Laboratorio di Fisica Atomica
CdL Fisica e Astrofisica

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Programma Lezioni

- 4 lezioni
  - Fasci Gaussiani — Mer. 10 Ottobre

    Soluzione eq. Maxwell parassiale, principali proprietà, propagazione, formulazione matriciale
  - Polarizzazione onde e.m. — Mer. 17 Ottobre

    Stati di polarizzazione, rappresentazione con vettore di Jones, birifrangenza ed ottiche polarizzanti (lamine di ritardo, polarizzatori)
  - Riflessione e rifrazione — Mer. 24 Ottobre

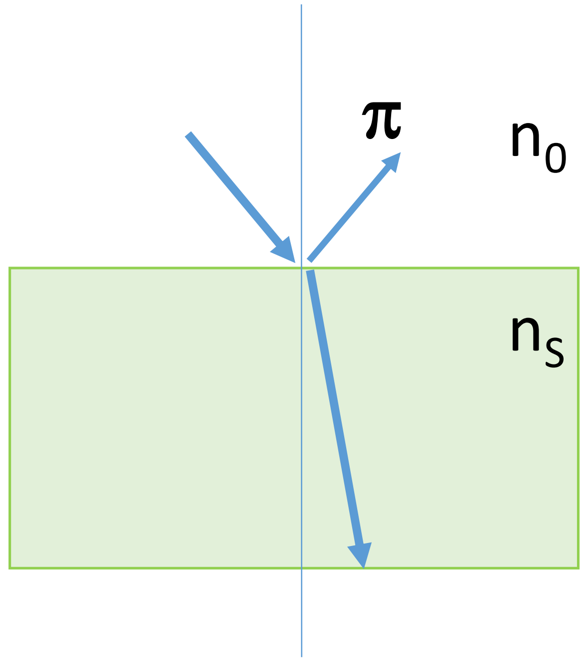
    Applicazioni eq. di Fresnel, riflessione totale, materiali, trattamenti (coatings) AR, HR
  - Propagazione guidata ed elementi elettro-ottici — Mer. 4 Dicembre

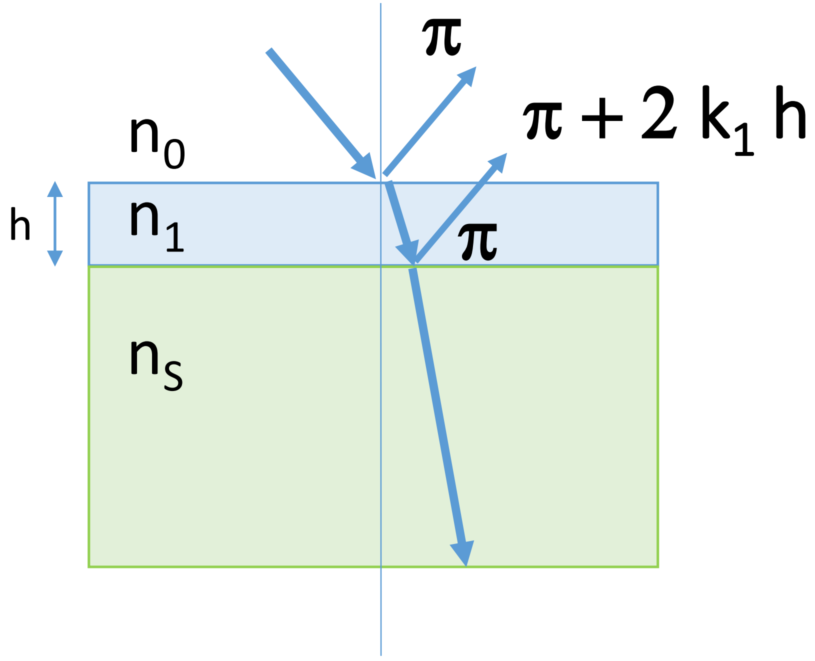
    Fibre ottiche, Acusto-ottici, elettro-ottici

Trattamenti AR

Incidenza quasi normale
E ortogonale

$n_0 < n_1 < n_S$





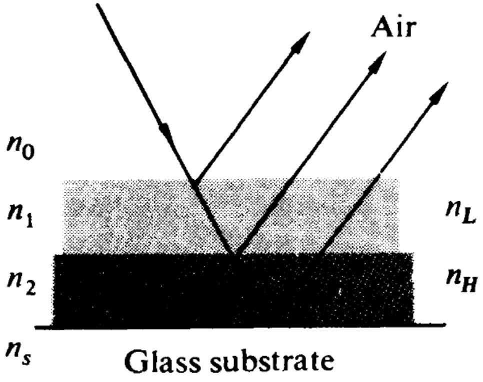
Interferenza distruttiva per $2\, k_1\, h = \pi$

