TECHNICAL UNIVERSITY OF CLUJ-NAPOCA ROMANIA

Faculty of Electronics, Telecom and Info Technology

Lecture 10

Optoelectronic Sensors with Industrial Applications

Optical Sensor Concepts (OS4): application examples

Associate prof Ramona Galatus
Basis of Electronics Department

Outline: Applications

- Optical materials
- Description of some application examples: Plastic optical fiber

I. Optical materials

These optical devices can be fabricated on the flat surface of materials such as:

- silica,
- silicon,
- semiconductor crystal, or
- plastic

Refractive index-reminder

REVIEW: INDEX OF REFRACTION

- Dimensionless number describing how electromagnetic radiation propagates through a medium

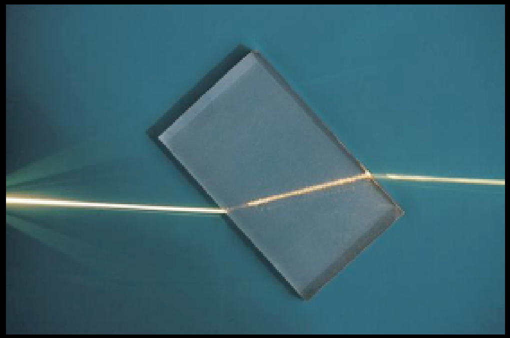
$$n = \frac{c}{v_{phase}}$$

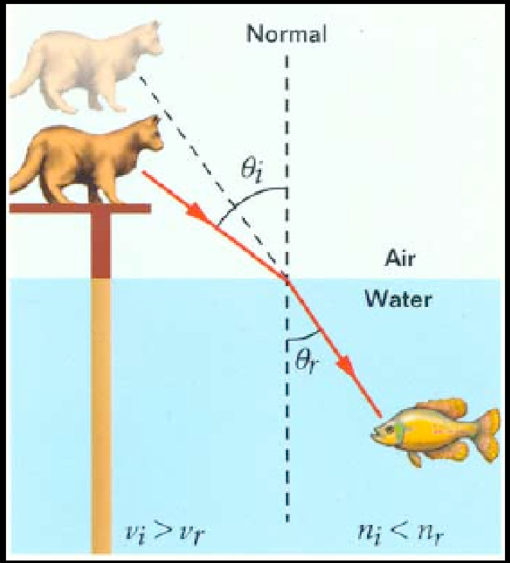
- Determines refraction of light in a material by **Snell's Law:**

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

- Refractive index is related to the electric permittivity and magnetic permeability by the Maxwell relation:

$$n^2 = \mu_r \epsilon_r$$





Images: Wikimedia Commons

Optical materials-equation

- The optical properties of a material can be completely described by its complex, wavelength - dependent index of refraction, $n'(\lambda)$:

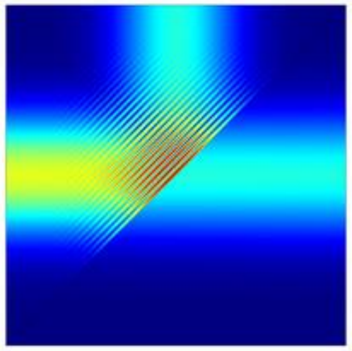
$$n'(\lambda) = n(\lambda) + i\kappa \quad (\text{where } i \,\hat{}\, 2 = 1).$$

- **The real part, $n(\lambda)$,** determines how light rays are refracted when

they cross an interface between two materials.

- **The imaginary part of the refractive index, $\kappa(\lambda)$,** is the extinction coefficient and describes absorption losses inside the material. Its wavelength dependence is represented by the material ’ s absorption spectrum

- Optical materials like glass or quartz usually show what is called “normal ” dispersion, which means that
  - Blue light has a higher refractive index than red light, and its
  - angle of refraction is larger
- Optical glass usually does not transmit ultraviolet light with wavelengths below about 320 nm
- Chalcogenide glass – mid IR devices
- As can be seen from the chart, this type of glass is perfectly transparent over the entire visible spectrum, from about 400 nm to about 800 nm, and also far into the infrared spectrum.



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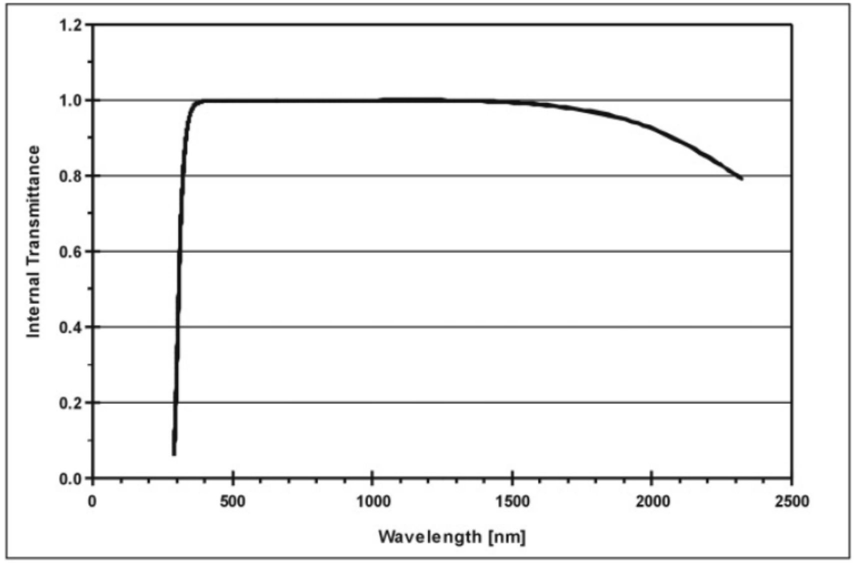
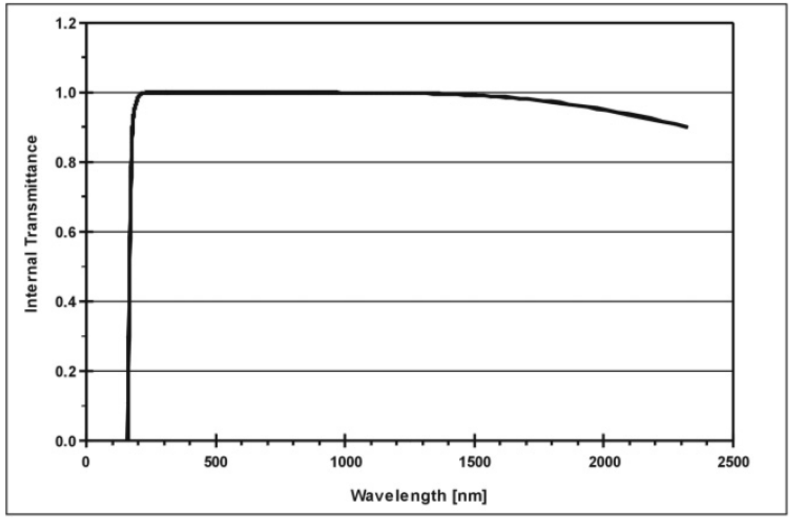
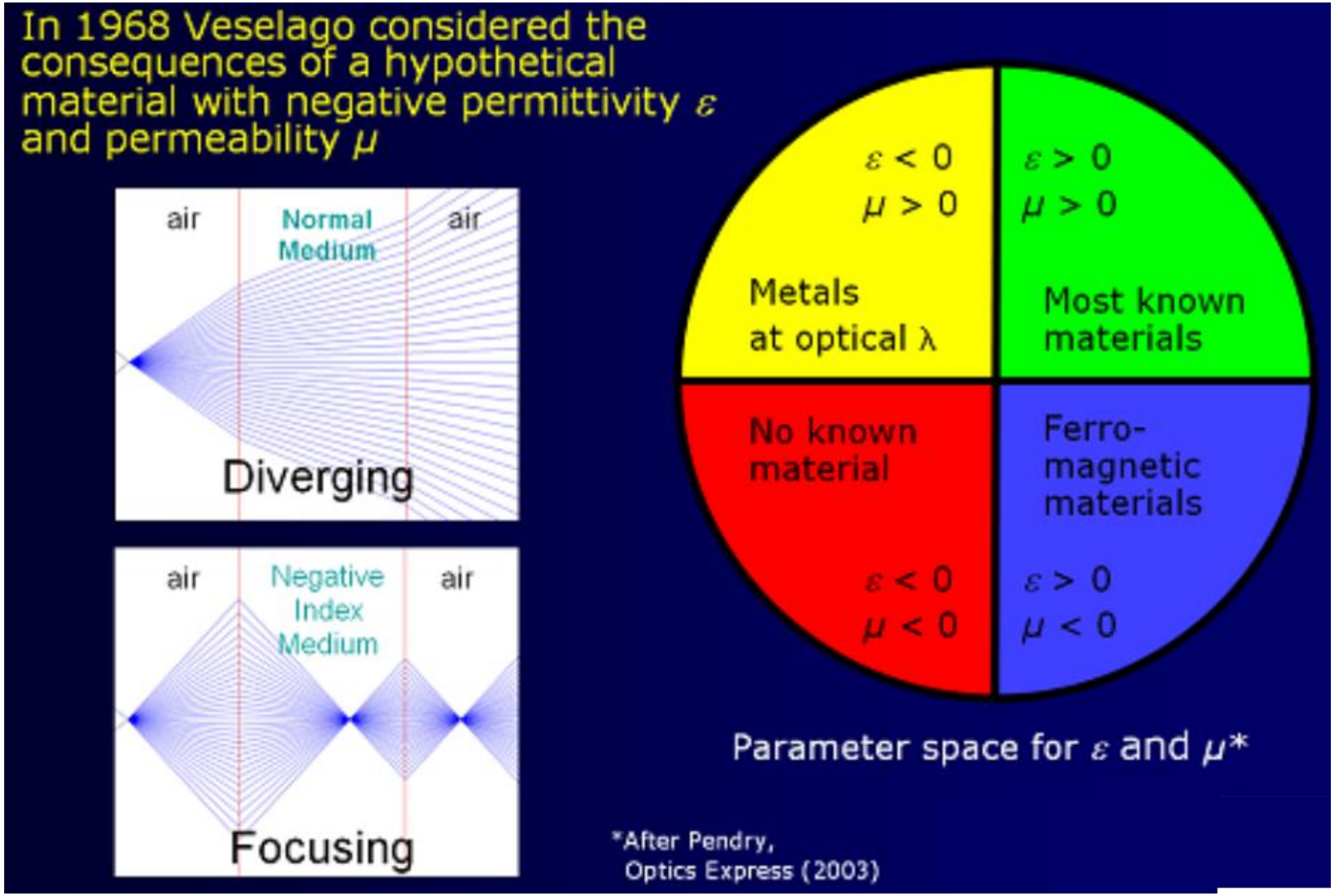
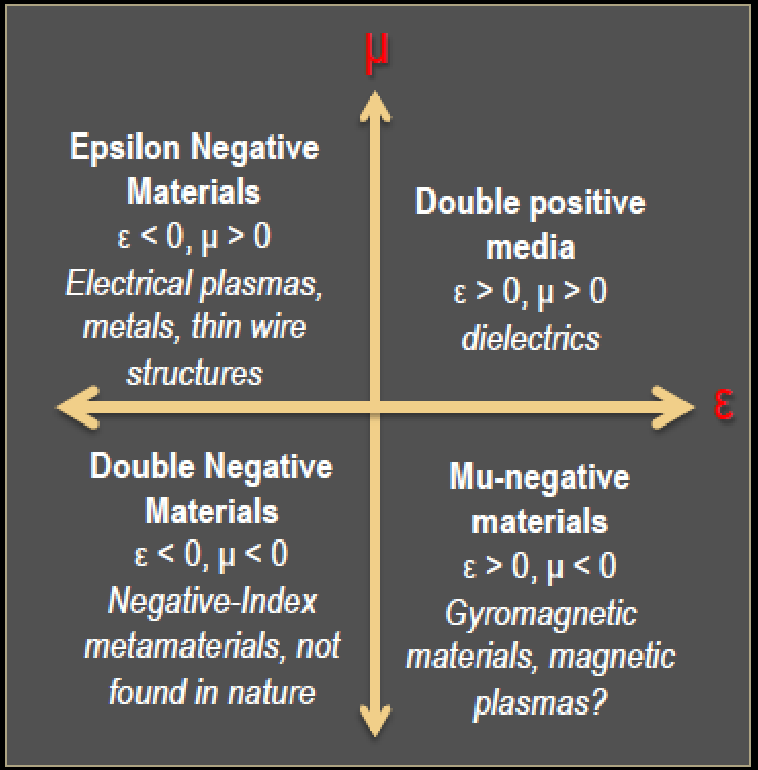


Typical internal transmittance (10 mm thickness) of an optical glass.



Typical internal transmittance (10 mm thickness)
an optical quartz glass for ultraviolet optics.



