Fundamentals of Optical fibers

2020. 10. 16.

Wikioptics

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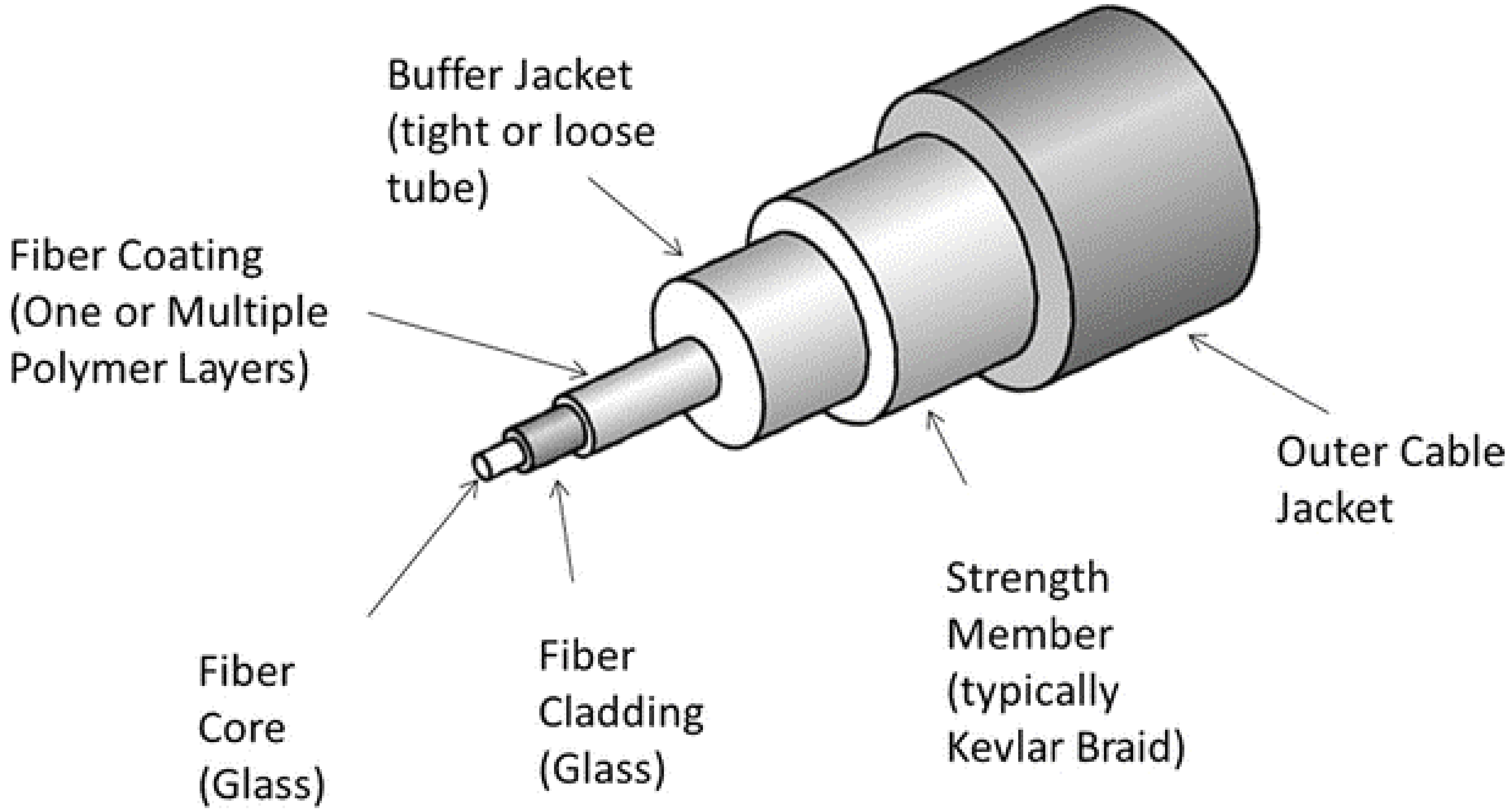
Basic structure of optical fibers



Méndez A. (2016) Optics in Medicine. In: Al-Amri M., El-Gomati M., Zubairy M. (eds) Optics in Our Time. Springer, Cham.

Dispersion: frequency dependent speed of light propagating in material

= wavelength change of light in material

$$v = \frac{c}{n} \qquad \lambda' = \frac{\lambda}{n}$$

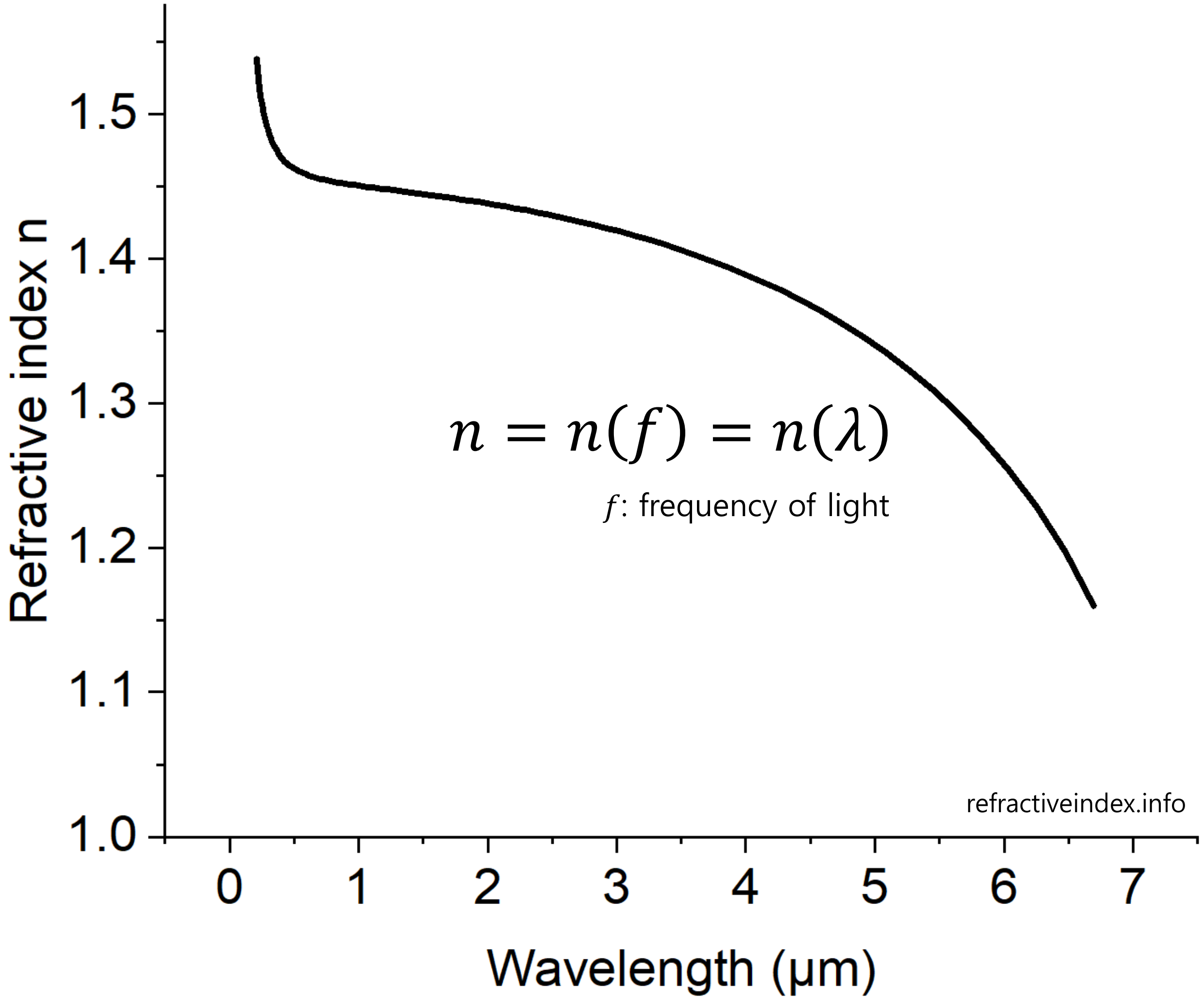
n: Refractive index of a material
c: Speed of light in the vacuum
v: Speed of light in a material
λ: Wavelength in the vacuum
λ': Wavelength in a material

Sellmeier equation for fused silica (SiO_2)

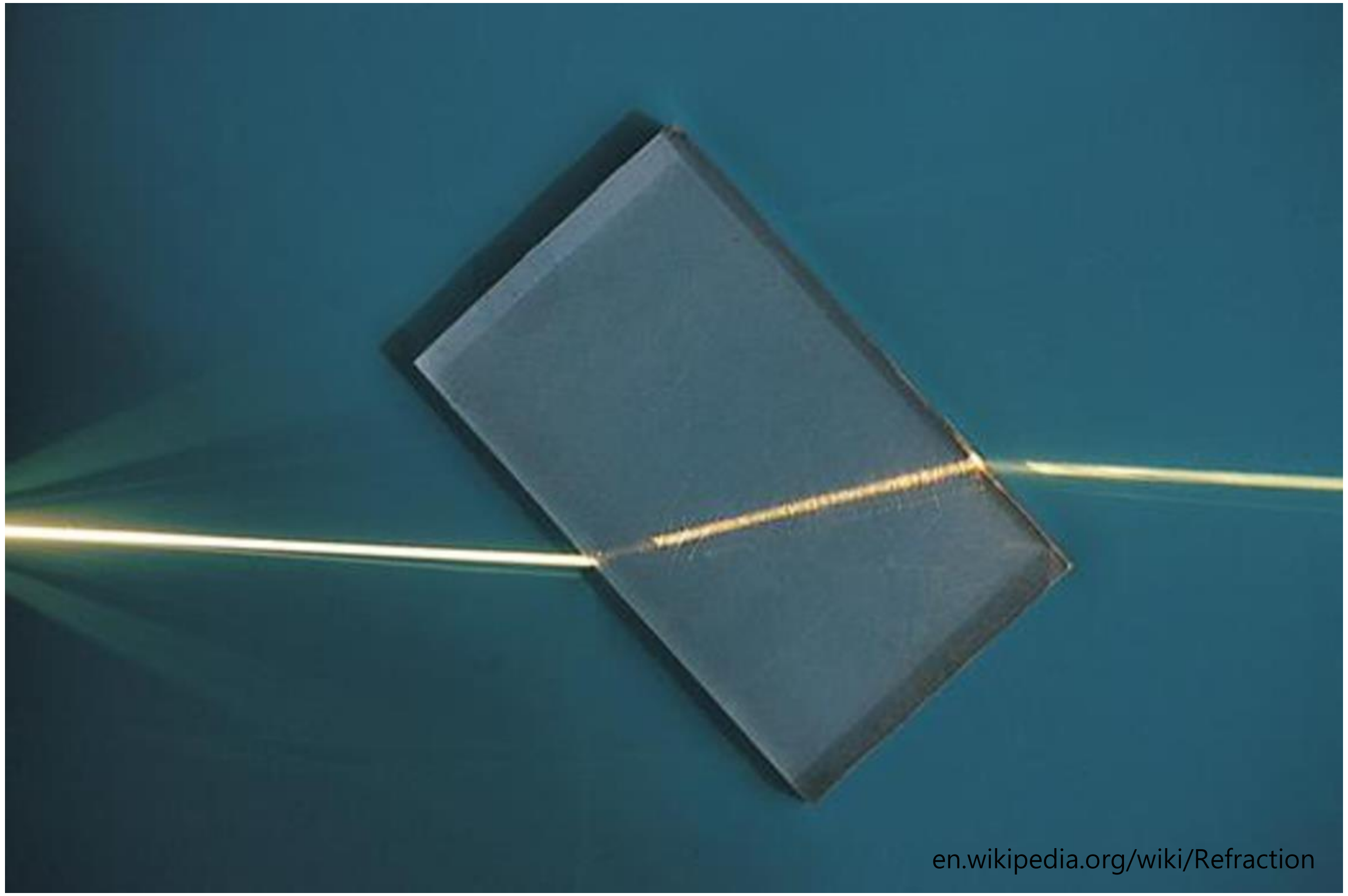
$$n(\lambda)^2 = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}$$

$B_1 = 0.696$ $\qquad$ $C_1 = 0.0047$
$B_2 = 0.551$ $\qquad$ $C_2 = 0.0135$
$B_3 = 6.592$ $\qquad$ $C_3 = 97.934$

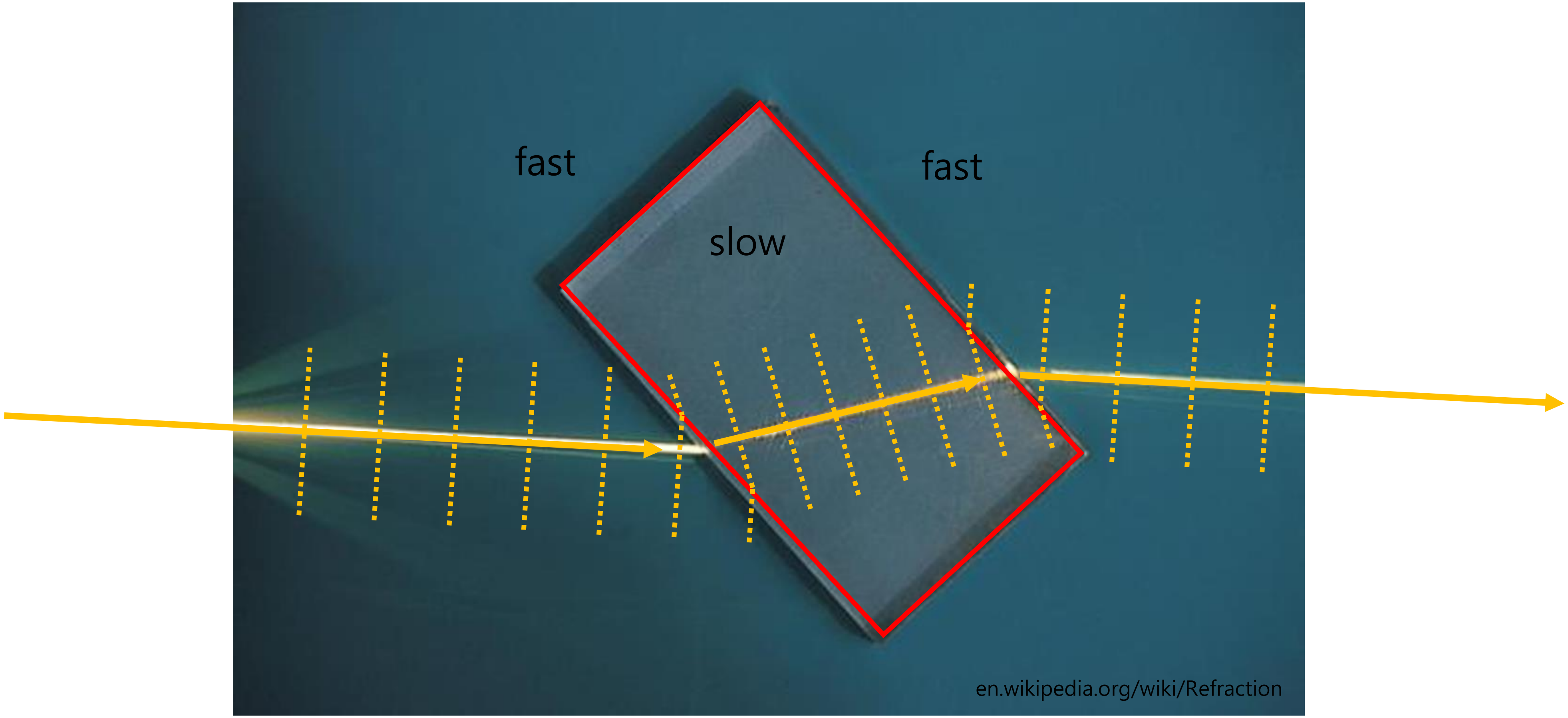
Refractive index of fused silica (SiO_2)



Refraction of light in material, due to the “dispersion”



Refraction of light in material, due to the "dispersion"

