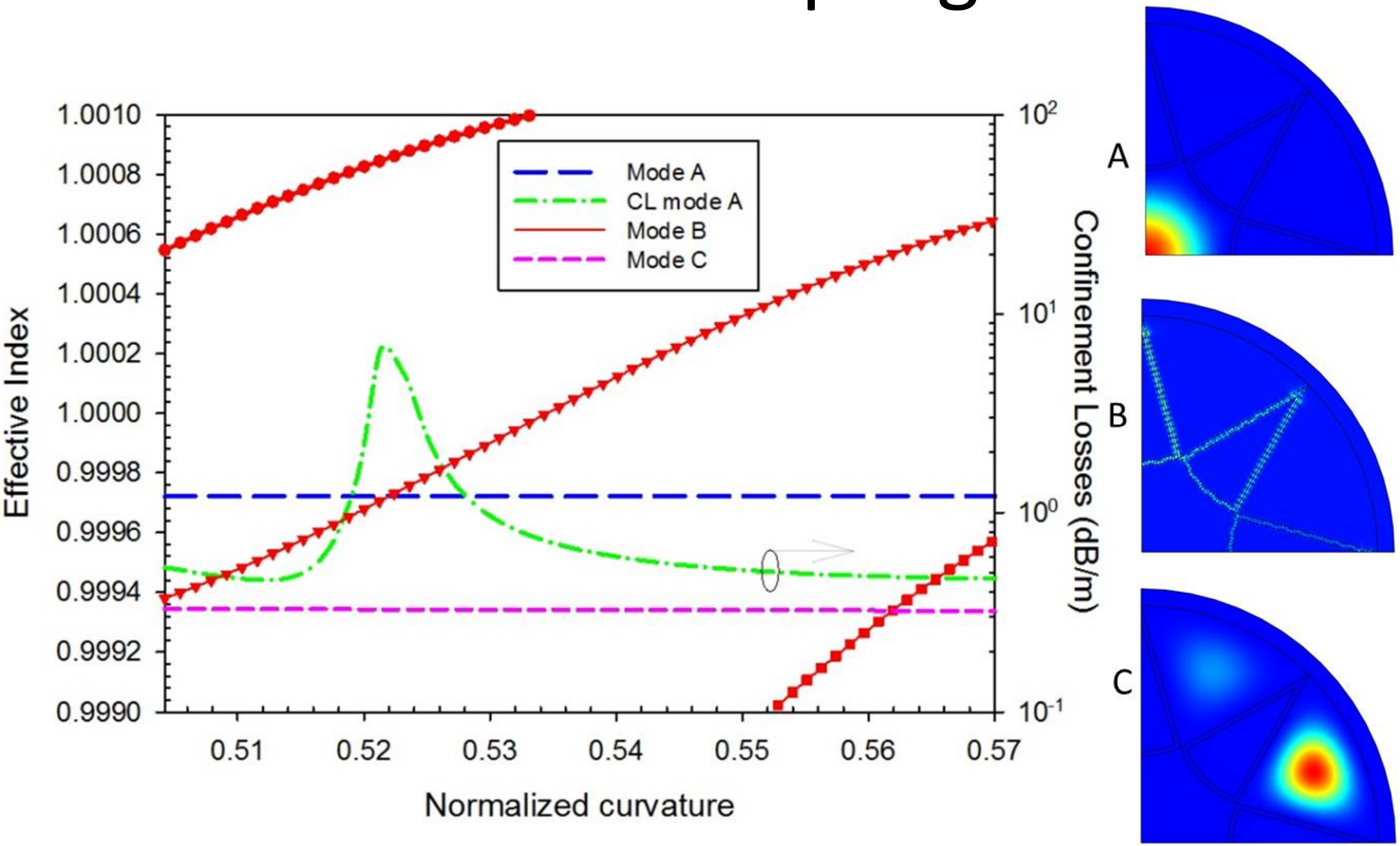
W. Belardi et al., " Effect of core boundary curvature on the confinement losses of hollow antiresonant fibers "
Optics Express **21**, 21912(2013)

Percentage of power



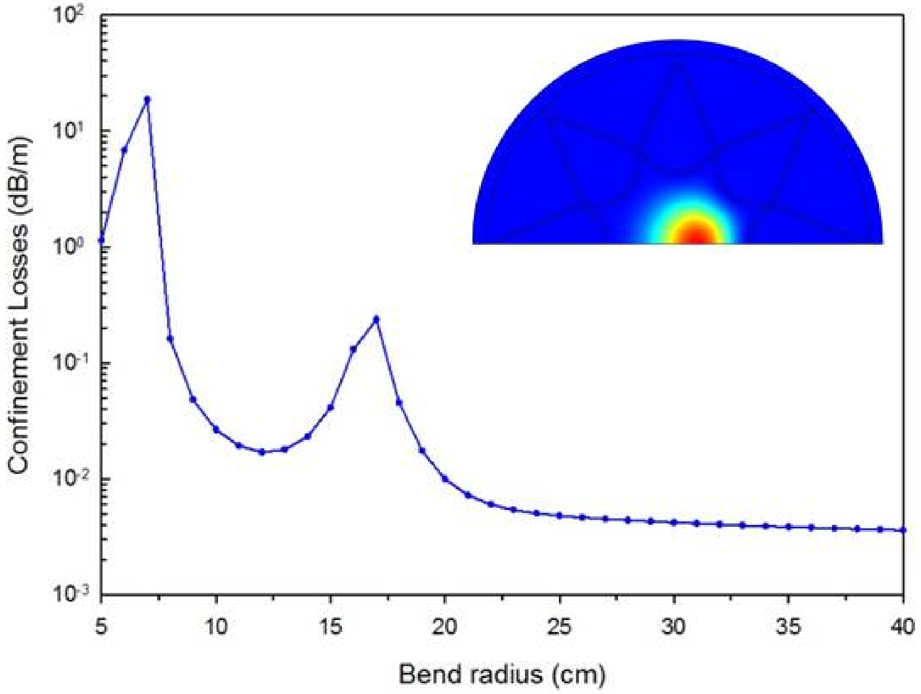
W. Belardi et al., " Effect of core boundary curvature on the confinement losses of hollow antiresonant fibers "
Optics Express **21,** 21912(2013)

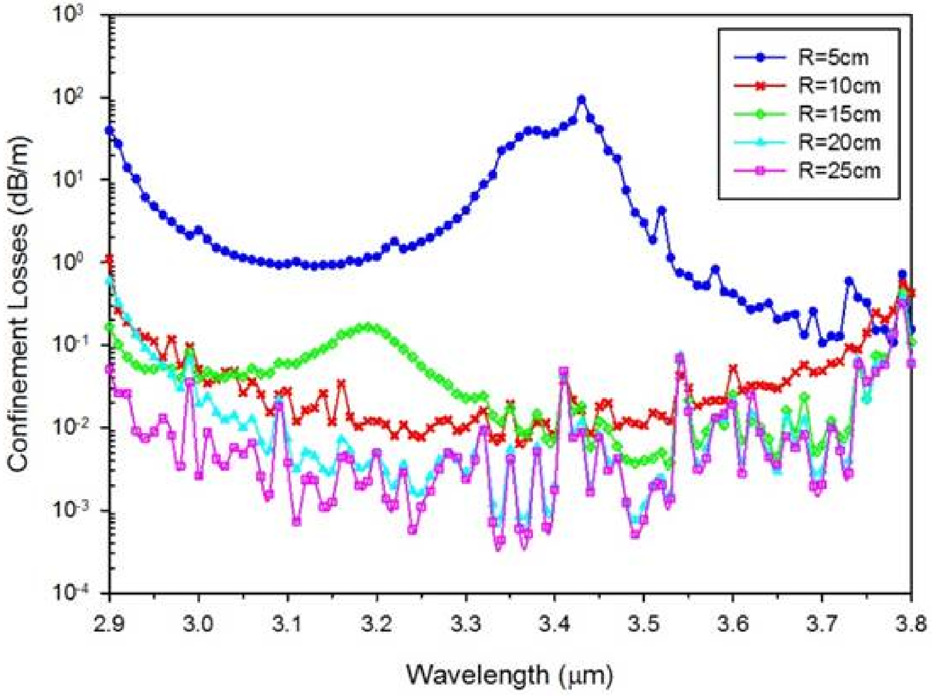
Power coupling



W. Belardi et al., " Effect of core boundary curvature on the confinement losses of hollow antiresonant fibers "
Optics Express **21**, 21912(2013)