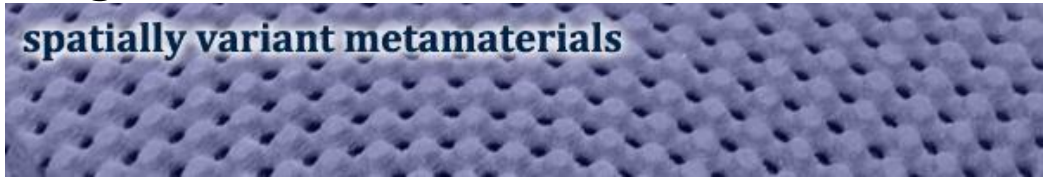


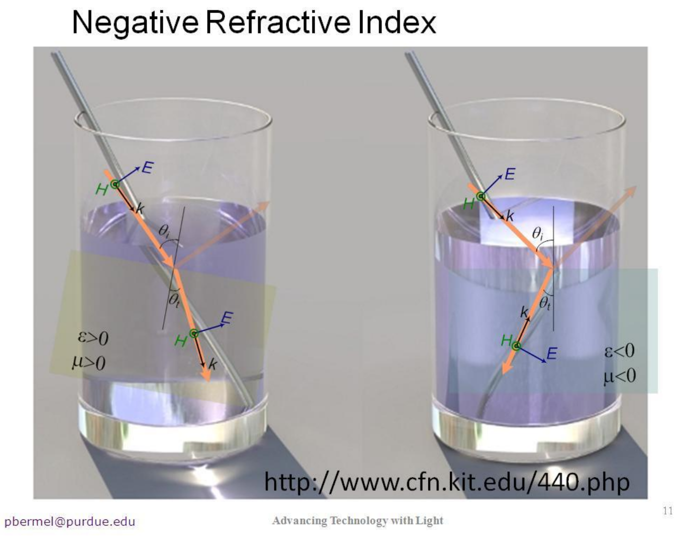
Classification of materials based on dielectric and magnetic properties

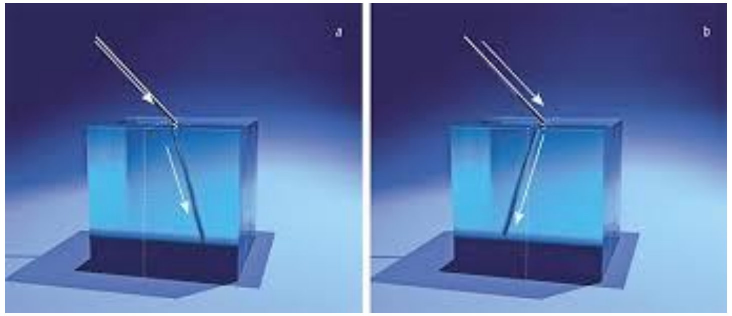
Materials with negative refractive index

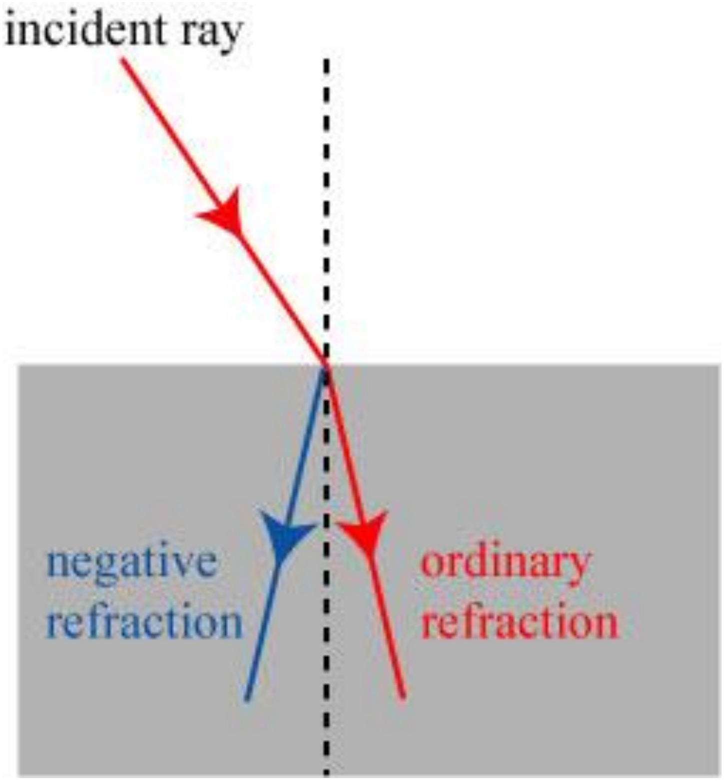
- **Negative-index metamaterial** or **negative-index material** (**NIM**) is a metamaterial whose refractive index for an electromagnetic wave has a negative value over some frequency range.
- **Negative refraction** is the name for an electromagnetic phenomenon where light rays are refracted at an interface in the reverse sense to that normally expected.
- Such an effect can be obtained using a **metamaterial** which has been designed to achieve a negative value for both (electric) permittivity ε and (magnetic) permeability μ, as in such cases the material can be assigned a negative refractive index. Such materials are sometimes called "double negative" materials.[1]
- "Metamaterials" may be described roughly as materials with a man-made structure on the scale of nanometers which gives them unusual optical properties not to be found in nature. Question: *Suppose you have constructed a piece of metamaterial of "everyday" size. What does it 'look' like to the unaided human eye?*
- metamaterials have the potential to produce interesting visual effects — including, possibly, invisibility!

https://www.sciencedirect.com/science/article/pii/S1369702106715735



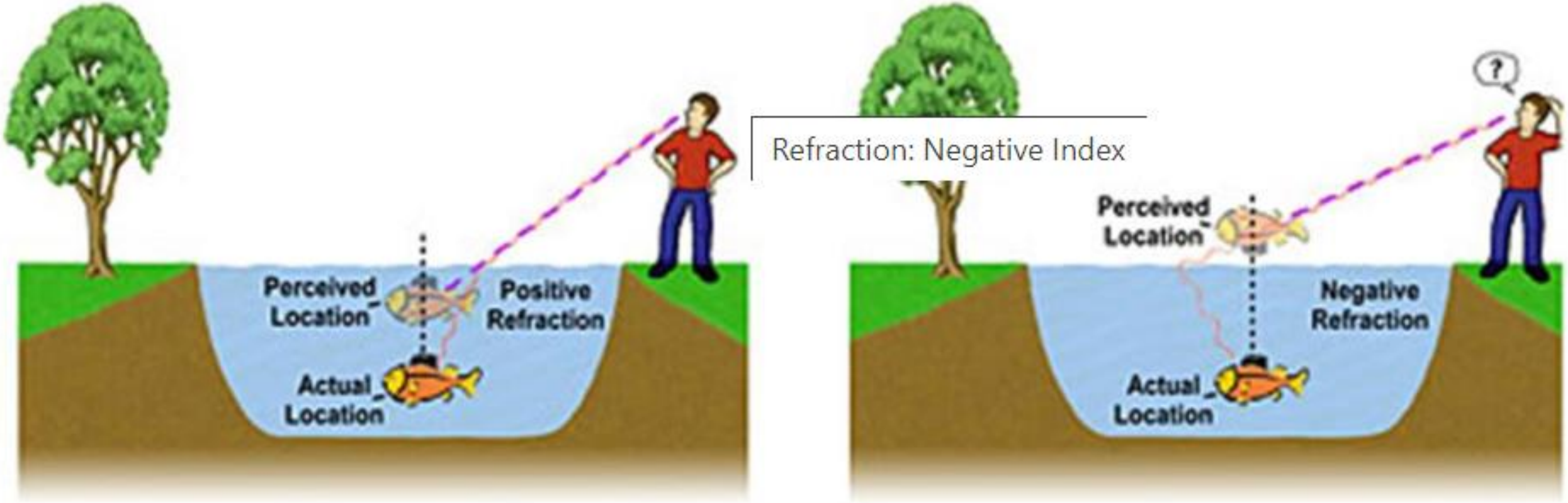






Electromagnetic “magic” of metamaterials

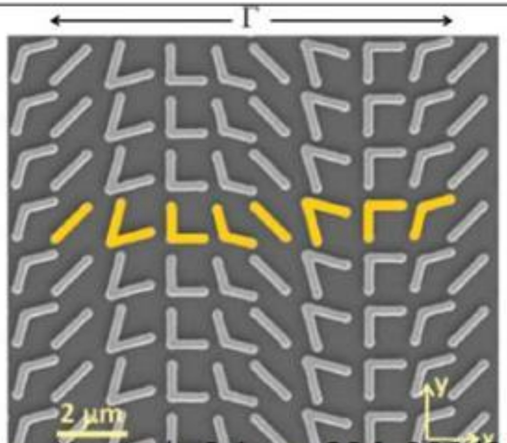
Refraction: Negative Index



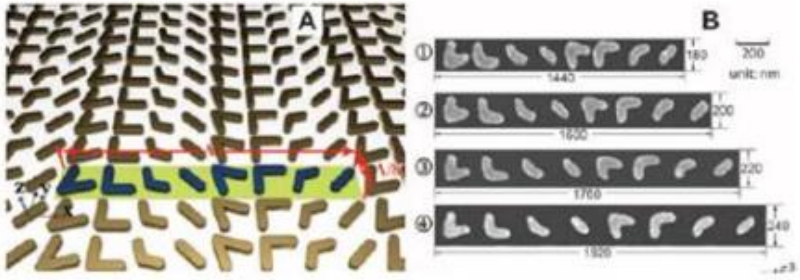
Refraction: Negative Index

Illustration: UC Berkeley

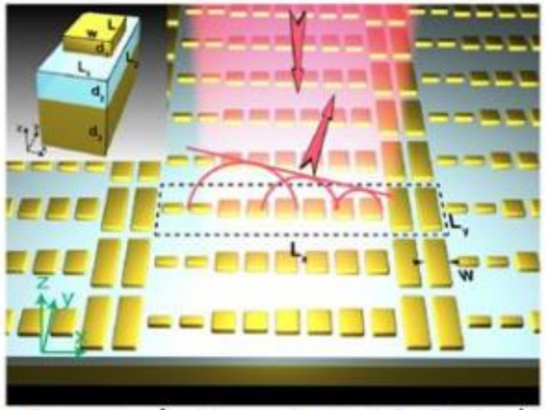
Generalized Snell's Law: Recent Work



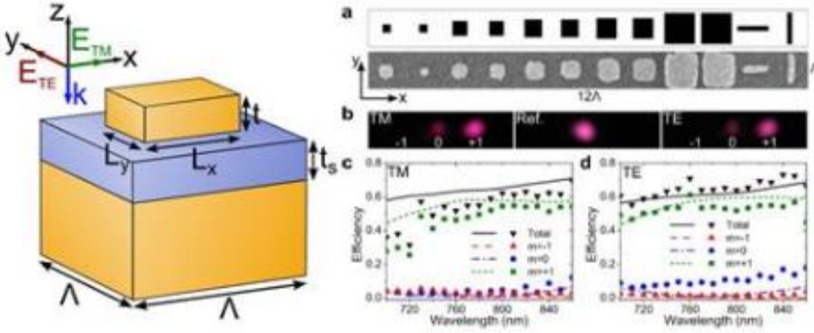
Nanfang Yu *et al.*, *Science* **334**, 333 (2011).



Xingjie Ni *et al.*, *Science* **335**, 427 (2012).



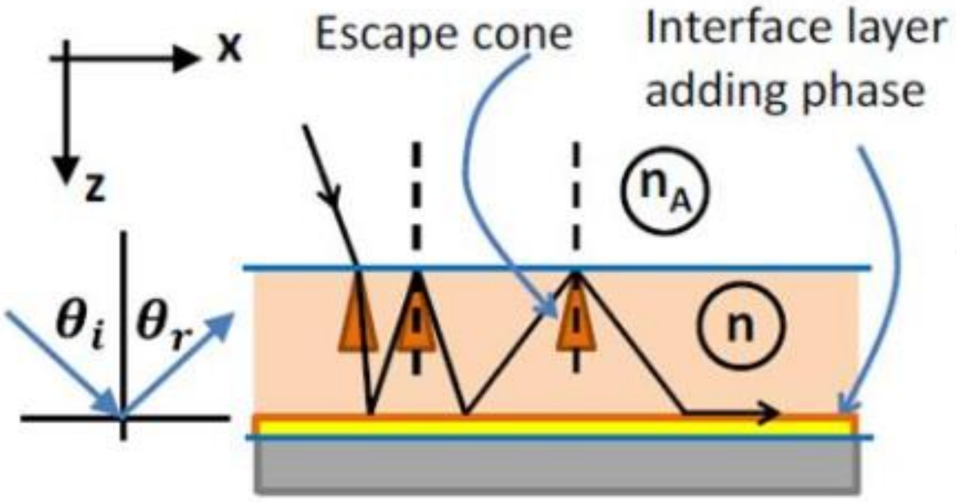
Shulin Sun *et al.*, *Nano Lett.* **12**, 6263 (2012).

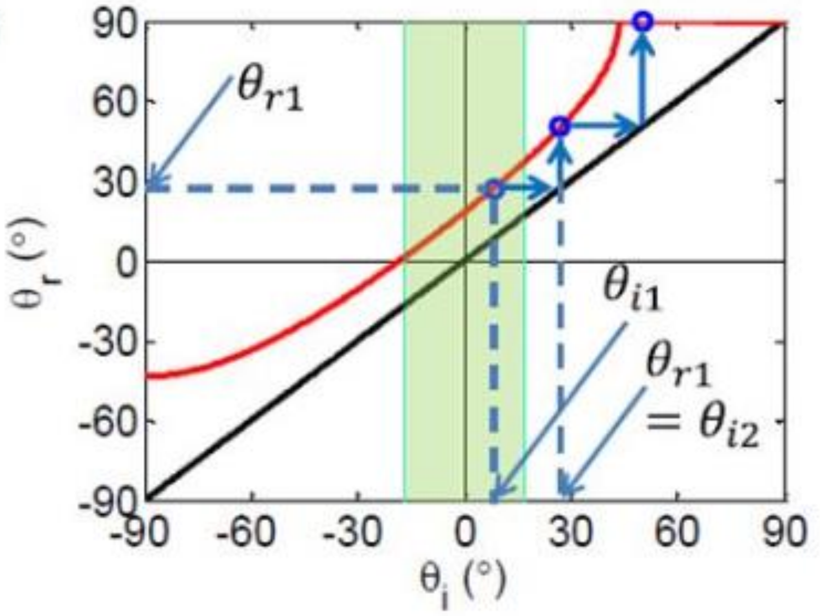


Anders Pors *et al.*, *Sci. Rep.* **3**, 2155 (2013).

Ge

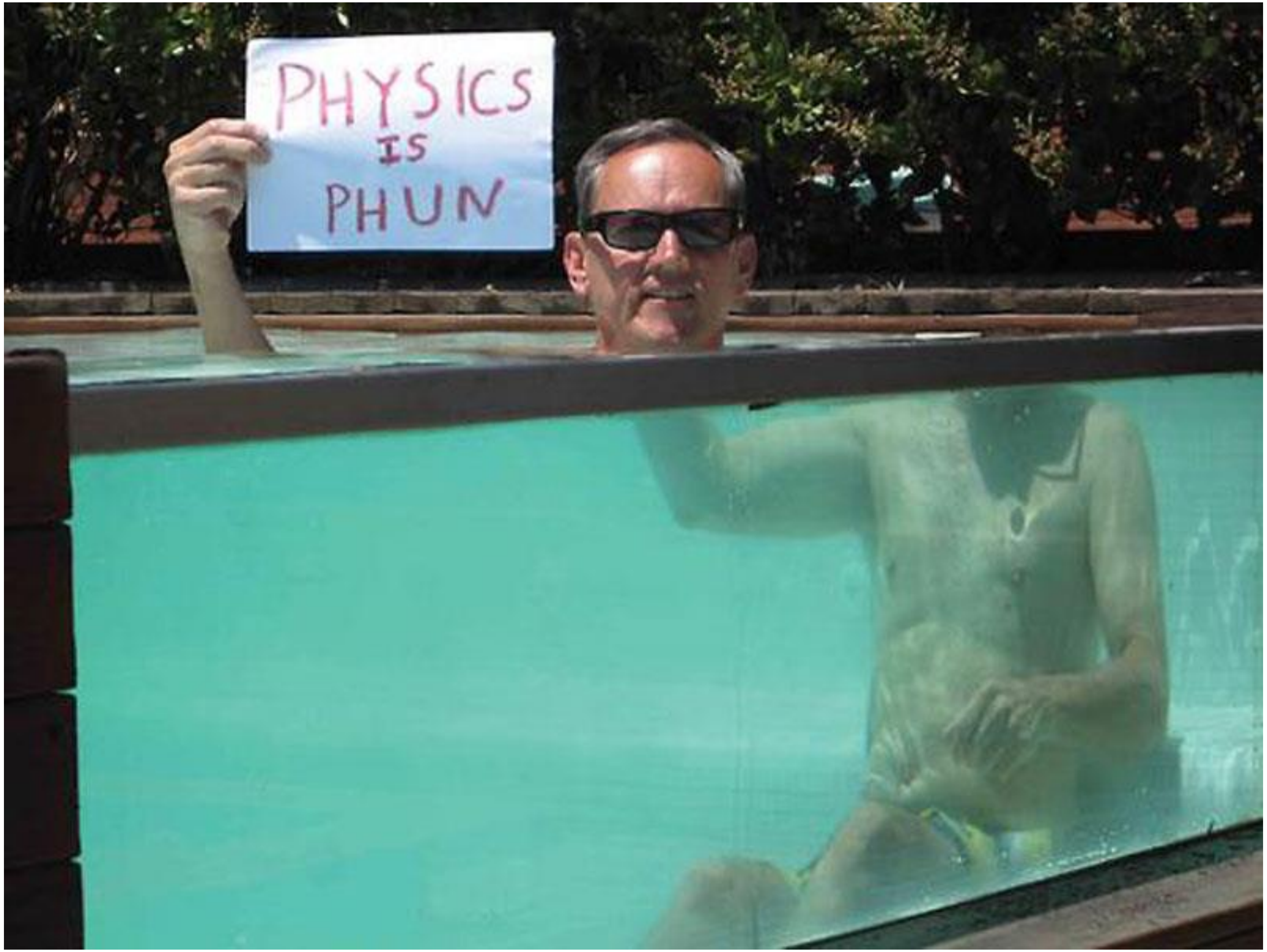
Ultra-thin Metasurface Absorbers/Emitters





Metasurface bends light at each reflection

Complete coupling with external radiation in ultrathin layers


PHYSICS
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Making objects invisible is no longer the stuff of fantasy but a fast-evolving science.