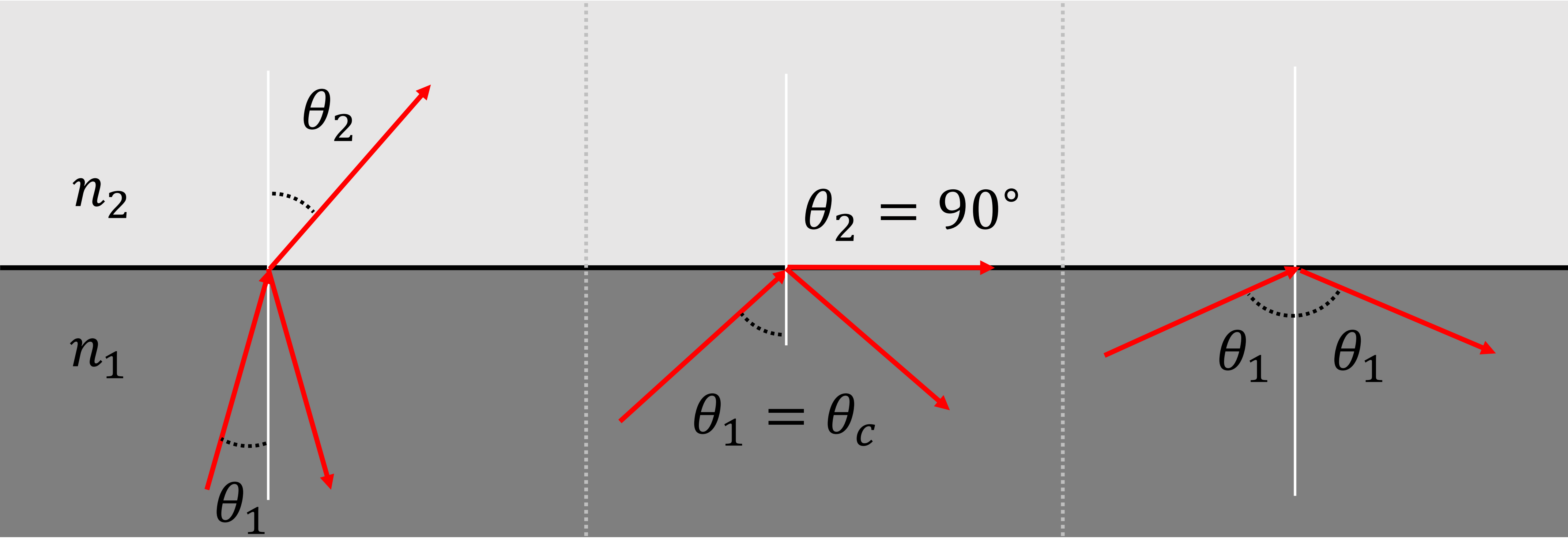


Snell's law for refraction and total internal reflection

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

$$n_1 \sin\theta_c = n_2$$

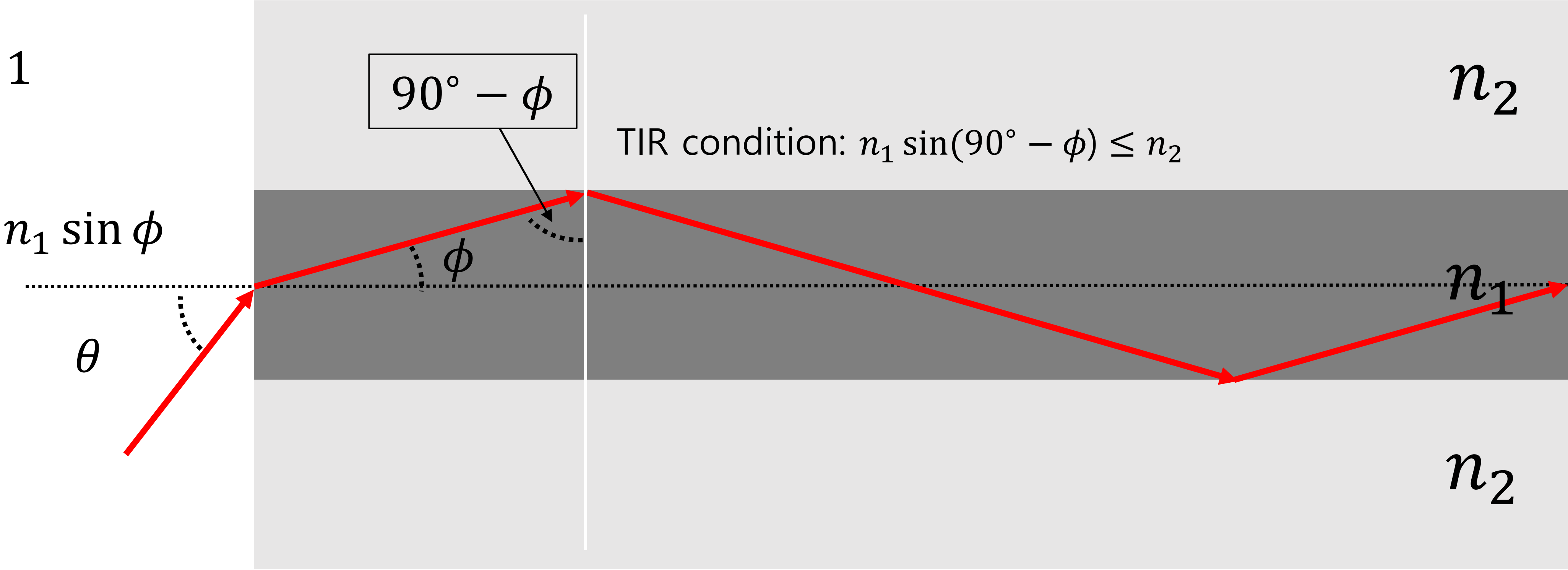
Total reflection



Guided wave, in geometric optics

$n_{air} \approx 1$

$\sin\theta = n_1 \sin\phi$



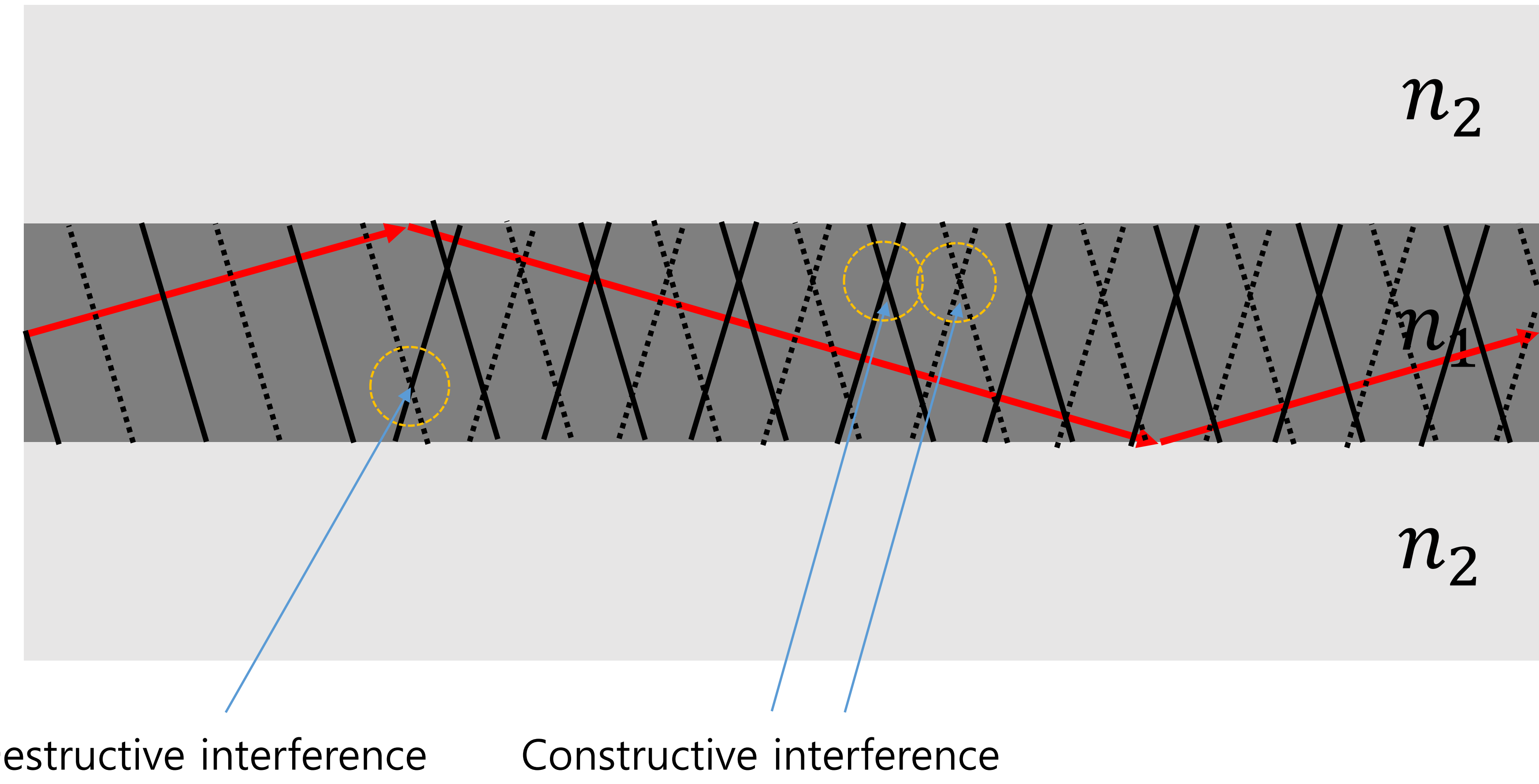
$$\cos\phi \le \frac{n_2}{n_1} \rightarrow \left(\frac{\sin\theta}{n_1}\right)^2 \le 1 - \left(\frac{n_2}{n_1}\right)^2 \rightarrow \sin\theta \le \sqrt{n_1^2 - n_2^2} \rightarrow \theta_{max} = \sin^{-1}\sqrt{n_1^2 - n_2^2}$$

Relative refractive index difference: $\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \cong \frac{n_1 - n_2}{n_1}$

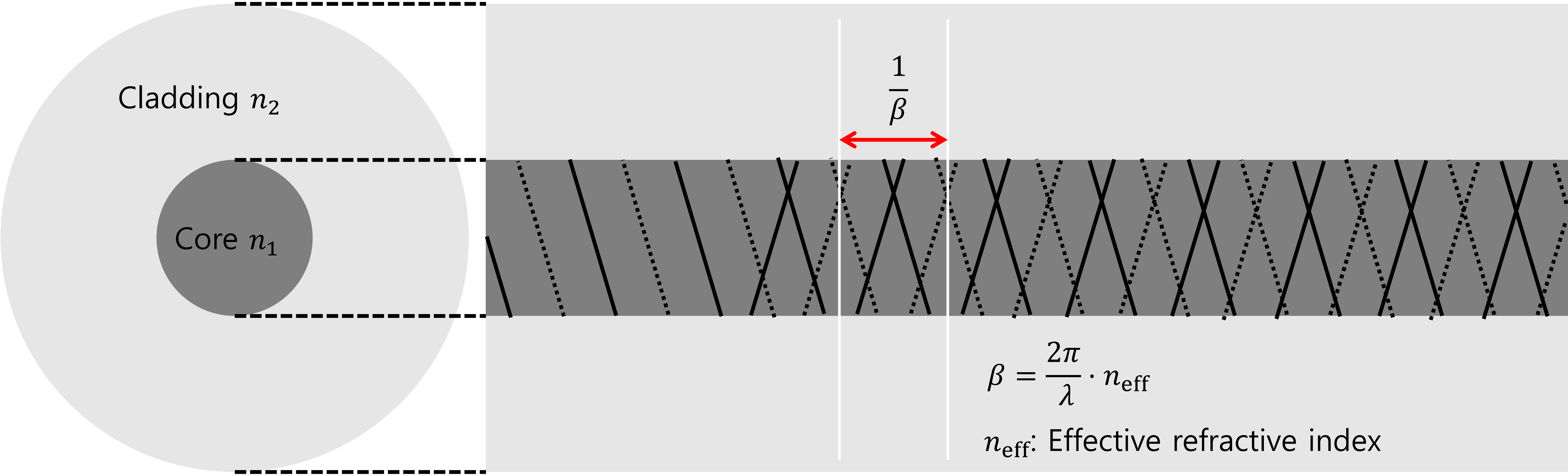
Maximum acceptance angle=Numerical aperture: $\mathrm{NA} = \theta_{max} = \sin^{-1}\sqrt{n_1^2 - n_2^2} \cong n_1\sqrt{2\Delta}$

Normalized frequency, or v parameter: $v = \frac{2\pi}{\lambda} a \cdot (\mathrm{NA})$

Guided wave, mode construction



Guided wave, mode construction



$$\beta = \frac{2\pi}{\lambda} \cdot n_{\text{eff}}$$

n_{eff}: Effective refractive index

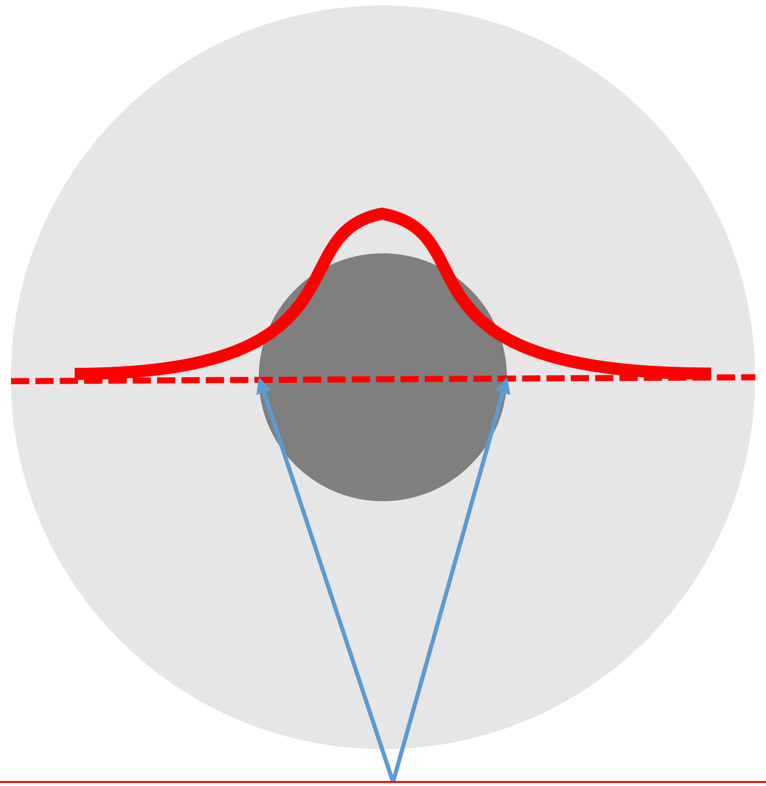
From Maxwell's equation…

$$\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \psi}{\partial z^2} + [k^2 n(r,\theta)^2 - \beta^2]\psi = 0$$

$\psi = E_z$ or H_z $\qquad k = \frac{2\pi}{\lambda}$ $\qquad n(r,\theta)$ refractive index distribution

Solve this, then you get the modes

Mode field distribution



Boundary condition: Field must be continuous and differentiable at the boundary

Field equation: $\frac{\partial^2\psi}{\partial r^2} + \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\psi}{\partial z^2} + [k^2 n(r,\theta)^2 - \beta^2]\psi = 0$

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$\psi = E_z$ or H_z $\qquad v^2 = u^2 + w^2$

$u = a\sqrt{k^2 n_1^2 - \beta^2}$

$w = a\sqrt{\beta^2 - k^2 n_2^2}$

Field solution: $\psi = \begin{cases} A J_\nu\left(\frac{u}{a}r\right)\cos(\nu\theta + \theta_0)\ (0 \le r \le a) \\ A\frac{J_\nu(u)}{K_\nu(w)} K_\nu\left(\frac{w}{a}r\right)\cos(\nu\theta + \theta_0)\ (r > a) \end{cases}$

Mode Determinant conditions from the boundary conditions:

TE modes: $\frac{J_1(u)}{uJ_0(u)} = -\frac{K_1(w)}{wK_0(w)}$ (for $E_z = 0$)

TM modes: $\frac{J_1(u)}{uJ_0(u)} = -\left(\frac{n_2}{n_1}\right)^2\frac{K_1(w)}{wK_0(w)}$ (for $H_z = 0$)

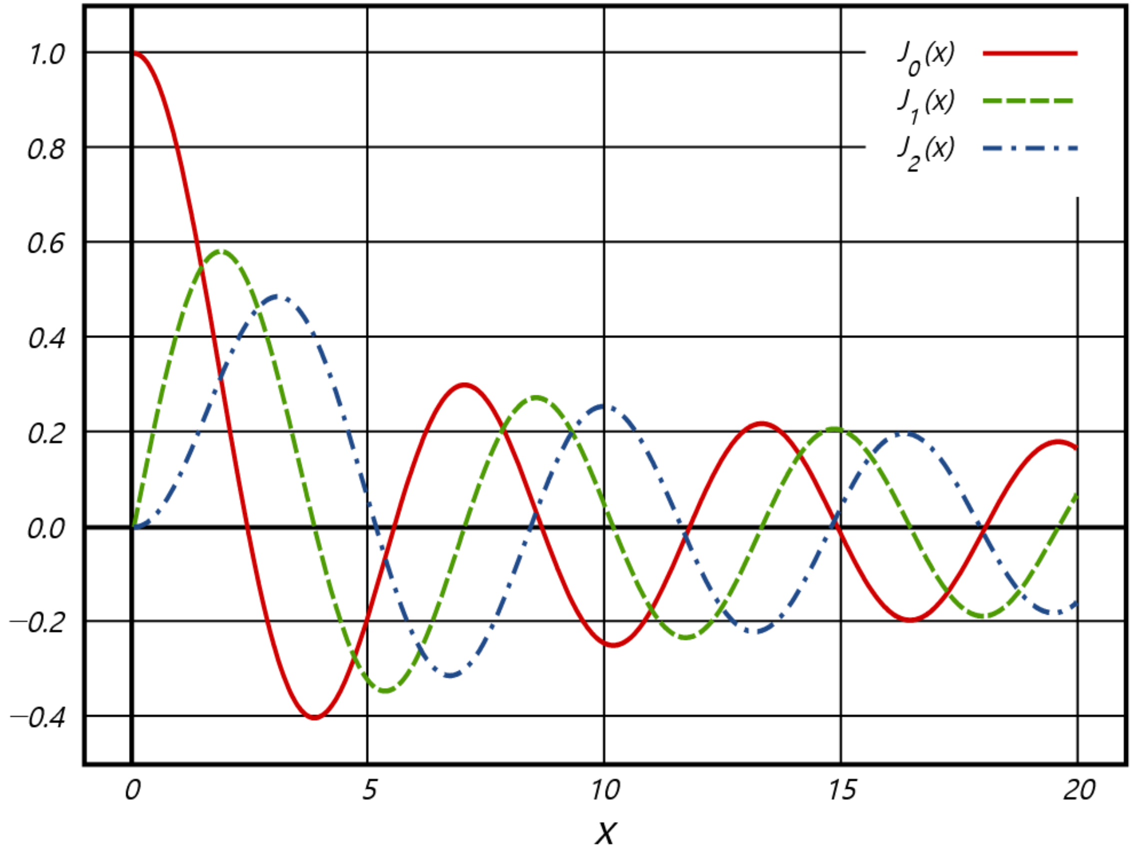
Hybrid modes:

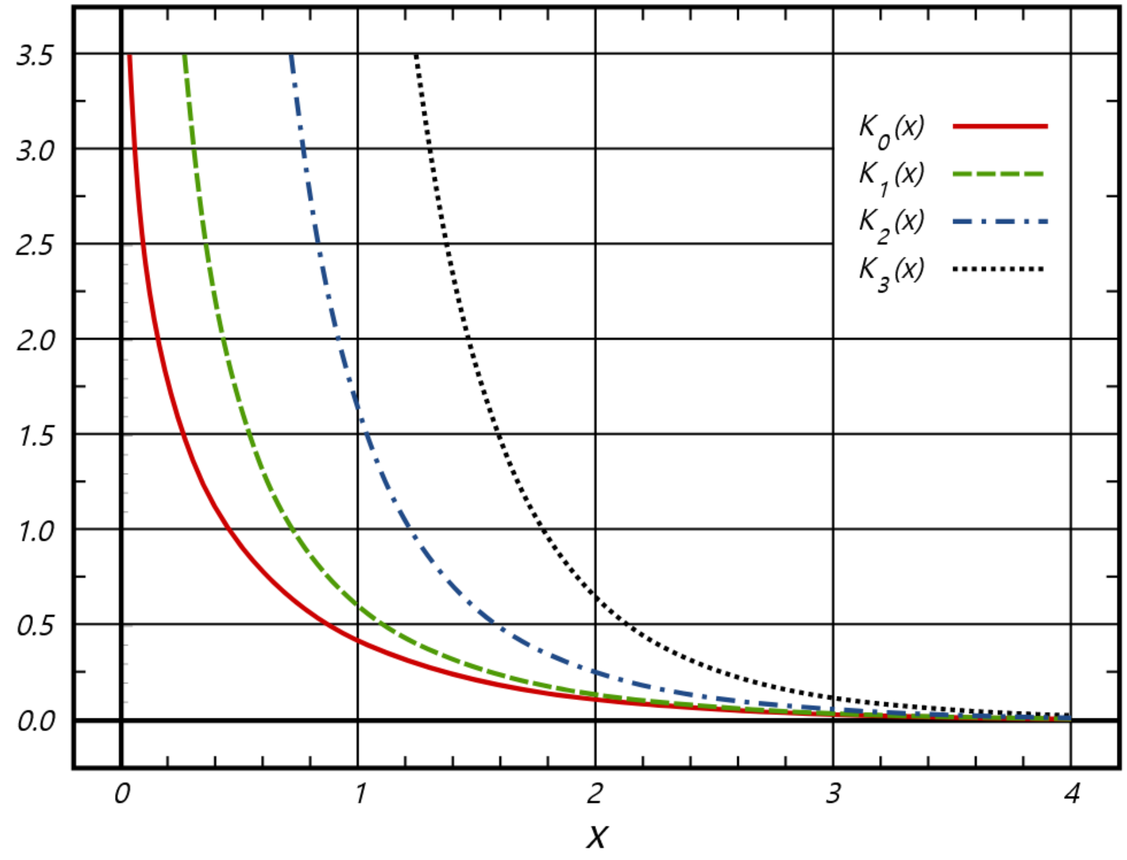
$$\left[\frac{J_\nu'(u)}{uJ_\nu(u)} + \frac{K_\nu'(w)}{wK_\nu(w)}\right]\left[\frac{J_\nu'(u)}{uJ_\nu(u)} + \left(\frac{n_2}{n_1}\right)^2\frac{K_\nu'(w)}{wK_\nu(w)}\right] = \nu^2\left(\frac{1}{u^2} + \frac{1}{w^2}\right)\left[\frac{1}{u^2} + \left(\frac{n_2}{n_1}\right)^2\frac{1}{w^2}\right]$$

$J_\nu(x)$: 1st kind ν-th order Bessel function

$K_\nu(x)$: 2nd kind ν-th order modified Bessel function

Bessel functions





$J_\nu(x)$: 1st kind ν-th order Bessel function
$K_\nu(x)$: 2nd kind ν-th order modified Bessel function

Effective refractive index

Mode Determinant conditions
from the boundary conditions:

TE modes:

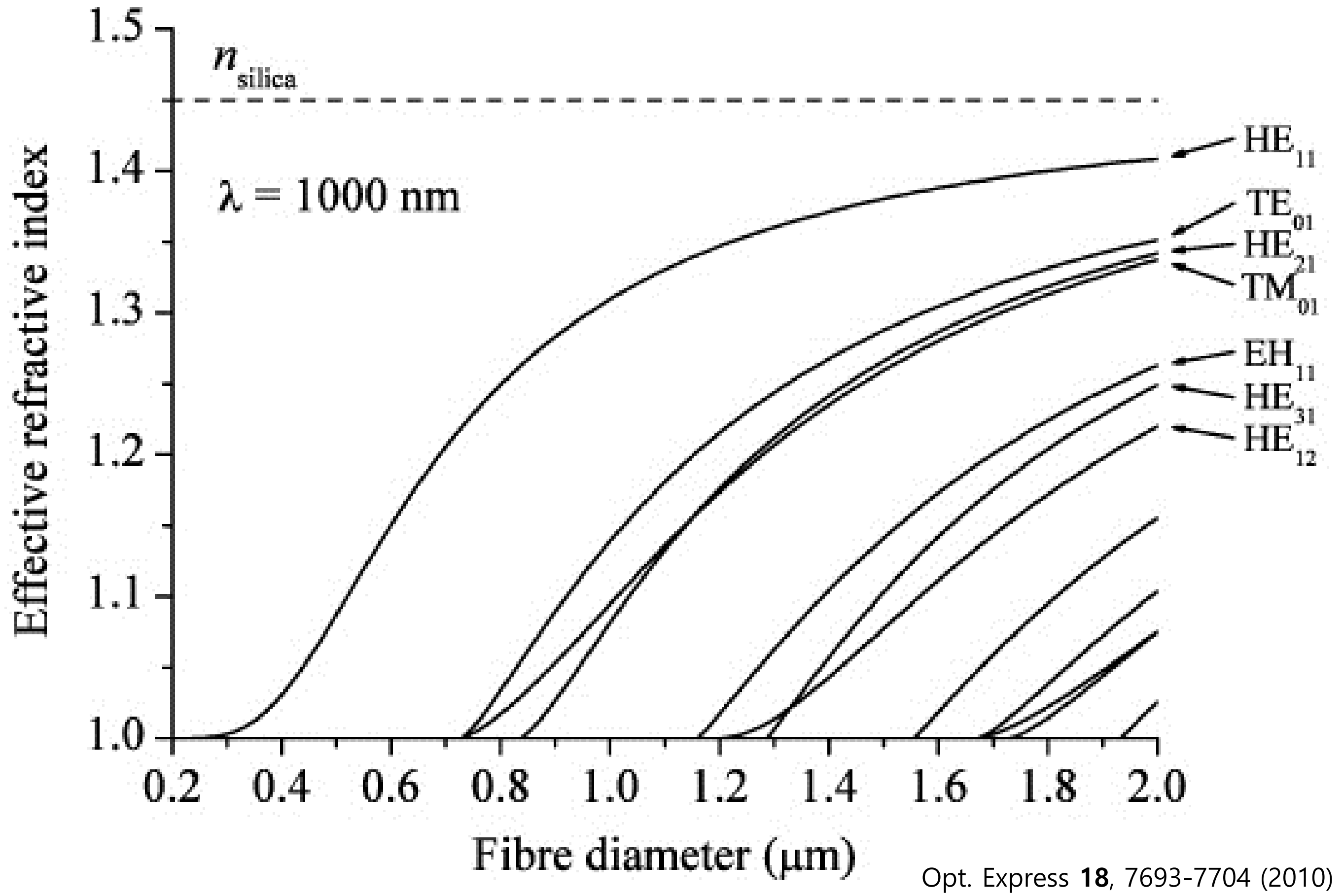
$$\frac{J_1(u)}{uJ_0(u)} = -\frac{K_1(w)}{wK_0(w)}$$

TM modes:

$$\frac{J_1(u)}{uJ_0(u)} = -\left(\frac{n_2}{n_1}\right)^2 \frac{K_1(w)}{wK_0(w)}$$

Hybrid modes:

$$\left[\frac{J_\nu'(u)}{uJ_\nu(u)} + \frac{K_\nu'(w)}{wK_\nu(w)}\right]\left[\frac{J_\nu'(u)}{uJ_\nu(u)} + \left(\frac{n_2}{n_1}\right)^2 \frac{K_\nu'(w)}{wK_\nu(w)}\right]$$
$$= \nu^2 \left(\frac{1}{u^2} + \frac{1}{w^2}\right)\left[\frac{1}{u^2} + \left(\frac{n_2}{n_1}\right)^2 \frac{1}{w^2}\right]$$