$h = \lambda /4$

Trattamenti HR

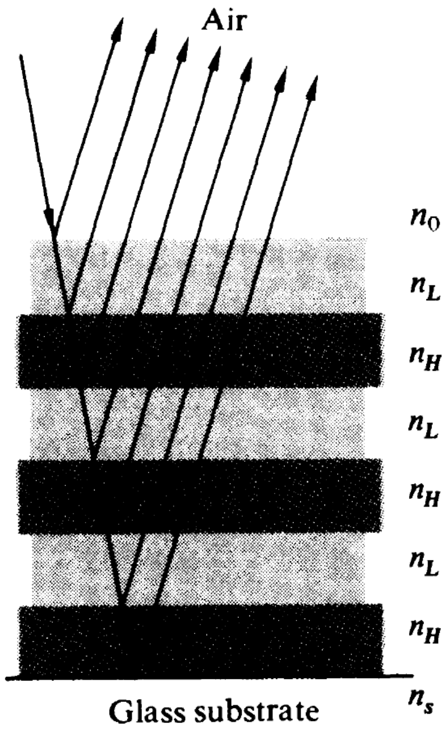
$$R = \frac{(1 - p)}{(1 + p)}$$

$$p = \left(\frac{n_H}{n_L}\right)^{N-1} \times \frac{n_H^2}{n_S}$$



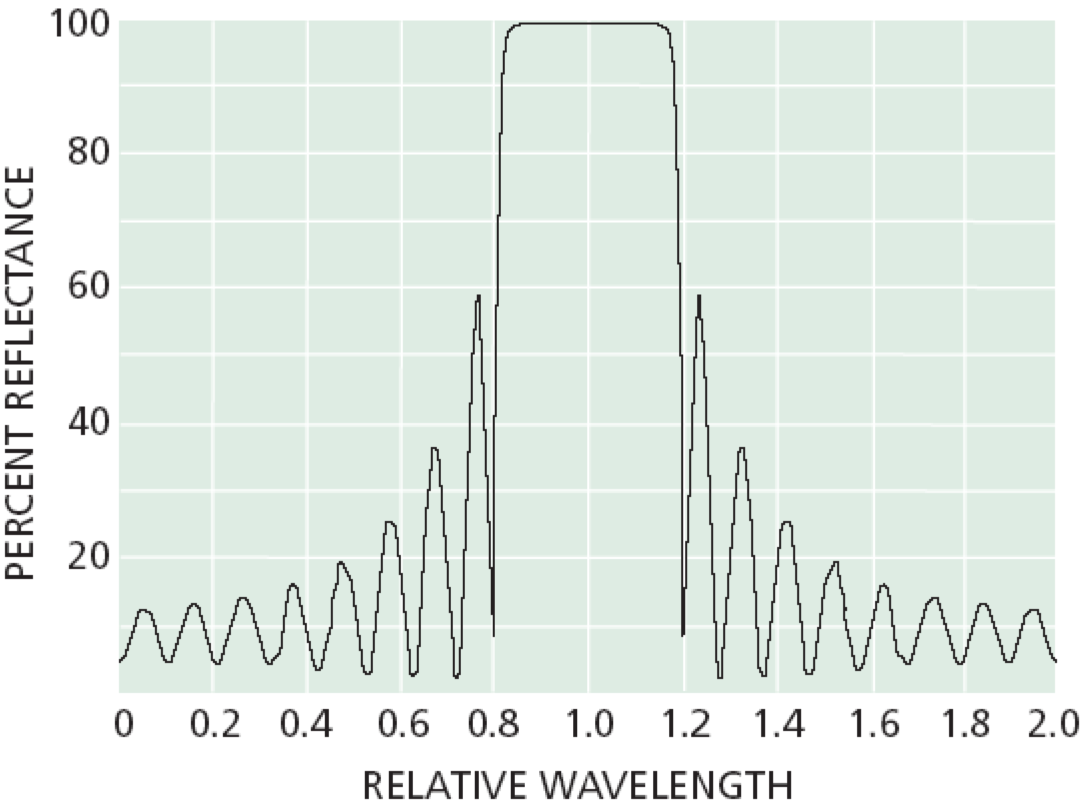
g HL a

Double-quarter

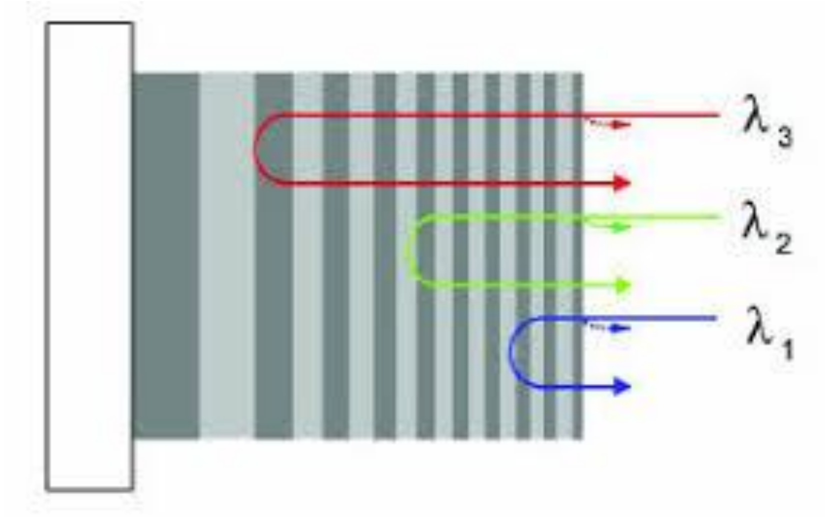


g HL HL HL a
$g(HL)^3a$

Quarter-wave stack

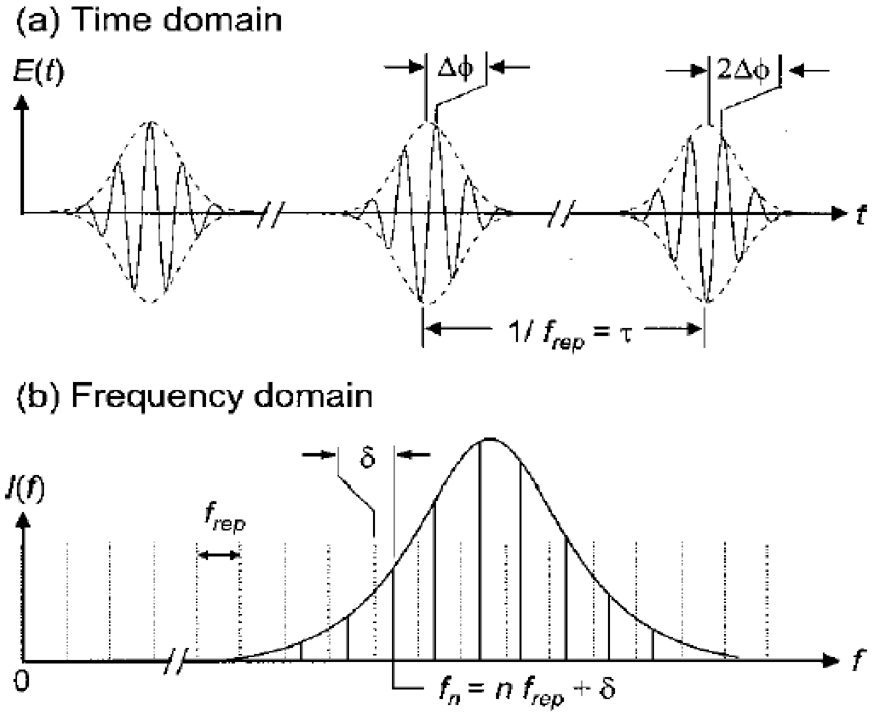


Specchi «Chirped»



- Servono per compensare la dispersione e/o comprimere un impulso

- Laser a femtosecondi

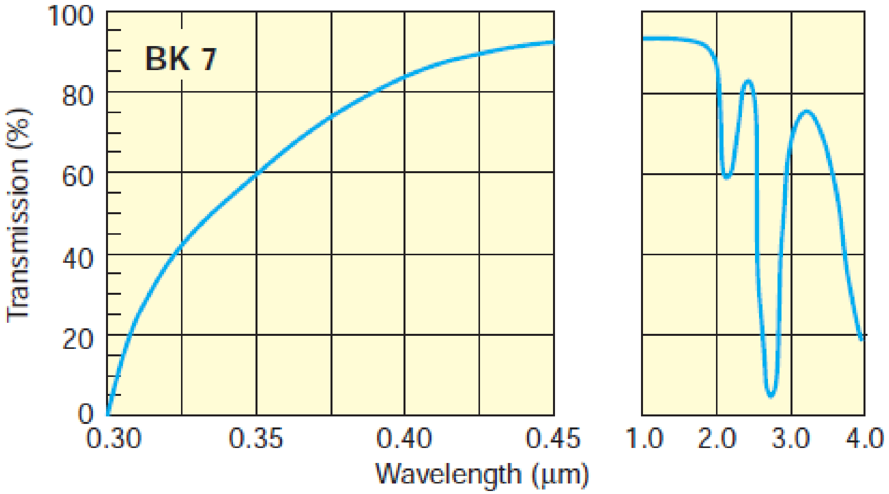


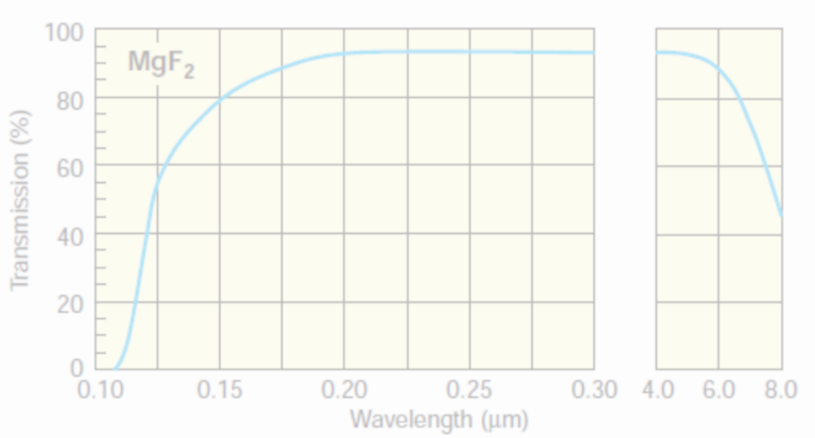
Materiali (substrati per specchi/finestre)

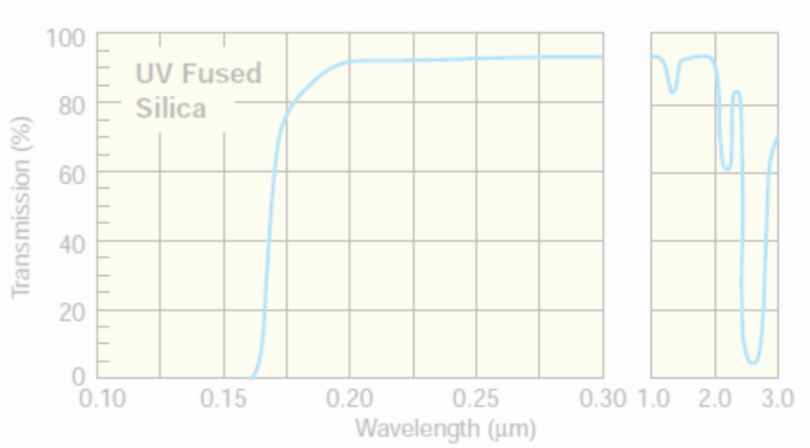
BK 7

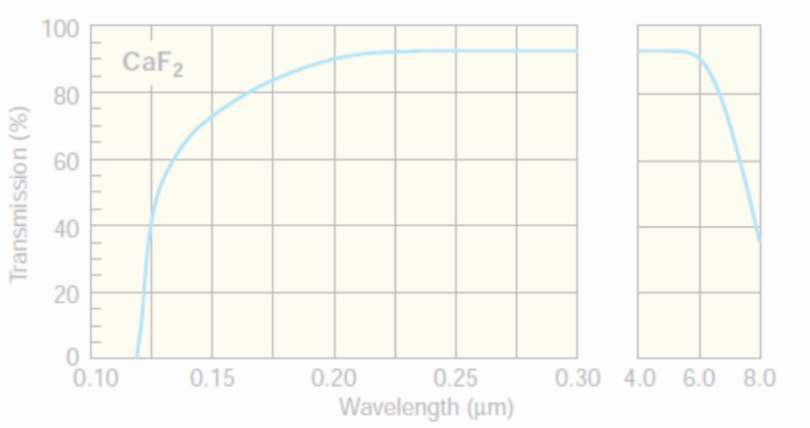
- most common borosilicate crown glasses
- used for VIS - NIR transmissive optics
- high homogeneity, low bubble content, and straightforward Manufacturability
- transmission range 380–2100 nm
- not recommended for temperature sensitive applications, such as precision mirrors

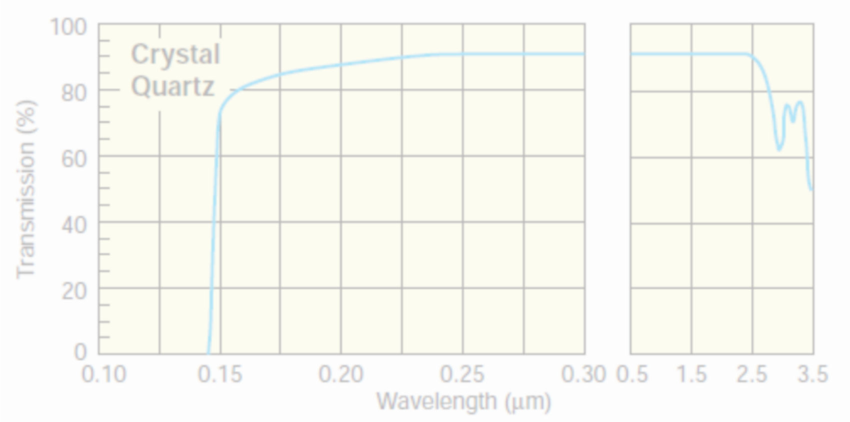
Newport catalogue

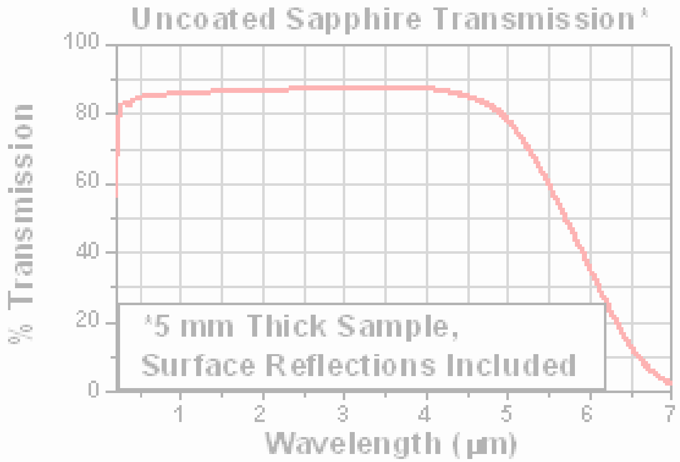












Materiali (substrati per specchi/finestre)