Essay example: Metamaterials and the Science of Invisibility — Prof. John Pendry

https://www.youtube.com/watch?v=f0iZraLdNuM

https://www.sciencedirect.com/science/article/pii/S1631070509000243

metamaterials—engineered materials that can bend rays of light around an object to make it undetectable

BUT

https://phys.org/news/2019-04-route-invisibility-metamaterials.html

Other essay titles

- Active devices and applications in sensing – review and recent perspectives
- Passive vs Active Sensors

Example Passive and active sensors in Remote Sensing https://gisgeography.com/passive-active-sensors-remote-sensing/

- *Peixoto, A.C.; Silva, A.F. (2017). "Smart devices: Micro- and nanosensors". Bioinspired Materials for Medical Applications. Braga, Portugal: Elsevier Ltd. pp. 297–329. ISBN 978-0-08-100741-9.* "section 11.4.6 Optical sensors", *ScienceDirect*

- Improvements in magnetic resonance imaging (MRI)
- Super-resolution microscopy (metamaterial lenses and superlenses)

Applied Plastics Engineering Handbook
https://www.sciencedirect.com/science/article/pii/B9780323390408000092

9.2.2.1 Separation of Plastic Resins

9.2.2.1.1 Manual

Perhaps the most basic separation technique and still the most commonly employed around the world is to utilize manpower to separate the plastics. An activity not limited to operations in developing countries, manual separation is employed in many US materials recovery facilities (MRFs) and other operations [74]. This low-tech option sees individuals sorting parts using predefined characteristics. For instance, HDPE milk and PET pop bottles may be extracted from household waste by hand as they are visually readily identifiable.

9.2.2.1.2 Density

Float-sink segregation uses density to separate different plastics. Parts are ground into small pieces and placed into a vessel containing a liquid. Those plastics with a density lower than that of the liquid will float whereas those with a density higher than the liquid will sink. Simple liquids such as water can be used in some situations but a saline solution, where the density can be more tightly controlled, is typically required to optimize resin separation [75]. Table 9.3 lists the density of the base resins of those plastics classified by SPI RICs [24].

Density separation is complicated in many cases because the density ranges of two given plastics may cross. Separation is further complicated by the incorporation of fillers, air (in foams), adhesives or other additives in some plastics as they can substantially change the density. For example, 15% talc filled PP has a density similar to that of ABS (1.02–1.20 g cm^{-3}) and may be used in similar applications resulting in a difficult mixture to separate [76]. An alternative to simple density separation would be required

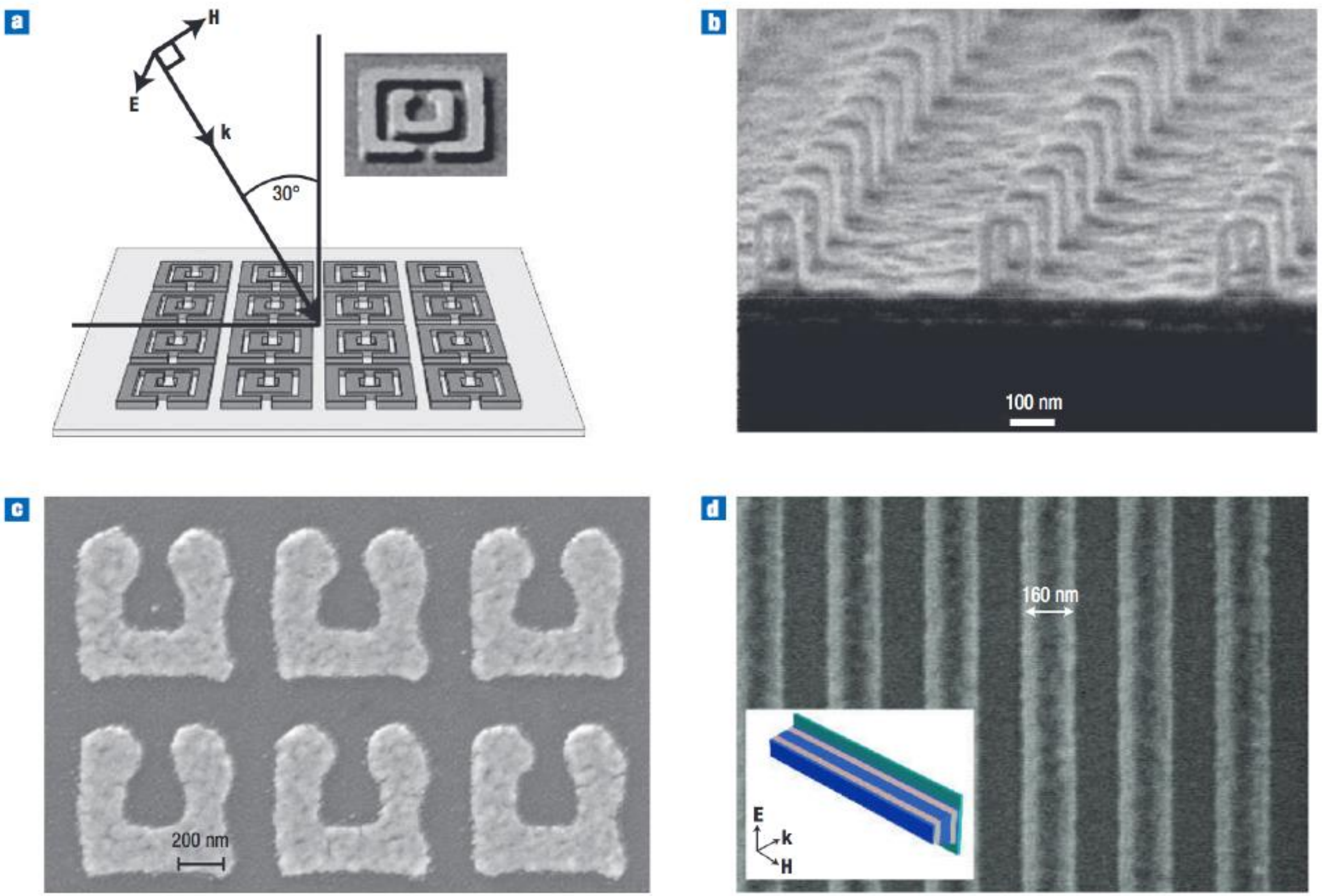
Air classification also uses density as the characteristic by which different plastics may be separated. A blast of air is blown through a steady stream of falling ground, mixed plastics. The dense plastics continue to fall while expanded foams and other lighter materials are blown into a separate collector. This technique is typically used to separate plastics with significantly different densities whereas liquid based density separations may be tuned more tightly.

9.2.2.1.3 Optical

Optical sensors can be used to separate plastics based on either color or transparency. This technique is used to separate bottles by color because clear PET has more value than colored PET. Developed from the coffee bean separators that are used to eliminate unripe green beans from the mix, these computer-controlled systems can rapidly differentiate between the various hues of the plastic regrind. The color of each piece of plastic is quickly established using a type of CCD camera and is either allowed to flow downward or is ejected with a puff of air into the *reject* or *collection* pile. Satake [77], for example, produces equipment that is specifically designed to separate plastics by color but their main business is still from the agricultural industry. Satake's Scan-Master IE, SE, and DE Optical Sorters are used to differentiate the colors of HDPE and PET materials in recycling operations.

9.2.2.1.4 Spectroscopic

Plastics identification by spectroscopic techniques has increasingly focused on the use of near-infrared and Raman spectroscopic techniques. LLA Instruments, in conjunction with Daimler–Chrysler [78]



Terahertz and optical magnetic metamaterials. a) double SSR with THz response. b) staple metamaterial with mid-IR magnetic resonance. c) single SRRs with negative permeability in the IR. d) Paired silver strips with negative permeability at 725 nm. Shalaev, V. (2007). Optical negative-index metamaterials. Nature Photonics, 1, 41-48. 12

http://faculty.washington.edu/goussiou/486_W15/Harvey_NIM.pdf

II.B PLATICS

Application: POF – plastic optical fiber

Increase of the necessity of installing optical systems in local environment (100 m).

For example : - Company (LAN)
- Vehicle (multimedia system, safety system)
- Home (FTTH, domotic, lighting technology) –Automation for home
- Aerospace (sensing)

⇒ **Development of cheaper optical systems and, in particular, a cheaper optical fibre.**

⇒ **POF fibres** (Polymer Optical Fibres)

Advantages : - Insensible to electromagnetic interferences.
- light, easy to install
- more cumbersome

Source to fiber coupling

We define the *coupling efficiency q* as the fraction of source power that is coupled into the fiber

$$\eta = \frac{P_f}{P_s}$$

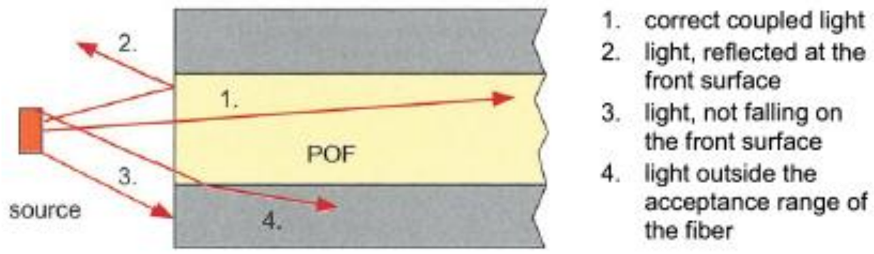


Fig. 6.7: Causes for losses when coupling to the POF

P_f is the power in the fiber and P_s, is the total power emitted by the source

The manufacturer specifies the optical power from the source *in the pigtail* and has optimized the coupling into the fiber. Typical optical powers coupled into the pigtail range from microwatts to a few milliwatts.

Coupling losses

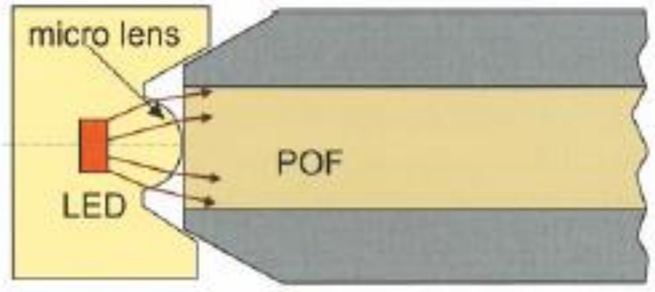


Fig. 6.10: Projection of the LED chip on to the POF via a micro-lens

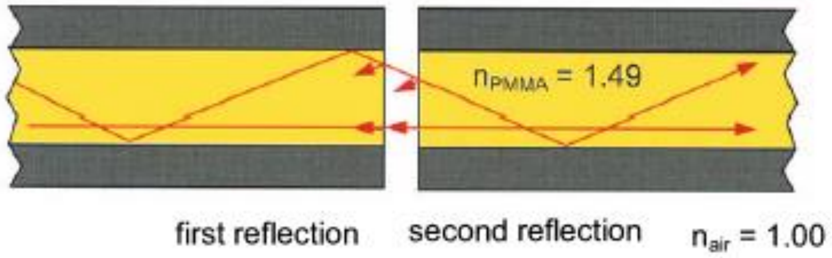


Fig. 6.35: Attenuation due to Fresnel reflection

For a vertical incidence, the reflection coefficient compared to air is as follows:

$$R = \left(\frac{n-1}{n+1}\right)^2 = 0.04$$

Fig. 6.30: Connector loss through differences in core diameter

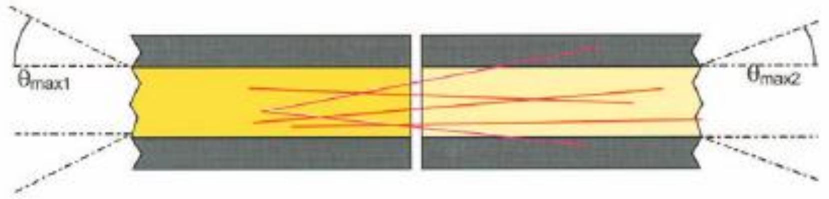


Fig. 6.31: Connector loss through differences in NA

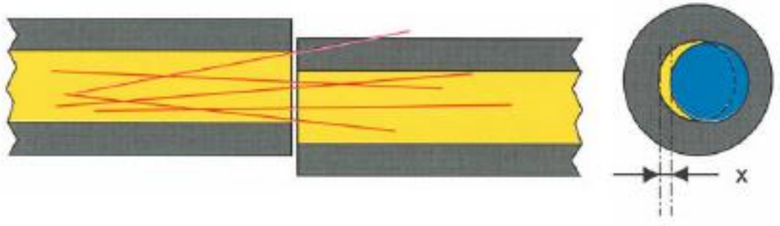


Fig. 6.32: Attenuation in the case of a lateral offset of fiber axes

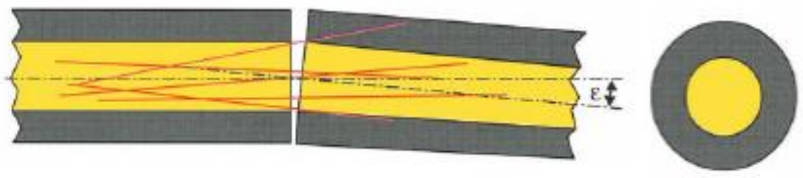


Fig. 6.34: Connector attenuation caused by an angle between the fiber axes

Coupling model

John Power – Optical Comm Syst

The spatial emission pattern from the source plays a key role in determining the value of light coupling efficiency

Generally, this pattern is two-dimensional and asymmetric for the edge-emitting LED and laser diode. The surface-emitting LED is symmetric in output.