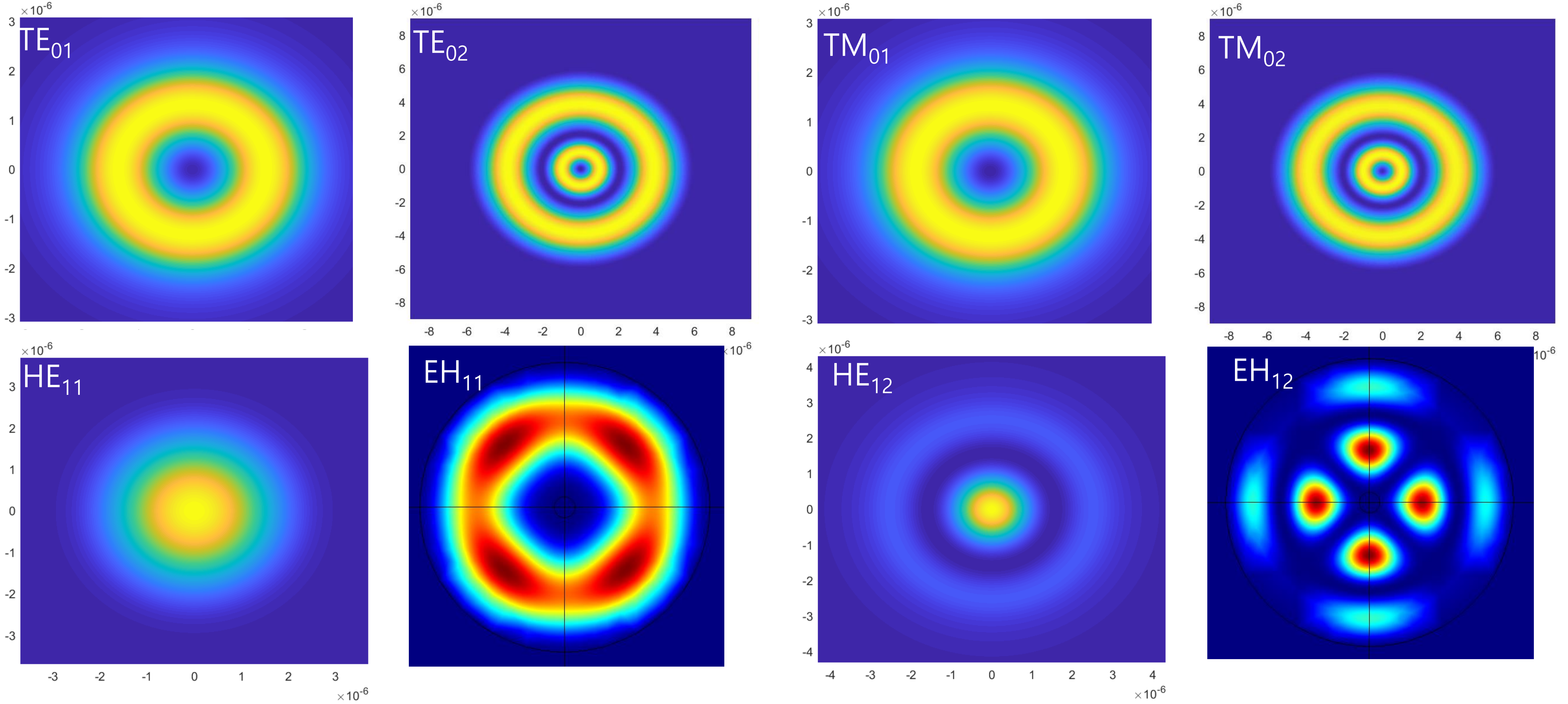


Opt. Express **18**, 7693-7704 (2010)

$$u = a\sqrt{k^2 n_1^2 - \beta^2}$$
$$w = a\sqrt{\beta^2 - k^2 n_2^2}$$

$$n(\mathrm{TE}_{01}) > n(\mathrm{TE}_{02}) > n(\mathrm{TE}_{03}) > \cdots > n(\mathrm{TE}_{0,m-1}) > n(\mathrm{TE}_{0m})$$
$$n(\mathrm{TM}_{01}) > n(\mathrm{TM}_{02}) > n(\mathrm{TM}_{03}) > \cdots > n(\mathrm{TM}_{0,m-1}) > n(\mathrm{TM}_{0m})$$
$$n(\mathrm{HE}_{l1}) > n(\mathrm{EH}_{l1}) > n(\mathrm{HE}_{l2}) > n(\mathrm{EH}_{l2}) > \cdots > n\left(\mathrm{HE}_{l,m}\right) > n(\mathrm{EH}_{lm}) > n\left(\mathrm{HE}_{l,m+1}\right) > \cdots$$

Some mode field distributions



Weakly guiding approximation: Vector mode to scalar mode

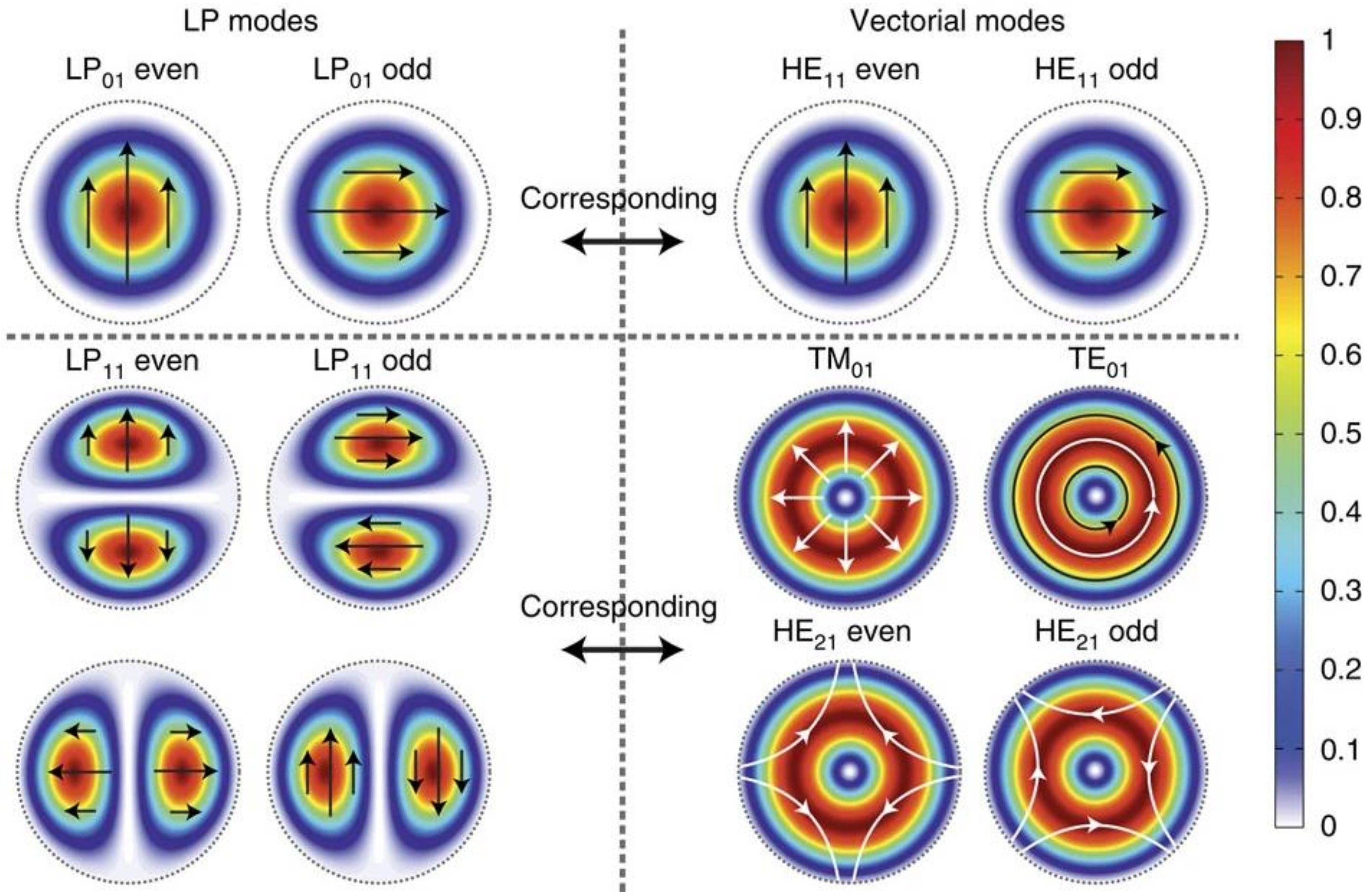
$n_1 \approx n_2$: Weakly guiding condition

Mode Determinant conditions with weakly guiding approximation:

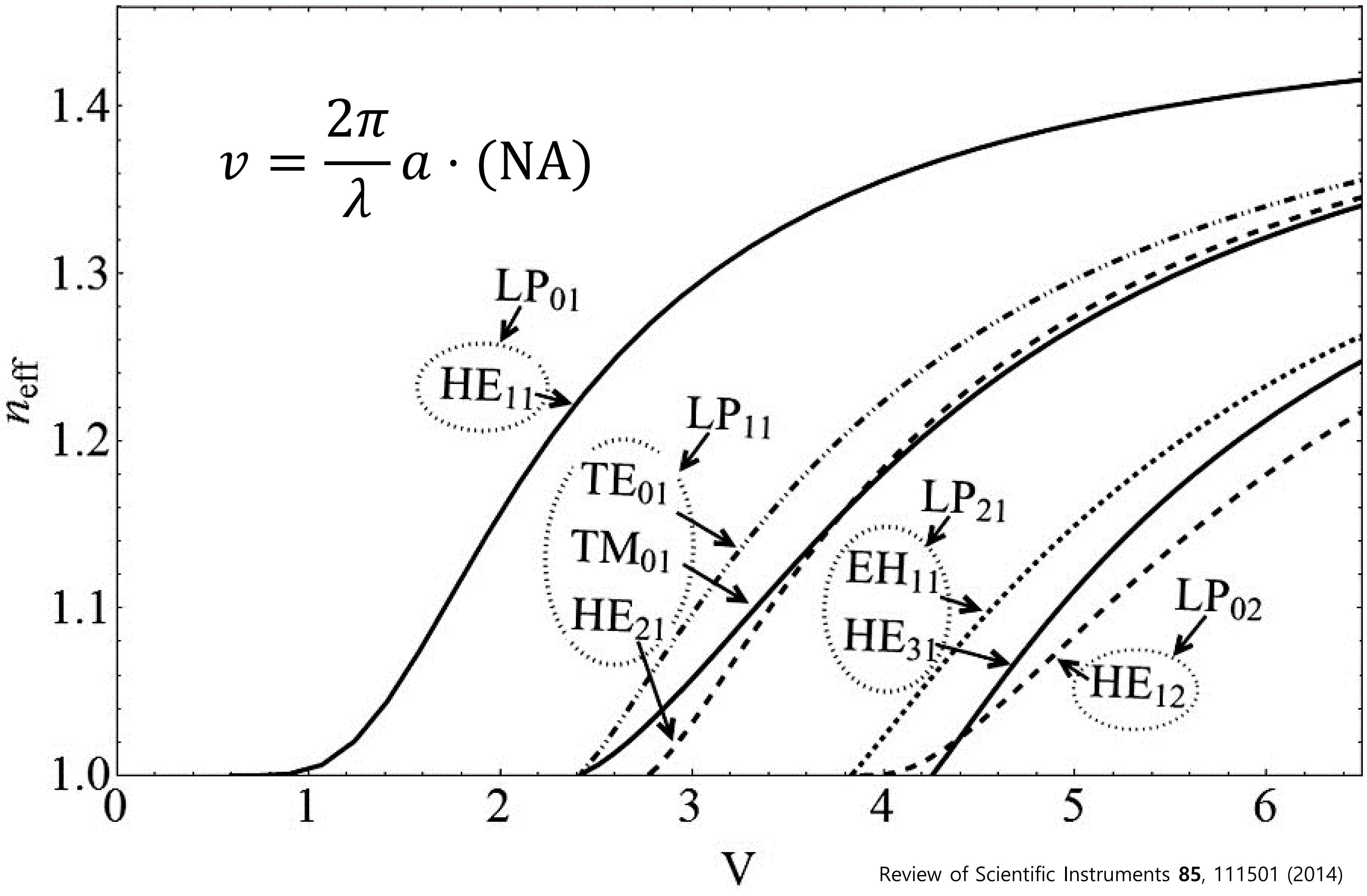
$$\frac{J_1(u)}{uJ_0(u)} = -\frac{K_1(w)}{wK_0(w)} \quad (\nu = 0)$$

$$\left[\frac{J'_\nu(u)}{uJ_\nu(u)} + \frac{K'_\nu(w)}{wK_\nu(w)}\right] = \pm\nu^2\left(\frac{1}{u^2} + \frac{1}{w^2}\right) \quad (\nu \neq 0)$$

$$\mathrm{TE}_{0m} \rightarrow \mathrm{LP}_{1m}$$
$$\mathrm{TM}_{0m} \rightarrow \mathrm{LP}_{1m}$$
$$\mathrm{HE}_{\nu m} \rightarrow \mathrm{LP}_{\nu-1,m}$$
$$\mathrm{EH}_{\nu m} \rightarrow \mathrm{LP}_{\nu+1,m}$$



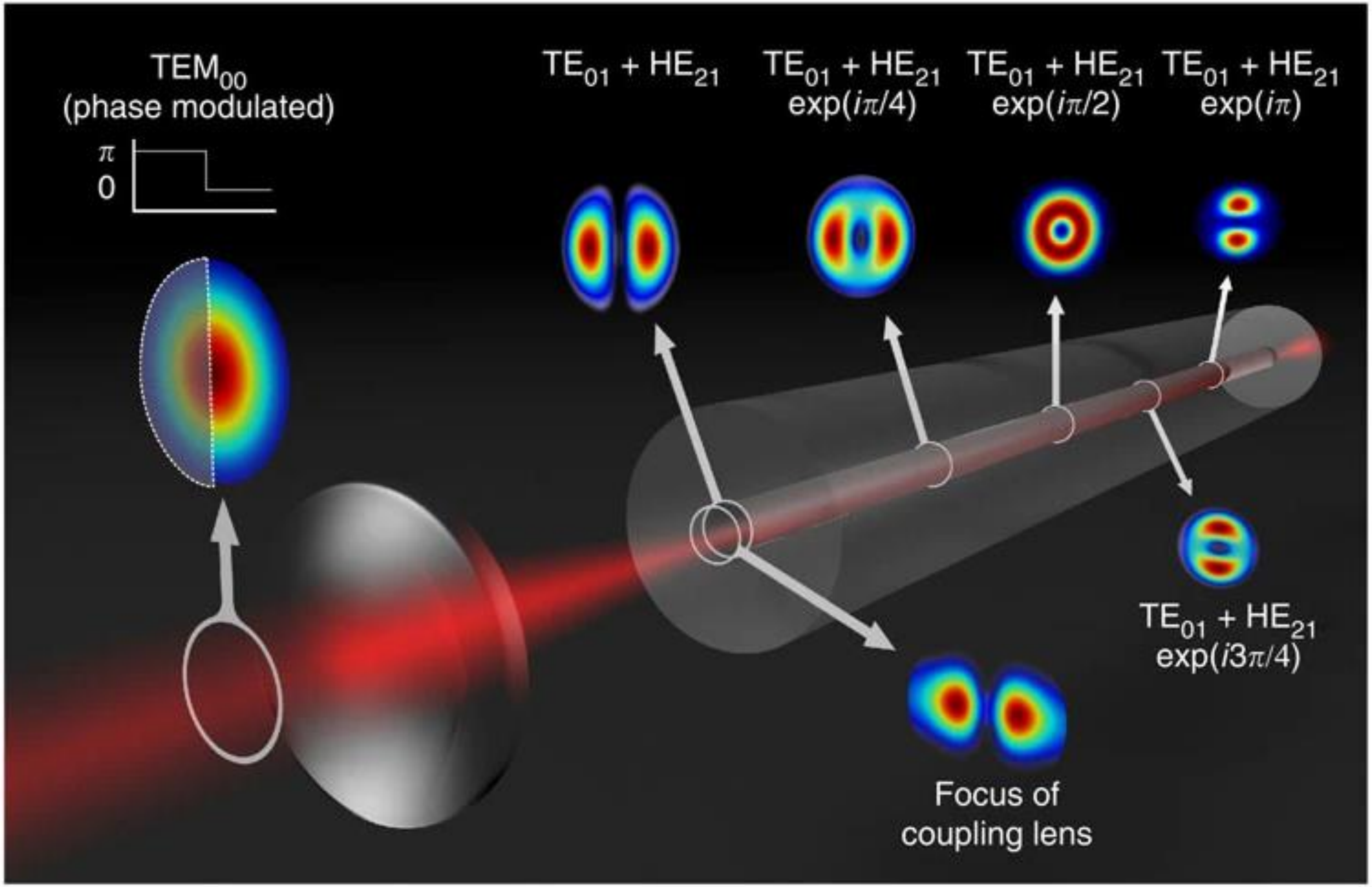
Nat Commun **5**, 5481 (2014)



Review of Scientific Instruments **85**, 111501 (2014)

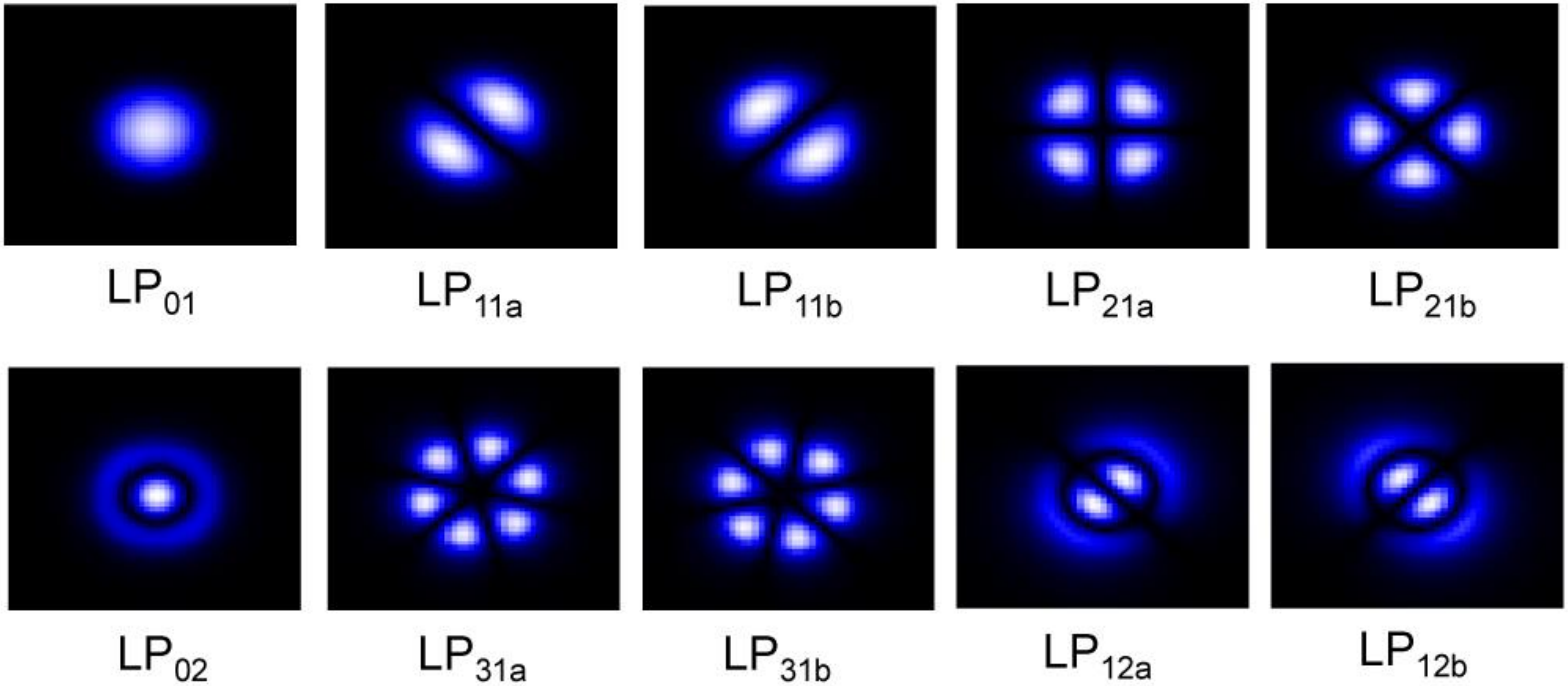
Single mode criterion: $v < 2.405$

Propagation of light in multi-mode fiber



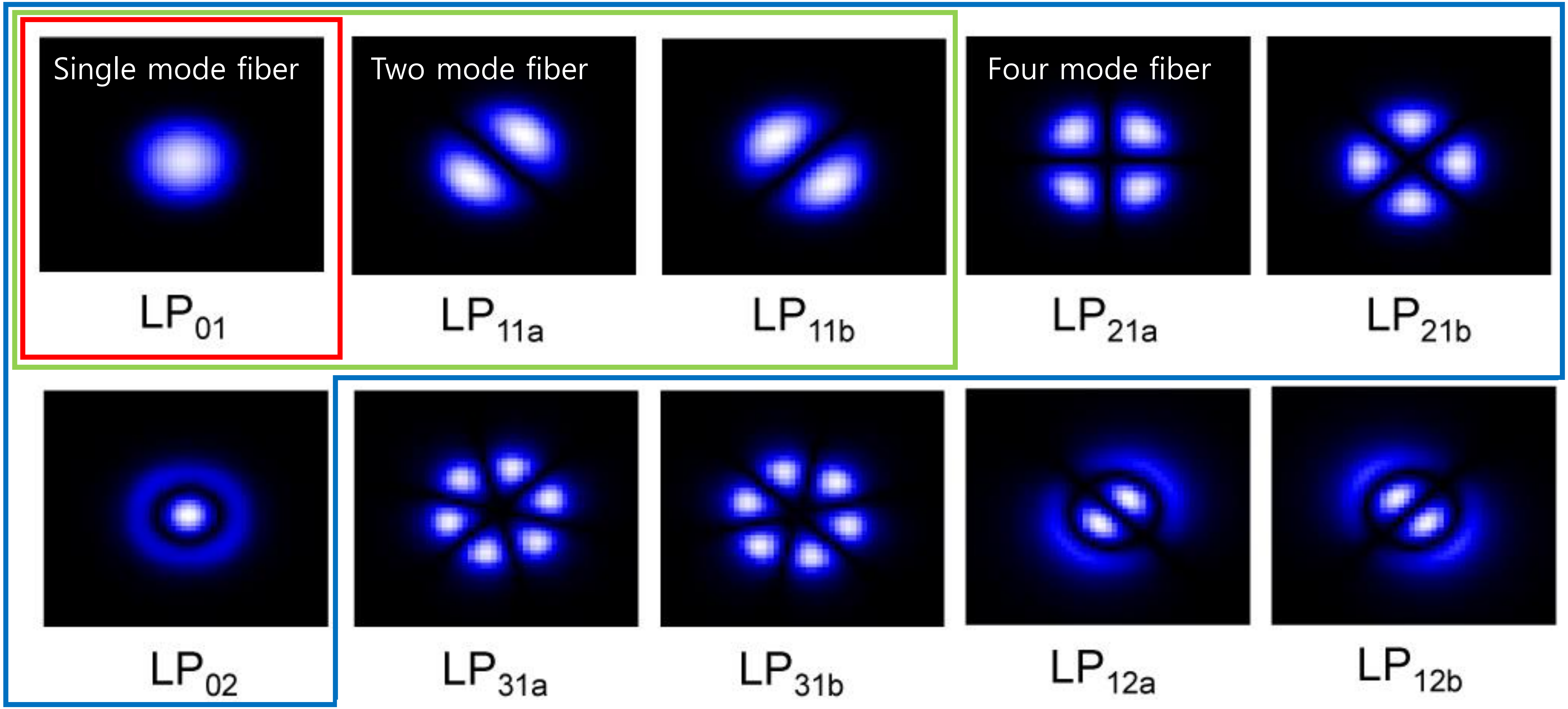
Nat Commun **5,** 5481 (2014)