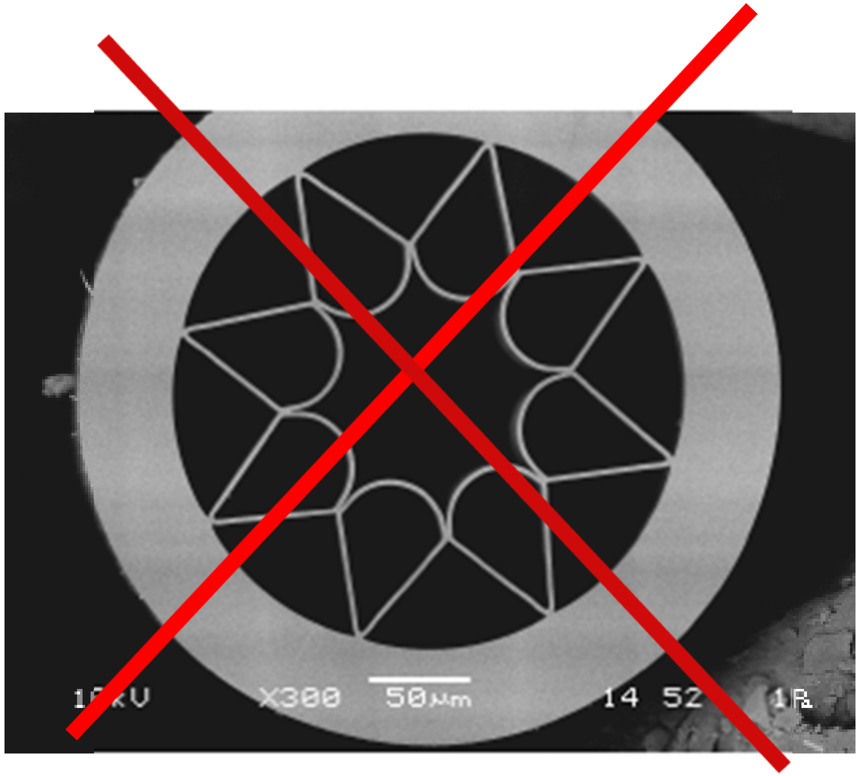
Bending Losses

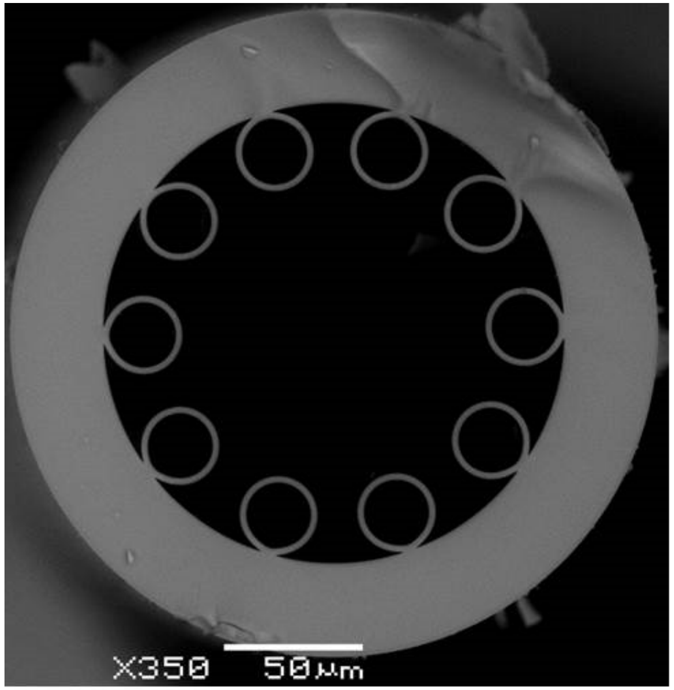




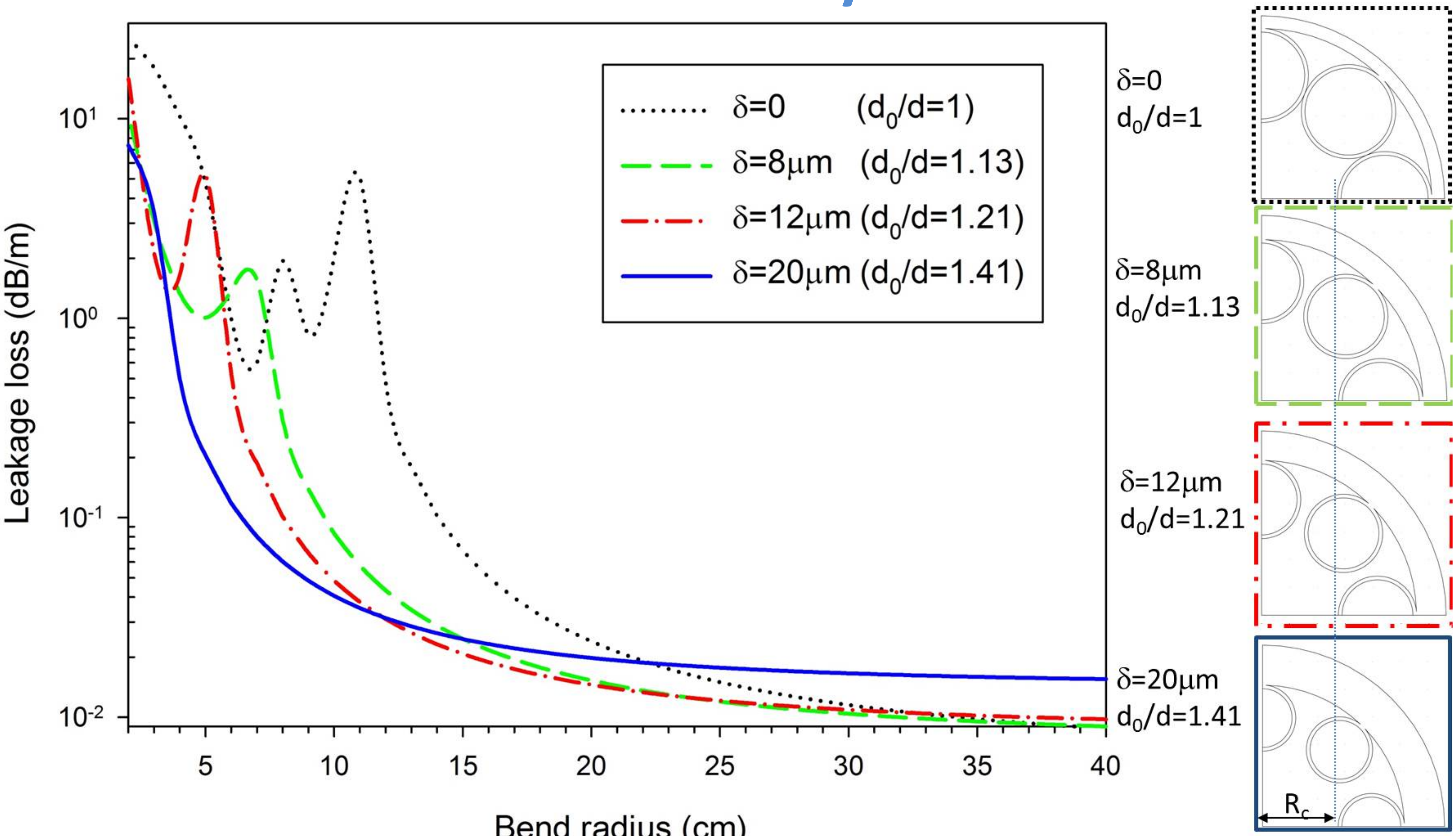
W. Belardi et al., " Effect of core boundary curvature on the confinement losses of hollow antiresonant fibers "
Optics Express **21**, 21912(2013)