Lambertian

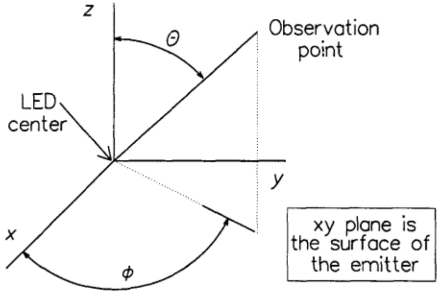
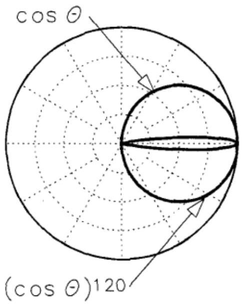


Figure 5.27 Emitter coordinate system.



Fiber	$r_s \leq a$	$r_s > a$
Step index	NA^2	$\mathrm{NA}^2 \left(\frac{a}{r_s}\right)^2$
Graded index	$\mathrm{NA}^2 \left[1 - \left(\frac{2}{g+2}\right)\left(\frac{r_s}{a}\right)^g\right]$	$\mathrm{NA}^2 \left(\frac{a}{r_s}\right)^2 \left(\frac{g}{g+2}\right)$

Table 5.2 Summary of coupling efficiencies (Lambertian emitter).

Rs– radius of the emitter surface
G– refractive index profile parameter

Fresnel reflection

The coupling efficiencies calculated above assume a perfect match of refractive index at the core-light source interface. The lack of such a match leads to additional losses due to the *Fresnel reflection losses* at the interface. Assuming perpendicular incidence, the power transmittance T at the interface between the medium and the core of a step-index fiber is

$$T = 1 - \left(\frac{n_1 - n}{n_1 + n}\right)^2$$

where n_1 is the index of refraction of the core and n is index of refraction of medium outside of the fiber core. Frequently a drop of index matching liquid is placed at this interface to minimize these losses. Another technique to reduce the reflection is to cut the fiber ends at a non-perpendicular angle to avoid retroreflections.

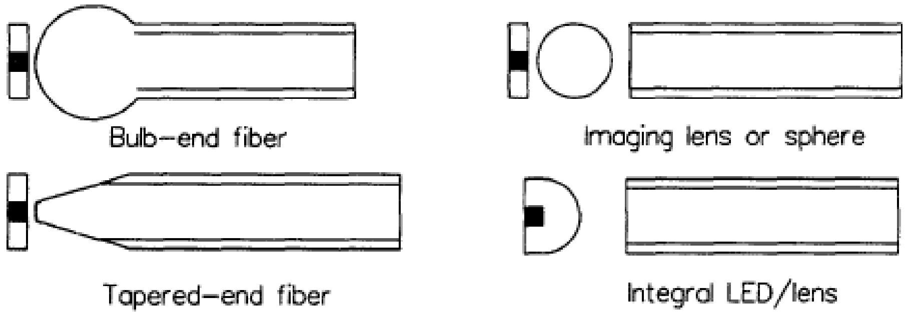
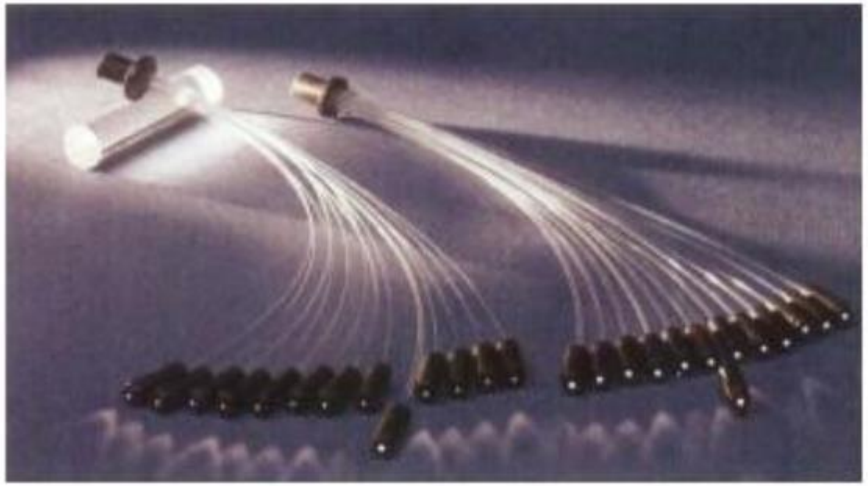


Figure 5.29 Source-fiber coupling using lenses.

POF fibres are used for lighting technology



From « Polymer Optical Fibers for Data Communication », Daum, Krauser, Zamzow and O. Ziemann, springer 2005.

Essay example: Applications with POF in lighting technology

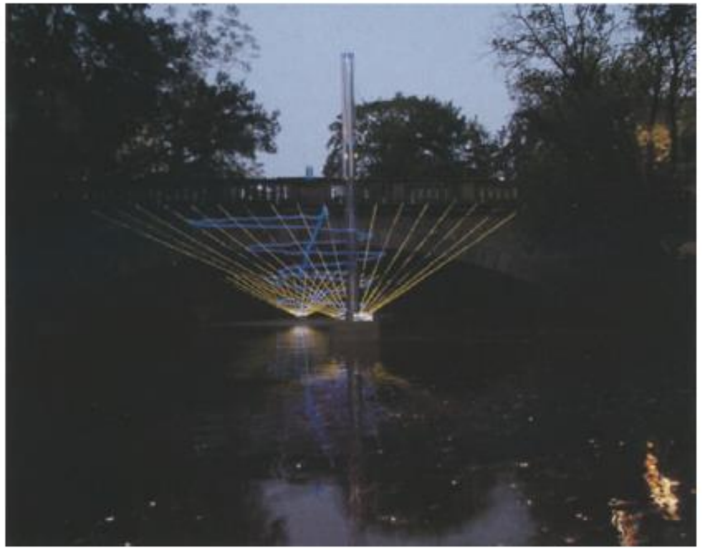


Fig. 10.20: Use of sidelight fibers in lighting technology (LBM Lichtleit-Fasertechnik Berching)

Fig. 10.31: Curved planar waveguide

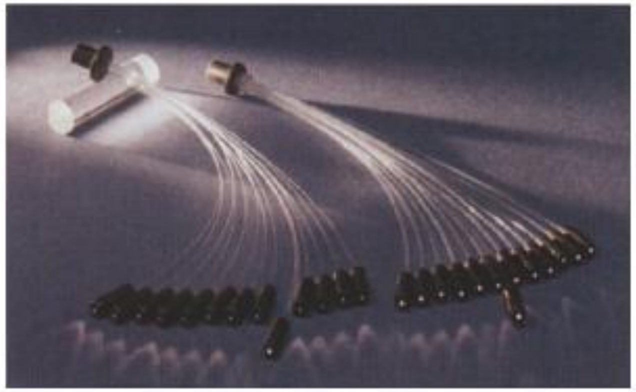


Fig. 10.17: POF bundles with individually capped fiber ends, e.g. for use as a ceiling star light ([Nich00])

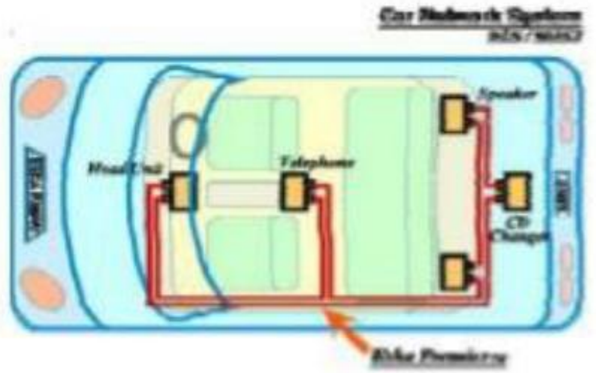
Olaf Ziemann

Polymer Optical Fiber Application Center of the FH Nürnberg

Prof. Dr.-Ing. Olaf Ziemann (35) studied physics at the University of Leipzig. Between 1990 and 1995 he did his doctorate degree at the Technical University of Ilmenau in the field of optical telecommunications engineering. His fields of work were optical super-heterodyne reception and optical code multiplexing. During this period he was recipient of a scholarship from the University Foundation of the German People. Between 1995 and March 2001 he worked in the research center of the Deutsche Telekom (T-Nova) in the specialized areas of hybrid access networks and building networks. Since 1996 he has been the chairman of the Information Technology Society-Sub-Committee "Polymer Optical Fibers" (ITG-SC 5.4.1). Since the beginning of 2001 he has been the scientific director of the POF-AC at the Nuremberg University of Applied Sciences (FH Nürnberg) and Prof. since Nov. 2001.

POF in Automation

BMW : "We are using two bus systems, one for all **multimedia applications** and one for **connecting all of the sensors in the safety devices**. There is no price advantage for using POF instead of copper. The advantages for us are high data rates, reduced weight, less packaging and no problems with electromagnetic interference." *(Optics.org)*



From http://www.physics.iitm.ac.in/~labs/iitmspie/Nampoori.pdf

From the BMW 7 booklet

Essay example: Applications with POF in automotive

Digital devices in automobiles - evolution

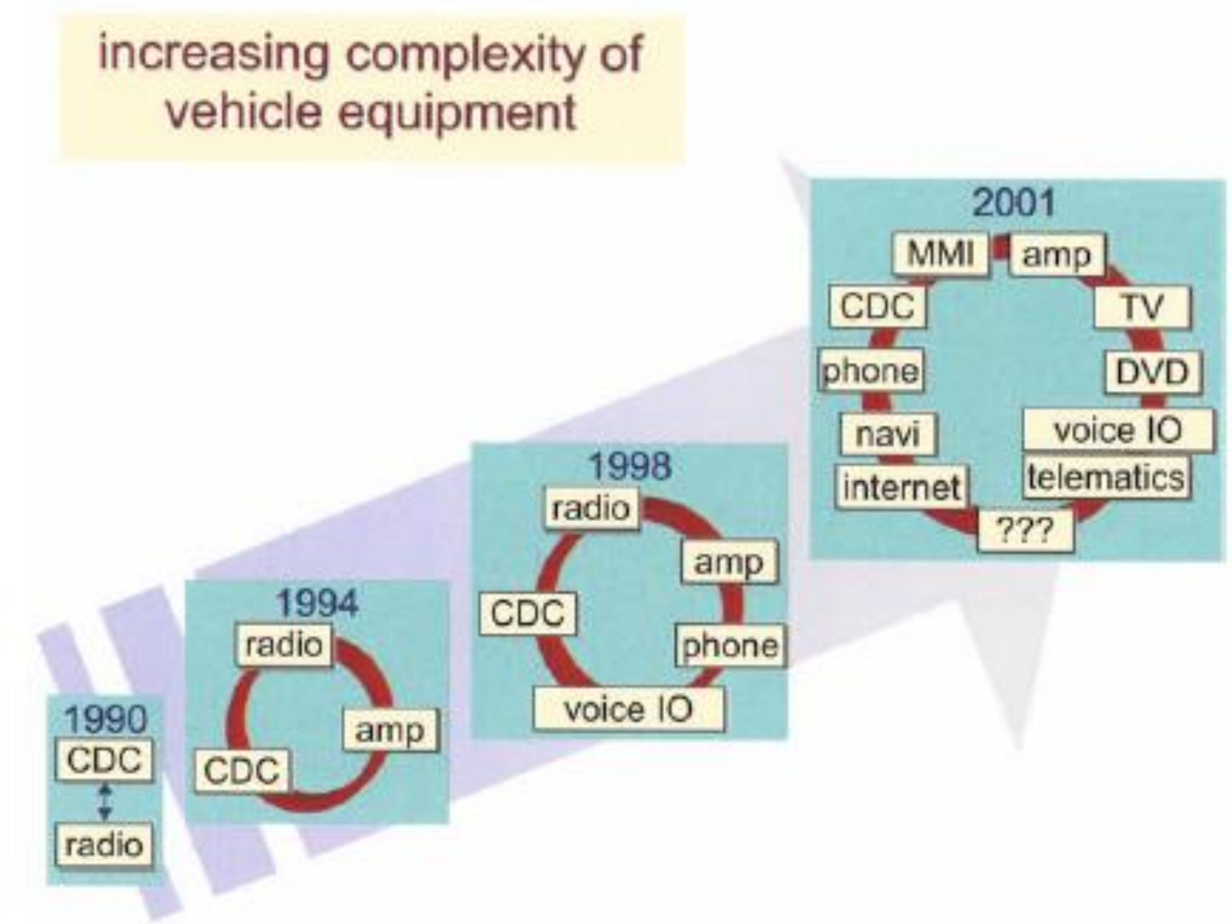
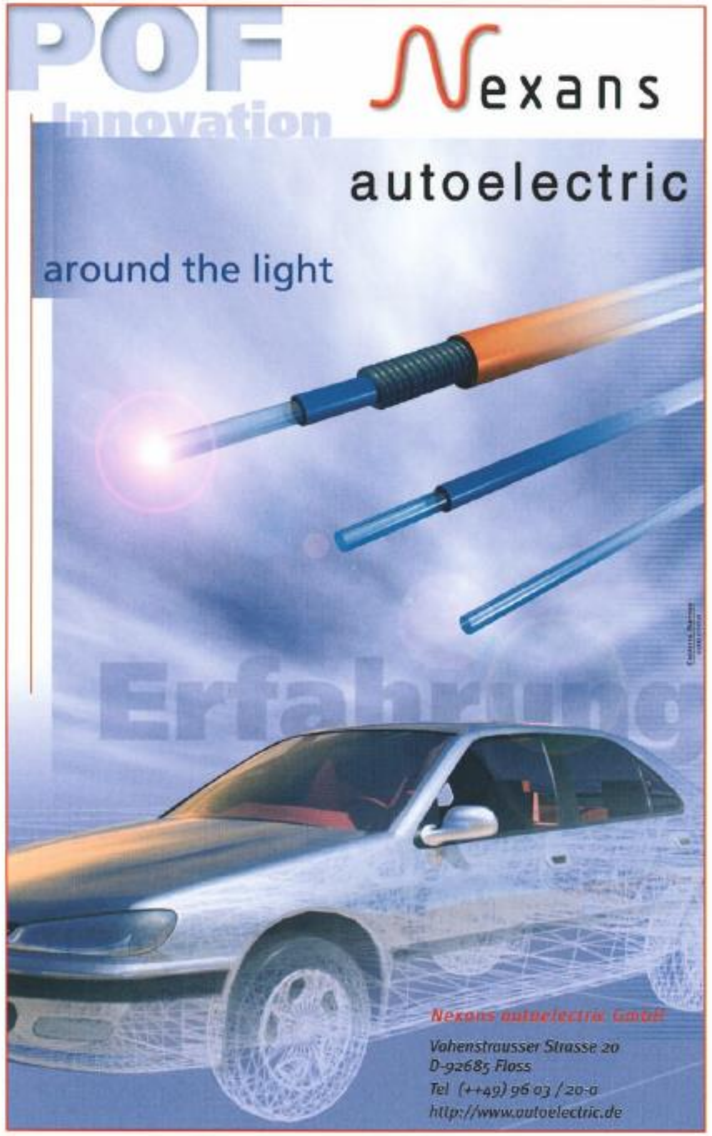