LP modes (Linear Polarized mode)



Opt. Express **22**, 20881-20893 (2014)

Single mode fiber and multi-mode fiber

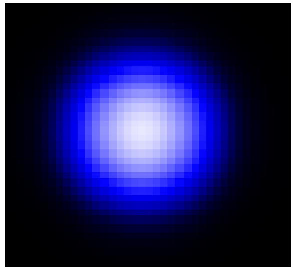


Opt. Express **22**, 20881-20893 (2014)

Beam size in optical fiber

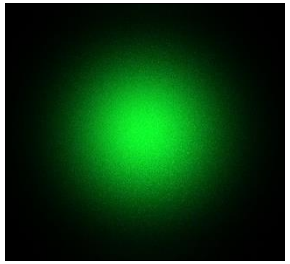
Intensity distribution of

LP_{01} beam

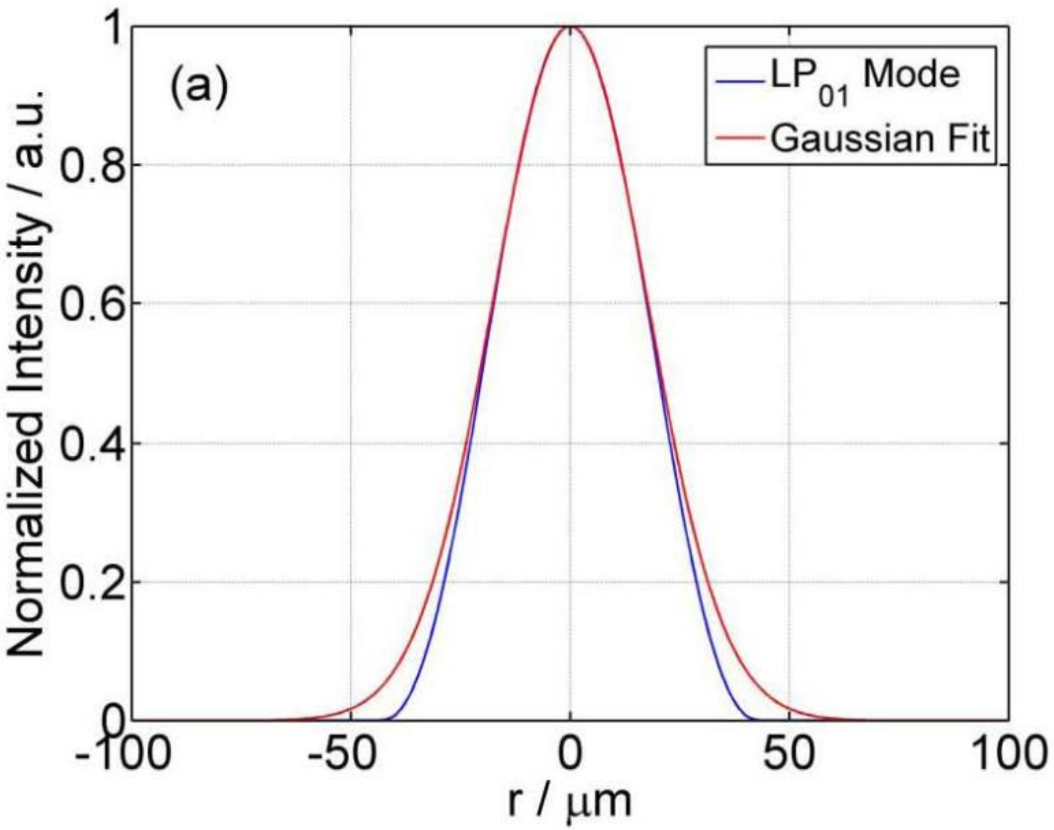


Opt. Express **22**, 20881-20893 (2014)

Gaussian beam



en.wikipedia.org/wiki/Gaussian_beam



Opt. Express **20**, 14604-14613 (2012)

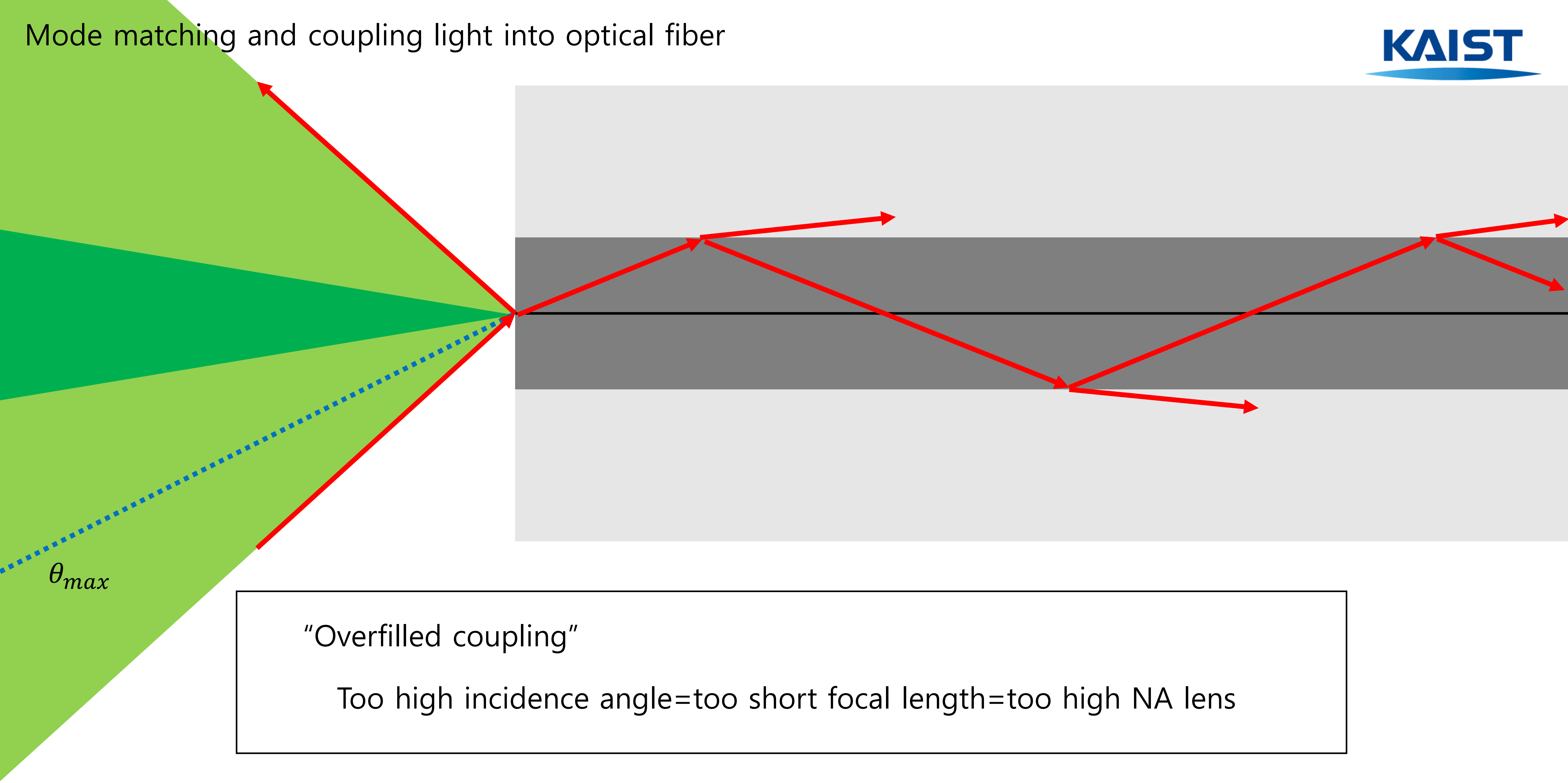
MFD =Full width of $\frac{1}{e^2}$ to peak intensity

$$\mathrm{MFD} = \frac{\lambda}{\pi}\sqrt{\frac{2\int_0^{90^\circ} I(\theta)\sin\theta\cos\theta\,\mathrm{d}\theta}{\int_0^{90^\circ} I(\theta)\sin^3\theta\cos\theta\,\mathrm{d}\theta}}$$

$$\mathrm{MFD} = 2a\left(0.65 + \frac{1.619}{v^{1.5}} + \frac{2.879}{v^6}\right)$$

Marcuse formula

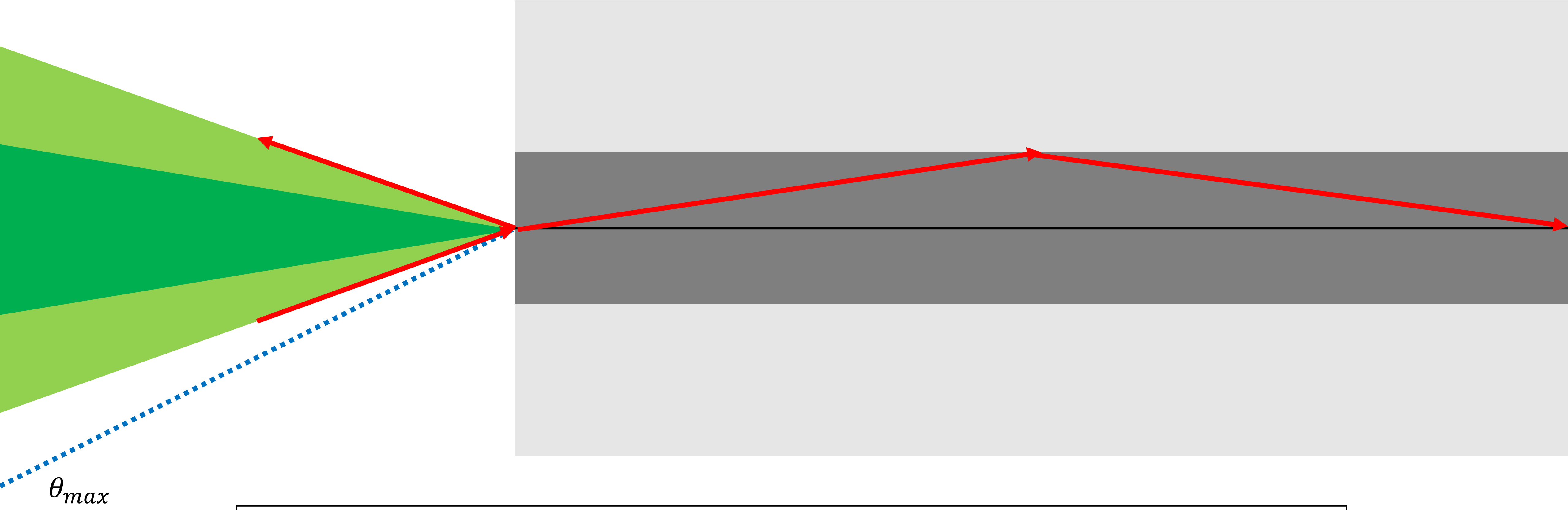
Fiber-launch stage



"Overfilled coupling"

Too high incidence angle=too short focal length=too high NA lens

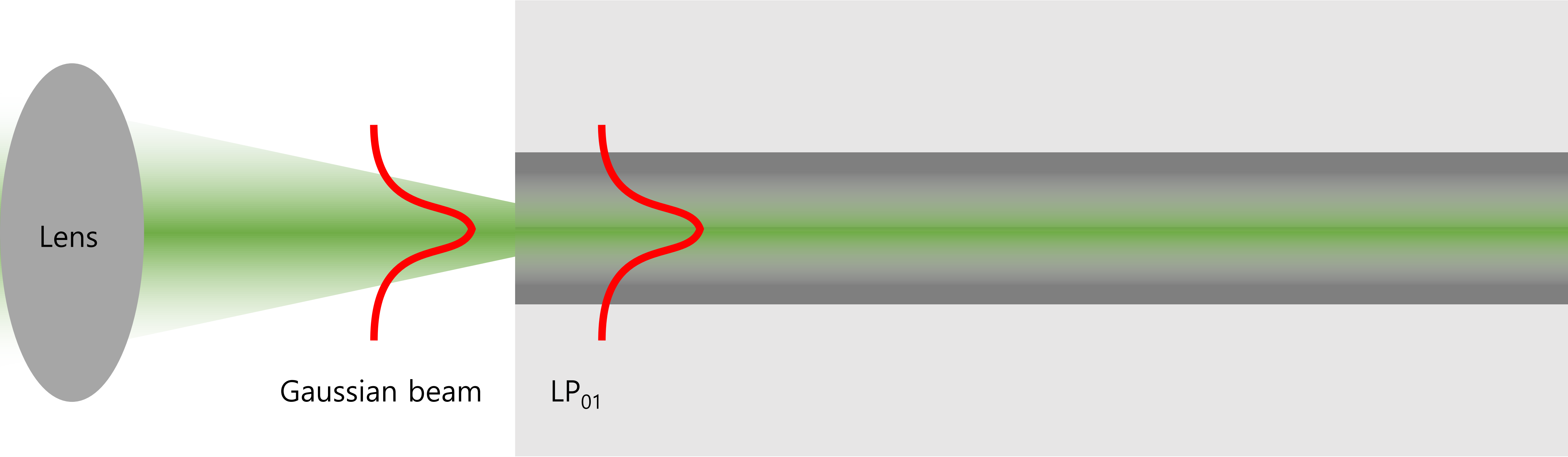
Mode matching and coupling light into optical fiber



"Underfilled coupling"

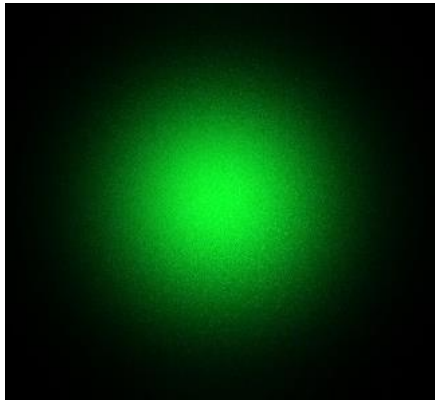
Too low incidence angle=too long focal length=too low NA lens

Mode matching and coupling light into optical fiber



Focal spot size

$$2w_0 = \frac{4\lambda}{\pi}\frac{f}{D}$$



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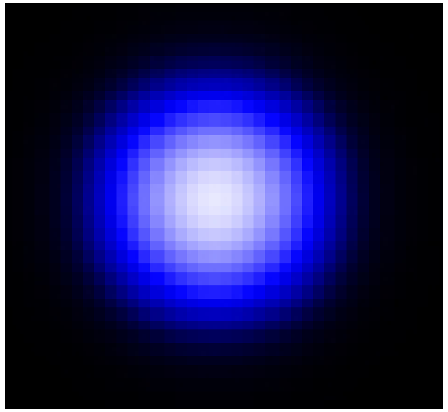


Mode field diameter

$$\mathrm{MFD} = 2a\left(0.65 + \frac{1.619}{v^{1.5}} + \frac{2.879}{v^{6}}\right)$$

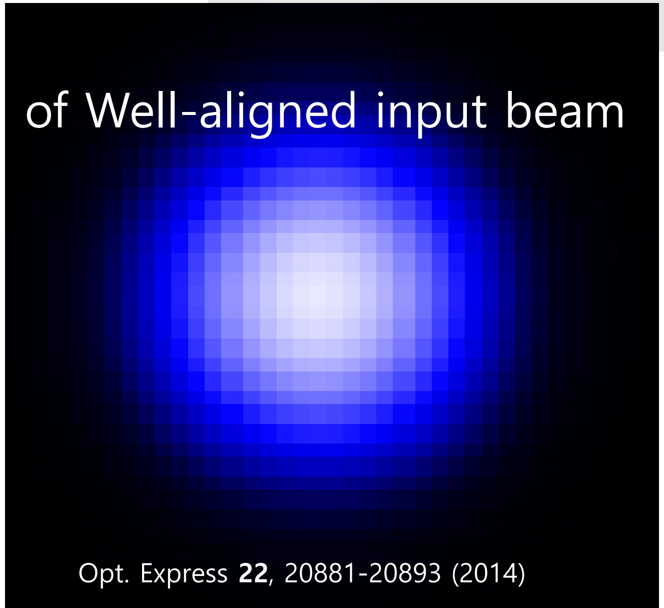
Waist radius of the input beam should be so mached well as possible to MFD of LP_{01} in the target fiber

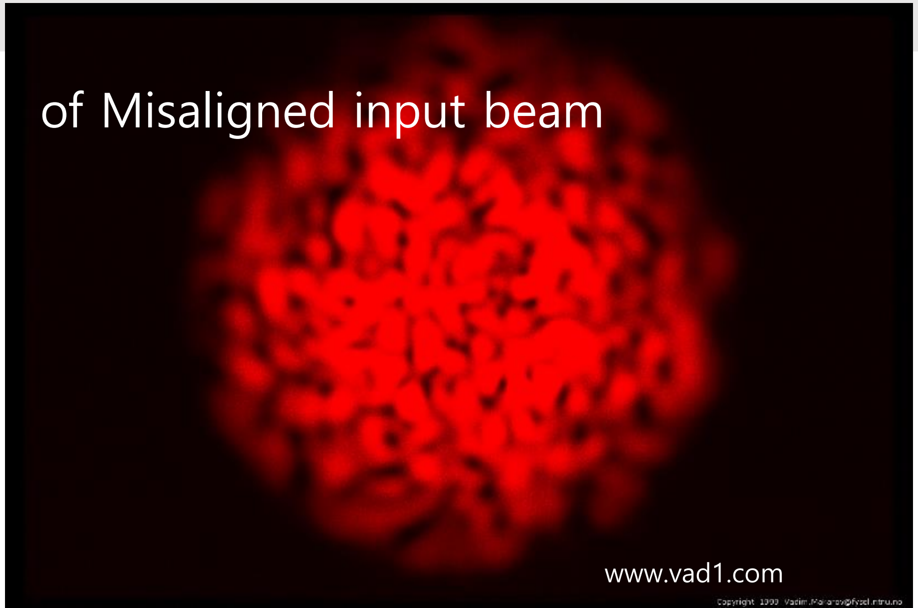
coupling light into a multi-mode optical fiber

Well-aligned input beam

Misaligned input beam

Output pattern:





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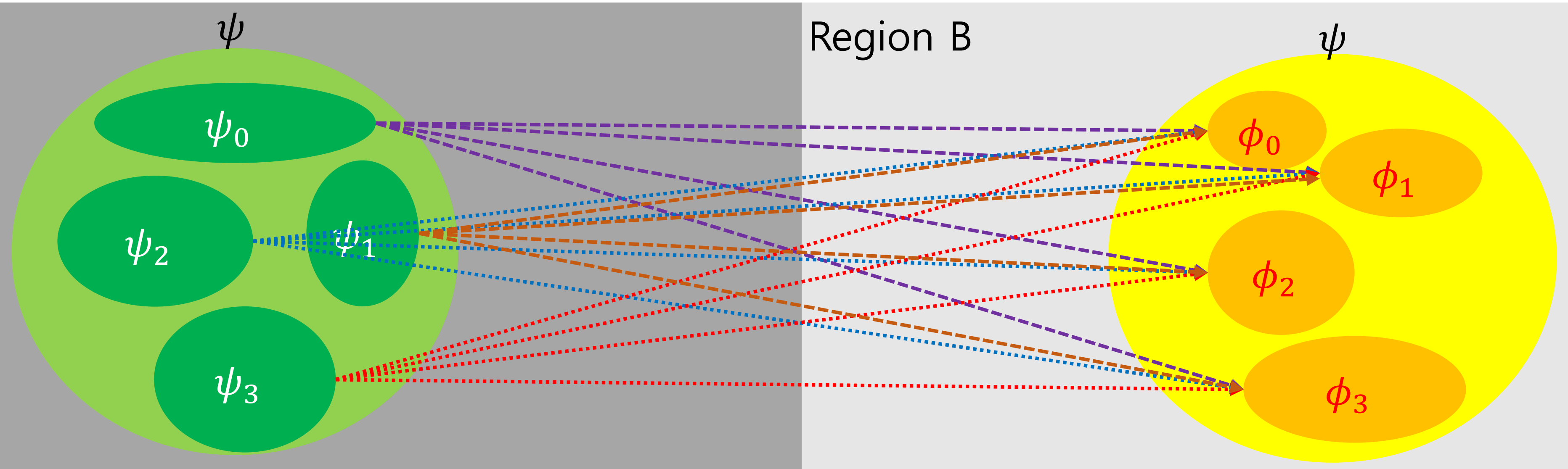
Region A