The need for a novel antiresonant fiber

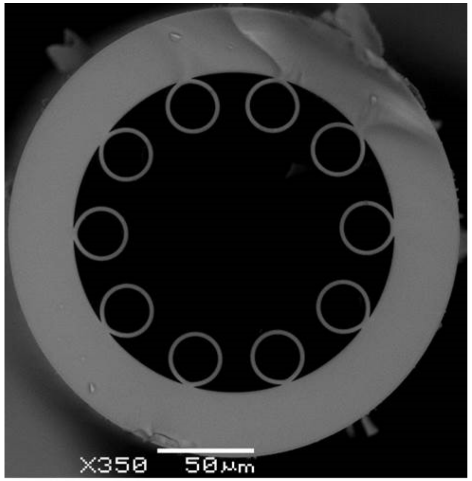


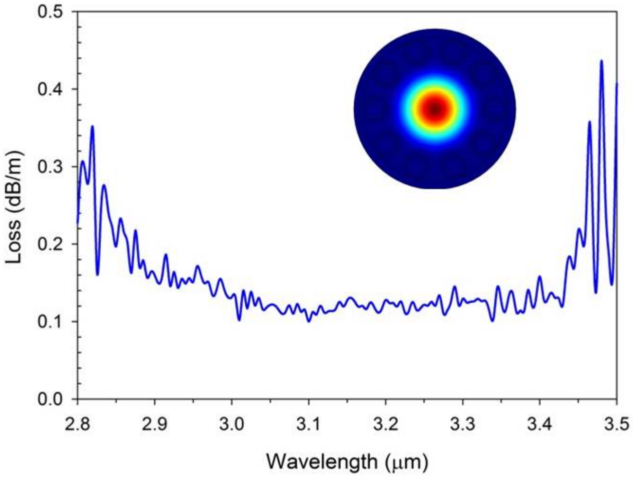


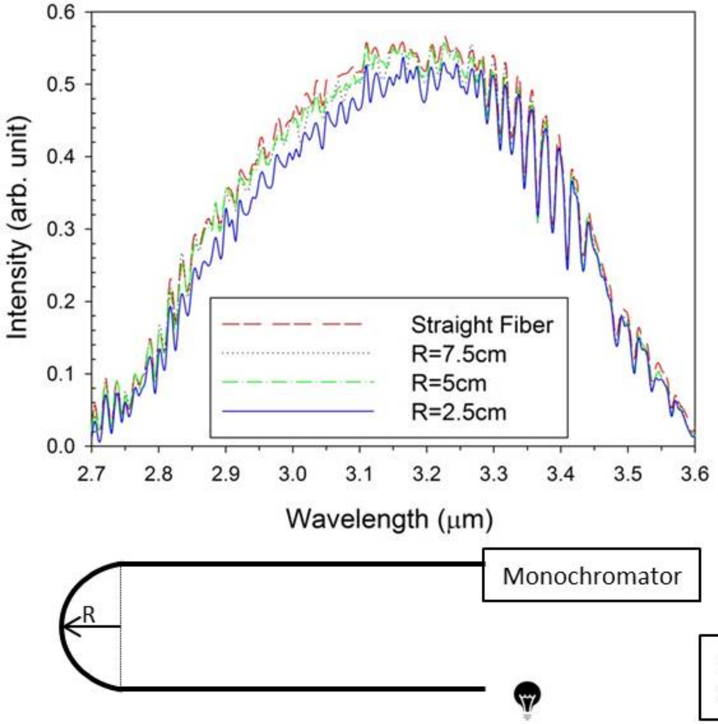
Free Boundary Fibre



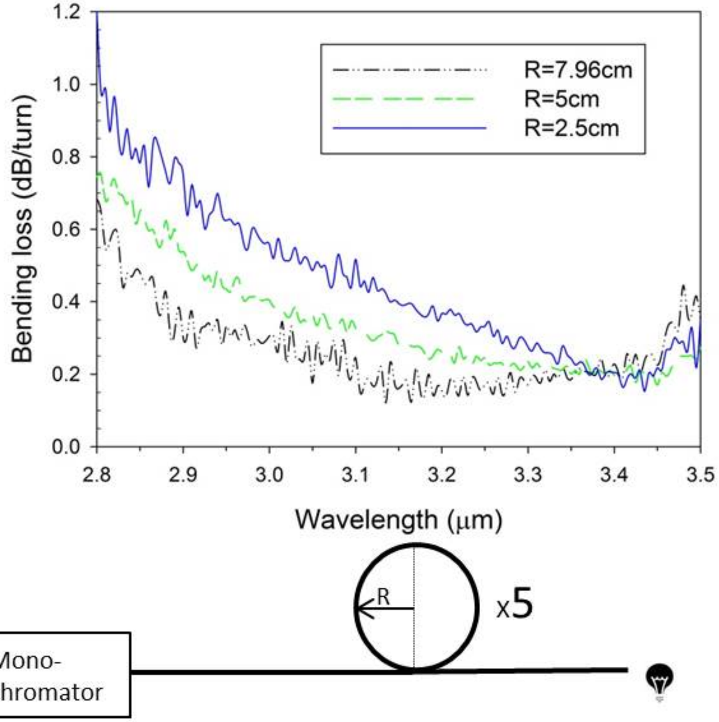
W. Belardi and J. C. Knight, "Hollow antiresonant fibers with low bending loss" Opt. Express **22**, 10091-10096 (2014).







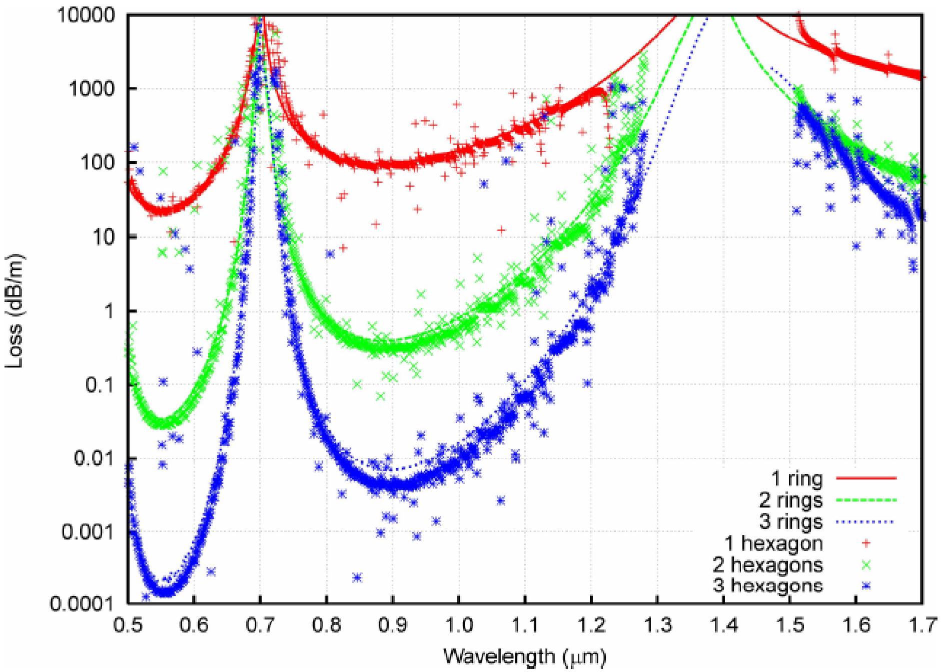
(a)

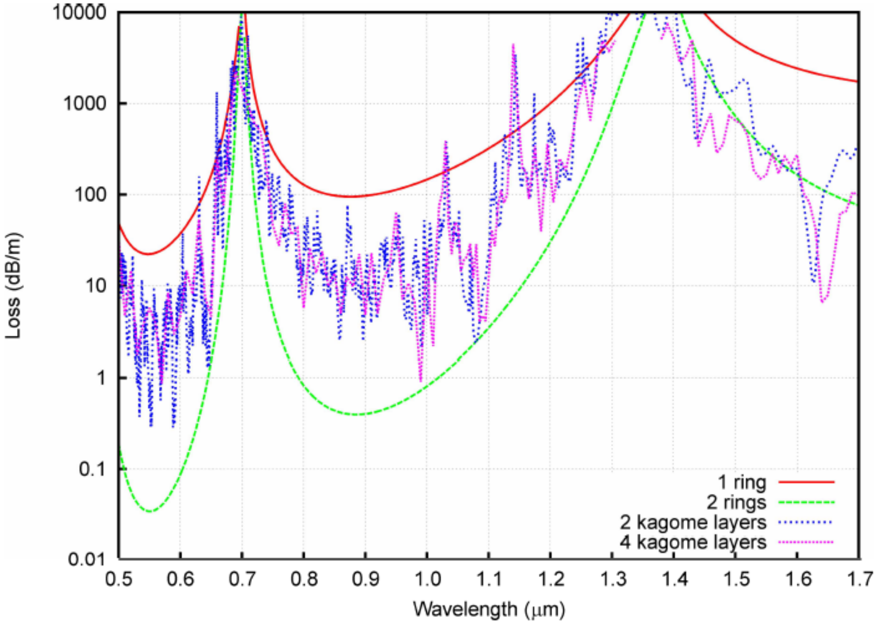


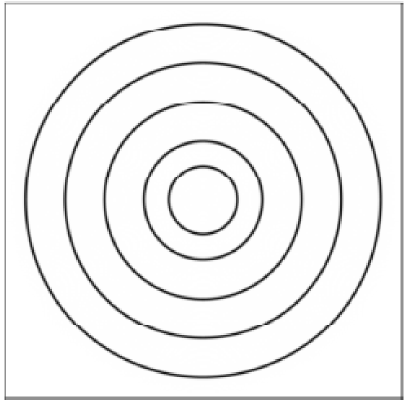
(b)

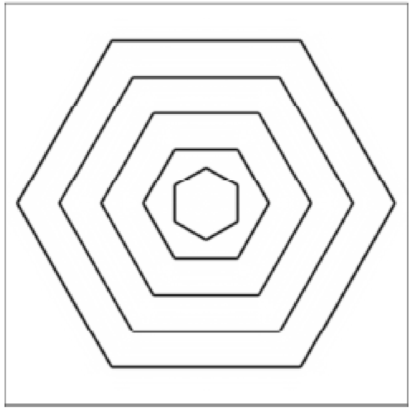
W. Belardi and J. C. Knight, "Hollow antiresonant fibers with low bending loss" Opt. Express **22**, 10091-10096 (2014).