Fig. 10.3: Development of digital devices in automobiles



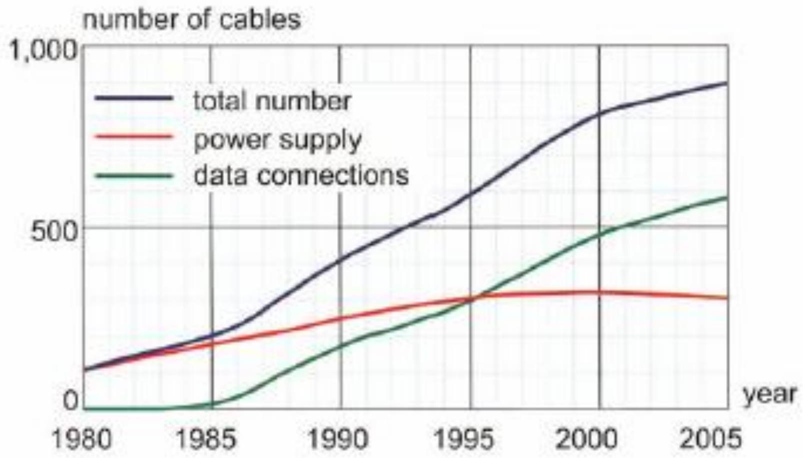


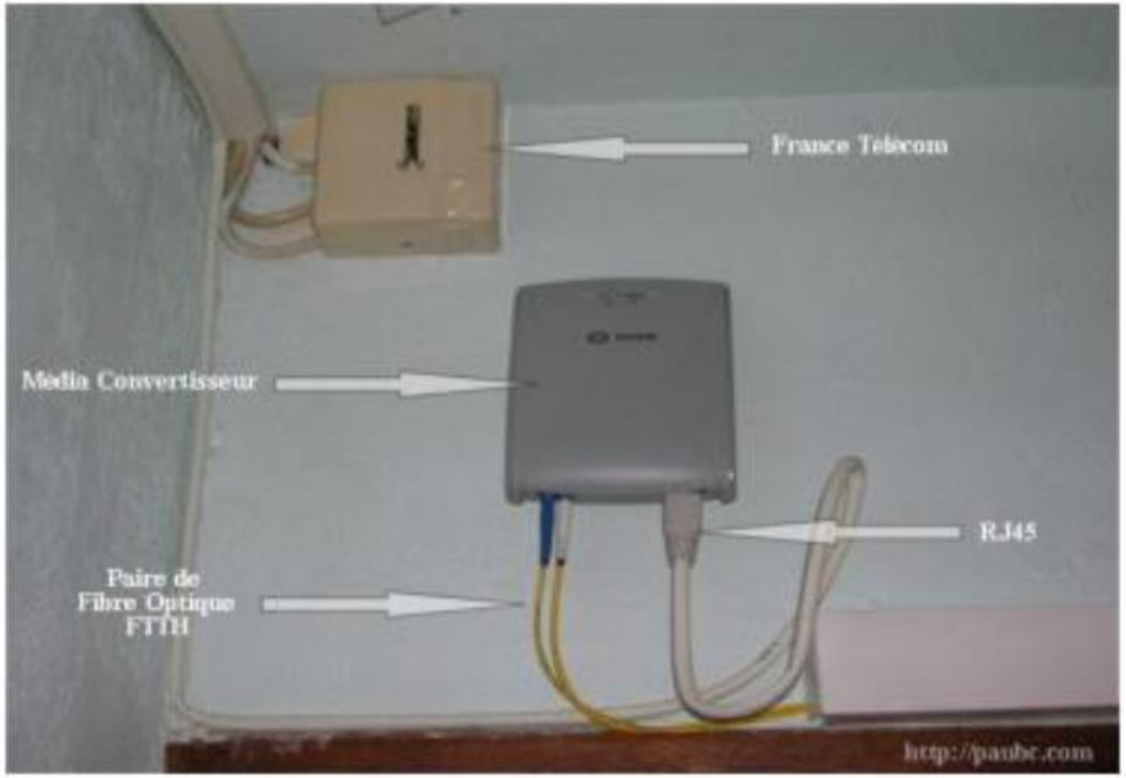
Fig. 10.1: Number of cables in cars

Since 1997, optical components for use in automobiles are available from Harman/Becker Automotive Systems([Schö01]). Since 1998, such components are standard features e.g. in the DaimlerChrysler Vaneo as of 2001, Fig. 10.2.

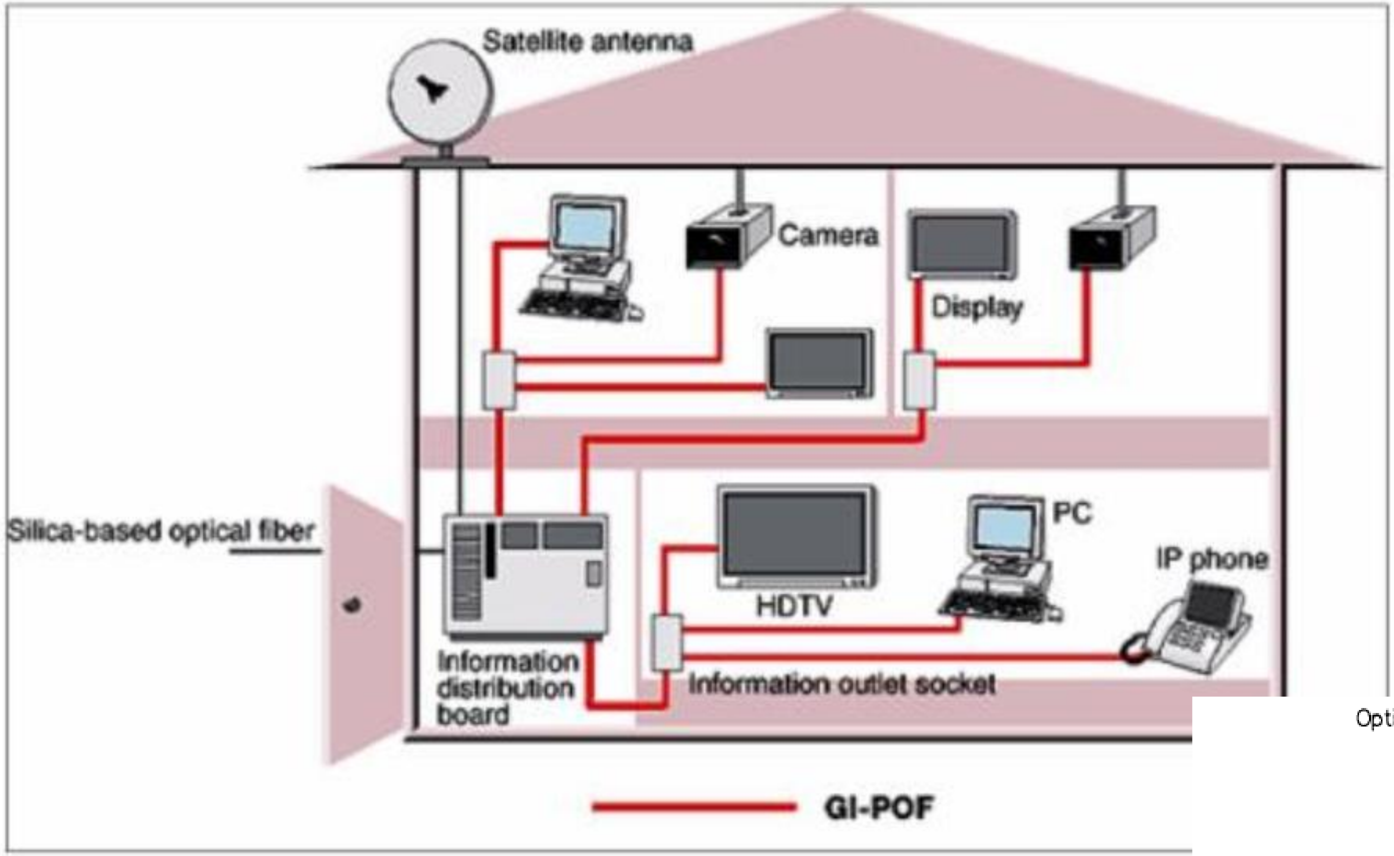
Fig. 10.2: Vaneo (DaimlerChrysler 2001)

POF fibres is a key element in FTTH systems

FTTH : Fibre To The Home



POF fibres in domotic: system centralization



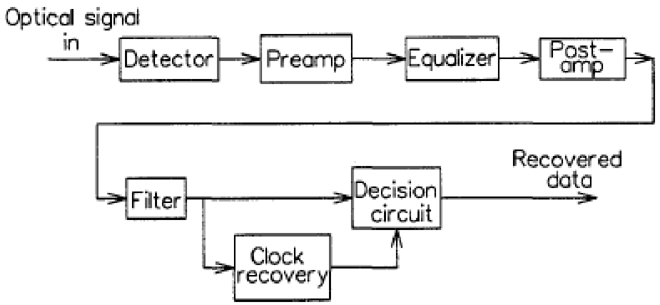
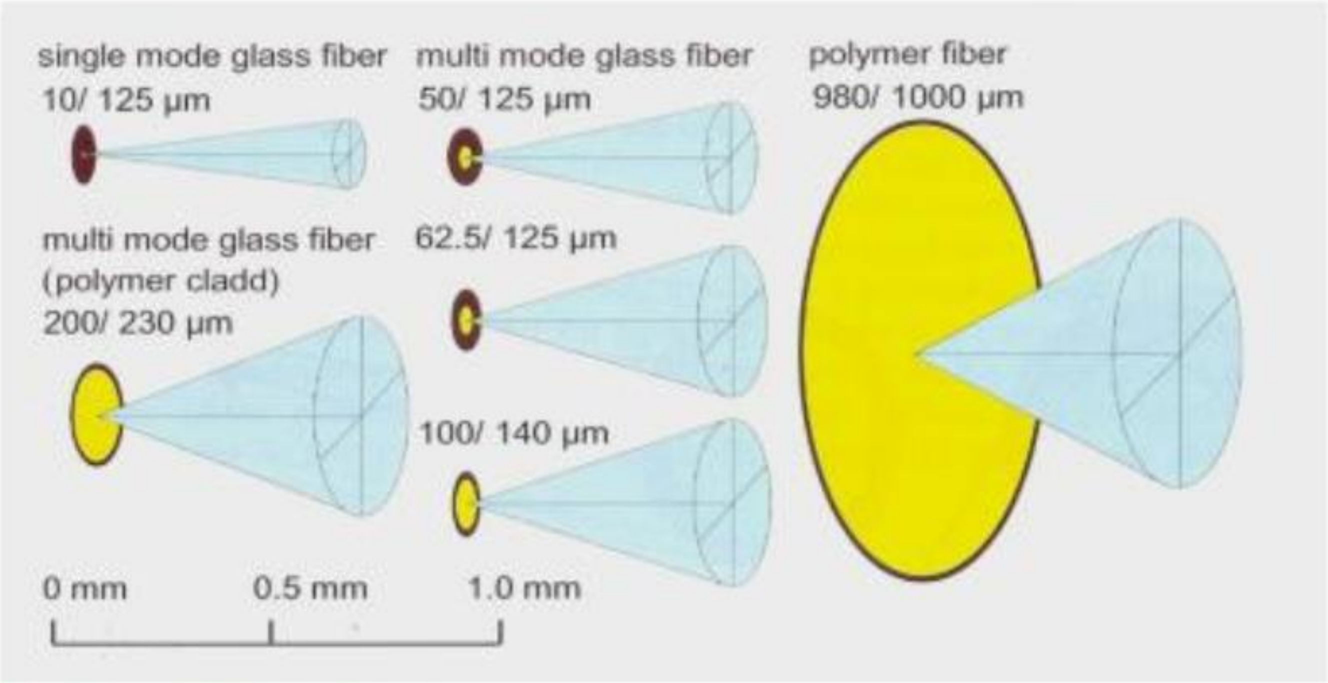


Figure 6.1 Block diagram of a representative optical receiver for a digital data link.

POF dimensions are big compared to glass fibres

POF fibres are characterized by - a high numerical aperture : (0.50 to 0.90)
- a high core diameter (1 mm)

⇒ Less demanding for connection technology and easier to manufacture
⇒ The cost is reduced compared to glass fibres



⇒ Multimode fibres
⇒ Ray optics can be used

N=4380000 for λ=520nm, NA=0.50 and d=980µm

From « Polymer Optical Fibers for Data Communication », Daum, Krauser, Zamzow and O. Ziemann, springer 2005.