Region B



$$\psi(x,y,z) = \sum_j a_j \psi_j(x,y) \exp\left(i\beta_j^A z\right)$$

$$\psi(x,y,z) = \sum_j b_j \phi_j(x,y,z) \exp\left(i\beta_j^B z\right)$$

$$\beta = \frac{2\pi}{\lambda} \cdot n_{\text{eff}}$$

$$b_j = \psi \cdot \phi_j = \exp\left(i(\beta_j^A - \beta_j^B)z\right) \int \psi(x,y,z)\phi_j(x,y,z)\mathrm{d}x\mathrm{d}y$$

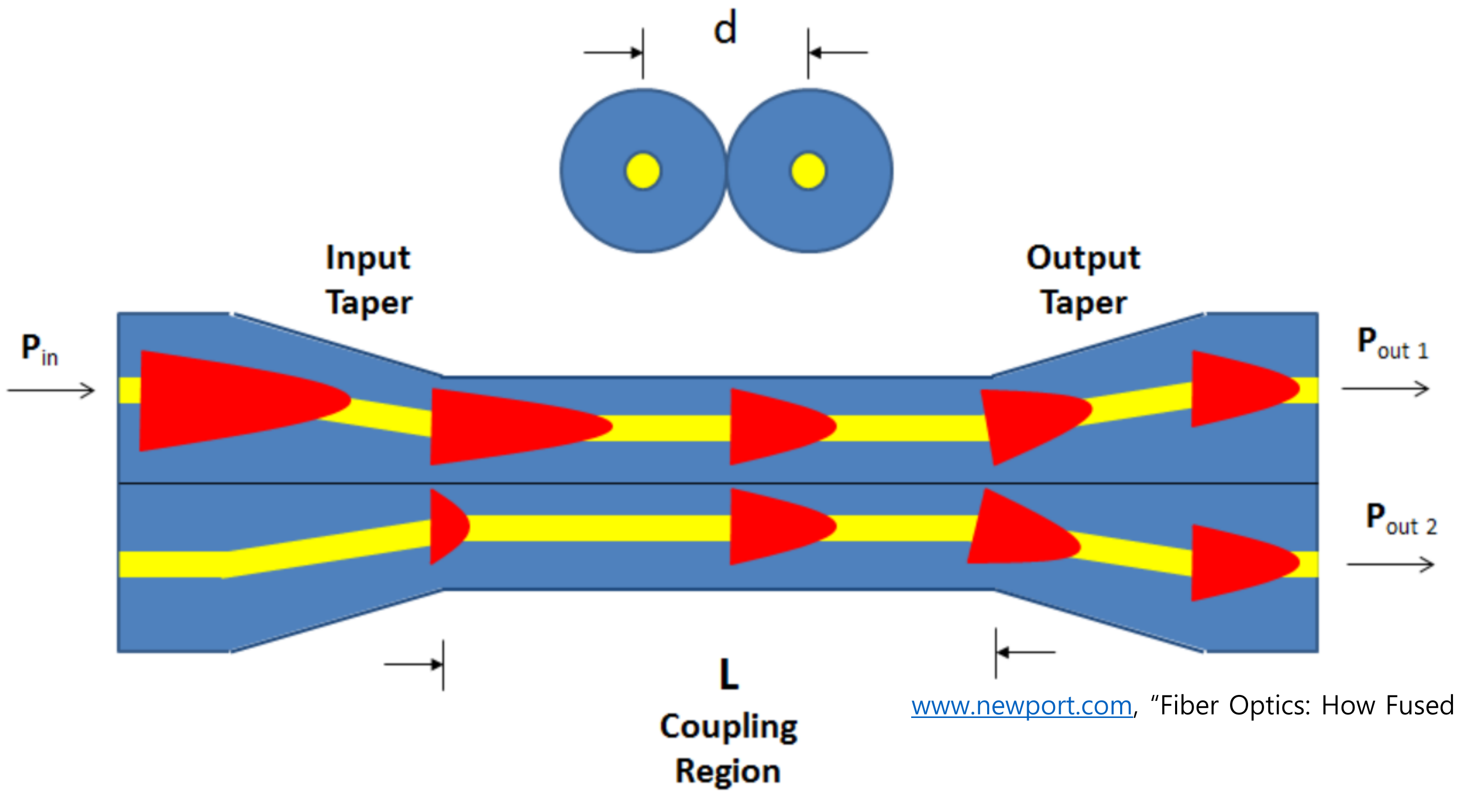
Phase matching condition: $\left|\beta_j^A - \beta_j^B\right| \ll 1 \rightarrow \exp\left(i\left(\beta_j^A - \beta_j^B\right)z\right) \approx 1 \rightarrow \left|n_j^A - n_j^B\right| \ll 1$ (The smaller, the better)

Overlap integral: $\int \psi(x,y,z)\phi_j(x,y,z)\mathrm{d}x\mathrm{d}y$ (The greater, the better)

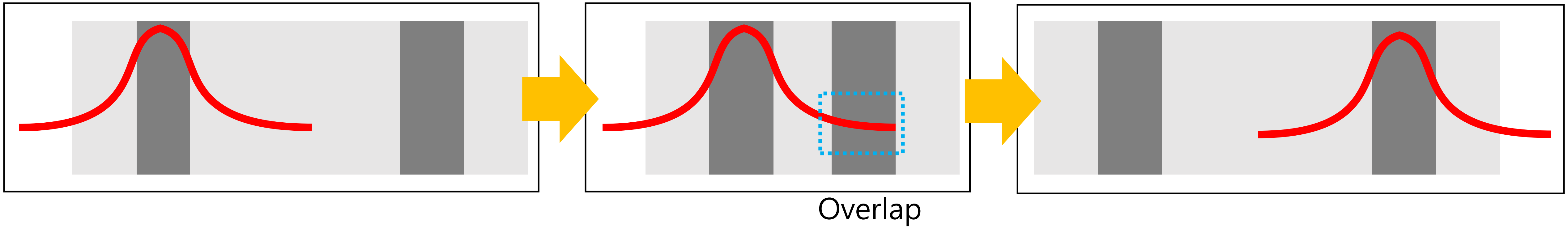
Fiber coupler

www.newport.com, "Fiber Optics: How Fused Fiber Optic Couplers Work"

Fiber coupler



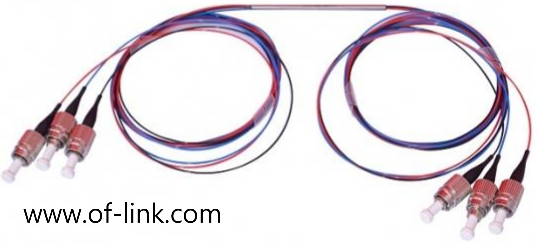
www.newport.com, "Fiber Optics: How Fused Fiber Optic Couplers Work"



Fiber couplers

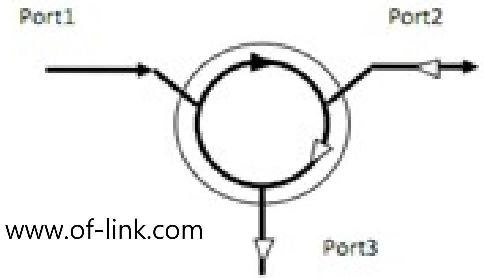
www.newport.com

2x2 coupler



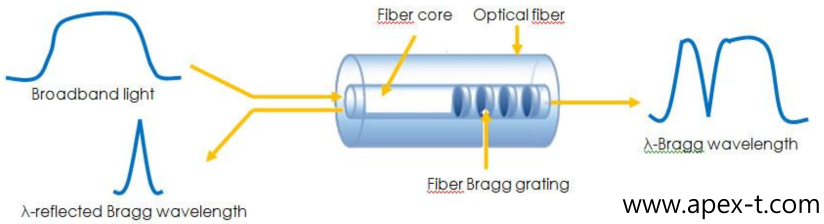
www.of-link.com

3x3 coupler



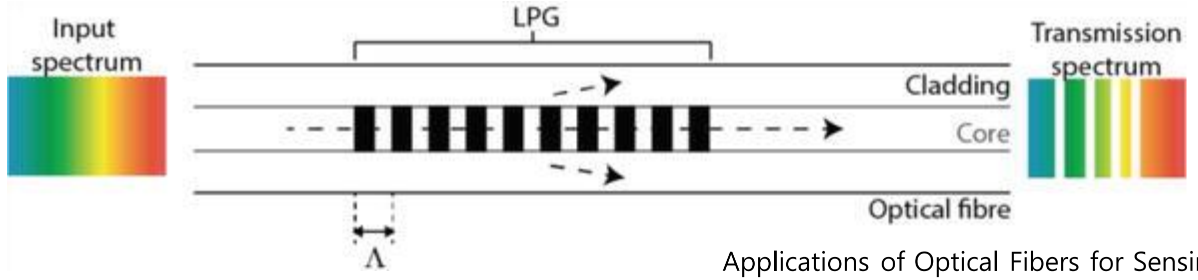
www.of-link.com

fiber circulator



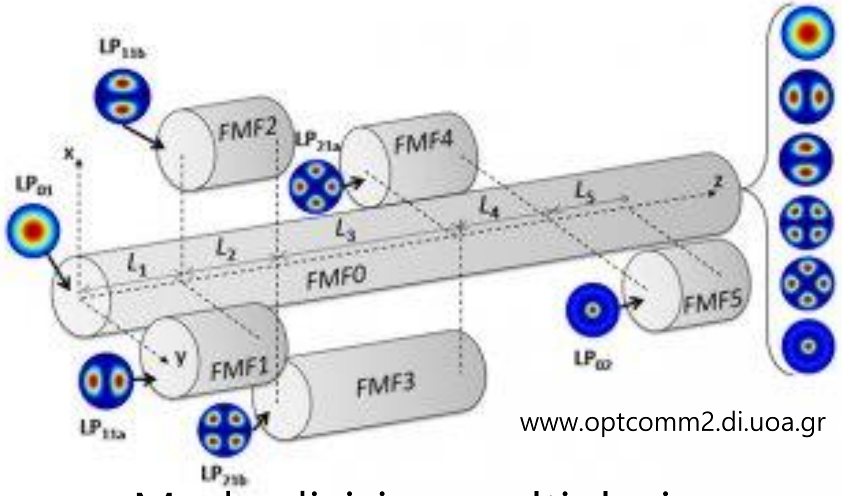
www.apex-t.com

fiber Bragg grating



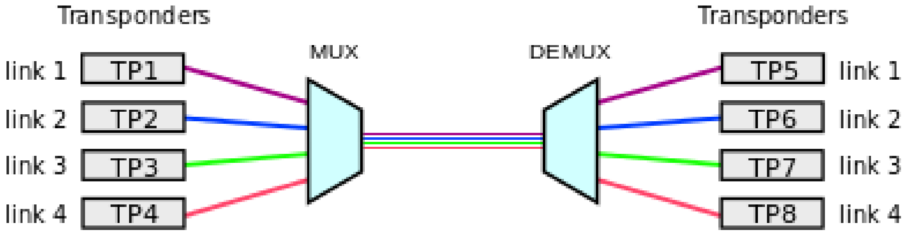
Applications of Optical Fibers for Sensing
(Edited by Christian Cuadrado-Laborde)

fiber long period grating



www.optcomm2.di.uoa.gr

Mode-division multiplexing



en.wikipedia.org/wiki/Wavelength-division_multiplexing

Wavelength division multiplexing

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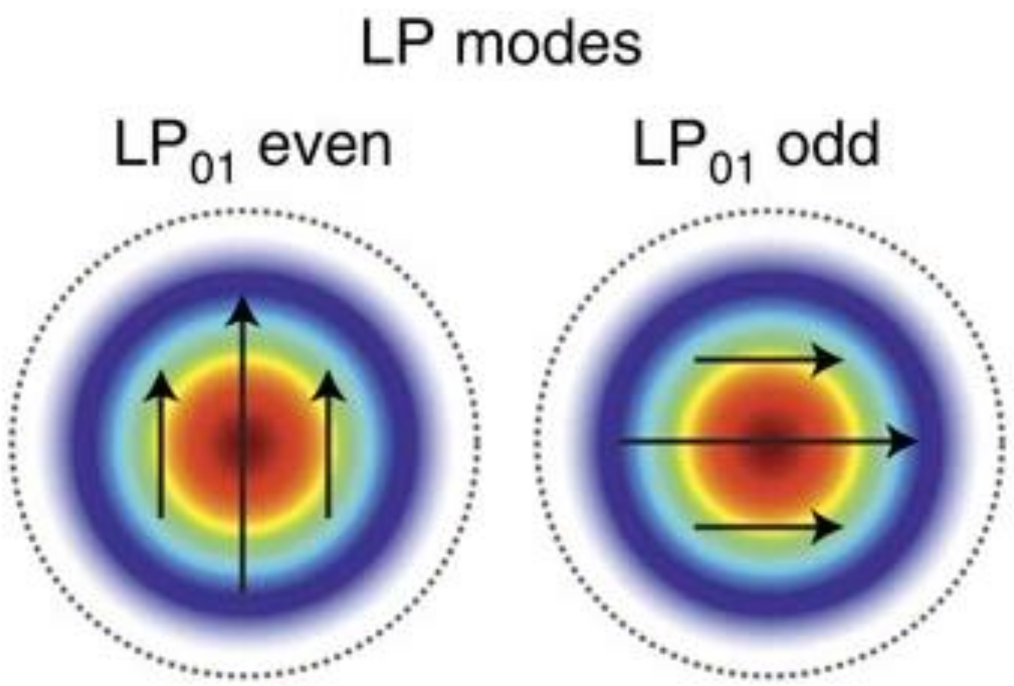
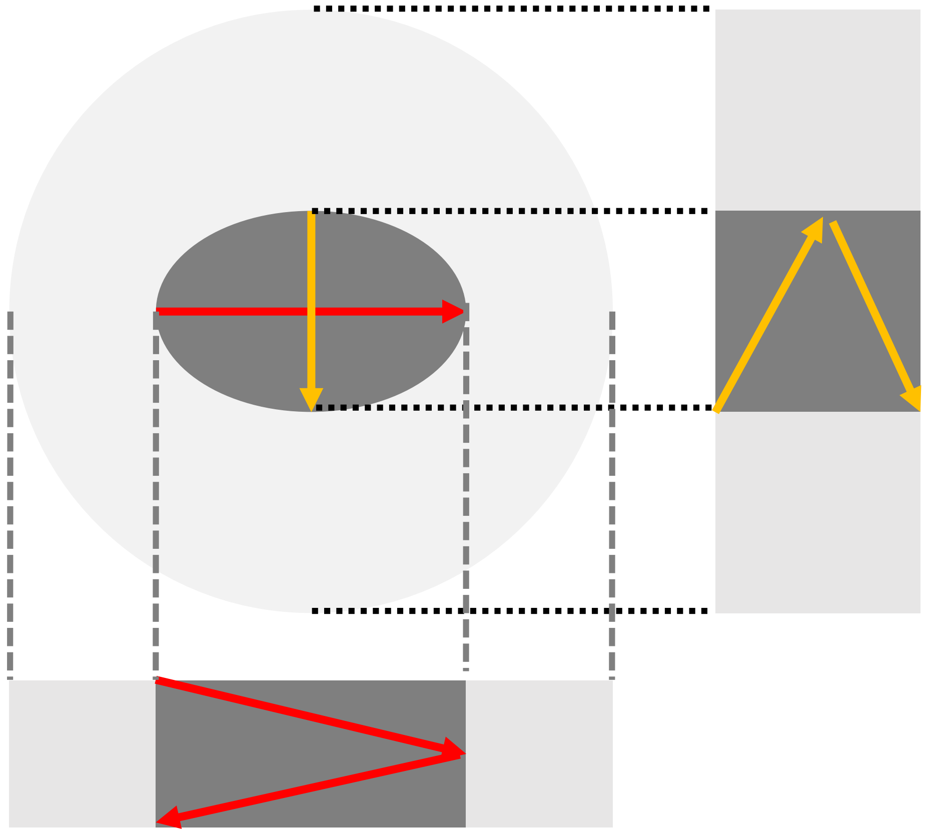


Nat Commun **5,** 5481 (2014)

If fiber is circular, no difference between effective refractive indices of two polarization modes.

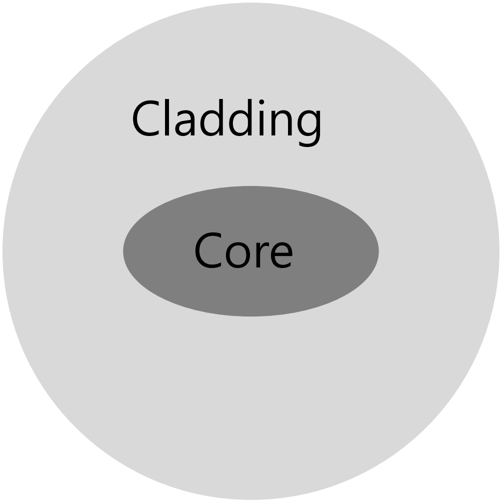
Elliptic core fiber



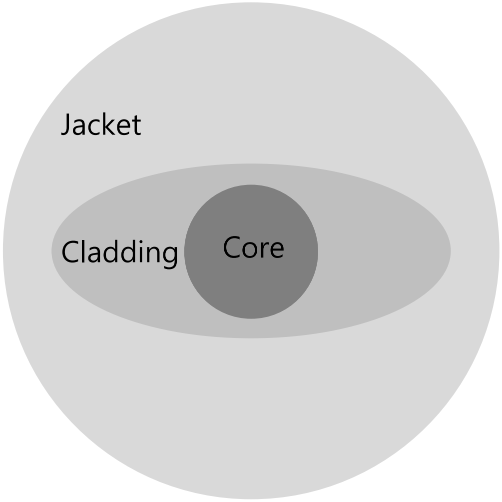
If fiber is not circular, two polarizations is running at the distinct speed in the fiber.