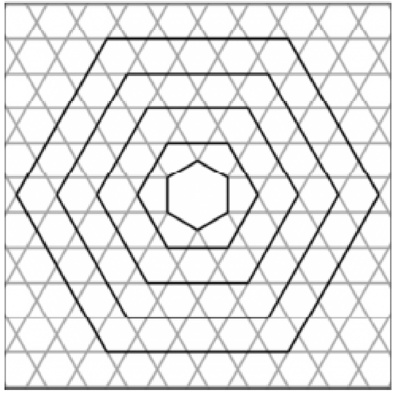
Multiple layer antiresonant fibers





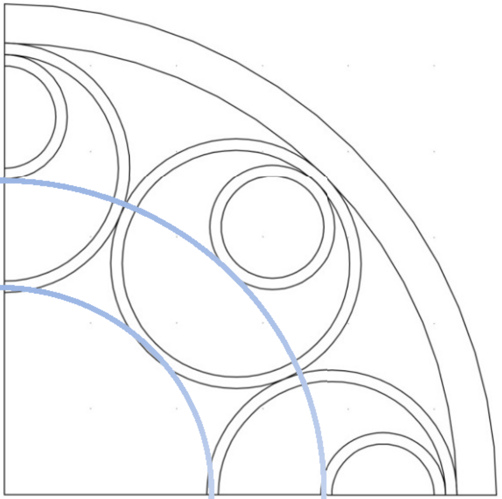




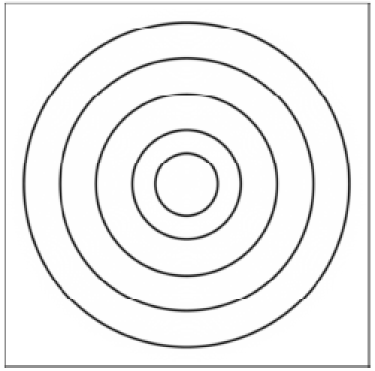


G. J. Pearce et al., "Models for guidance in kagome-structured hollow-core photonic crystal fibres,"
Opt. Express **15**, 12680-12685 (2007)

“Multiple Layer” Negative Curvature Fibers

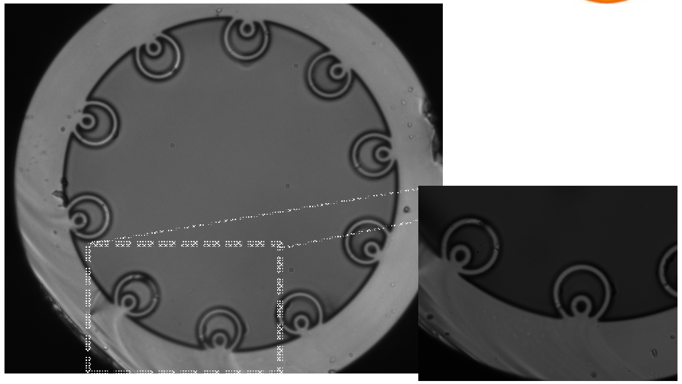


Negative Curvature “layer”



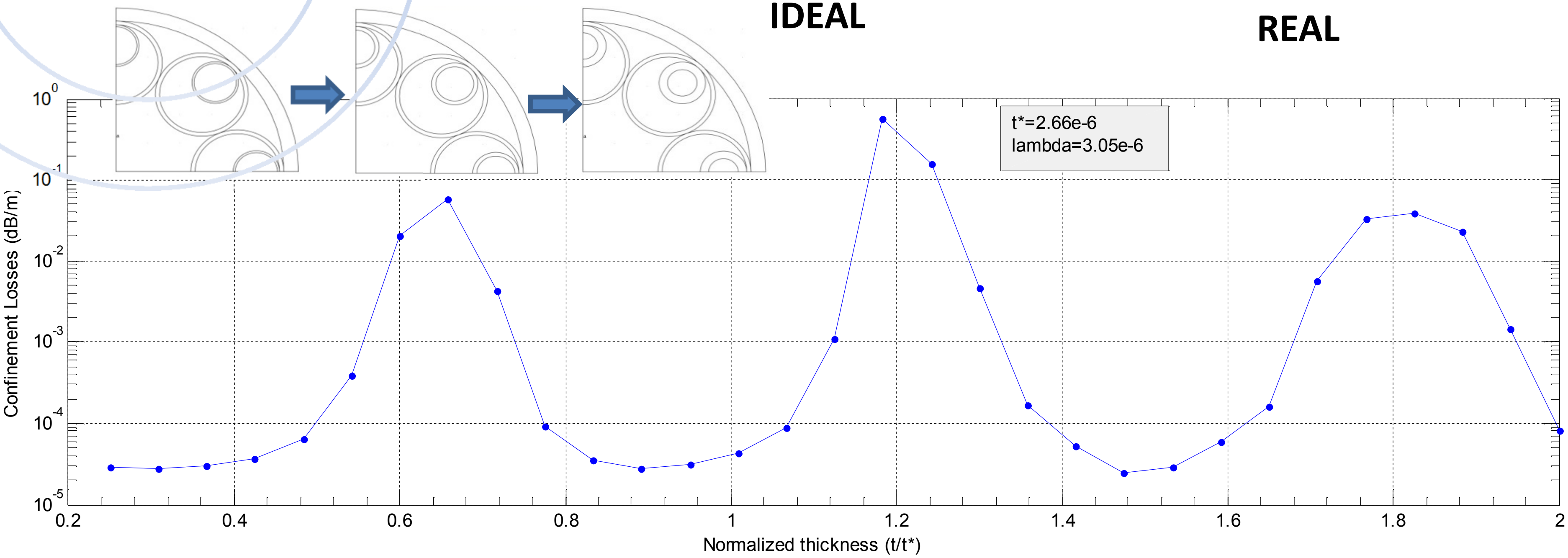
Positive Curvature layer

IDEAL

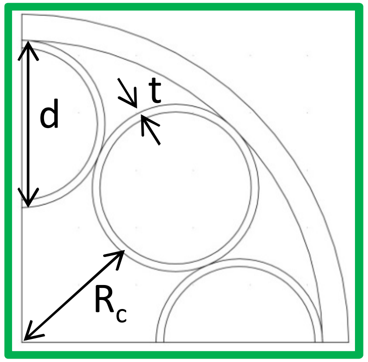


Negative Curvature “layer”