The theory developed for glass fibres is still applicable

The mode calculus is identical to glass fibre

In particular, **two phenomena** are not negligible in POF fibres :

- **Mode coupling** : energy transfer between propagation modes
- **Mode conversion** : a mode can convert into another mode when propagating

Losses are due to intrinsic and extrinsic phenomena

Intrinsic losses

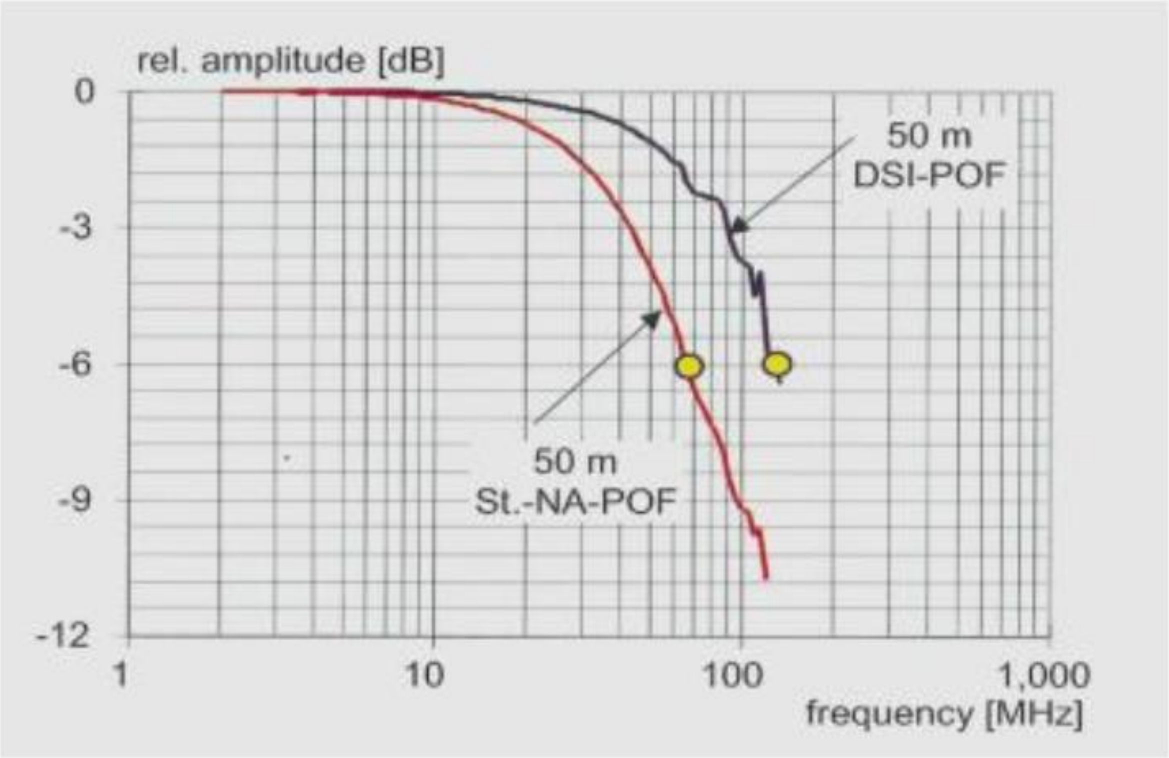
- Absorption through electronic transition (UV)
- Absorption through molecular vibrations (C-H in POF, IR)
- Rayleigh scattering (proportional to $1/\lambda^4$)

Extrinsic losses

- Absorption by doping atoms/molecules
- Scattering at impurities in the fibre and imperfections at the core/cladding interface

POF with lower NA give a larger bandwidth

Lower NA decreases the number of modes ⇒ the intermodal dispersion is reduced ⇒ The bandwidth is increased

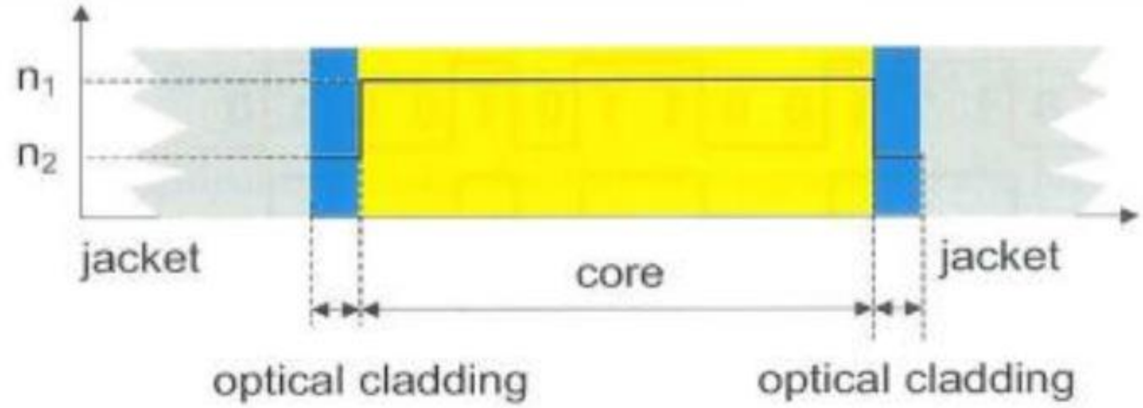


From « Polymer Optical Fibers for Data Communication », Daum, Krauser, Zamzow and O. Ziemann, springer 2005.

Nowadays system performances

- The first POF was manufactured by DuPont at the end of the 60's (1000 dB/km).
- During the 70's: reduction to 125 dB/km
- Meanwhile, silica fibres (1 dB/km) have been developed for long-range transmission. Short-range transmission was adequatly operated with copper wires up to 10 Mbit/s ⇒ POF without interest for long-rang transmission.
- During the 90's, the increasing demand of bandwidth for short-range networks (home, company, cars,…) generated a market for POF fibres
- POF fibres have continuously been upgraded to meet the increasing demand of bandwidth

The first POF was a step-index fibre (SI-POF)



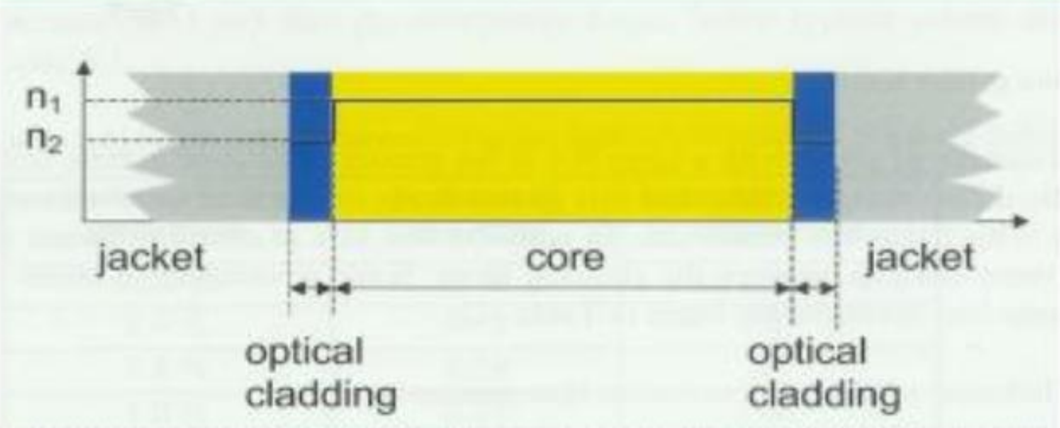
From « Polymer Optical Fibers for Data Communication », Daum, Krauser, Zamzow and O. Ziemann, springer 2005.

+ NA = 0.50 ⇒ easy for injection and reduction bending losses
d = ± 1mm ⇒ easy for connection technology

- NA = 0.50 ⇒ low bandwidth due to high intermodal dispersion

⇒ BW = **40 MHz over 100m** (sufficient until the necessity of replacing copper wires for 155 Mbit/s bit rates over 50m (ATM)

Low-NA POF fibres increase the bandwidth



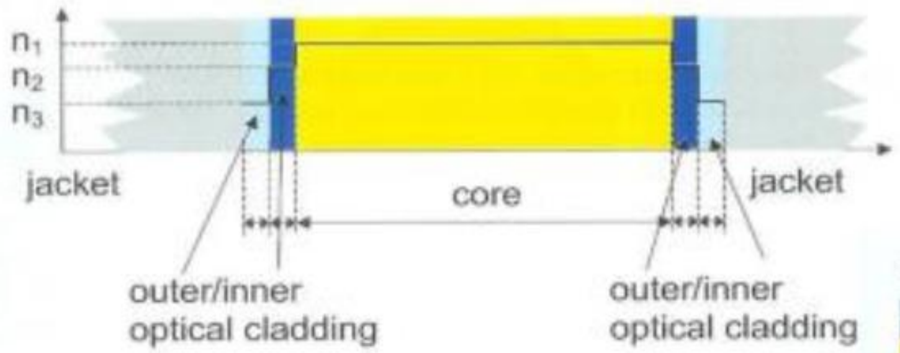
From « Polymer Optical Fibers for Data Communication », Daum, Krauser, Zamzow and O. Ziemann, springer 2005.

+ NA = 0.30 ($\Delta n < 2\%$) $\Rightarrow$ easy for injection and reduction bending losses
$\Rightarrow$ bandwidth is larger compared to standard POF
d = ± 1mm $\Rightarrow$ easy for connection technology

- NA = 0.30 $\Rightarrow$ high sensitivity to bending

$\Rightarrow$ BW = **100 MHz over 100m** (sufficient until the necessity of replacing copper wires for 155 Mbit/s bit rates over 50m (ATM))

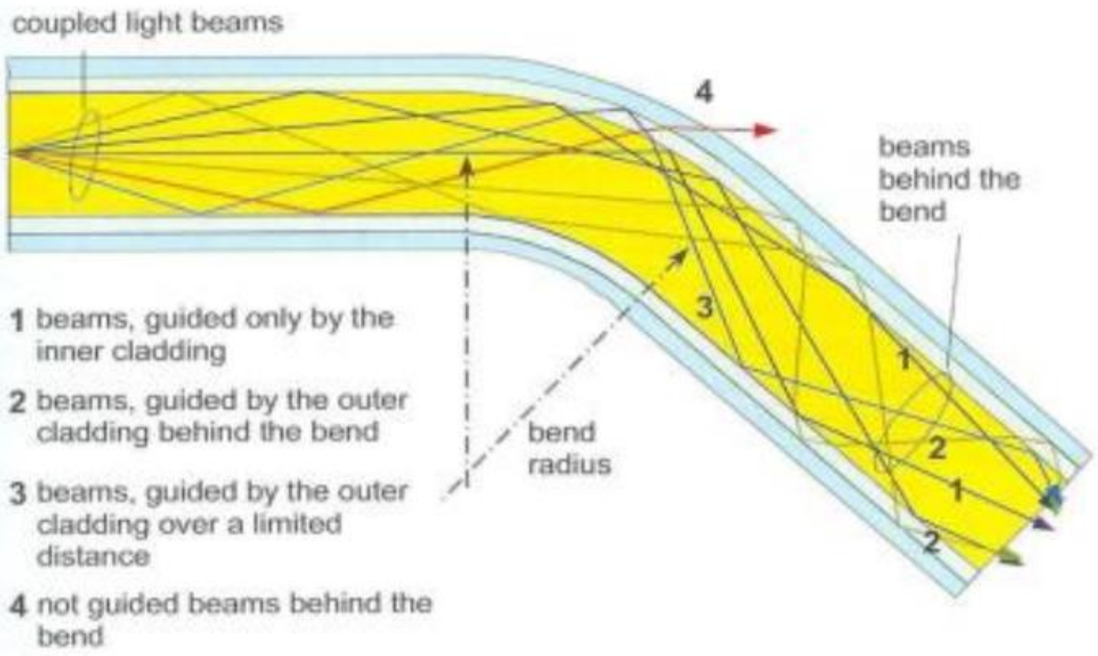
The bending sensitivity can be reduced using double-step index POF (DSI-POF)



NA = 0.30 ⇒ easy for injection and reduction bending losses

+

DSI configuration alleviates the bending losses

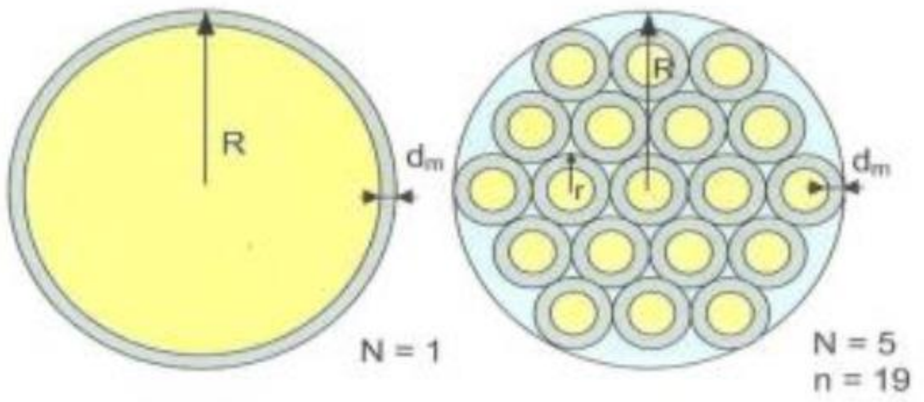


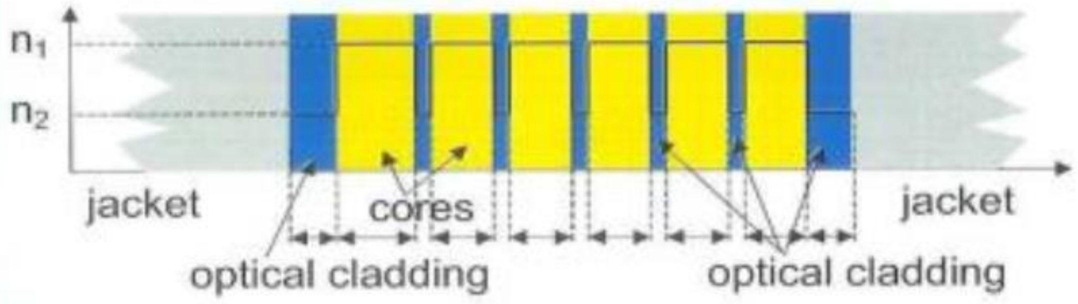
Figures from « Polymer Optical Fibers for Data Communication », Daum, Krauser, Zamzow and O. Ziemann, springer 2005.

Multicore POF fibres also alleviate the bending losses (MC-POF)

The fibre core can also be reduced to decrease the bending sensitivity but the advantage of easy and cheap connection technology is lost.

⇒ Solution: **MC-POF fibre**: a high number (19 to 200) of core+clading structures are put together to give an effective diameter of ± 1mm

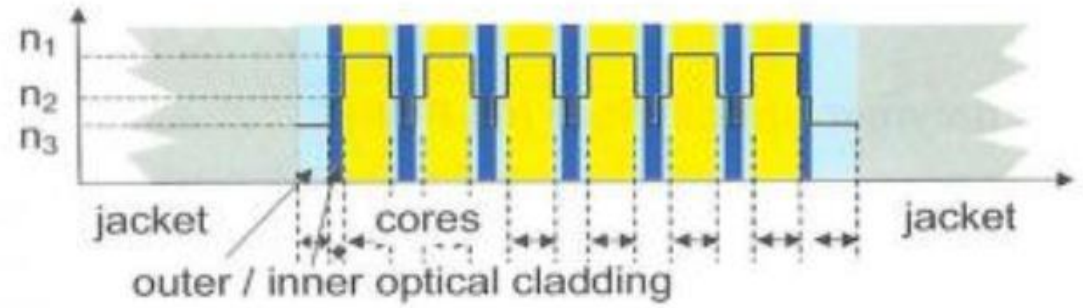


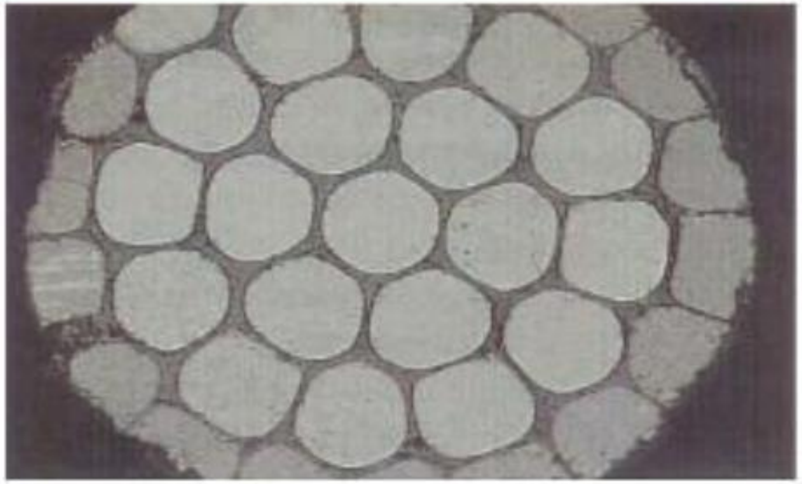


NA = 0.30

From « Polymer Optical Fibers for Data Communication », Daum, Krauser, Zamzow and O. Ziemann, springer 2005.