Induced birefringent fibers

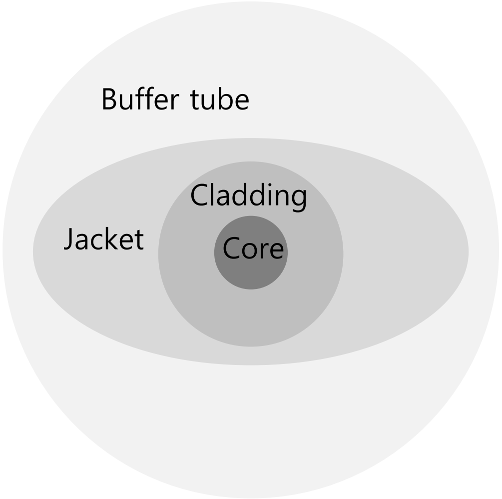
Elliptic core



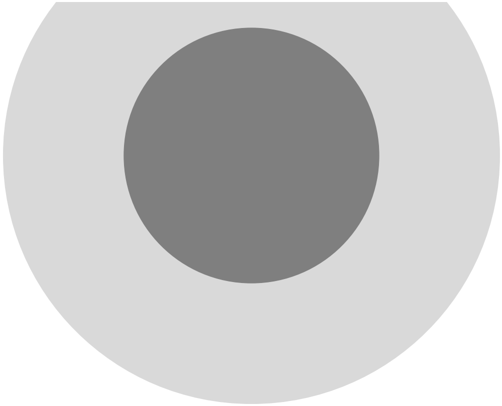
Elliptic cladding



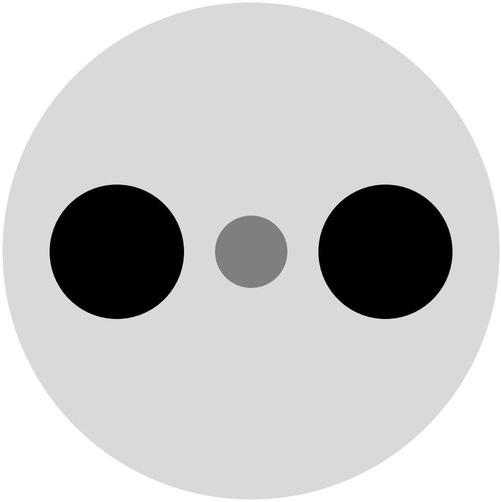
Elliptic jacket



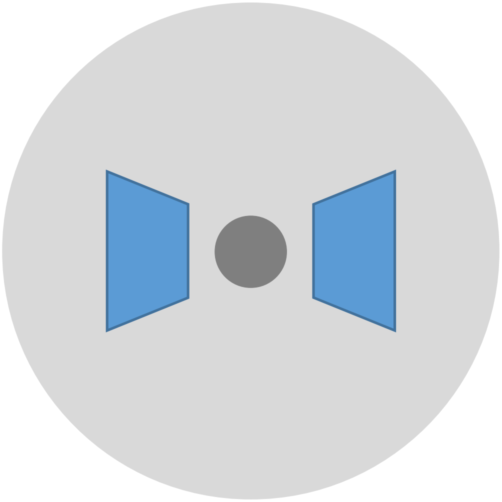
D-shape fiber



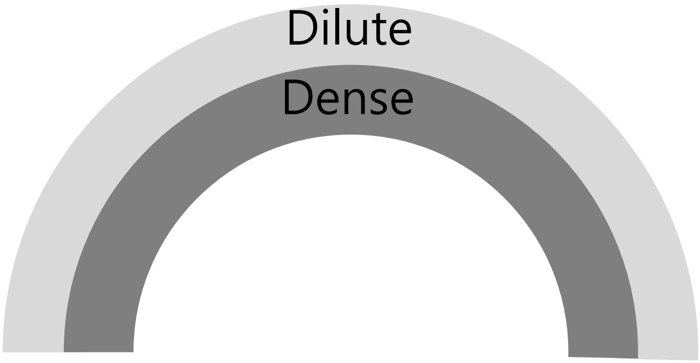
Panda fiber



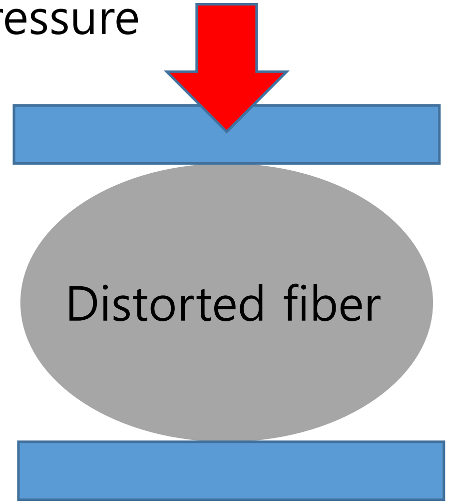
Bow-tie fiber



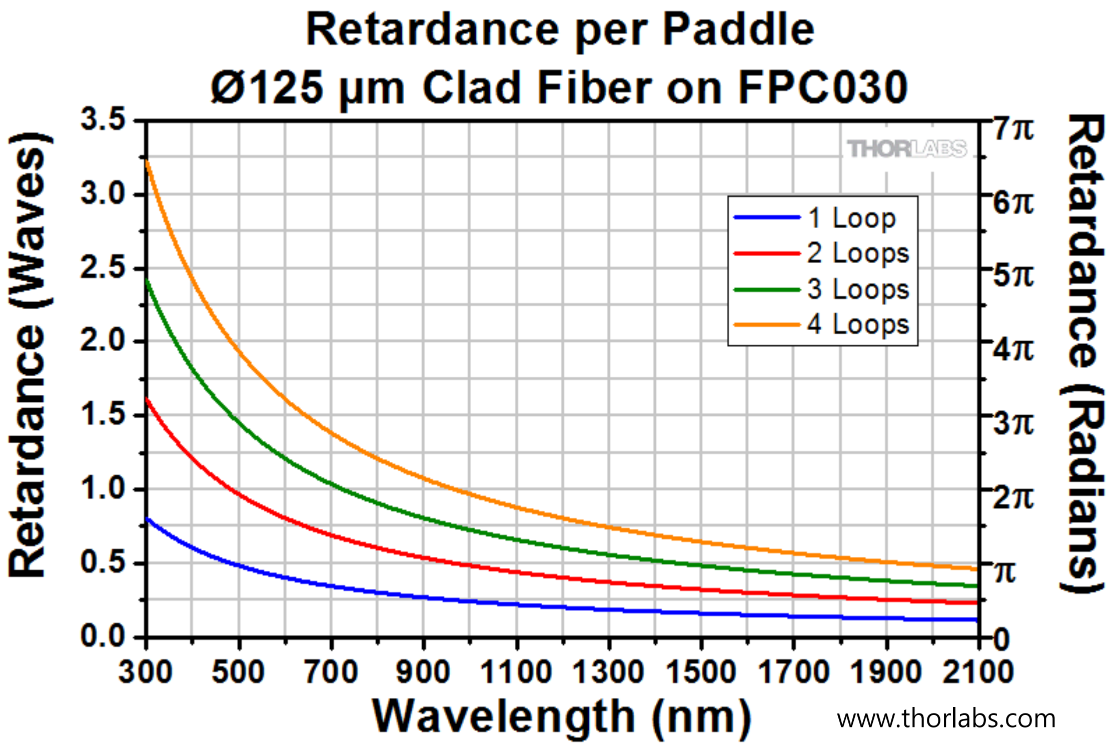
Bending



Pressure



Polarization controller of light in fiber



Looping fiber

->Induced birefringence

->follow-up the fiber direction

->polarization changed after twisted paddles

To cover whole Poincaré sphere, 3 paddles are required.

$$\phi(\mathrm{rad}) = \frac{2\pi^2 a N d^2}{\lambda D}$$

D: Loop diameter

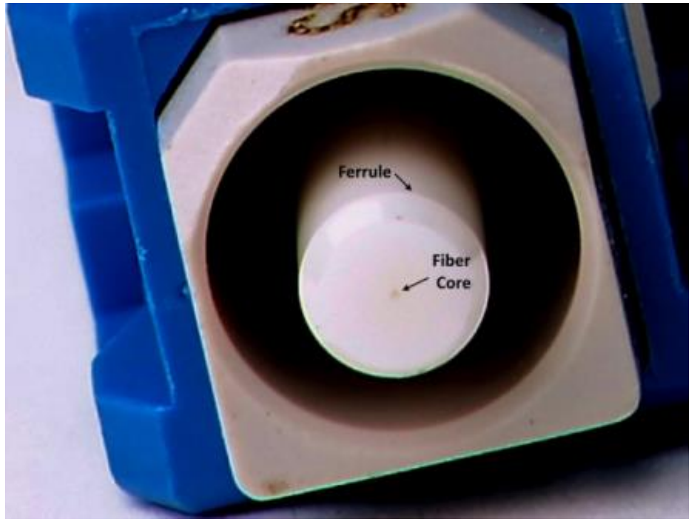
d: fiber cladding diameter

a: material constant (0.133 for silica fiber)

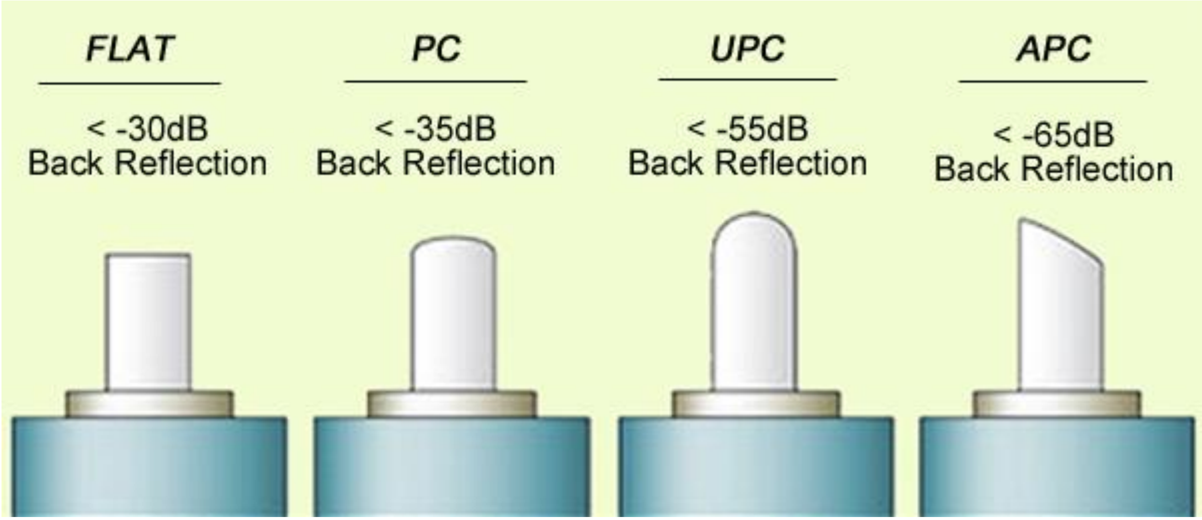
N: the winding number of the Loop

λ: wavelength

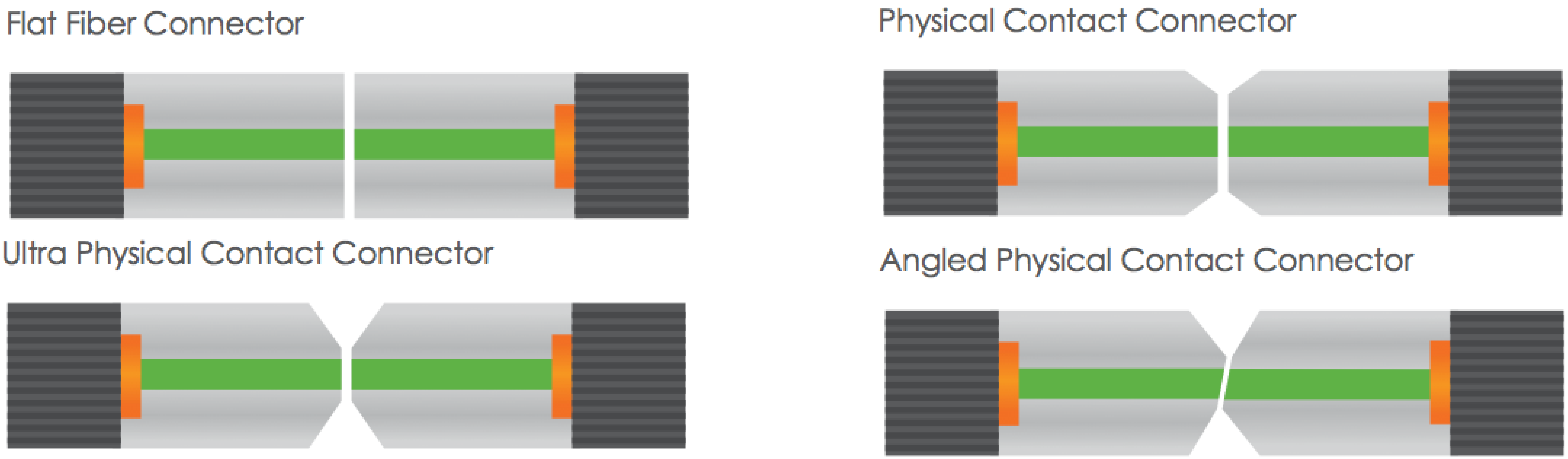
Physical contacts types of fiber connection



http://www.doubleclick.com.my

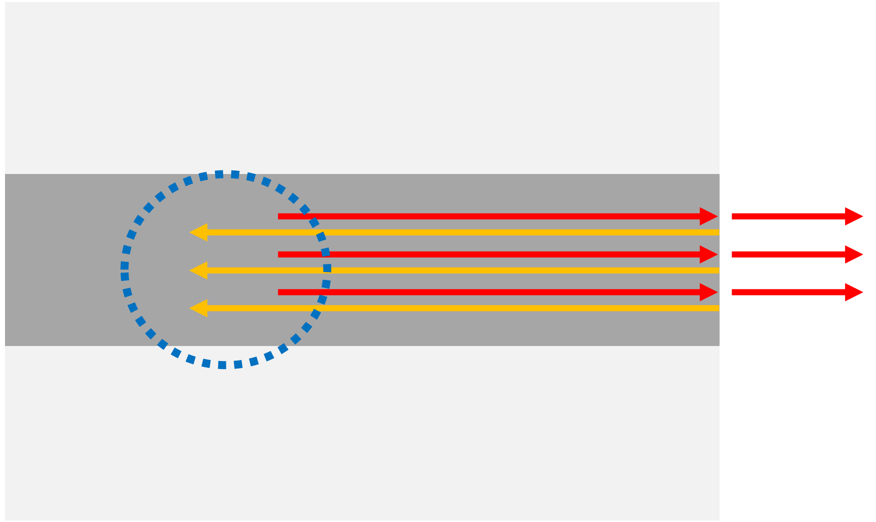


www.fiber-optic-solutions.com/evolution-of-flat-pc-upc-and-apc-fiber-connectors.html

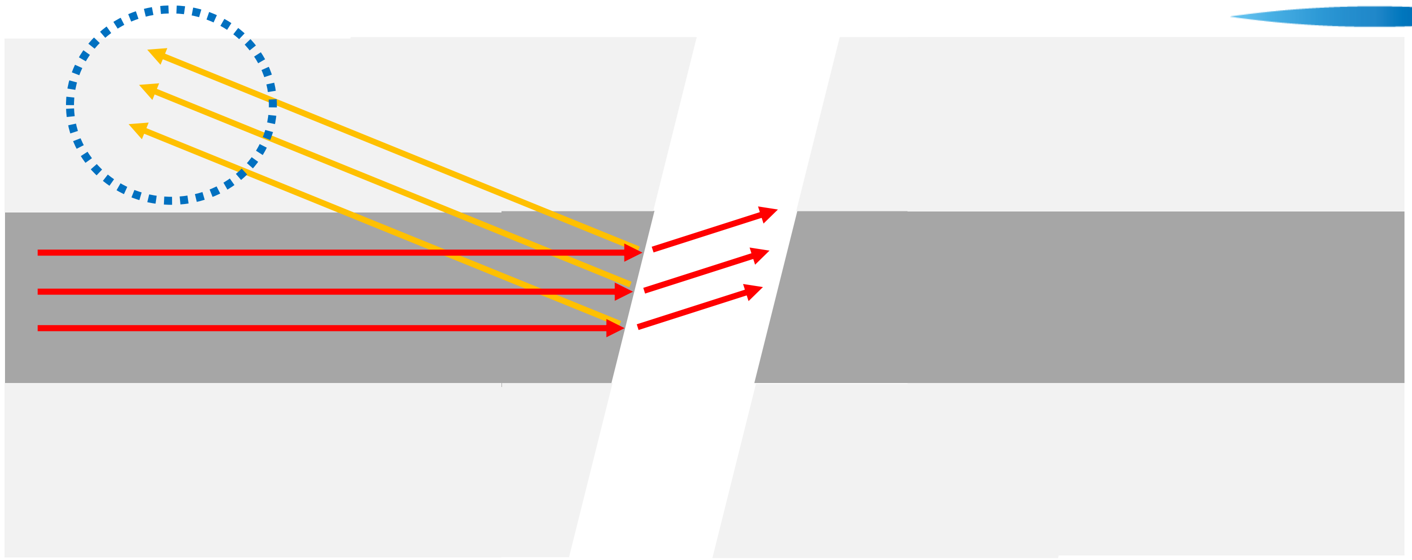


www.fiber-optic-solutions.com/evolution-of-flat-pc-upc-and-apc-fiber-connectors.html

Physical contacts types of fiber connection

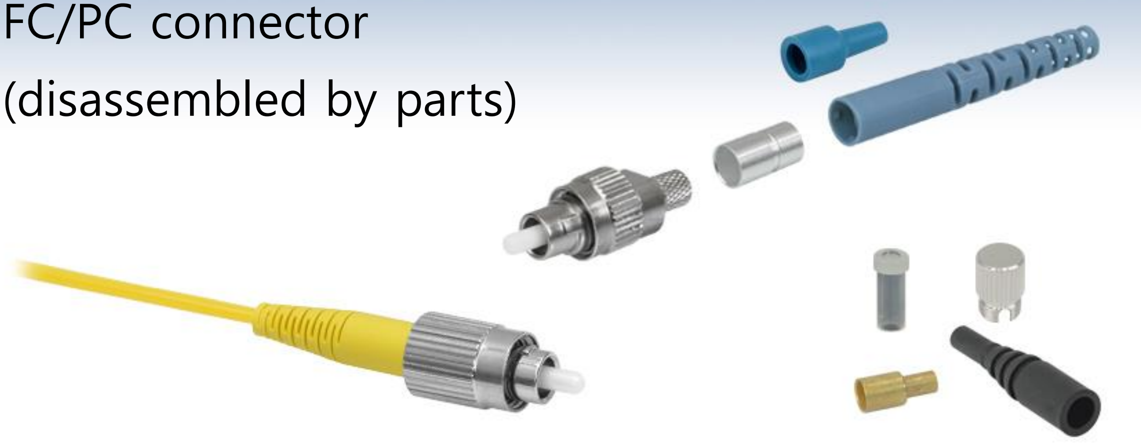


Reflected light has large overlap
to the fiber mode
-> high back reflection



Reflected light has large overlap
to the fiber mode
-> low back reflection

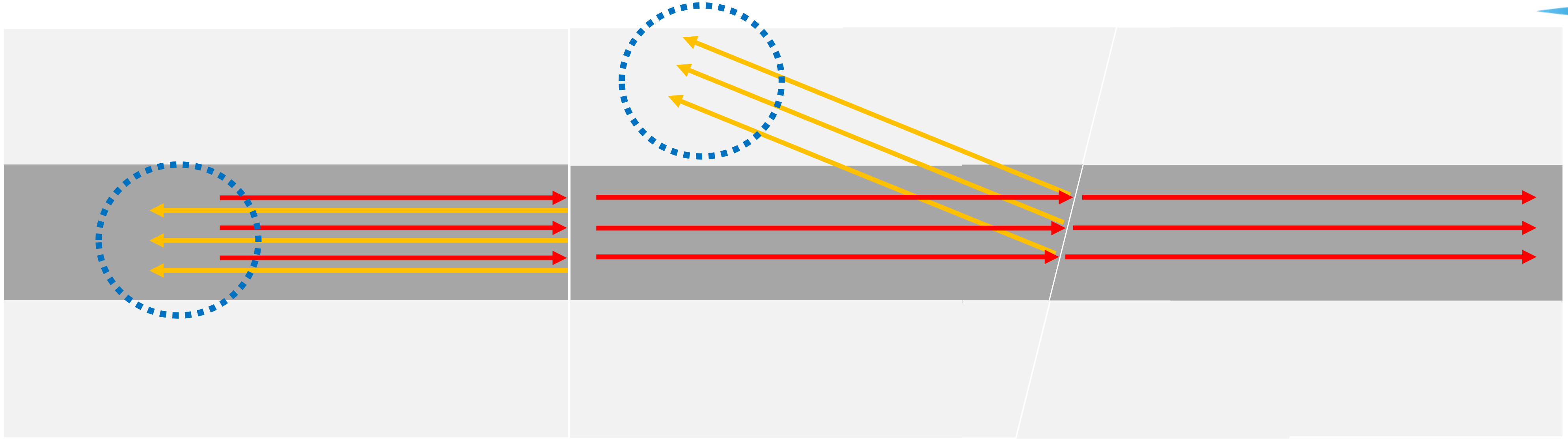
FC/PC connector
(disassembled by parts)



FC/APC connector
(disassembled by parts)

www.thorlabs.com

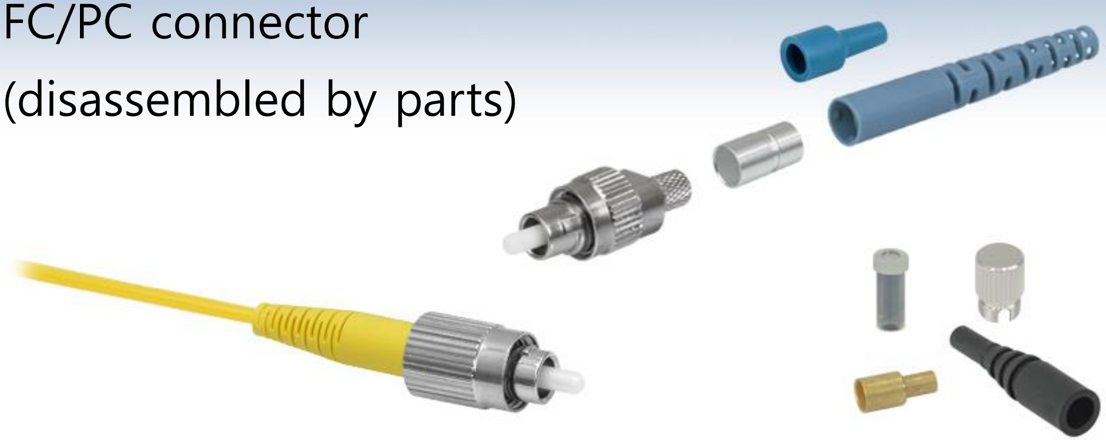
Physical contacts types of fiber connection



Reflected light has large overlap
to the fiber mode
-> high back reflection

Reflected light has large overlap
to the fiber mode
-> low back reflection

FC/PC connector
(disassembled by parts)



FC/APC connector
(disassembled by parts)

www.thorlabs.com

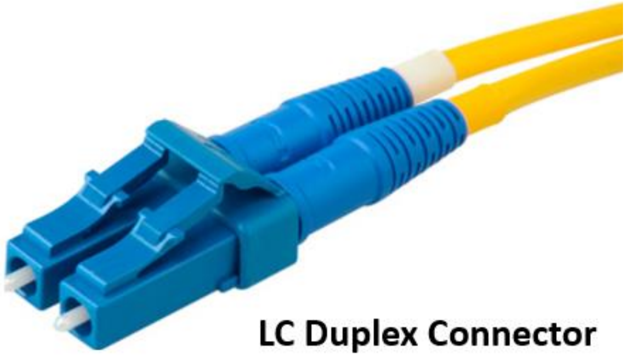
Fiber connecter types

www.flukenetworks.com

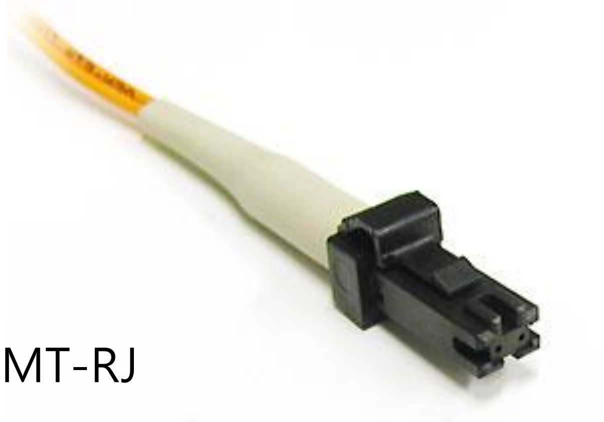
www.flukenetworks.com

SMA

www.amphenol.com



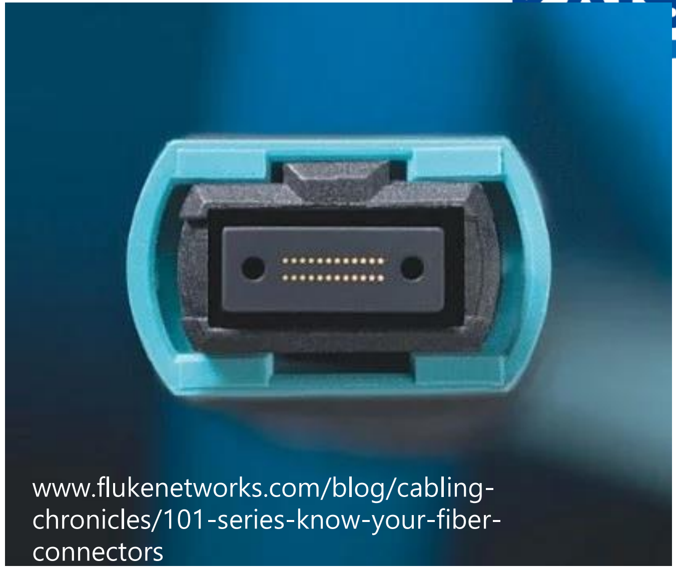
www.flukenetworks.com



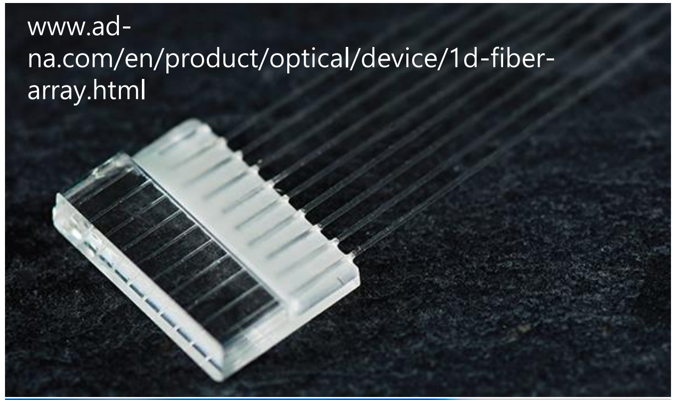
MT-RJ

www.timbercon.com

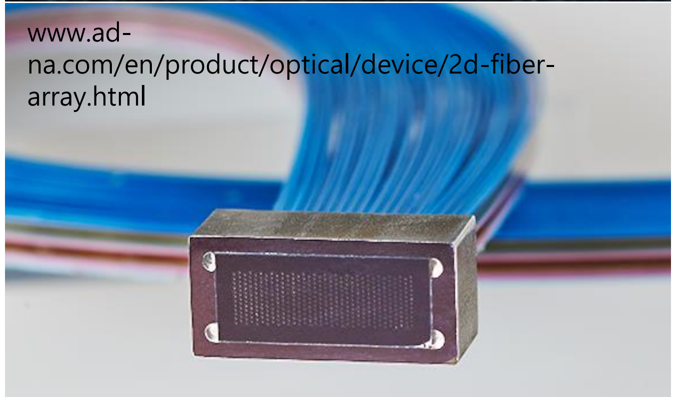
Array connectors



www.flukenetworks.com/blog/cabling-chronicles/101-series-know-your-fiber-connectors