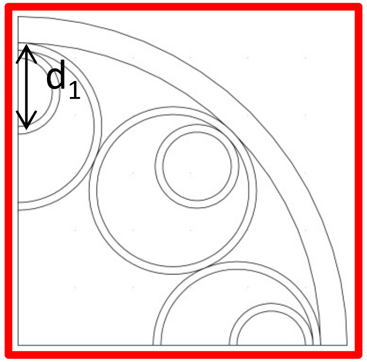
REAL



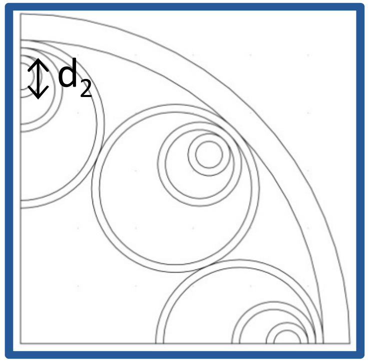
Multiple Antiresonant Elements Fibre



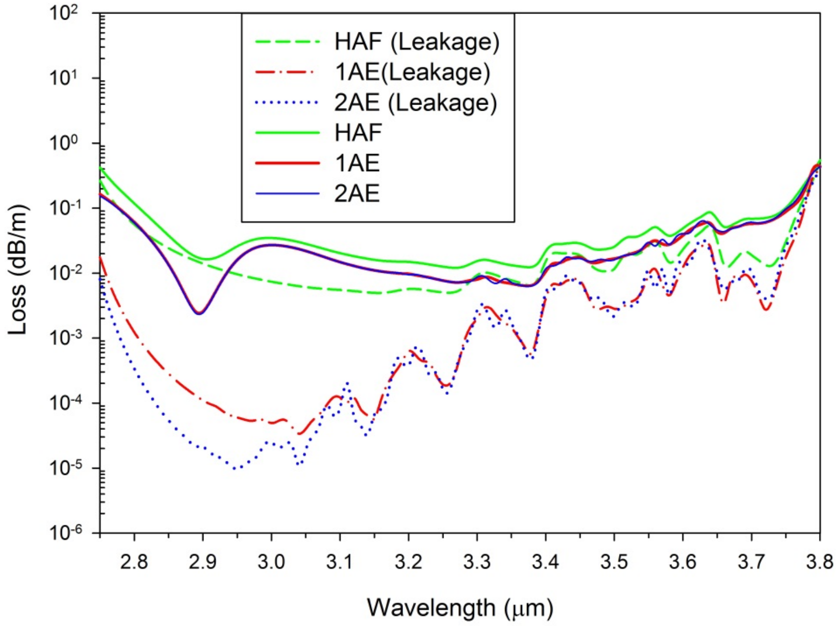
HAF

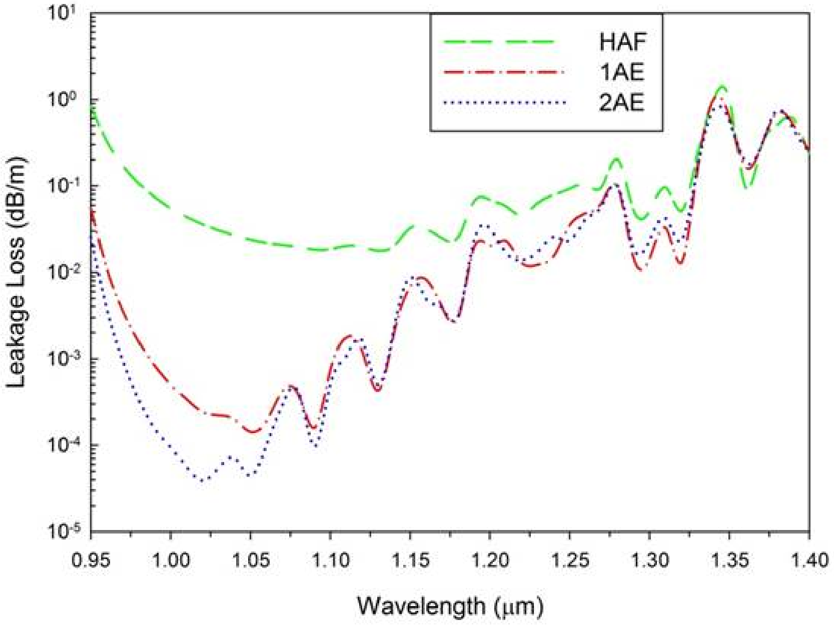


1AE



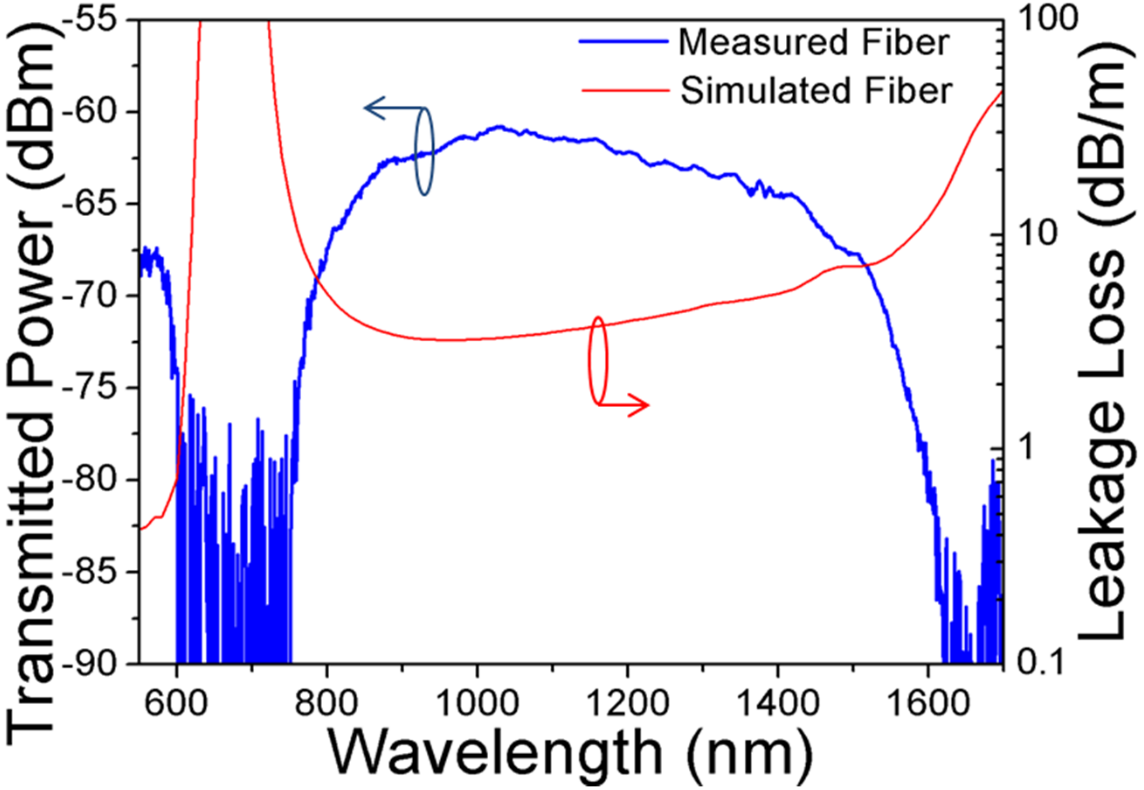
2AE

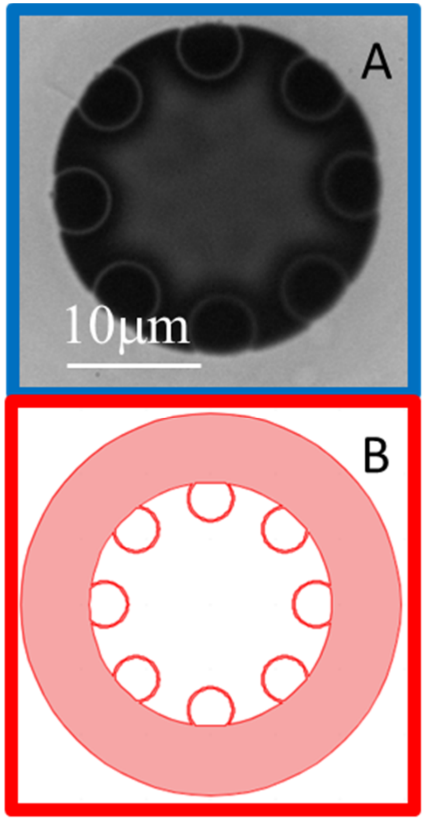




W. Belardi and J. C. Knight, "Hollow antiresonant fibers with reduced attenuation" Opt. Letters **39**, 1853-1856 (2014).

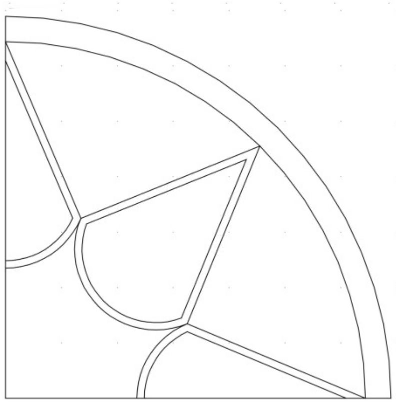
Large Bandwidth
Hollow antiresonant fibres





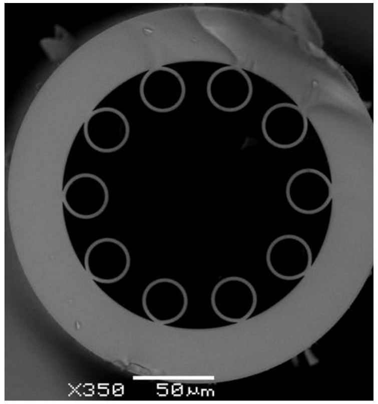
W. Belardi “Design and properties of hollow antiresonant fibers for the visible and near infrared spectral range" IEEE J. Light. Techn. 33, 4497 (2015).