DSI-MC POF fibres also exist



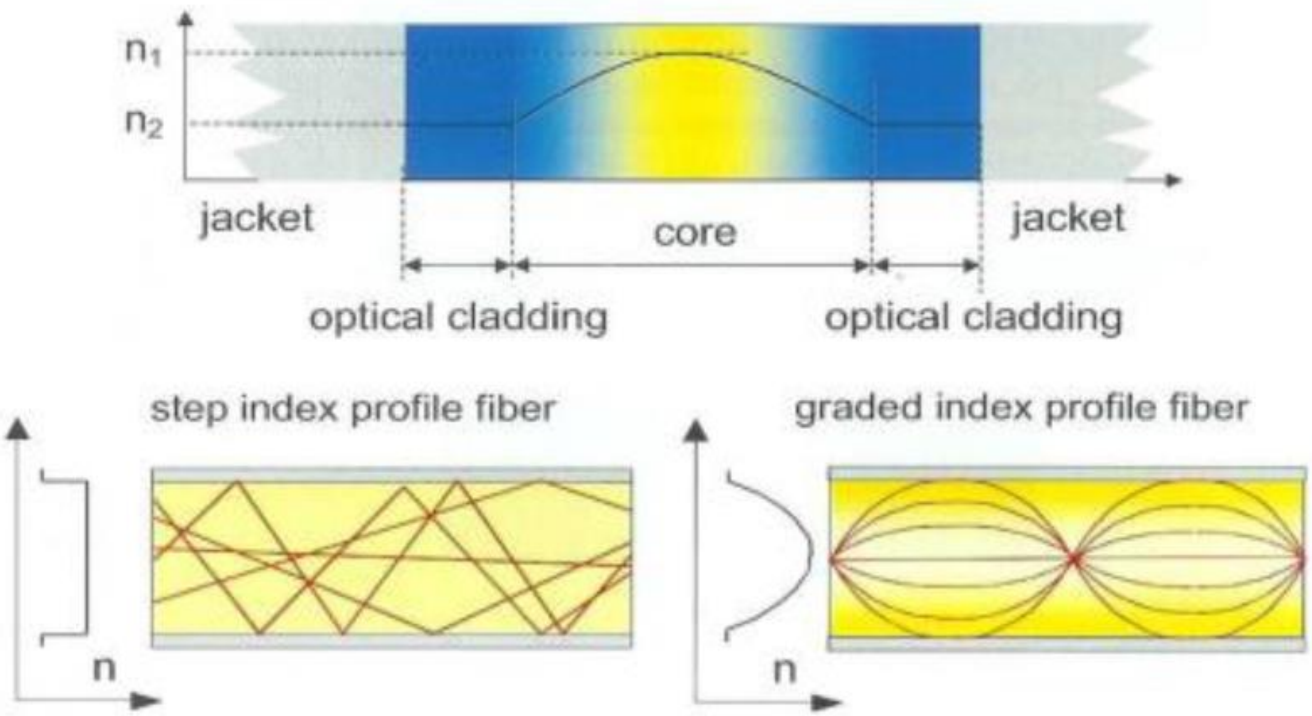


type	ref.	cores	index profile	NA	attenuation at 650 nm	bandwidth
NMC-1000	POF'94	19	SI	0.25	125 dB/km	170 MHz·100 m
-	POF'98	37	DSI	0.19	155 dB/km	700 MHz·50 m
-	POF'98	37	DSI	0.25	160 dB/km	-
-	POF'98	37	DSI	0.33	160 dB/km	-
NMC-1000	data'98	37	DSI	0.25	160 dB/km	500 MHz·50 m
PMC-1000	data'98	37	DSI	0.19	160 dB/km	-
PMC-1000	data'96	200	SI	0.15	270 dB/km	-
MCS-1000	data'97	217	SI	-	320 dB/km	-
-	POF'98	217	SI	0.50	160 dB/km	-
-	POF'98	217	SI	0.33	160 dB/km	-

The bandwidth is also increased in MC-POF by reducing the index difference

From « Polymer Optical Fibers for Data Communication », Daum, Krauser, Zamzow and O. Ziemann, springer 2005.

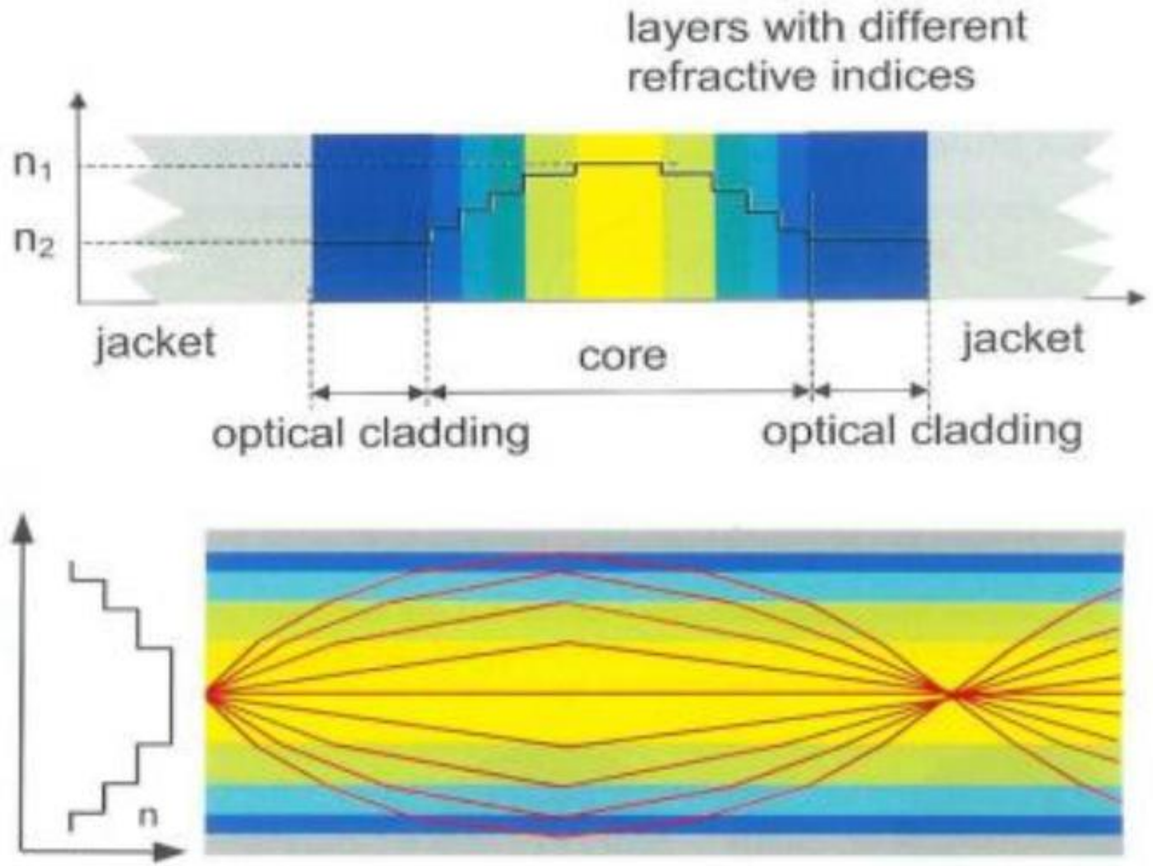
Higher bandwidth can be achieved by graded index POF fibres (GI-POF)



The bandwidth can be 2 or 3 times larger with the GI configuration
but it is rather difficult to manufacture and the profile deteriorates with time

Figures from « Polymer Optical Fibers for Data Communication », Daum, Krauser, Zamzow and O. Ziemann, springer 2005.

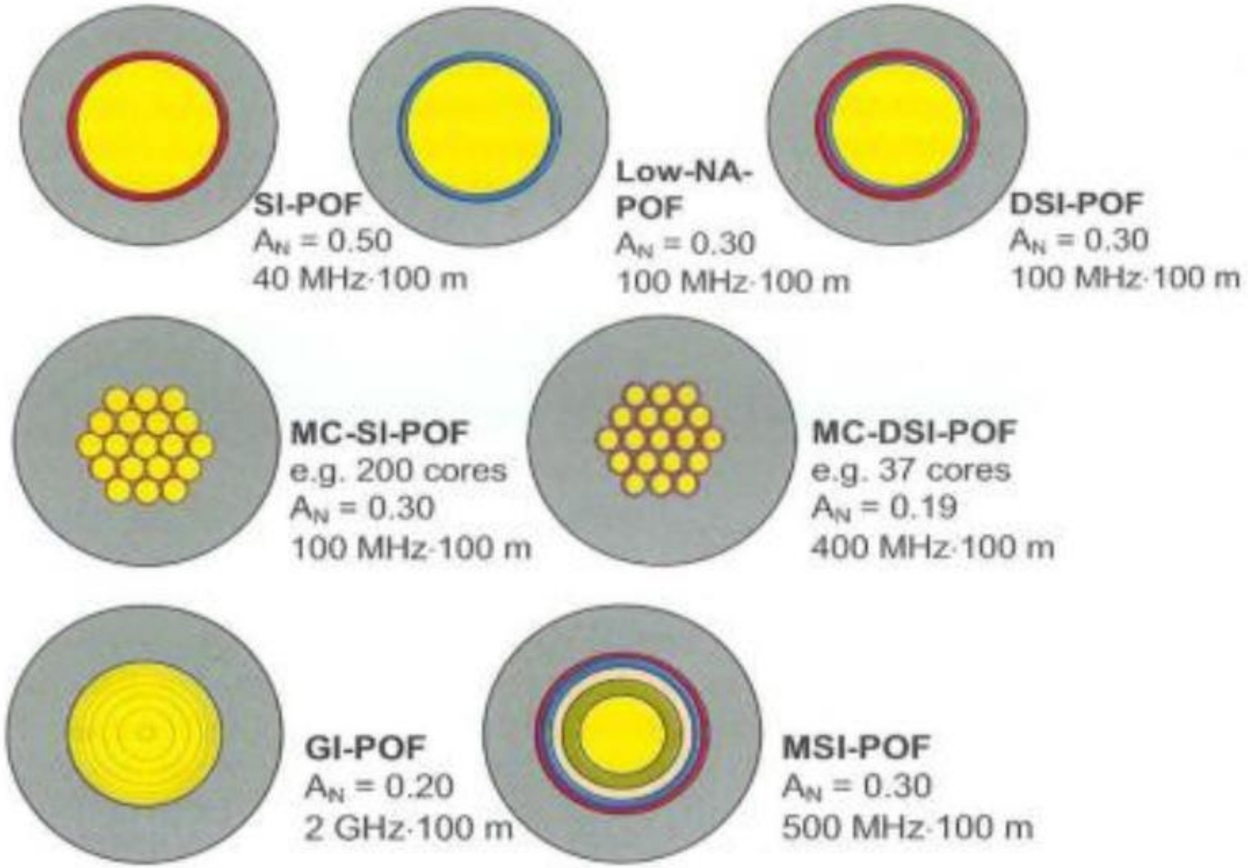
A comparable profile can be obtained usong multi step POF fibres (MSI-POF)



- ⇒ More stable with time
- ⇒ Increase of bandwith compared to standard POF but less than GI-POF

From « Polymer Optical Fibers for Data Communication », Daum, Krauser, Zamzow and O. Ziemann, springer 2005.

Nowadays system performances



From « Polymer Optical Fibers for Data Communication », Daum, Krauser, Zamzow and O. Ziemann, springer 2005.

Characteristics of existing PMMA-POF

ref.	year	company	product	$Ø_{core}$ µm	loss dB/km	at λ nm	NA	remarks
[Min94]	1963	Du Pont	CROFON	-	1,000	650	St.	first POF
[Koi97a]	1964	Du Pont		-	500	650	St.	
[Koi96c]	1968	Du Pont		-	500	650	St.	first SI-POF
[Sai92]	1976	Mitsubishi	Eska	-	300	650	St.	
[Min94]	1978	Mitsubishi	Super Eska	-	300	650	St.	
[Koi95]	1982	NTT		-	55	568	St.	
[Sai92]	1983	Mitsubishi	Eska Extra	-	124	650	St.	4 MHz·km
[Sai92]	1983	Mitsubishi	Eska Extra	-	65	570	St.	
[Koi95]	1983	Mitsubishi		1,000	110	570	St.	
[Min94]	1984	Mitsubishi	Eska Extra	-	150	650	St.	
[Koi95]	1985	Asahi		-	80	570	St.	
[Sai92]	1991	Mitsubishi	Eska Extra	-	125	650	St.	at 85 °C
[Sai92]	1991	Mitsubishi	Eska Extra	-	65	570	St.	
[Koi95]	1991	Hoechst		1,000	130	650	St.	
[Tesh92]	1992	Asahi Chemical	Luminous-F	-	175	660	0.50	310 MHz·10m $A_{N,LED}$=0.50, 105 °C
[Tesh92]	1992	Asahi Chemical	X-1	-	-	-	0.37	540 MHz·10m $A_{N,LED}$ = 0.50
[Tesh92]	1992	Asahi Chemical	X-2	-	-	-	0.28	>1,000 MHz·10m $A_{N,LED}$ = 0.50
[Eng96]	1992	Höchst	EP51	970	190	650	St.	90 MHz·100 m for 650 nm LED
[Kit92]	1992	Mitsubishi	Eska Premier	1000	135	650	0.51	up to 85 °C
[Lev93]	1993	CIS	Sveton MN-Series, Grade U	200-600	150	650	0.45	up to 70 °C
[Lev93]	1993	CIS	Sveton MF-Series, Grade U	200-1,000	120	650	0.48	up to 70 °C
[Non94]	1994	Sumitomo	-	480	150	650	0.51	200 MHz·50 m Δn = 0.055
[Koe98]	1998	Mitsubishi	-	1,000	110	650	0.47	80 MHz·100 m