UV grade Fused Silica

- synthetic amorphous silicon dioxide, extremely high purity

- very low CTE

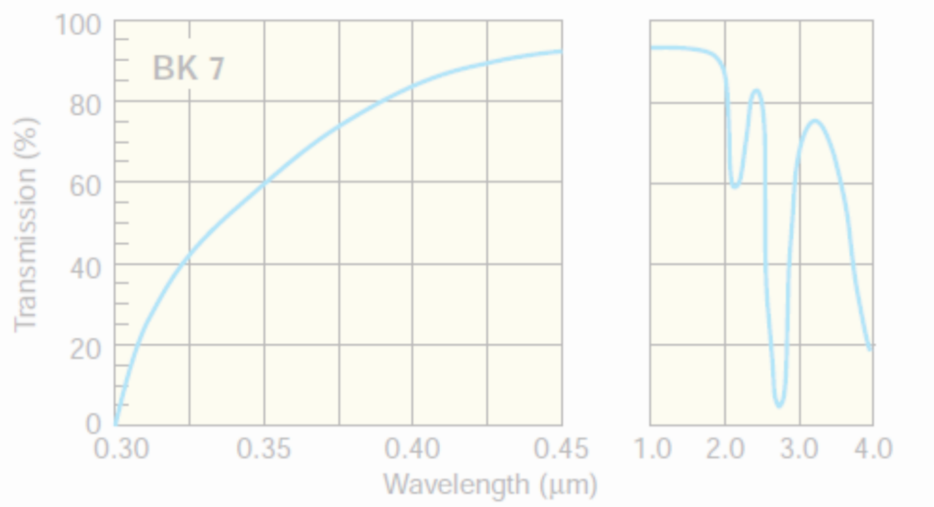
- excellent transmittance in the UV
- used for transmissive and reflective optics

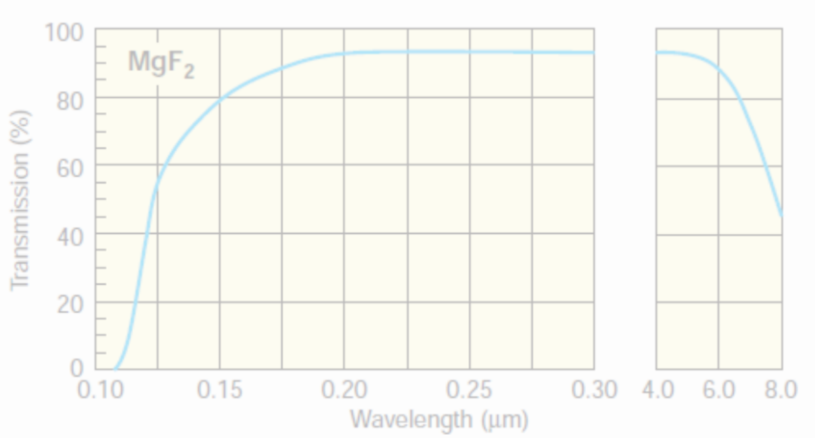
- high laser damage threshold

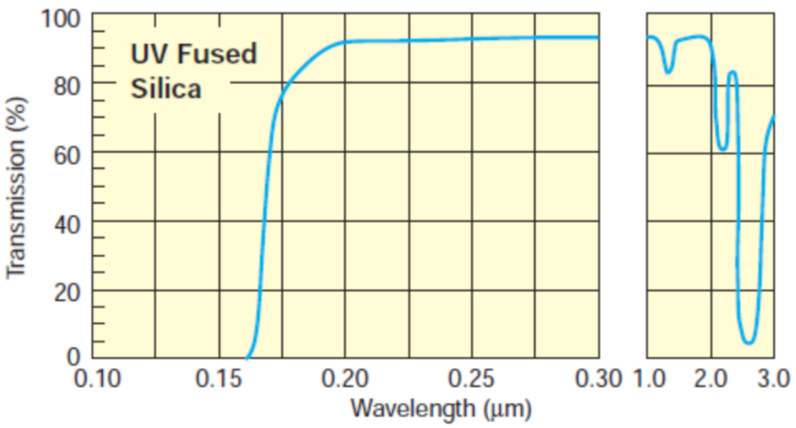
- transmission and homogeneity

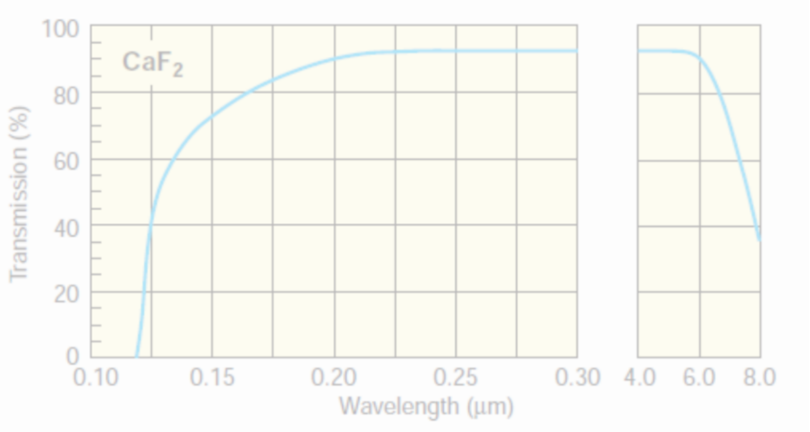
> crystalline quartz
(without orientation
temperature instability probl.)