Hollow antiresonant fibers



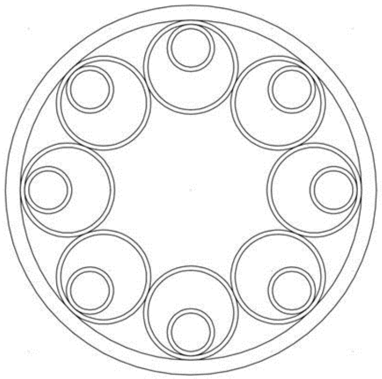
W. Belardi et al.
Optics Express **21**, 21912
(**2013**)

Overlap of optical power on the glass of only 0.01%



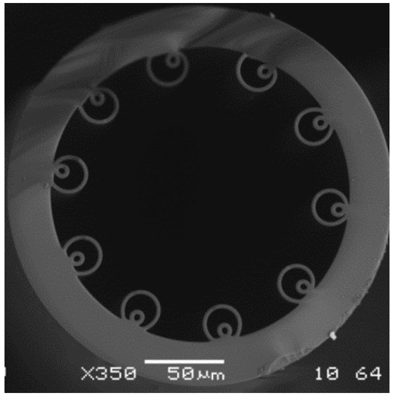
W. Belardi et al.
Optics Express **22**, 10091
(**2014**)

Low bending loss with a core size of 110µm (at 3.2µm)



W. Belardi et al.
Optics Letters **39**, 1853
(**2014**)

Low leakage loss with multiple AR elements in the cladding space



W. Belardi
J. Lightwave Techn.**33**, 4497
(**2015**)

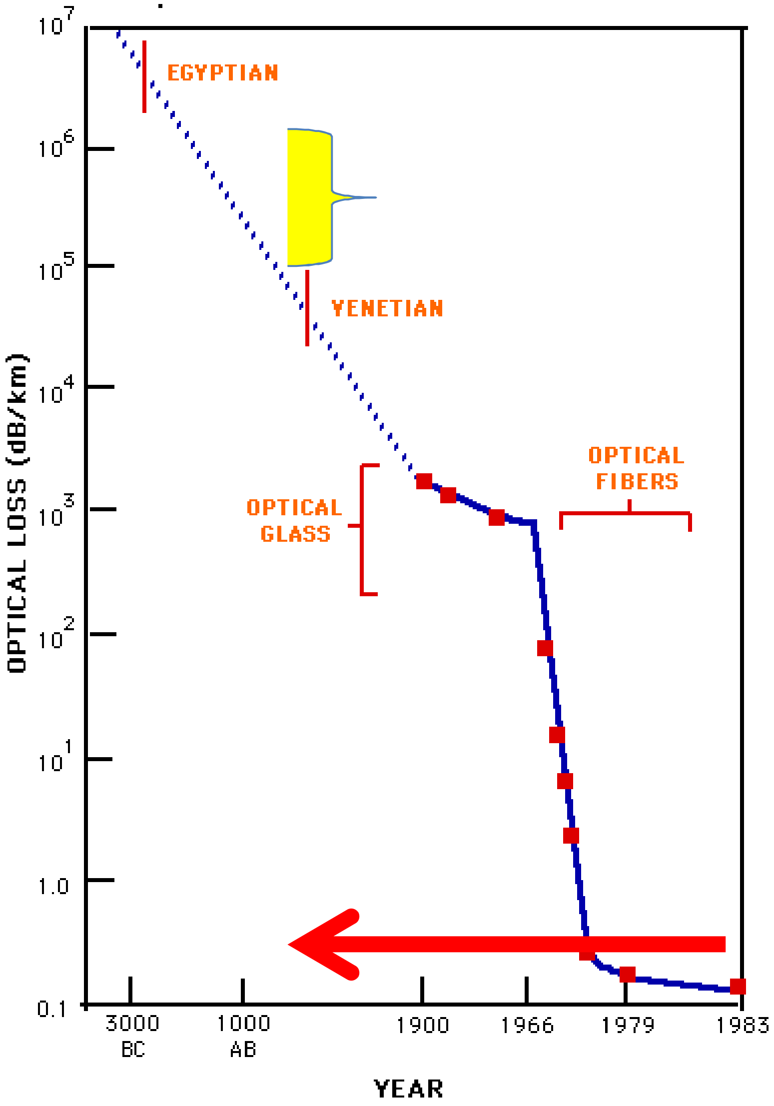
Low leakage loss and Ultra-wide bandwidth

Common Glass

For everybody

Optical grade

Hystory of Glass



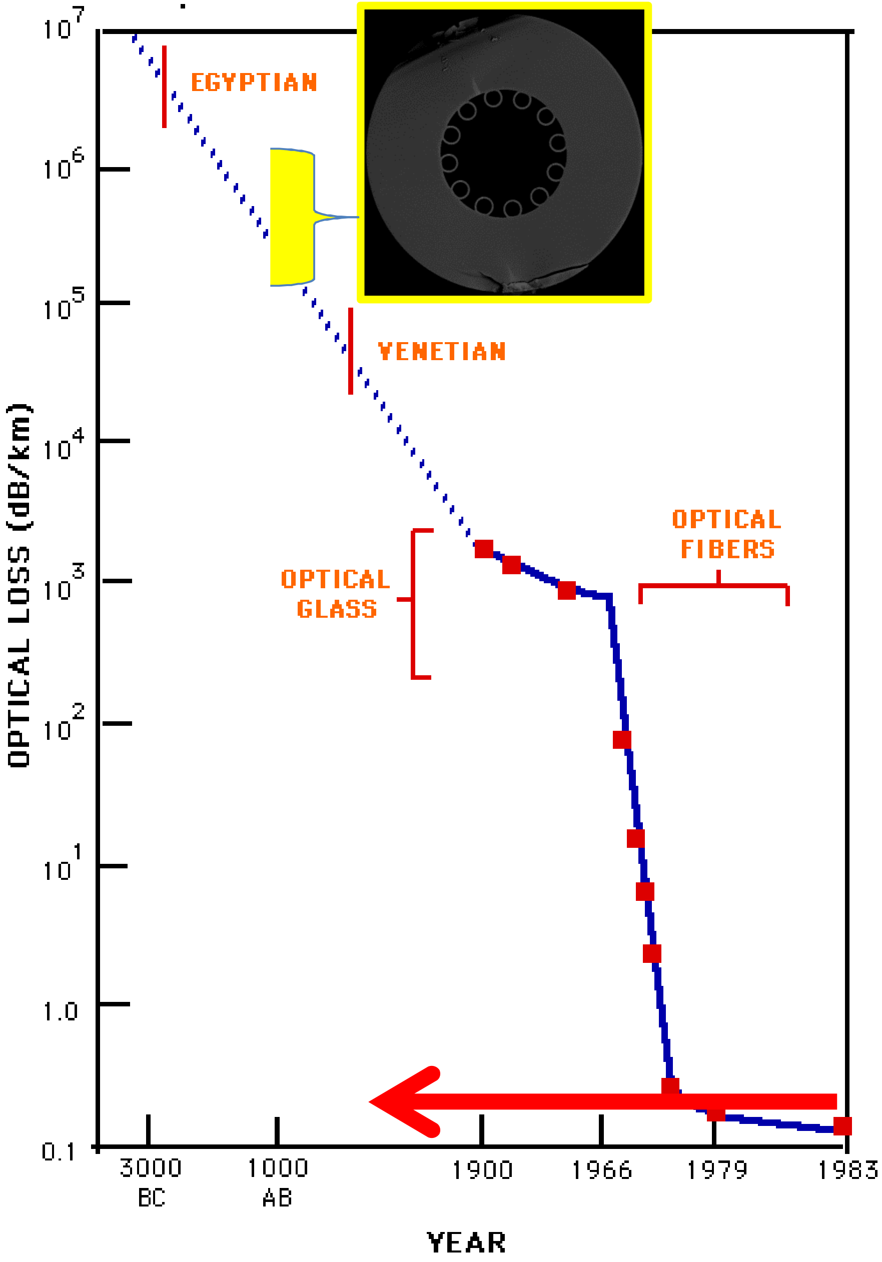
- Improving glass purity has allowed a reduction of attenuation of 4 orders of magnitude in the last 50 years

- However the required glass processing involve issues related to cost (or time consumption, or pollution or safety).