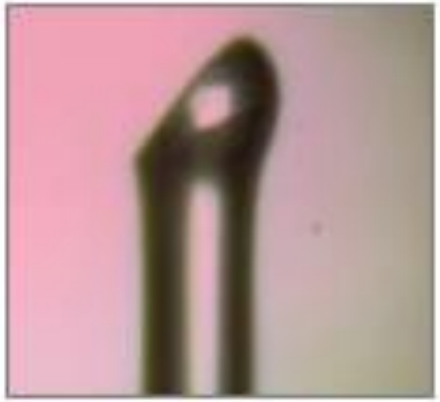


www.ad-na.com/en/product/optical/device/1d-fiber-array.html



www.ad-na.com/en/product/optical/device/2d-fiber-array.html

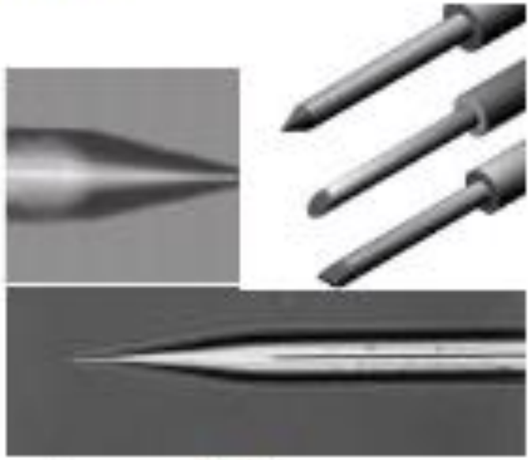
Product images



Perpendicular Lens Fiber

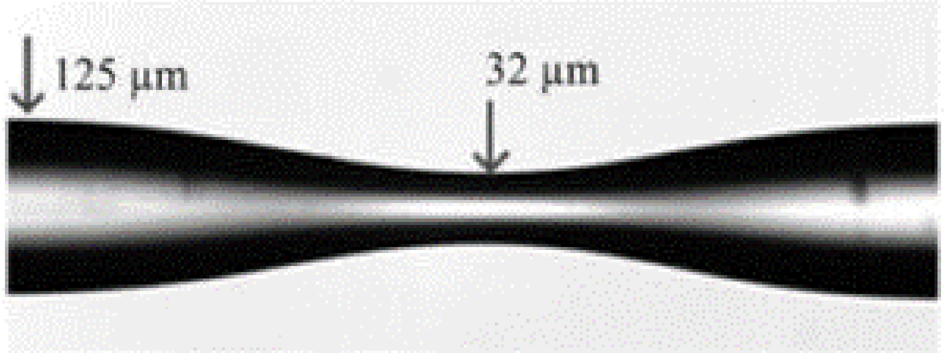
Ball Lensed

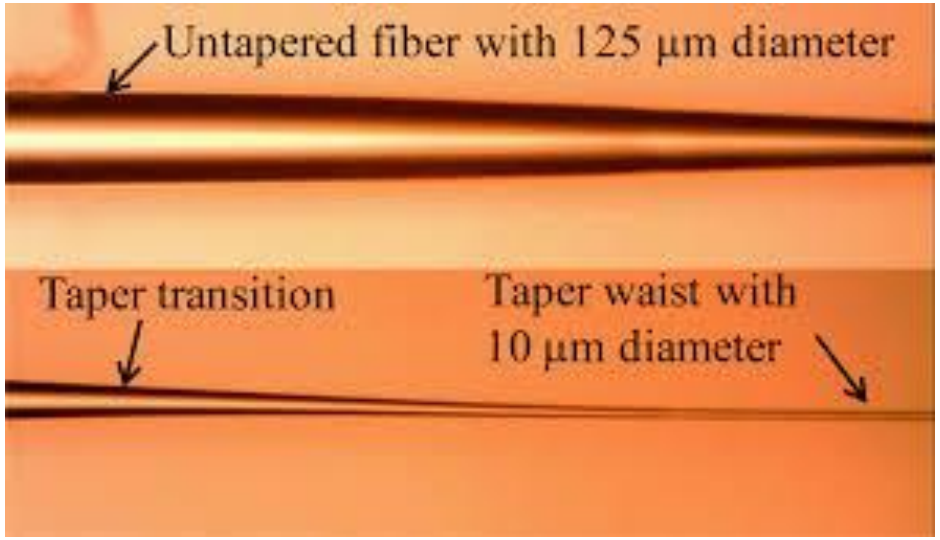
Angled Fiber



Lensed Fibers

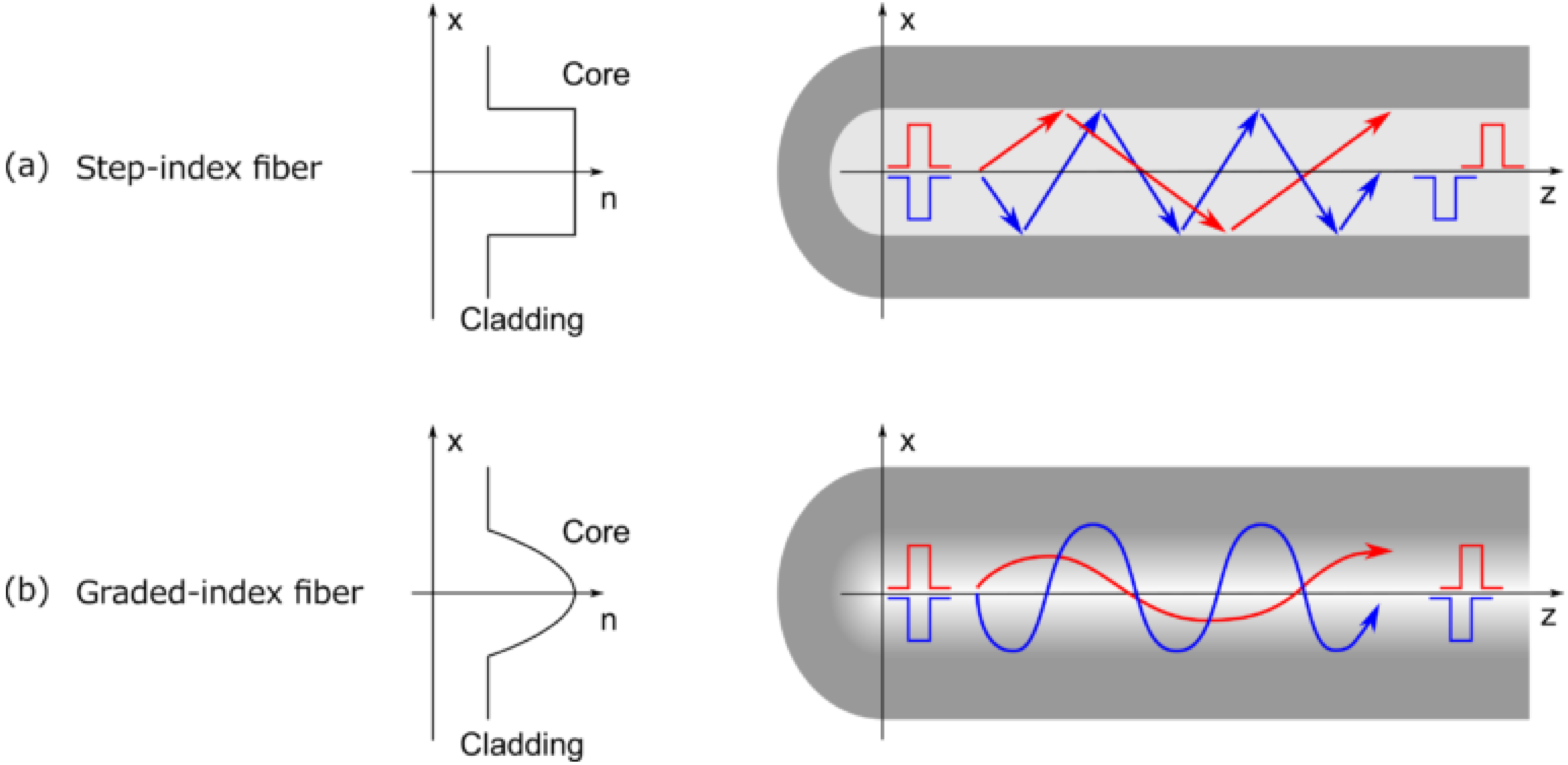
Tapered optical fibers





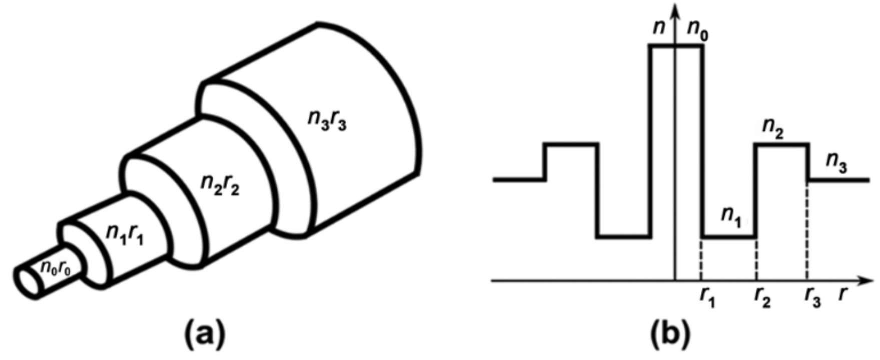
laseoptics.com/lensed-fibers/

Graded index fiber (GRIN fiber)

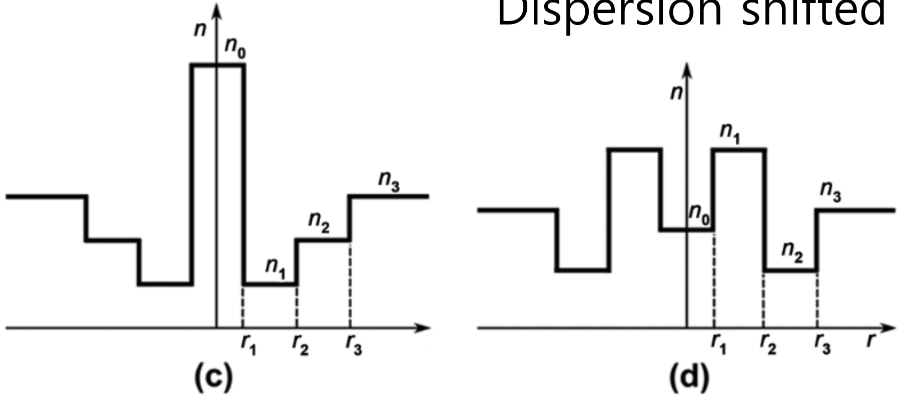


www.fiberlabs.com/glossary/optical-fiber/

Dispersion managed fibers



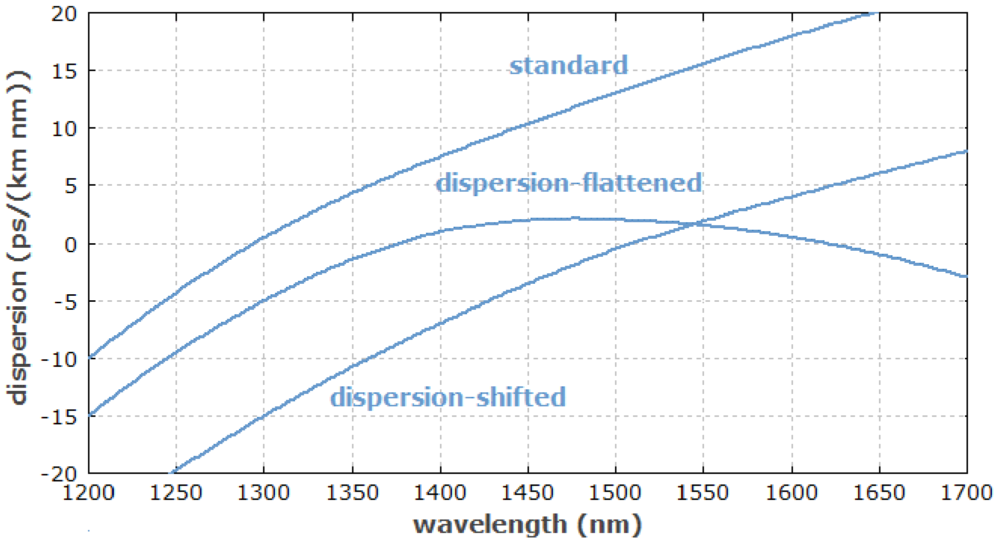
Dispersion shifted fiber



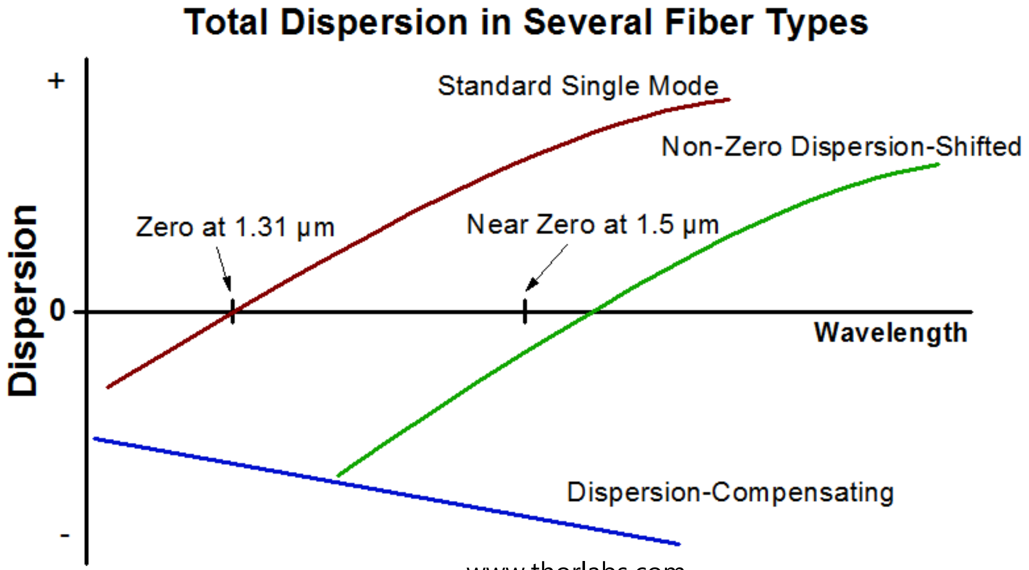
Dispersion flattened fiber

Dispersion compensated fiber

Journal of Optical Communications, *37*(2), 193-198.

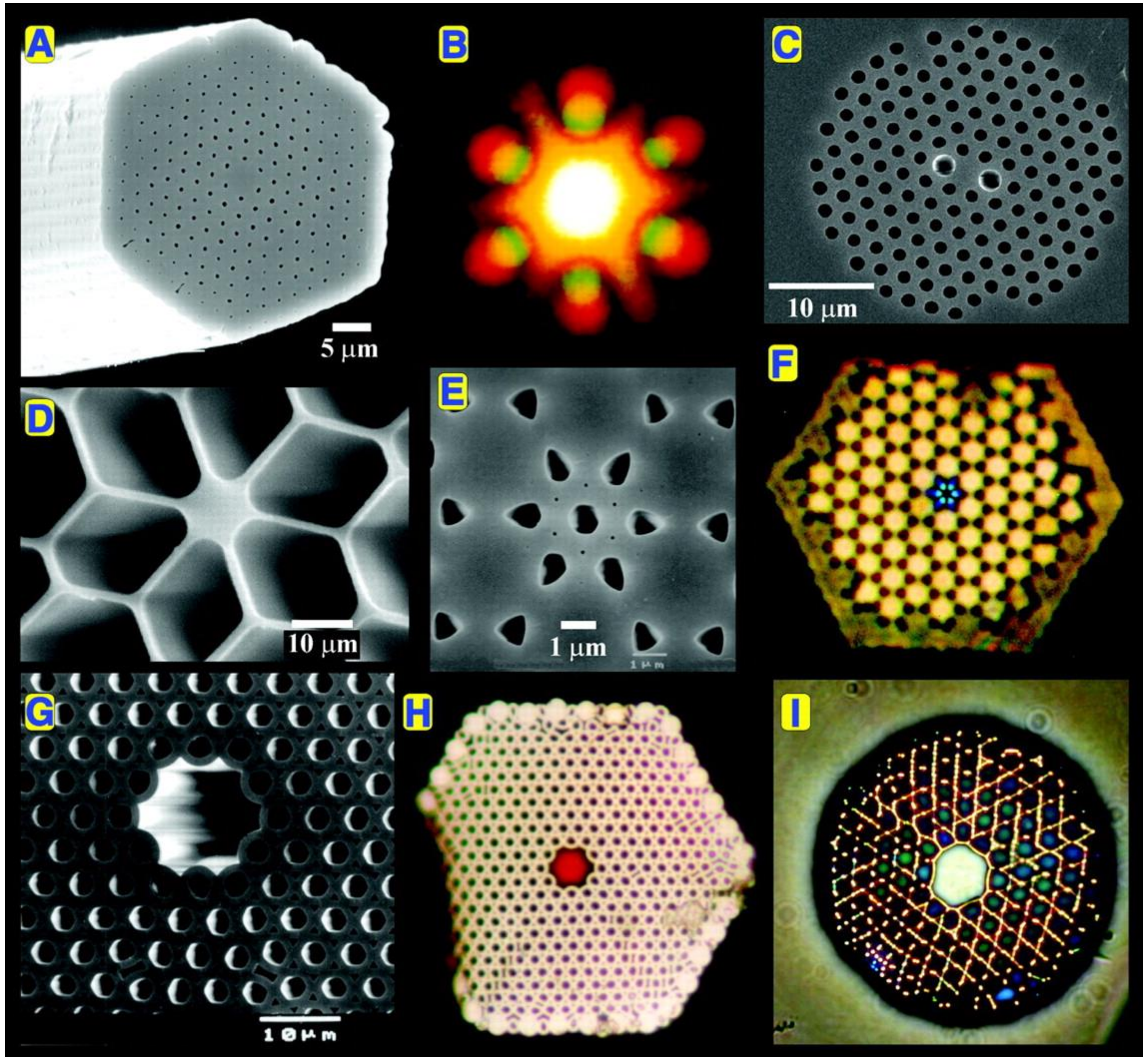


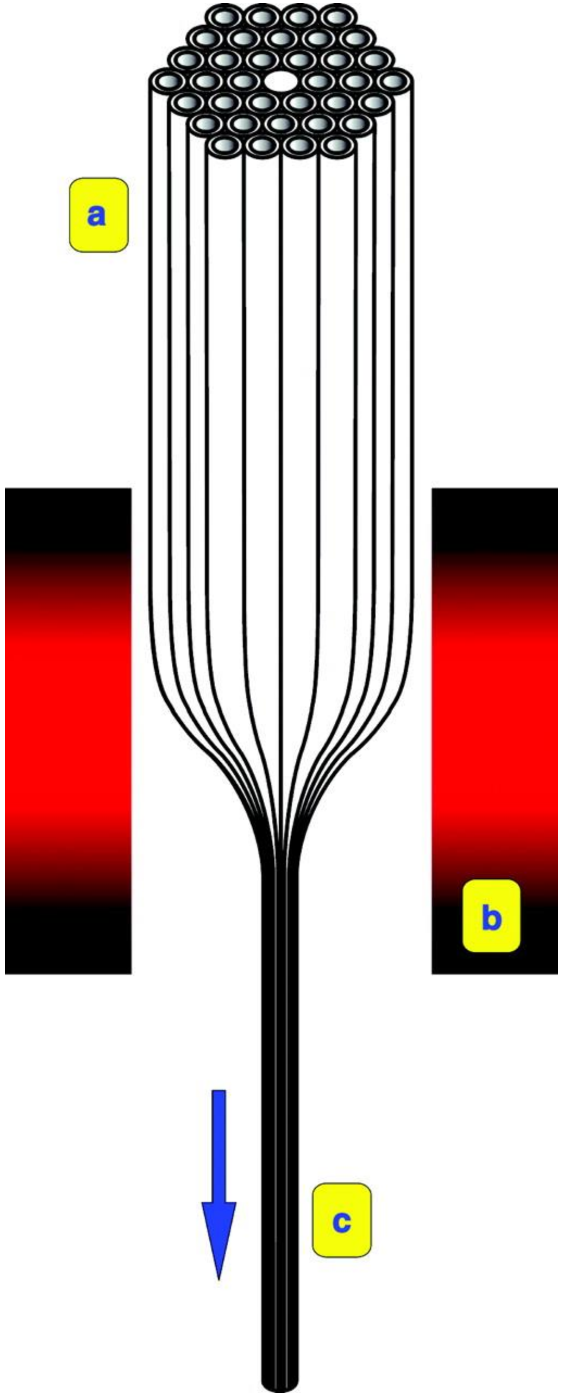
www.rp-photonics.com/dispersion_shifted_fibers.html