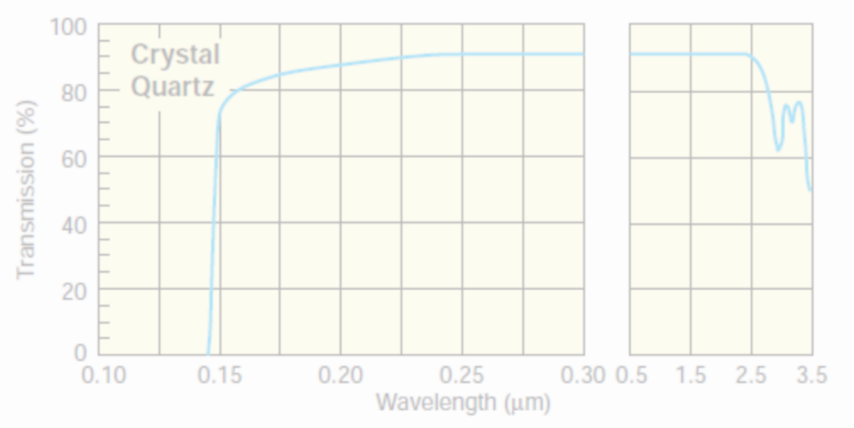
<u>Newport catalogue</u>

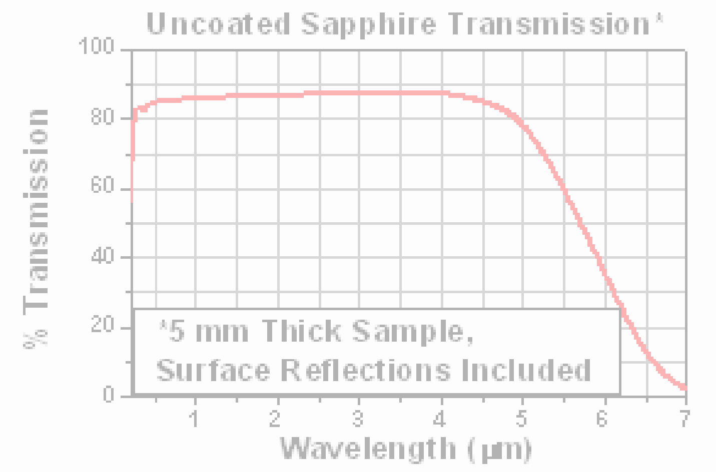








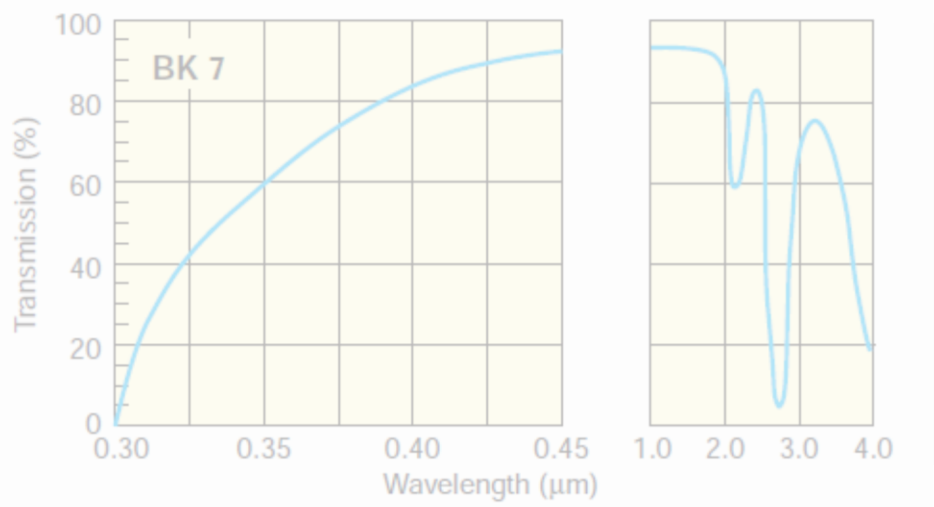


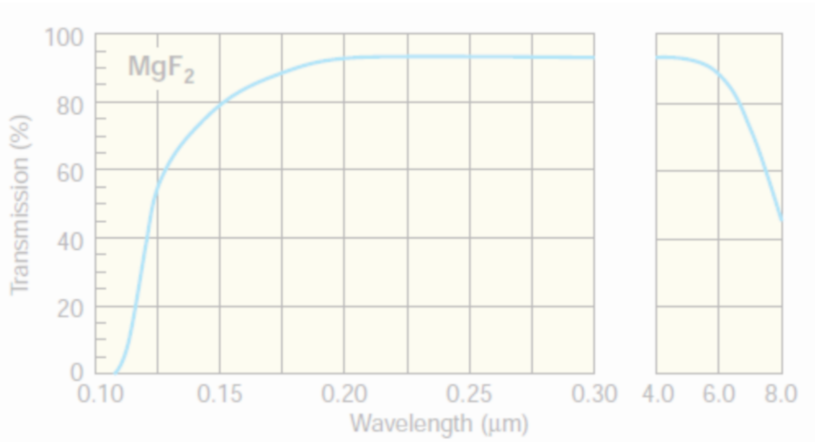


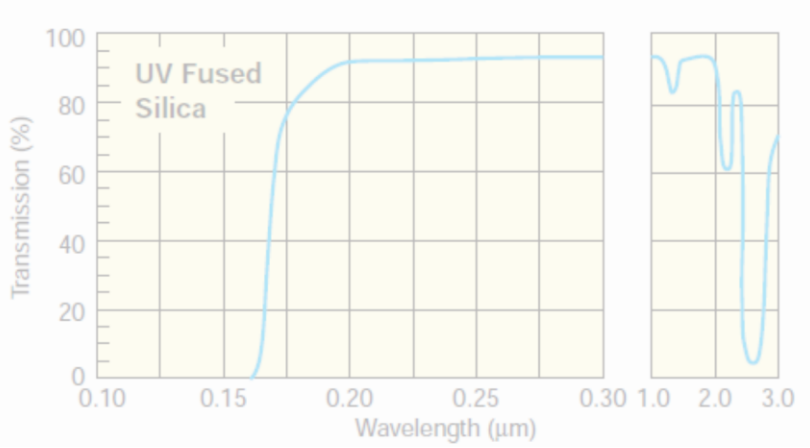
Materiali (substrati per specchi/finestre)

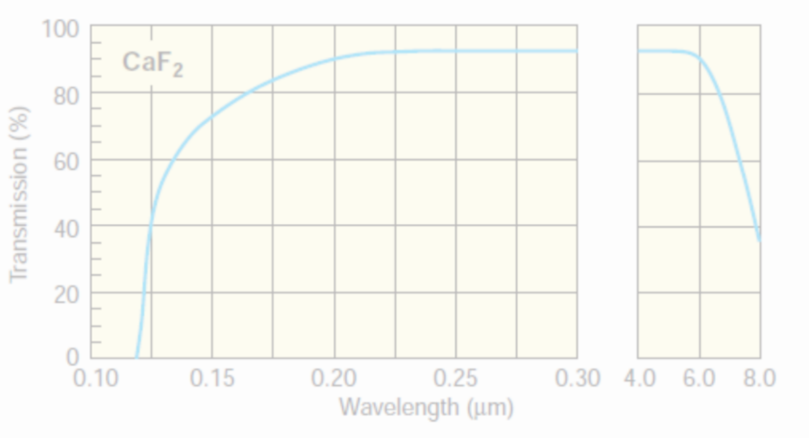
Crystal Quartz

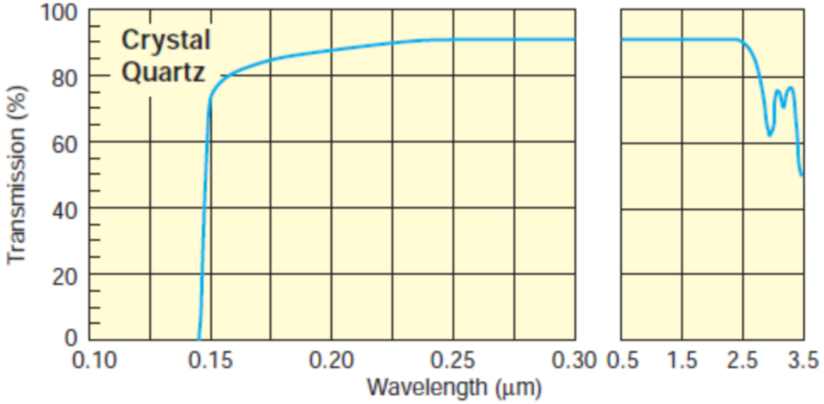
- positive uniaxial birefringent
- good transmission from the vacuum UV to the NIR.
- commonly used for wave plates

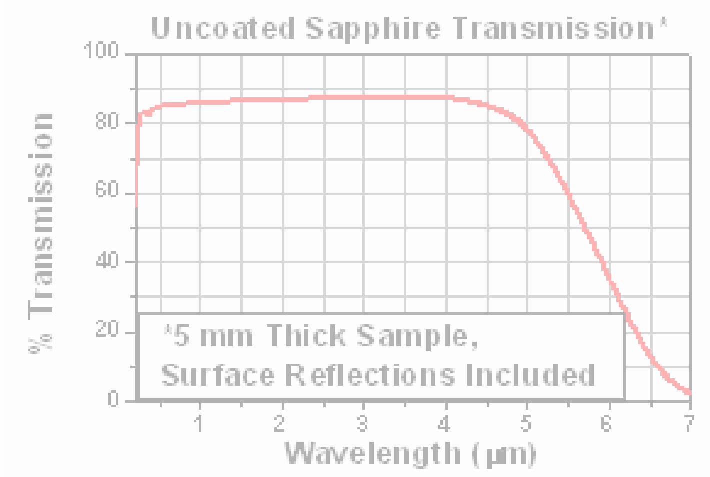










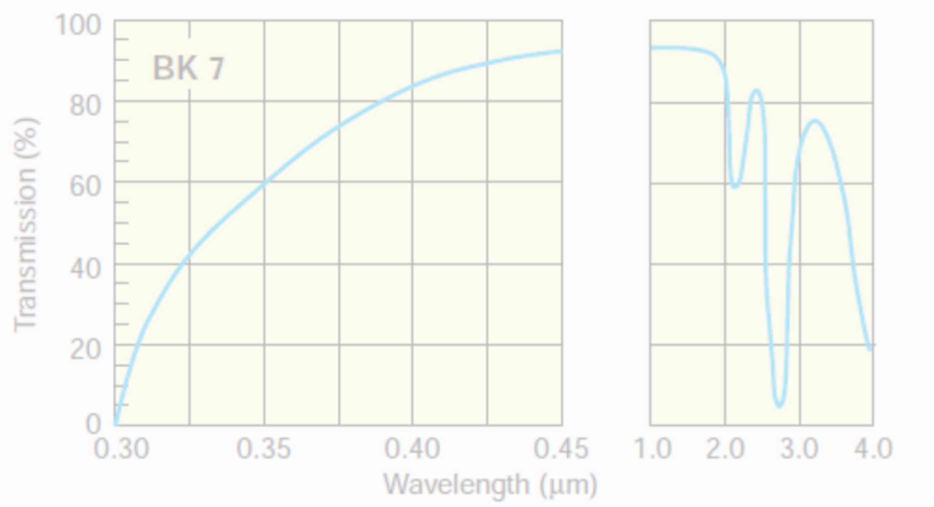


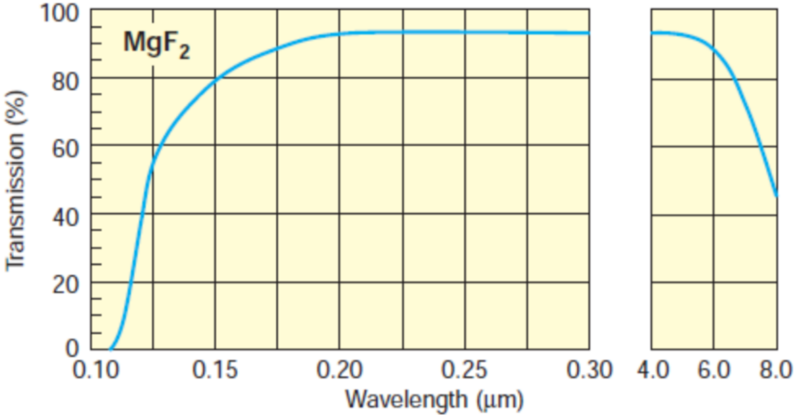
Newport catalogue

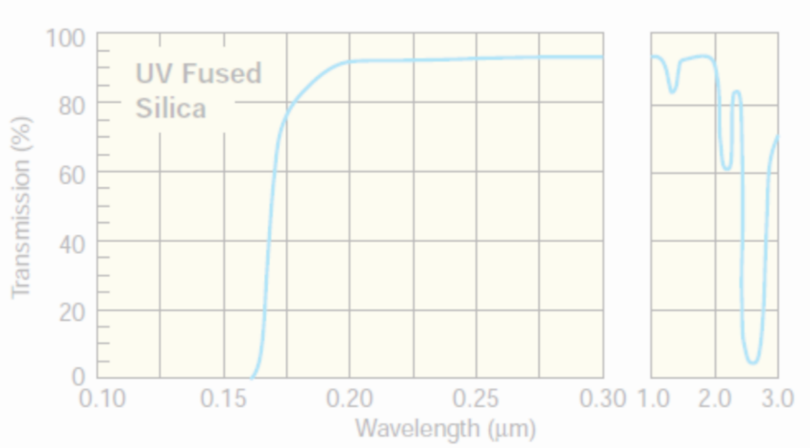
Materiali (substrati per specchi/finestre)