SI

GI

ref.	year	company	material	$Ø_{core}$ µm	loss dB/km	at λ nm	NA	remarks
[Koe98]	1998	Mitsubishi	n.Info.	1,000	110	650	0.47	80 MHz·100 m
[Koi95]	1982	Keio Univ.	MMA/VPAc	n.Info.	1,070	670		first GI-POF
[Koi96c]	1990	Keio Univ.	PMMA	n.Info.				670 nm: 300 MHz km
[Koi95]	1990	Keio Univ.	MMA co VB	n.Info.	130	650		
[Koi90]	1990	Keio Univ.	MMA-VB	n.Info.	134	652		IGPT; 260 MHz·1 km
[Koi90]	1990	Keio Univ.	MMA-VPAc	n.Info.	143	652		IGPT;125 MHz 1·km
[Koi92]	1992	Keio Univ.	PMMA	200-1500	113	650		IGPT; 1,000 MHz·km
[Koi92]	1992	Keio Univ.	PMMA	200-1500	90	570		
[Non94]	1994	Sumitomo	PMMA	400	160	650	0.26	Δn=0.014; 8GHz·50m
[Shi95]	1995	BOF	PMMA	600	300	650	0.19	3 GHz·100 m
[Ish95]	1995	Keio Univ.	PMMA-DPS	500-1,000	150	650		585 MHz·km
[Koi97b]	1997	Keio Univ.	PMMA	n.Info.				2 GHz·100 m
[Tak98]	1998	Kurabe	PMMA	500	132	650		2 GHz·100m; PFM
[Tak98]	1998	Kurabe	PMMA	500	145	650		2 GHz·90m; PFM
[Tak98]	1998	Kurabe	PMMA	500	159	650		680 MHz·50m; PFM
[Tak98]	1998	Kurabe	PMMA	500	329	650		PFM
PMMA-MC-POF								
[Tesh98]	1998	Asahi Chem	PMMA	1,000	200	650	0.50	
[Tesh98]	1998	Asahi Chem	PMMA	1,000	200	650	0.33	217 cores
[Tesh98]	1998	Asahi Chem	PMMA	1,000	200	650	0.19	DSI, 217 cores
[Tesh98]	1998	Asahi Chem	PMMA	1,000	160	650	0.33	217 cores
[Tesh98]	1998	Asahi Chem	PMMA	1,000	160	650	0.25	DSI, 37 cores
[Tesh98]	1998	Asahi Chem	PMMA	1,000	155	650	0.19	700 MHz· 50m DSI, 37 cores
MSI-POF								
[She99]	1997	Mitsubishi	PMMA	700	210	650	0.30	500 MHz·50m 4-7 steps (?)
[Lev99]	1999	RPC Tver	PMMA/4FFA	800	400	650		7 steps 310 MHz·100 m

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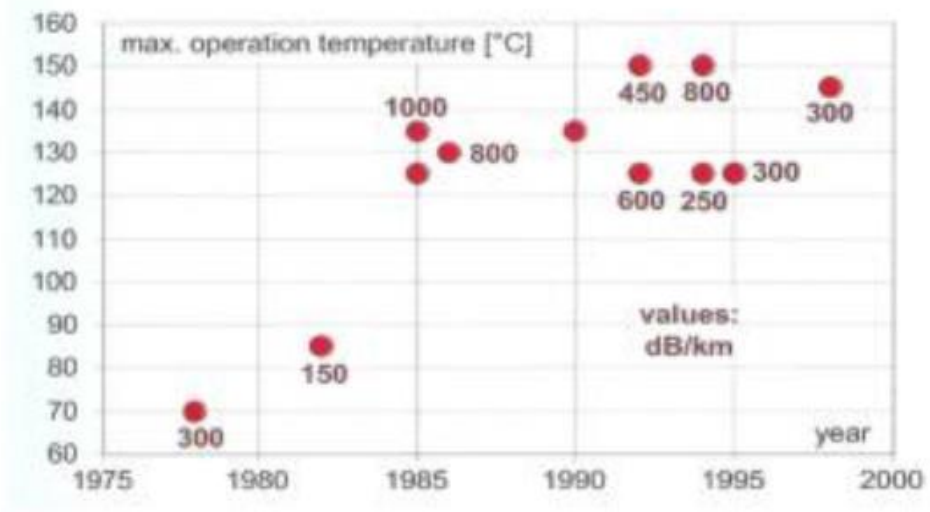
The maximum temperature is now 800°C

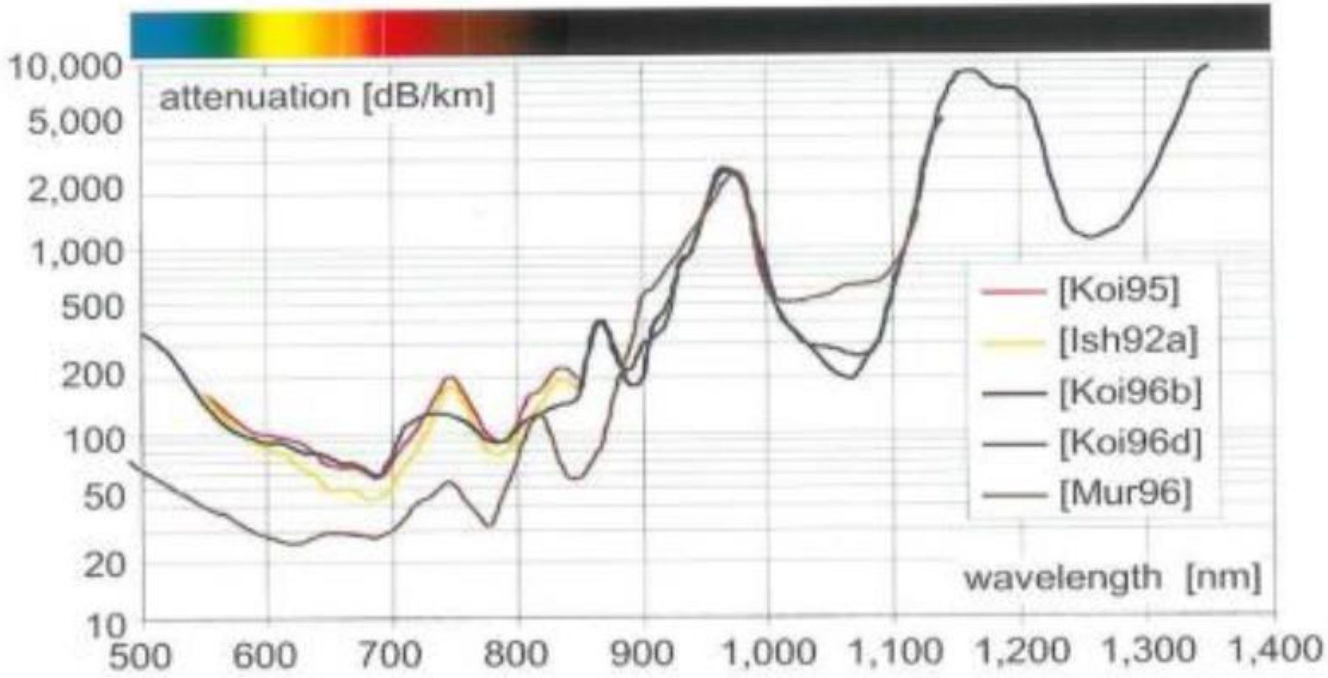


From « Polymer Optical Fibers for Data Communication », Daum, Krauser, Zamzow and O. Ziemann, springer 2005.

ref.	year	company type	material	$Ø_{core}$ µm	loss dB/km	at λ nm	NA	remarks
[Kit90]	1983	Mitsubishi	PMMA	1,000	-			Eska EH, 85 °C
[Sai92] [Kit92]	1985	Mitsubishi ESKA PH4011	PC	1,000	1,000	770	0.70	up to 135 °C
[Ish92b]	1986	Fujitsu	PC	-	800	660		up to 130 °C
[Koi95]	1986	Fujitsu	PC	-	450	770		
[Koi95]	1987	Hitachi	thermoset resin	-	660	650		
[Ish92b]	1992	Bridgestone Rubber Opt. Fiber	silicon elastomer	-	450 700	770 660	0.54	up to 150 °C
[Tesh92]	1992	Asahi Chem. Luminous-H	PC	-	600	660	0.78	170 MHz·10 m, up to 125 °C
[Ish92b]	1992	Hitachi	thermosetting acrylic	-	1,500	660		up to 150 °C
[Koi95]	1993	Bridgestone	Silicon	-	800	650		
[Suk94]	1994	Fujitsu	ARTON	1,000	1,200	660		T_g= 171 °C
[Suk94]	1994	Fujitsu	ARTON	1,000	800	680		T_g= 171 °C
[Suk94]	1994	Fujitsu	ARTON	1,000	1,200	780		T_g= 171 °C
[Tan94a]	1994	Toray	copolymer	1,000	250	650		T_g= 135 °C
[Irie94]	1994	Furukawa D-POF	thermoplastic resin	910	420 400	660 760		up to 145 °C
[Min94]	1994	n.Info.	PC	-	500	650		heat resistant
[Min94]	1994	n.Info.	PC	-	450	765		
[Tan95]	1995	Toray	MMA/ipr-MID	1,000	300	650		up to 125 °C
[Hatt98]	1998	Furukawa	PC(AF)	500	460 300	660 780	0.53	up to 145 °C T_g = 165 °C
[Hatt98]	1998	Furukawa	PC(AF)	500	300	780	0.35	200 MHz·100 m

Deuterium can be used to increase the power budget

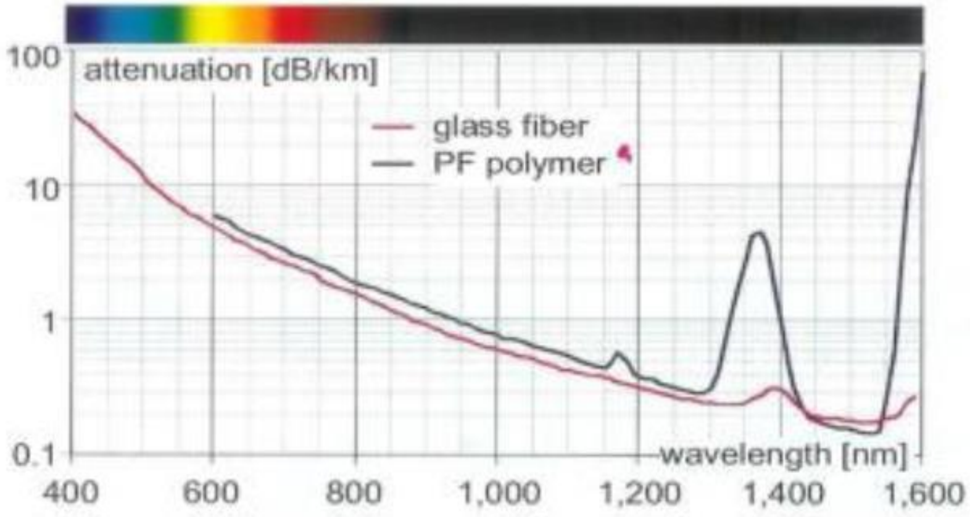
A significant reduction in the absorption losses of polymers can be axhieved by substituting the hydrogen with **deuterium**



Practical problem:
water vapor present in the atmosphere slowly replace the deuterium and a special protection coating would be too expensive. Let's no forget that the main advantage of POF is to be cheap !

From « Polymer Optical Fibers for Data Communication », Daum, Krauser, Zamzow and O. Ziemann, springer 2005.

The fluorine is a potential solution

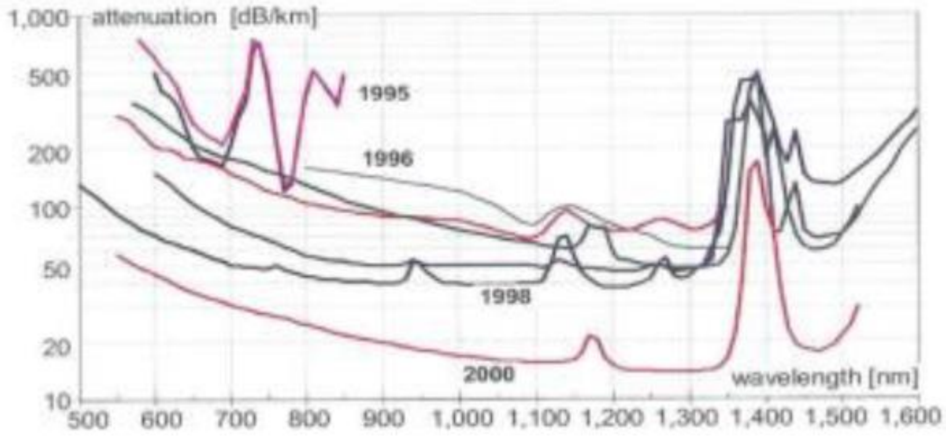


Fluorinated POF fibres can theoretically reach **0.2 dB/km**

15 dB/km in practice

Practical difficulties of manufacturing (research in progress !)

Impossiblities to realize SI-POF. PF have a very low *n (1.340 at 650nm)* ⇒ difficult to find a material for the cladding



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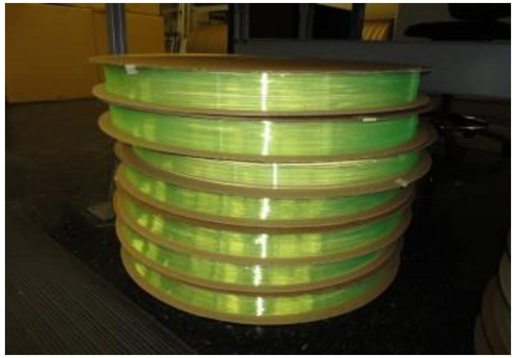
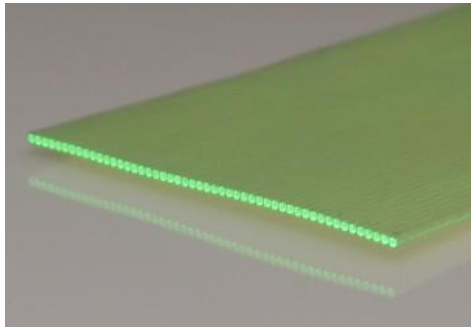
Active POF-scintillating fibers



Flexibility to conform to the surface shape, yielding geometries superior to those of other types of detectors. Examples are detectors for monitoring pipes or barrels.

Saint-Gobain Crystals manufactures a variety of plastic scintillating, wavelength-shifting and light-transmitting fibers used for research and industry.

Neutron imaging
Particle discrimination
Calorimeters
Cosmic ray telescopes
Real-time imaging systems
Flow cells
Tracking detectors



Active POF-scintillating fibers types

Fiber Type	Emission Color	Emission Peak, nm	Decay Time, ns	# of Photons per MeV**	Characteristics/ Applications
BCF-10	blue	432	2.7	~8000	General purpose; optimized for diameters >250μm
BCF-12	blue	435	3.2	~8000	Improved transmission for use in long lengths
BCF-20	green	492	2.7	~8000	Fast green scintillator
BCF-60	green	530	7	~7100	3HF formulation for radiation hardness
BCF-91A	green	494	12	n/a	Shifts blue to green
BCF-92	green	492	2.7	n/a	Fast blue to green shifter
BCF-98	n/a	n/a	n/a	n/a	Clear waveguide

** For Minimum Ionizing Particle (MIP), corrected for PMT sensitivity

Conclusions

- Refractive index and new materials
- Metamaterials
- Plastics
    - POF fibers evolution
    - POF applications
    - POF types – active and passive