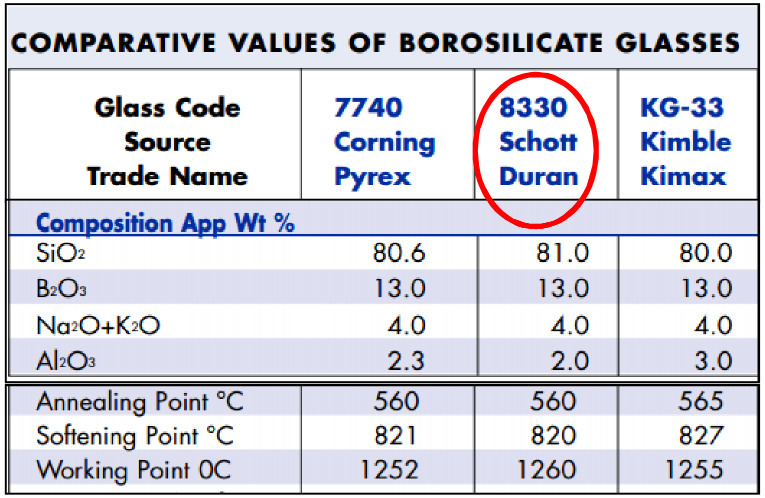
- Can we make low loss optical fibers with low optical quality glass ?

- Is there any specialty optical fiber that we can use ?

Nagel S. , " Optical fiber: the expanding medium ", IEEE Circuits Devices Magaz. March, 36 (1989)

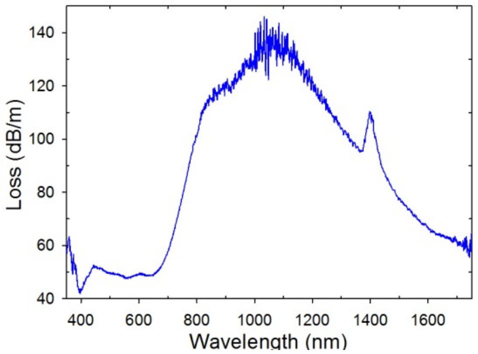


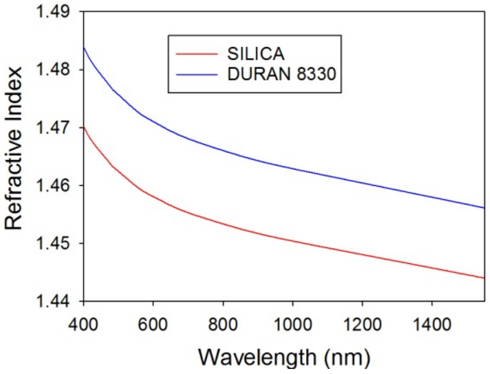
Nagel S. , " Optical fiber: the expanding medium ", IEEE Circuits Devices Magaz. March, 36 (1989)



COMPARATIVE VALUES OF BOROSILICATE GLASSES			
Glass Code Source Trade Name	**7740 Corning Pyrex**	**8330 Schott Duran**	**KG-33 Kimble Kimax**
Composition App Wt %			
SiO_2	80.6	81.0	80.0
B_2O_3	13.0	13.0	13.0
Na_2O+K_2O	4.0	4.0	4.0
Al_2O_3	2.3	2.0	3.0
Annealing Point °C	560	560	565
Softening Point °C	821	820	827
Working Point 0C	1252	1260	1255

Scattering loss ∝ surface roughness ∝ Tg/γ~ 0.65 that of silica





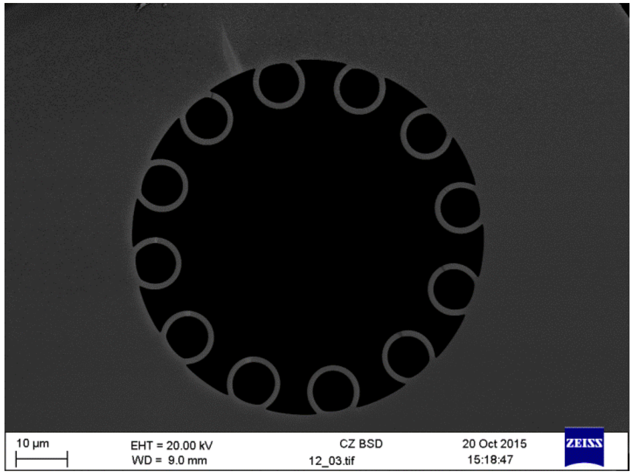
W. Belardi et al. " Hollow core antiresonant fibers in borosilicate glass ", WSOF 2015, Hong Kong 4-6 Nov. 2015

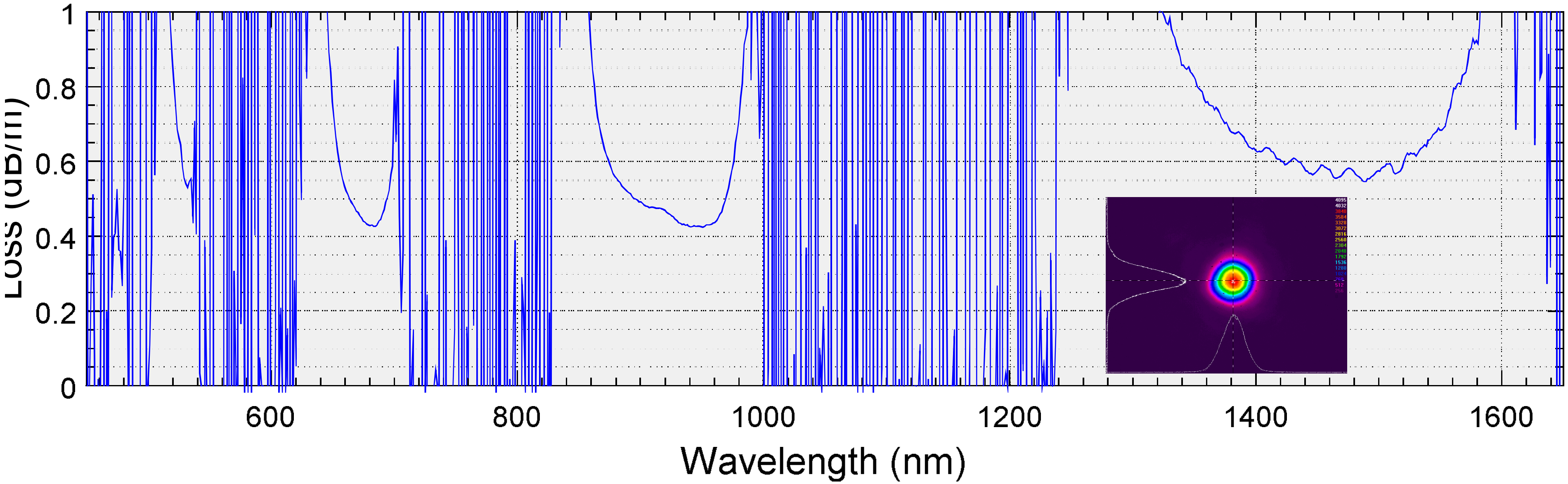
Fiber

- Loss of 420dB/km at 680nm and 950nm
- Loss of 520 dB/km at 532nm !!

(comparable to that of silica based hollow core fibers !)