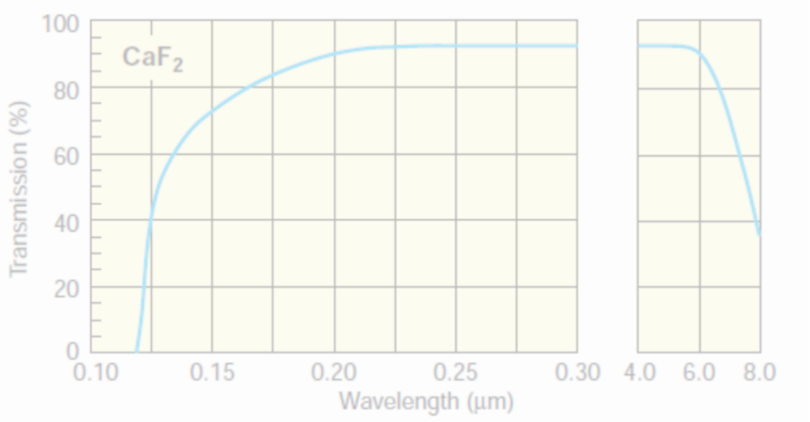
MgF2

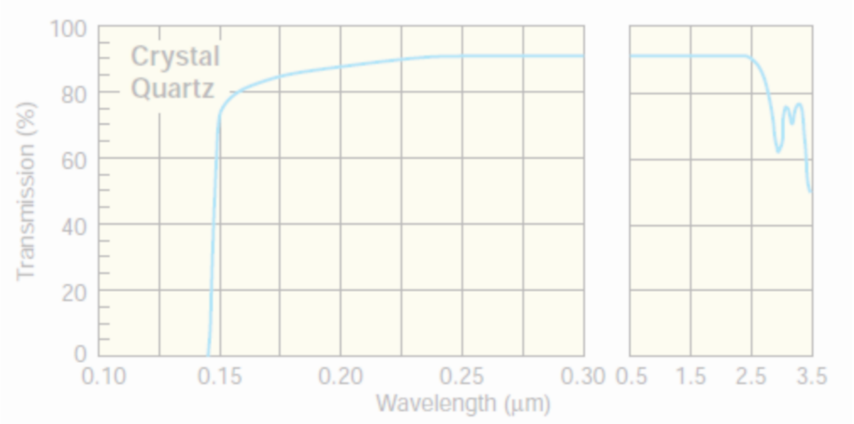
- Positive birefringent crystal
-
- typically oriented with the c axis parallel to the optical axis to reduce birefringent effects.
- good transmission from vacuum UV (150 nm) to IR (6 μm)
- used for lenses, windows, and polarizers for Excimer lasers
- MgF2 is resistant to thermal and mechanical shock.

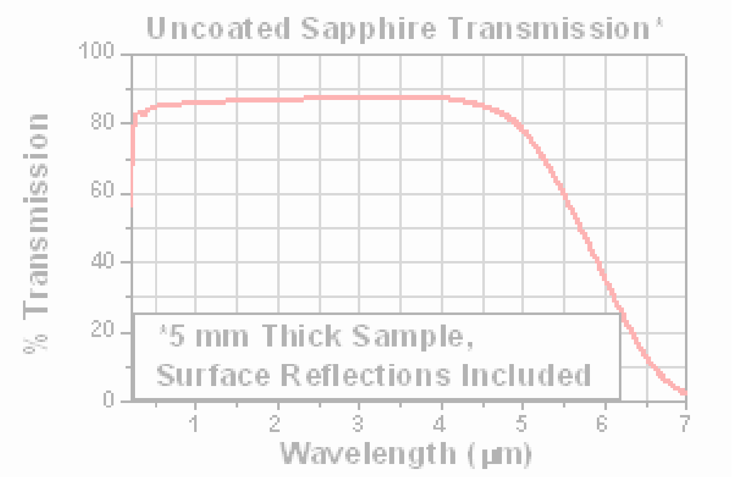










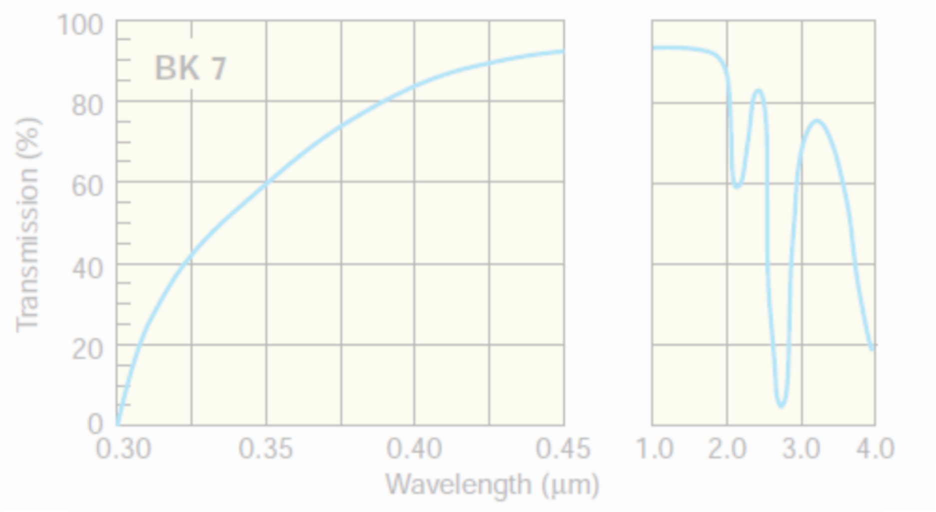


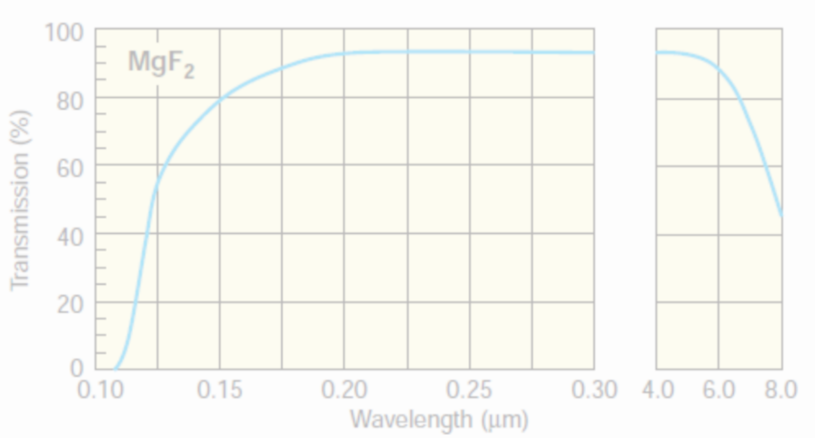
Newport catalogue

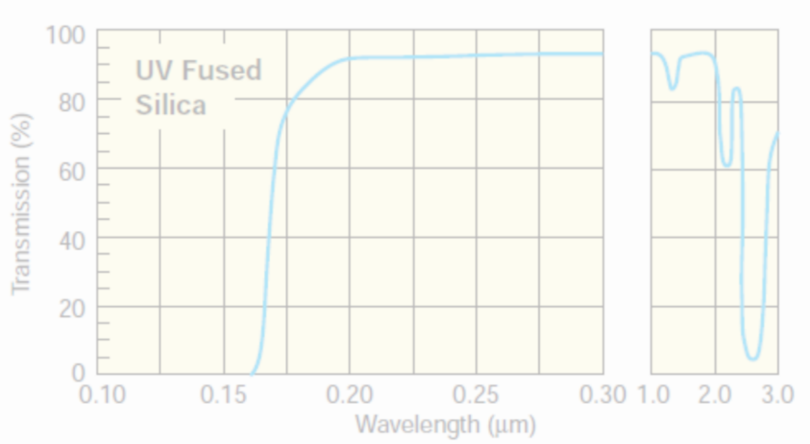
Materiali (substrati per specchi/finestre)

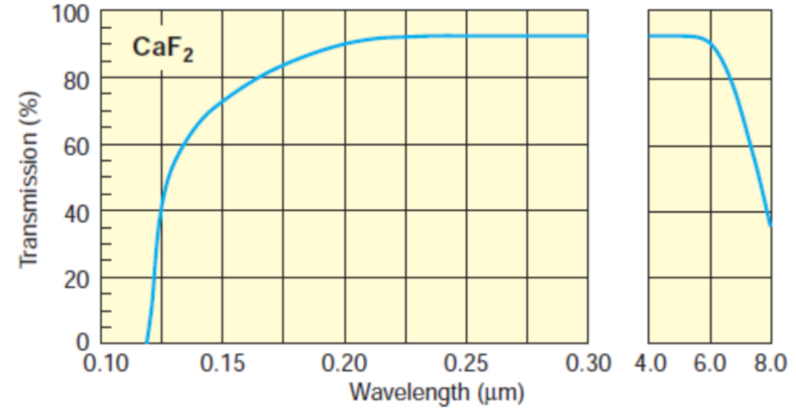
CaF2

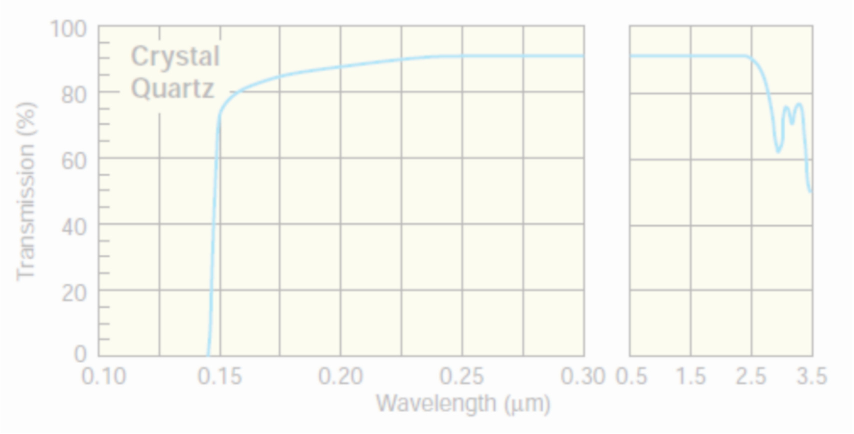
- cubic single crystal
- excellent UV transmission, down to 170 nm
- non-birefringent properties make it ideal for deep UV transmissive optics.
- CaF2 is sensitive to thermal shock (care must be taken during handling)