www.thorlabs.com

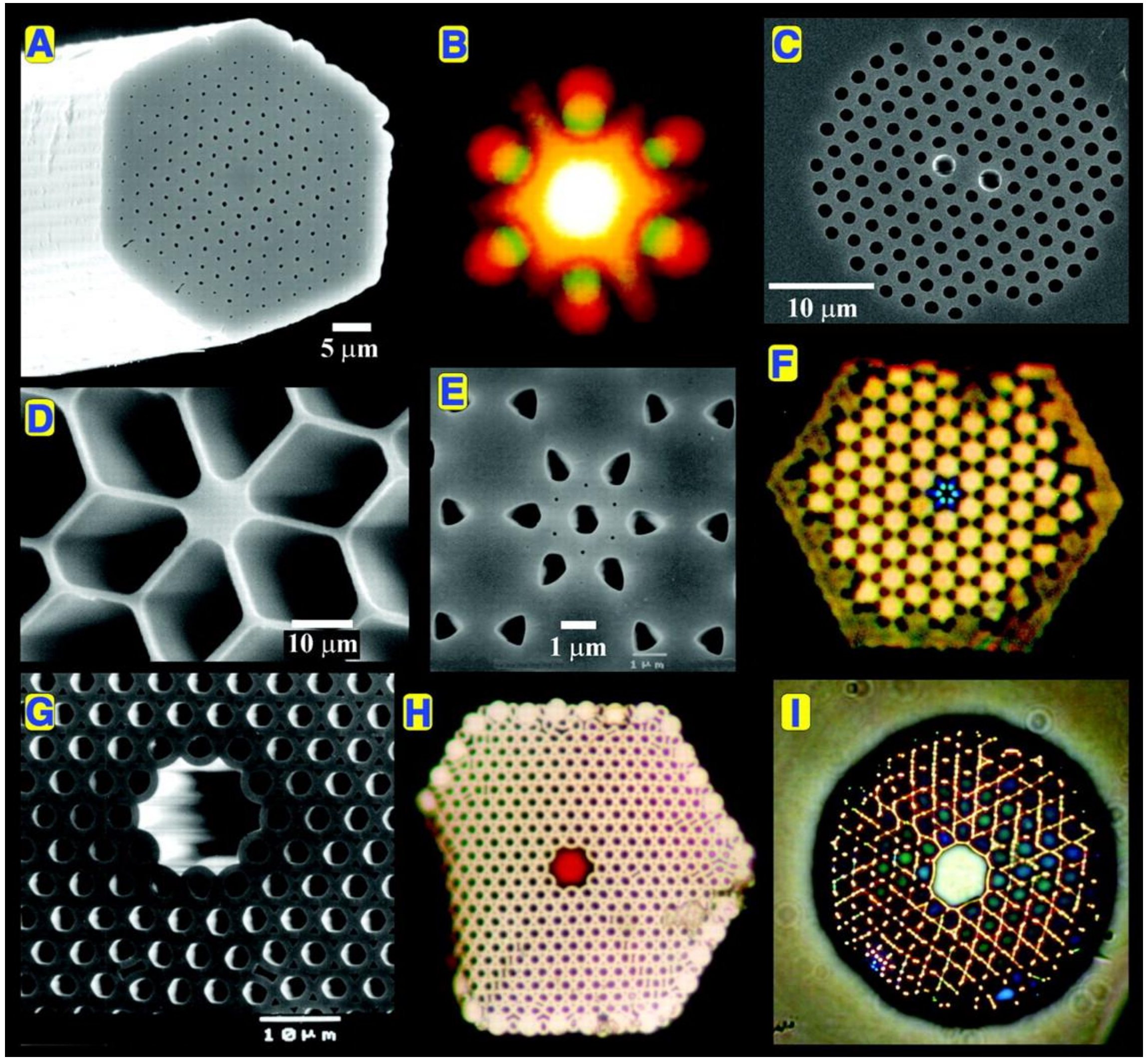
Photonic crystal fibers

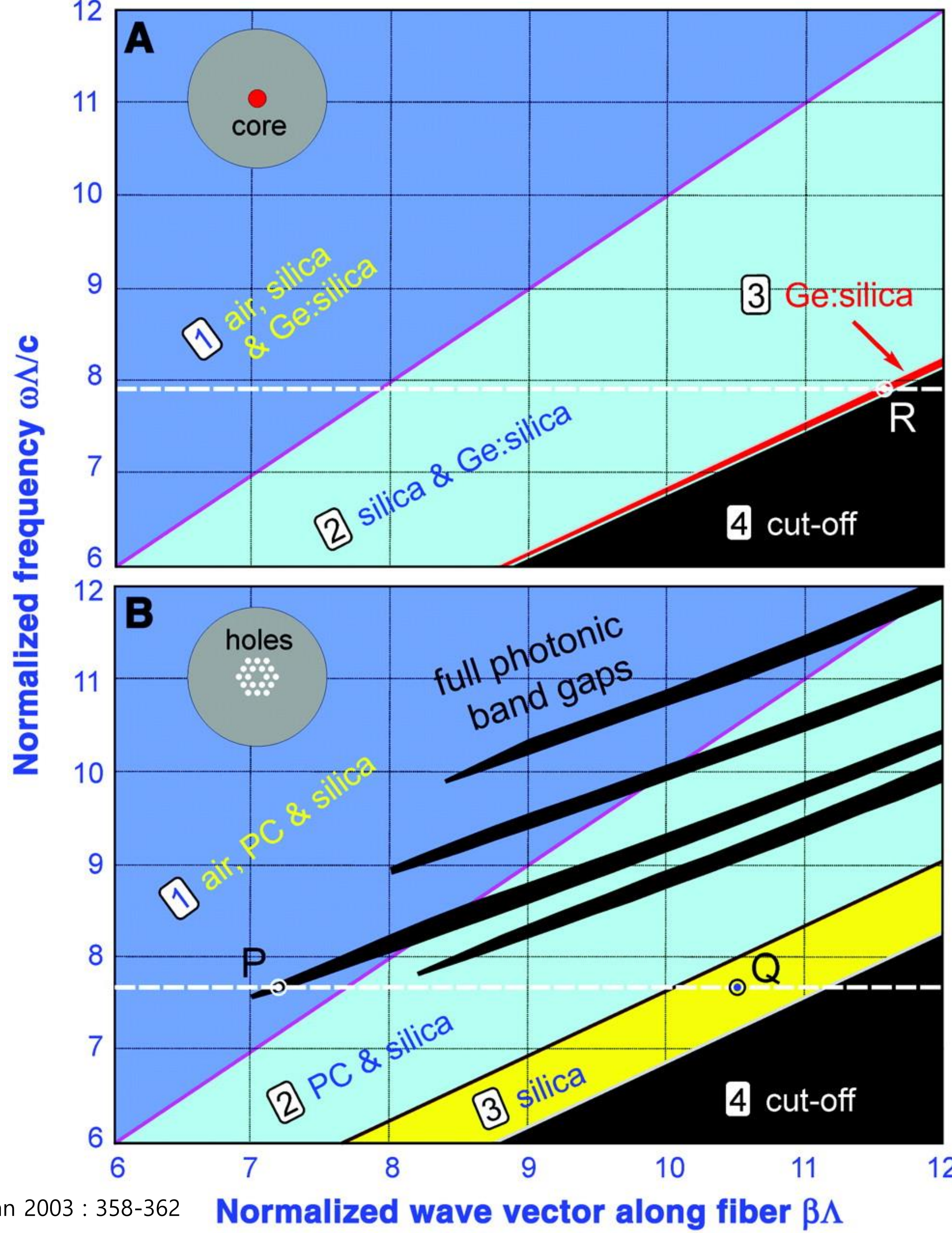




Science 17 Jan 2003 : 358-362

Photonic crystal fibers





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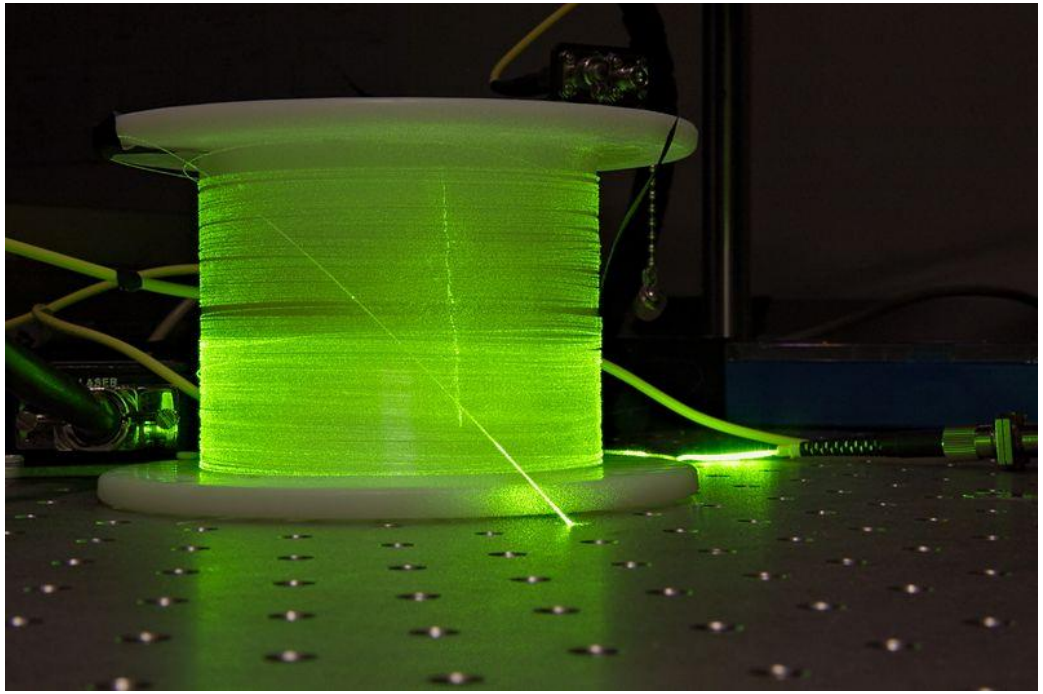
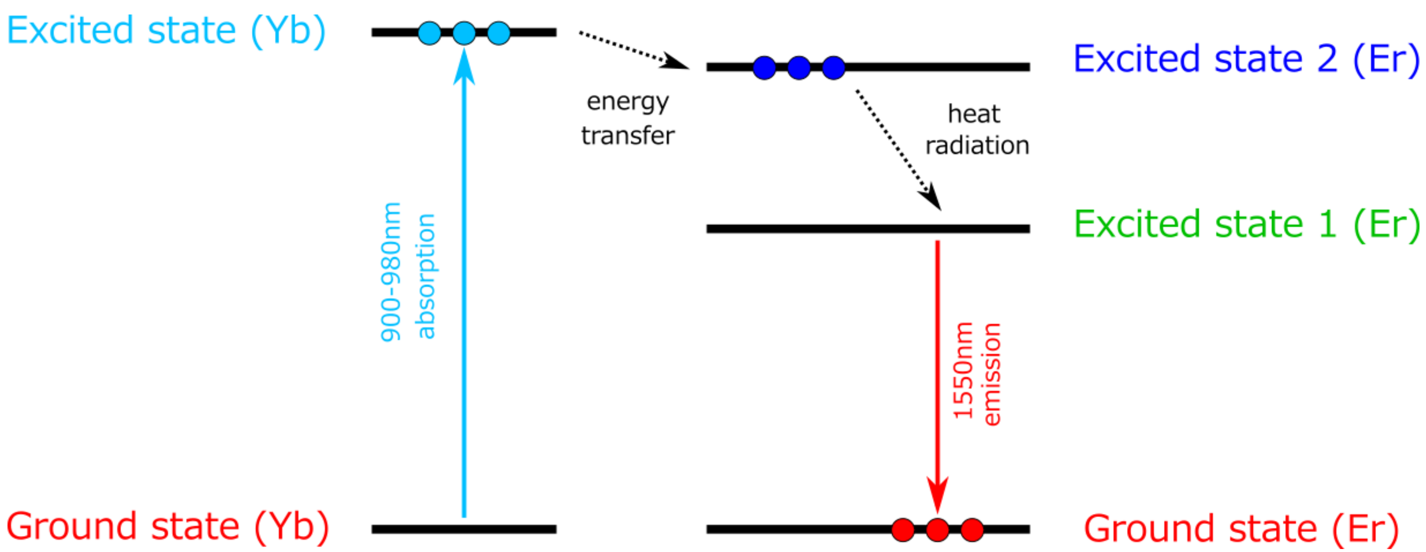
Active fiber (rare-earth doped optical fibers)

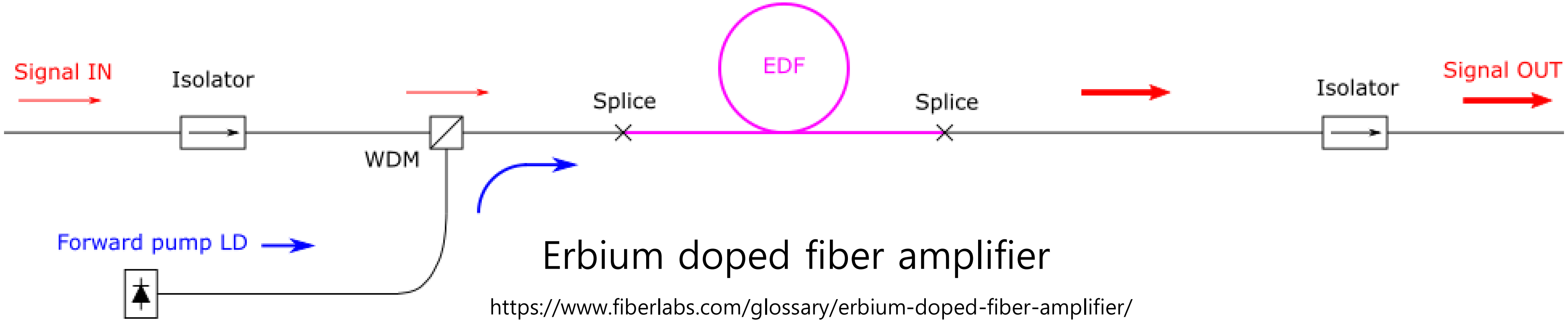


https://commons.wikimedia.org/wiki/File:Erbium-doped_fiber_with_green_light.jpg

Level diagram of EDF



https://www.fiberlabs.com/glossary/erbium-doped-fiber-amplifier/



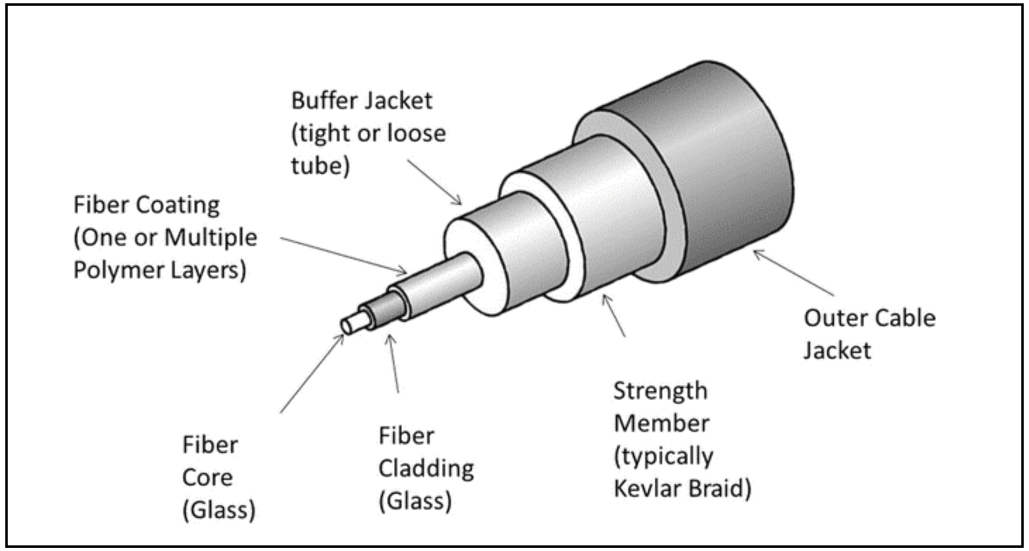
Erbium doped fiber amplifier

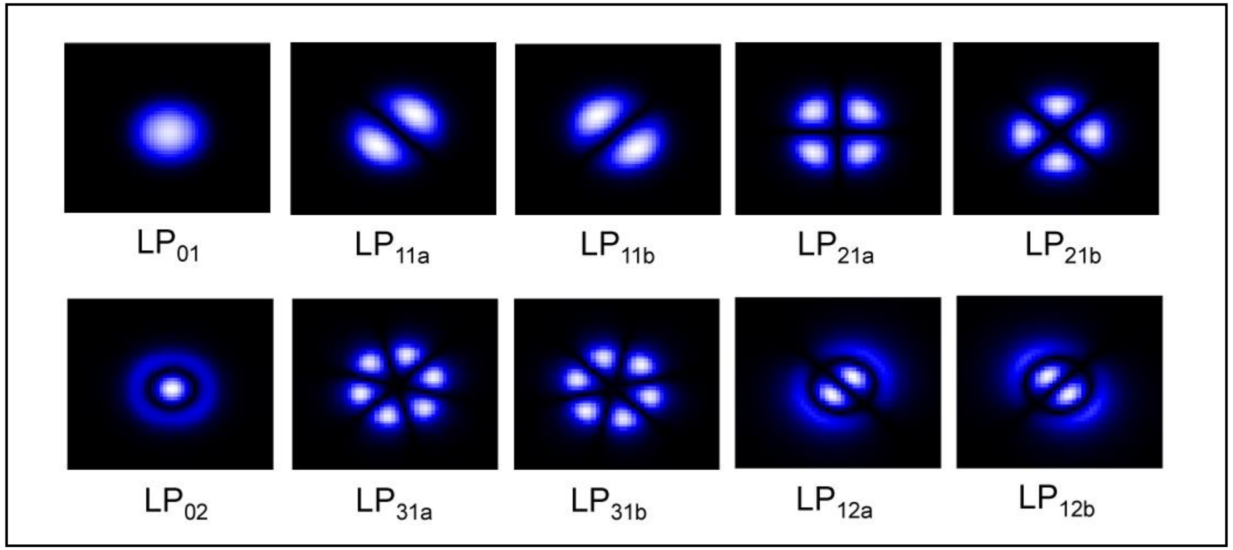
https://www.fiberlabs.com/glossary/erbium-doped-fiber-amplifier/

Summary

v parameter: $v = \frac{2\pi}{\lambda} a \cdot (\text{NA})$

Phase matching condition: $|n_j^A - n_j^B| \ll 1$





Useful references:

- Fundamentals of photonics (B. E. A. Saleh and M. C. Teich, Wiley)
- Fundamentals of optical waveguids (K. Okamoto, Academic press)
- Fundamentals of optical fibers (J. A. Buck, Wiley)
- Guided optics (J. Bures, Wiley)
- Principles of optical fiber measurements (D. Marcuse, Academic press)
- 초고속 광통신 기술 (신상영 외, 홍릉과학출판사)
- Understanding Optical Communications (H. J. R. Dutton, Prentice Hall)

Thank you for your attention

…any question?

Parameters of optical fibers

Corning, SMF-28e

Cable Cutoff Wavelength (λ_{ccf})

$\lambda_{ccf} \leq 1260$ nm

Mode-Field Diameter

Wavelength (nm)	MFD (μm)
1310	9.2 ± 0.4
1550	10.4 ± 0.5

Dispersion

Wavelength (nm)	Dispersion Value [ps/(nm•km)]
1550	≤18.0
1625	≤22.0

Zero Dispersion Wavelength (λ_0): 1302 nm $\leq \lambda_0 \leq$ 1322 nm
Zero Dispersion Slope (S_0): ≤ 0.089 ps/(nm²•km)

Polarization Mode Dispersion (PMD)

	Value (ps/√km)
PMD Link Design Value	≤0.06*
Maximum Individual Fiber	≤0.2

*Complies with IEC 60794-3: 2001, Section 5.5, Method 1, (m = 20, Q = 0.01%), September 2001.

Performance Characterizations

Characterized parameters are typical values.

Core Diameter	8.2 μm
Numerical Aperture	0.14 *NA is measured at the one percent power level of a one-dimensional far-field scan at 1310 nm.*
Zero Dispersion Wavelength (λ_0)	1313 nm
Zero Dispersion Slope (S_0)	0.086 ps/(nm²•km)
Refractive Index Difference	0.36%
Effective Group Index of Refraction (N_{eff})	1310 nm: 1.4677 1550 nm: 1.4682
Fatigue Resistance Parameter (N_d)	20
Coating Strip Force	Dry: 0.6 lbs. (3N) Wet, 14-day room temperature: 0.6 lbs. (3N)
Rayleigh Backscatter Coefficient (for 1 ns Pulse Width)	1310 nm: -77 dB 1550 nm: -82 dB
Individual Fiber Polarization Mode Dispersion	0.02 ps/√km

Dimensional Specifications

Glass Geometry

Fiber Curl	≥ 4.0 m radius of curvature
Cladding Diameter	125.0 ± 0.7 μm
Core-Clad Concentricity	≤ 0.5 μm
Cladding Non-Circularity	≤ 0.7%

Coating Geometry

Coating Diameter	245 ± 5 μm
Coating-Cladding Concentricity	<12 μm