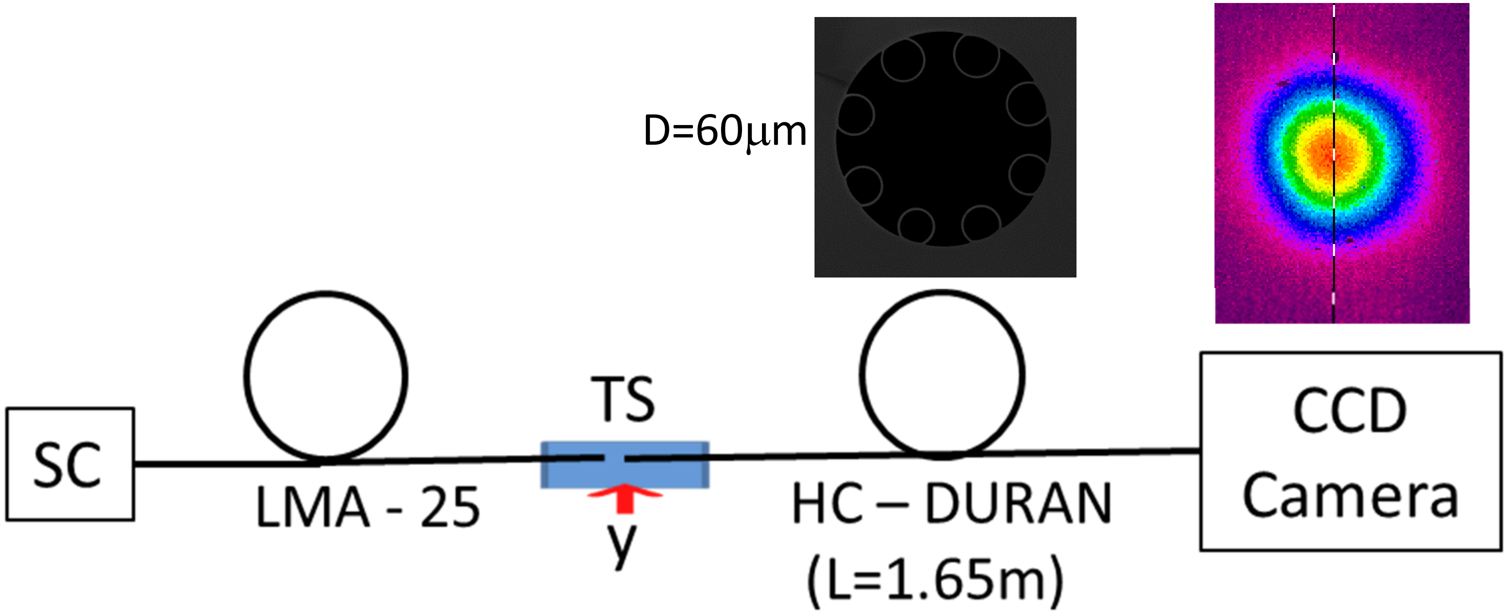
- Negligible bending loss

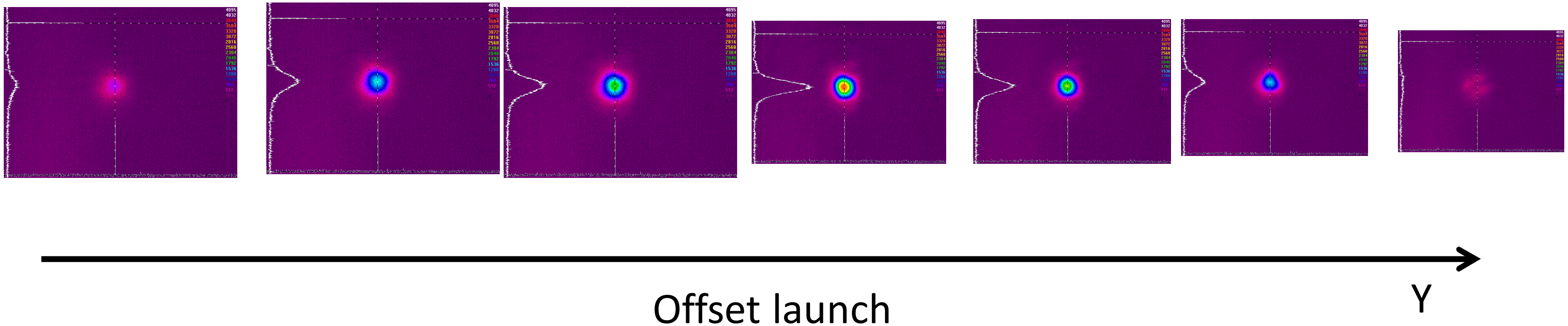




W. Belardi et al. " Hollow core antiresonant fibers in borosilicate glass ", WSOF 2015, Hong Kong 4-6 Nov. 2015

Single Mode operation

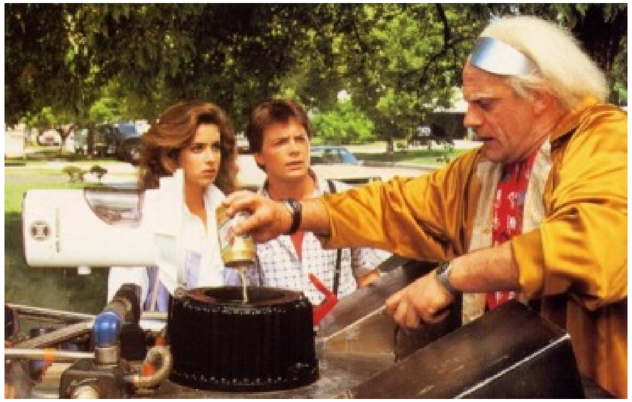


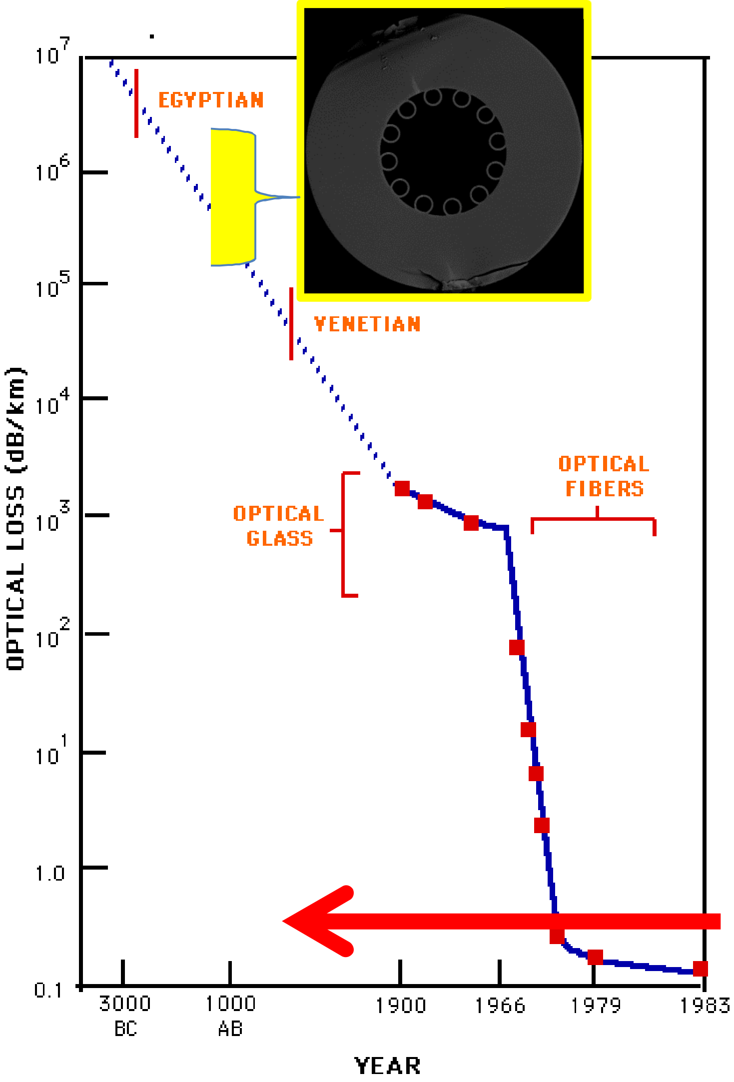


W. Belardi et al. " Hollow core antiresonant fibers in borosilicate glass ", WSOF 2015, Hong Kong 4-6 Nov. 2015

Back to the…past

- Optical fibers based on **cheap** borosilicate glass (140dB/m loss) can be made and show attenuations comparable to silica based hollow core optical fibers in the visible spectral range (0.5dB/m at 532nm), where they should also have lower scattering loss.
- The high glass attenuation and AR structure provide strong single mode guidance without any cladding mode over short fiber lengths (<1.65m) and with large core diameters (>60μm)





W. Belardi et al. ″ Hollow core antiresonant fibers in borosilicate glass “, WSOF 2015, Hong Kong 4-6 Nov. 2015

Conclusions

- Telecommunication fibres have loss of 0.15dB/km at 1550nm (the fundamental limit given by Rayleigh scattering is almost reached)
- ANTIRESONANCE is the fundamental mechanism capable of allowing efficient light propagation in air
- Loss limit in Hollow Core fibres is dictated by surface scattering that largely decreases at longer (unconventional) wavelengths and can be reduced by using a different type of glass
- A negative curvature of the hollow core boundary can decrease the confinement losses up to 4 orders of magnitude (or more)
- The introduction of multiple antiresonant layers allows further reduction of the total loss of hollow core fibers and keep alive the dream of beating standard fiber technology
- Although the dream is far to come, its presence stimulates interest and curiosity in optical science.

THANK YOU !

Grazie !