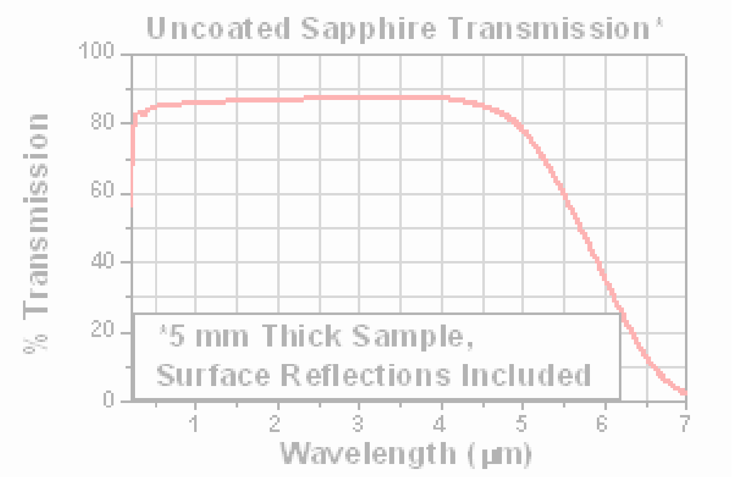








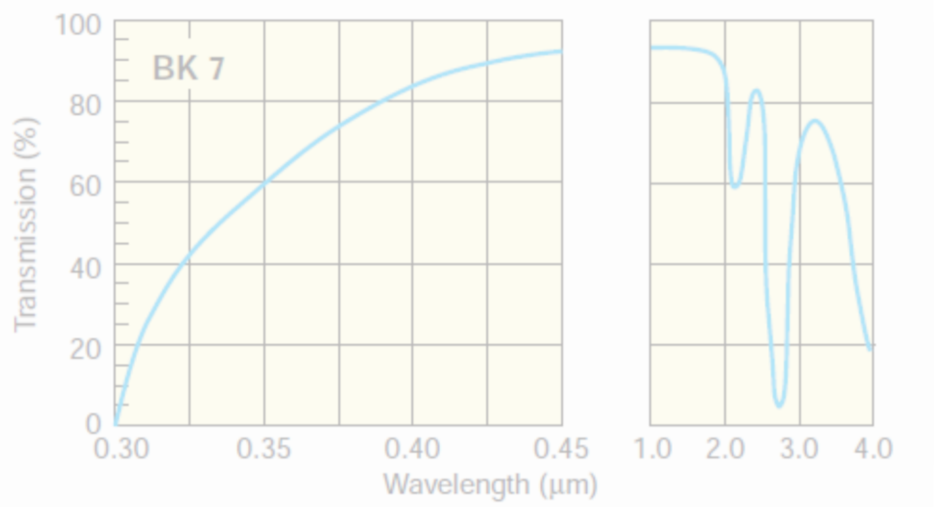


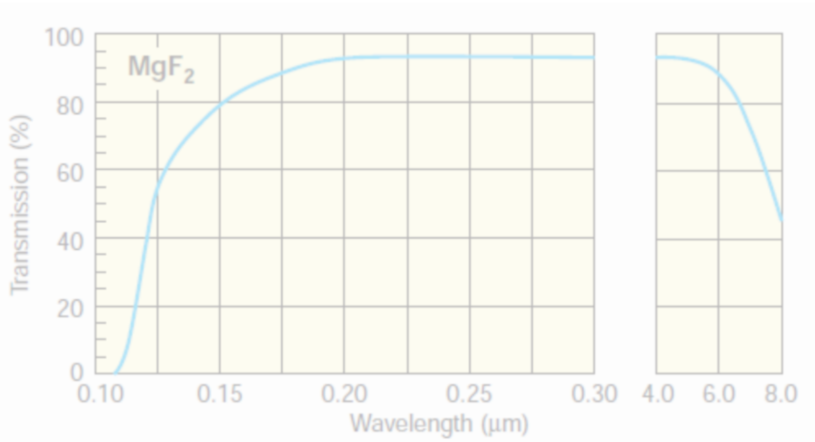


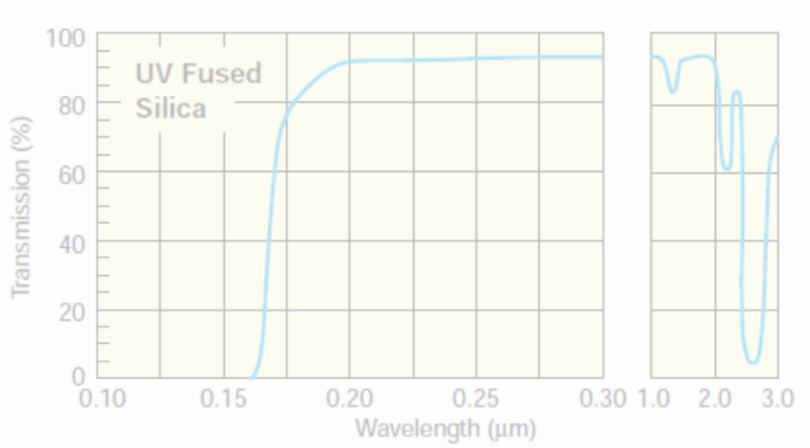
Newport catalogue

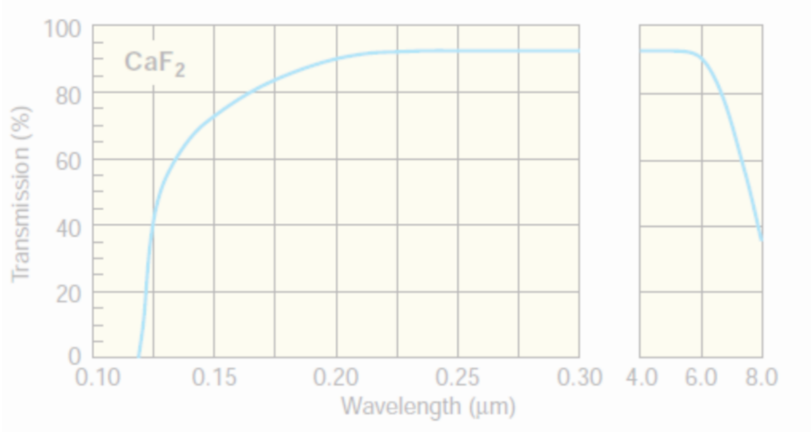
Materiali (substrati per specchi/finestre)

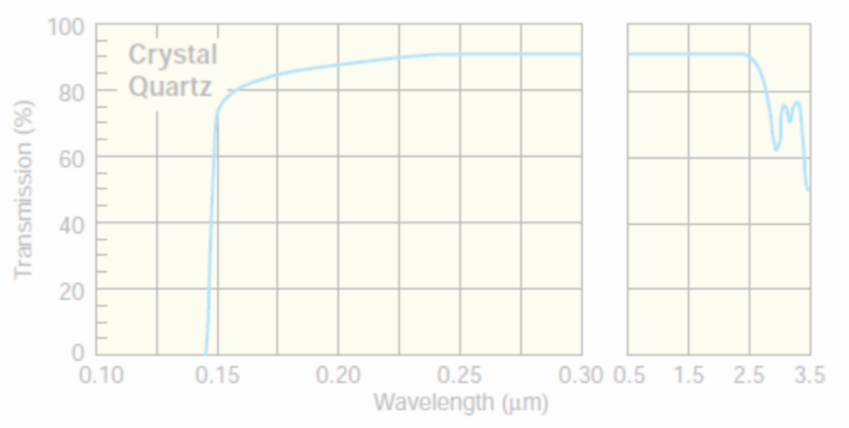
Sapphire

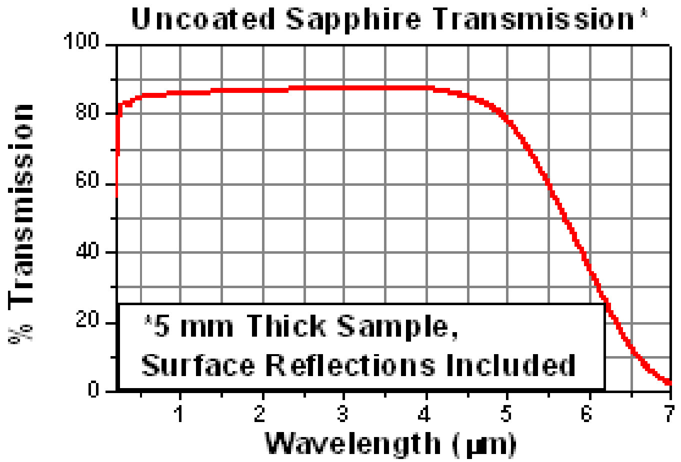








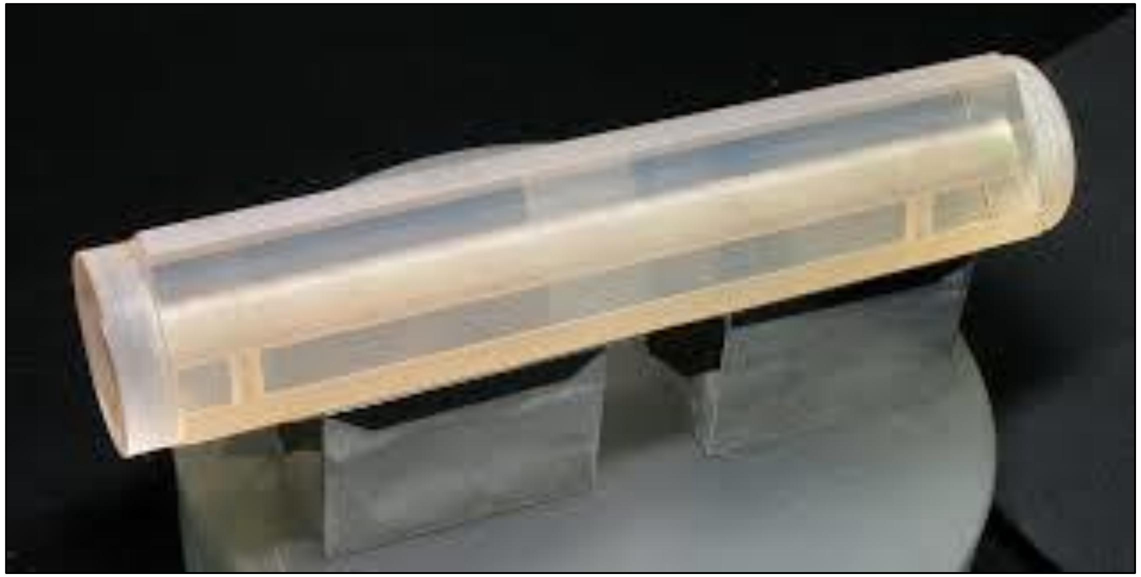


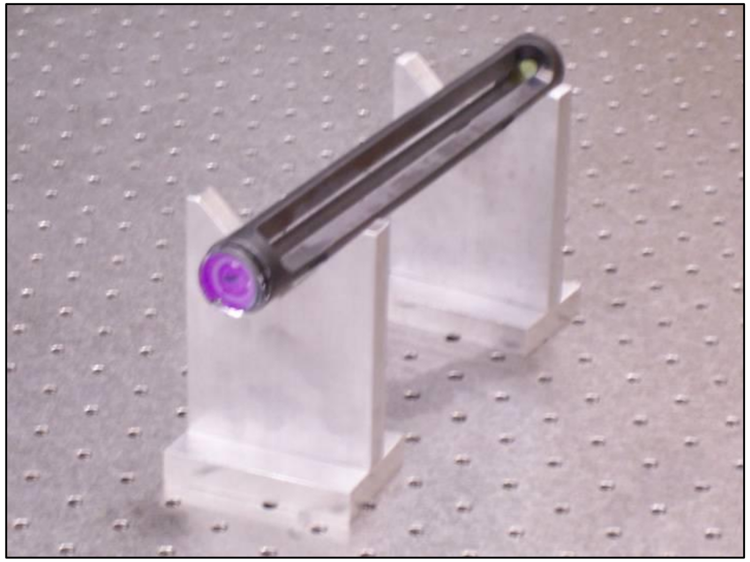


Newport catalogue

Zerodur, ULE, Invar

- Usati per costruire sistemi che abbiano una grande stabilità termica e meccanica



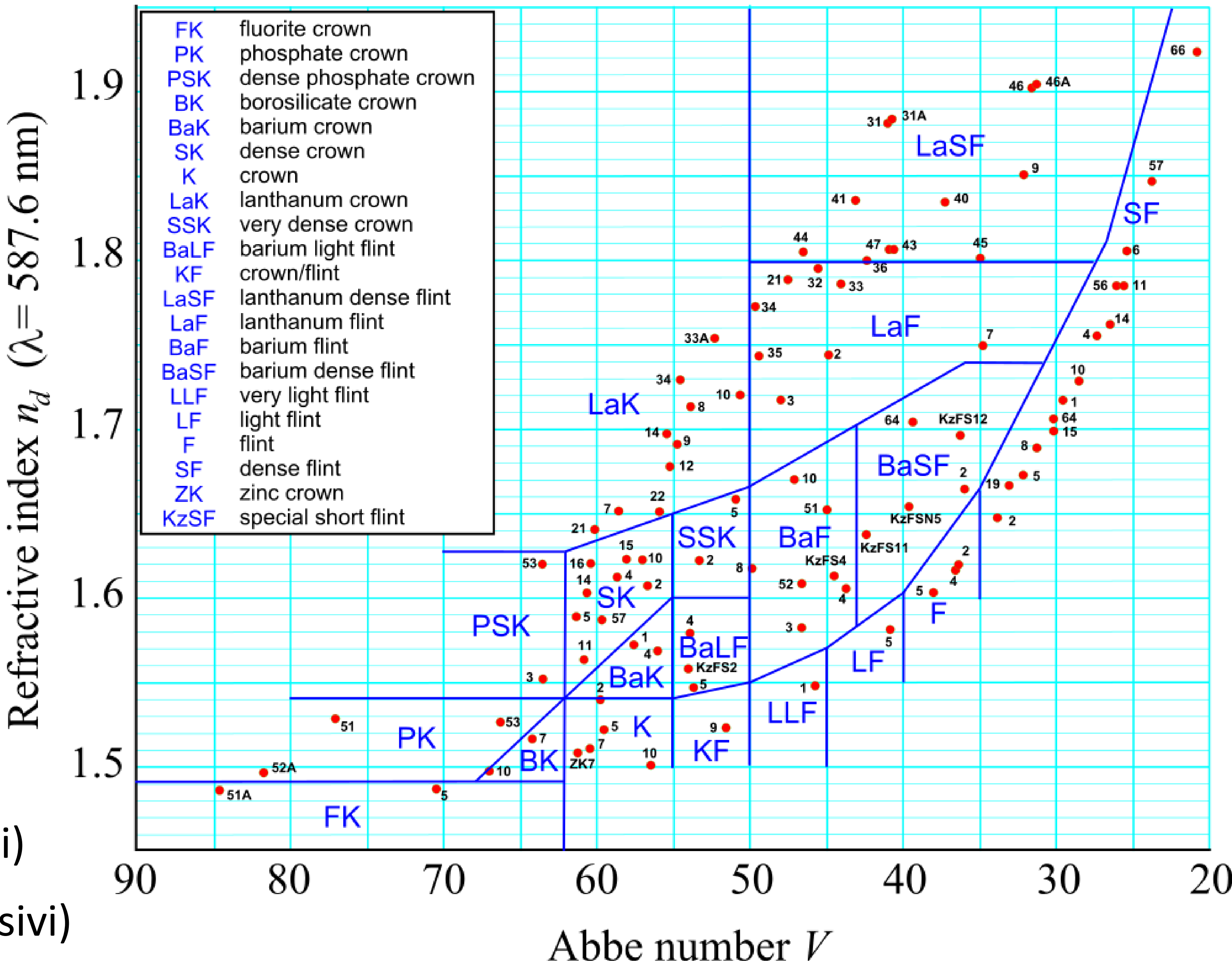


ACCIAIO	CTE = 12 ppm/°C	
INVAR (FeNiCo)	CTE = 0.55 ppm/°C	← Nobel 1920 Charles-Edouard Guillaume
ULE (7972 Corning)	CTE < 30 ppb/°C	

Numero di Abbe

$$V = \frac{n_D - 1}{n_F - n_C}$$

n_D, n_F e n_C
indici di rifrazione @
D (589,2 nm)
F (486,1 nm)
C (656,3 nm)



Vetri *CROWN* V< (più dispersivi)

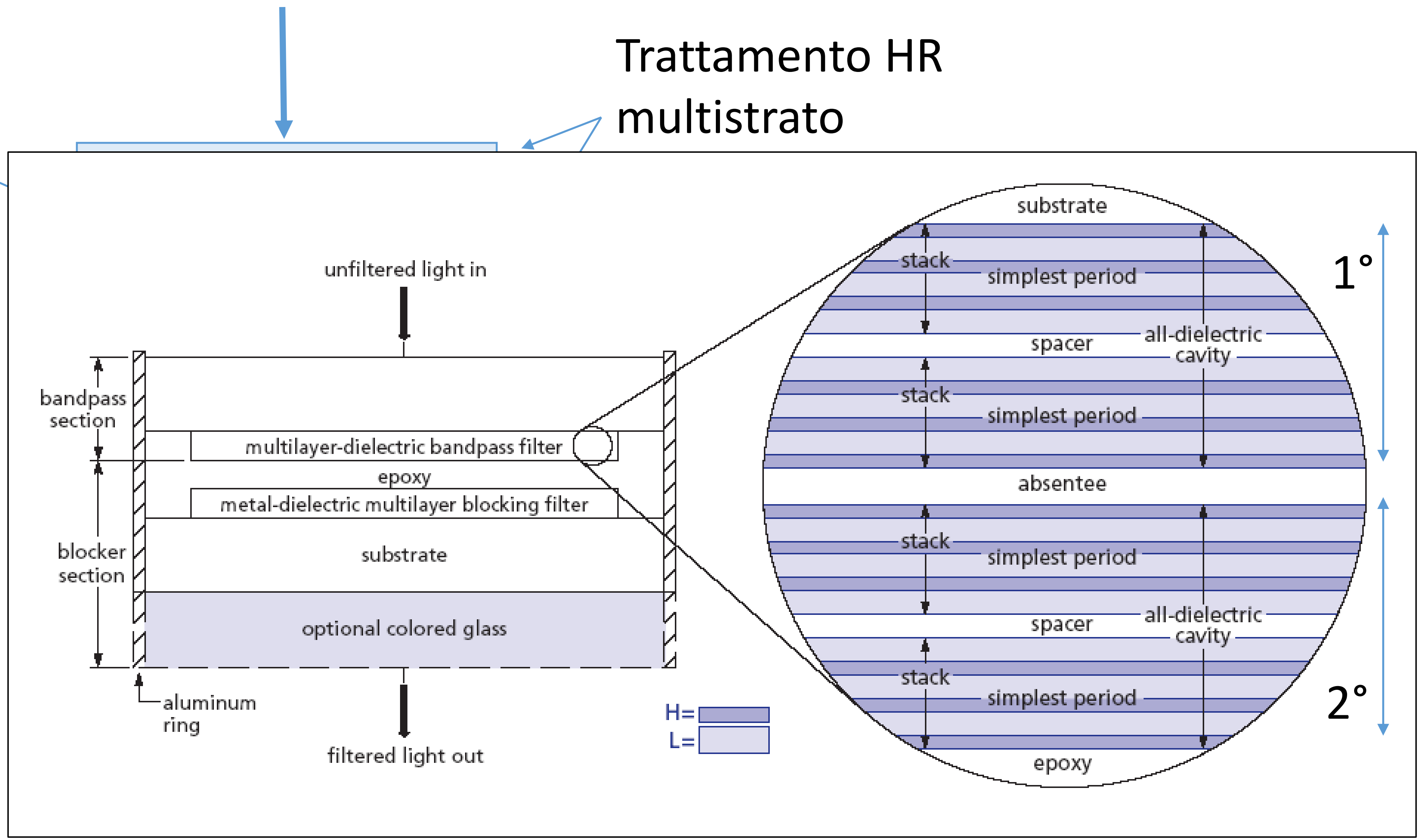
Vetri *FLINT* V> (meno dispersivi)

Filtri interferenziali

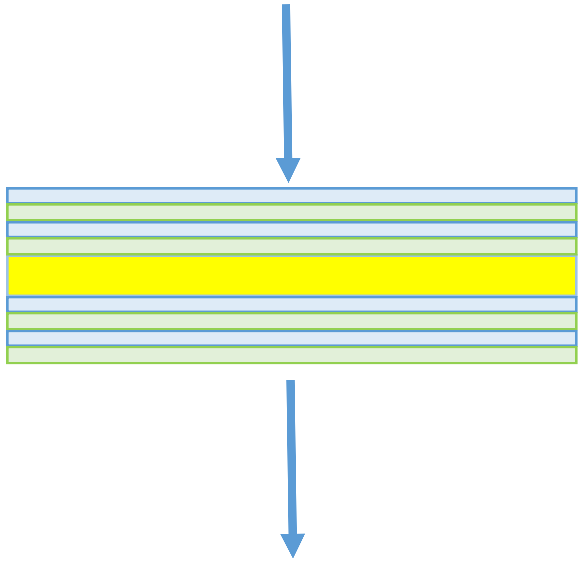
singolo
strato dielettrico
(spessore $\lambda/2$)

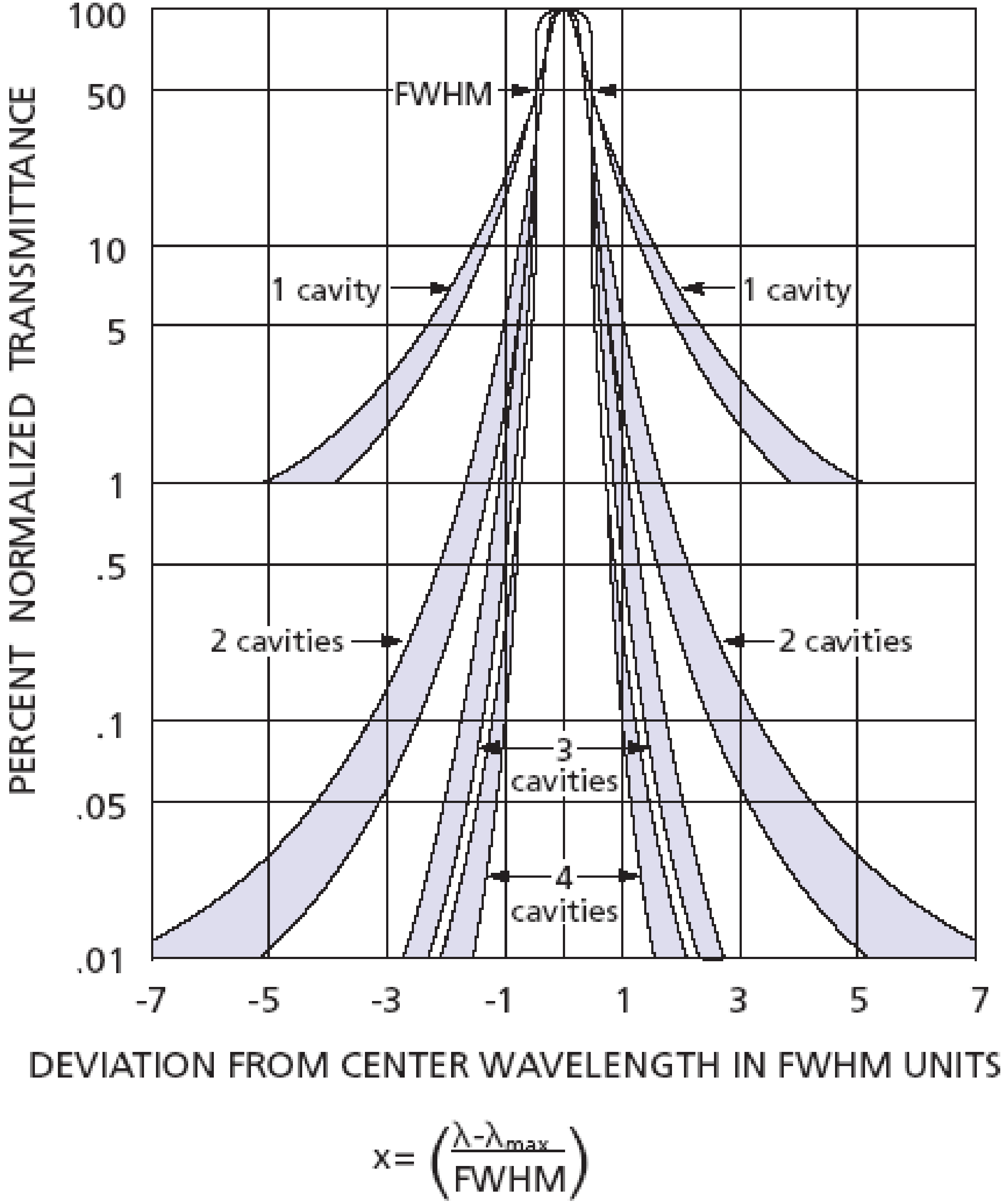
Trattamento HR
multistrato

Singole o
multiple
cavità ottiche



Filtri interferenziali





Singole o
multiple
cavità ottiche

Propagazione guidata

- Testi/articoli di riferimento:

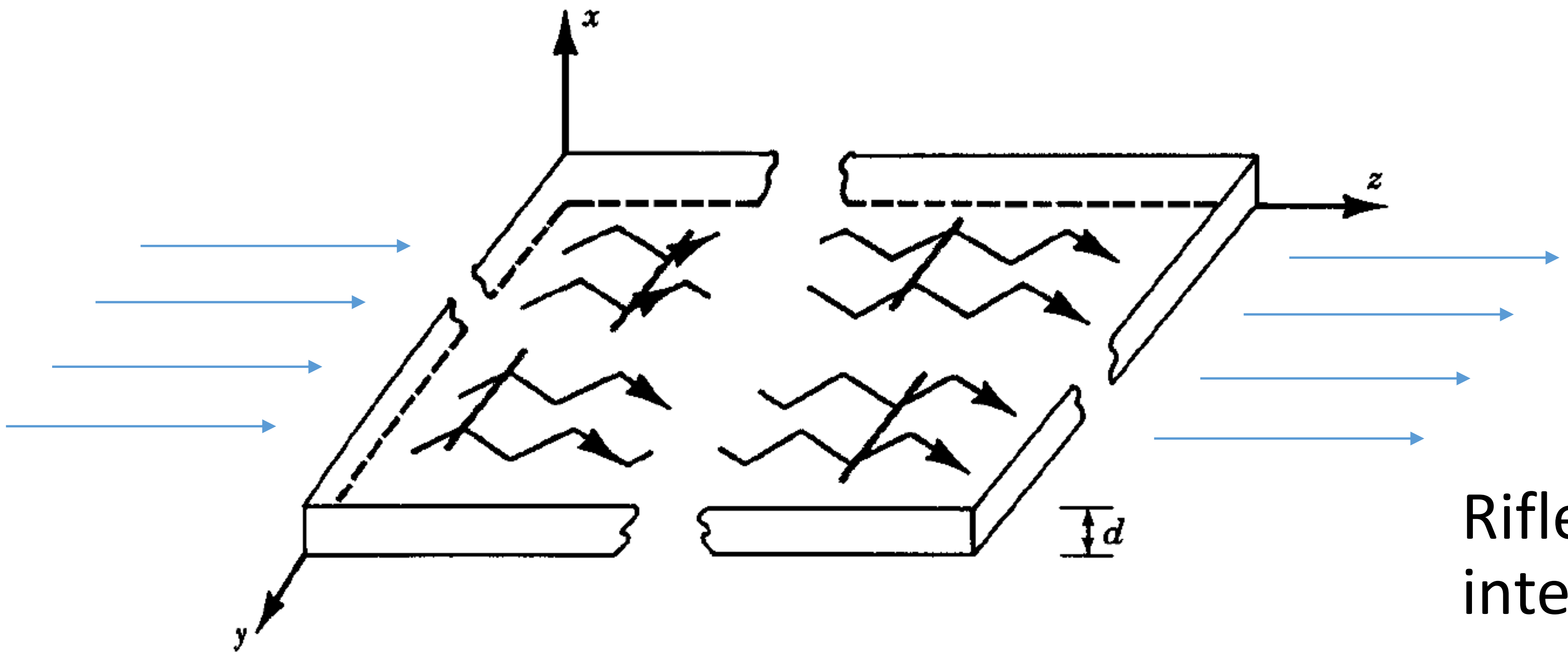
  - E. Hecht «Optics»

  - G. R. Fowles "Introduction to modern optics"

  - R.D. Guenther «Modern Optics»

Propagazione guidata

- Guida d’onda planare

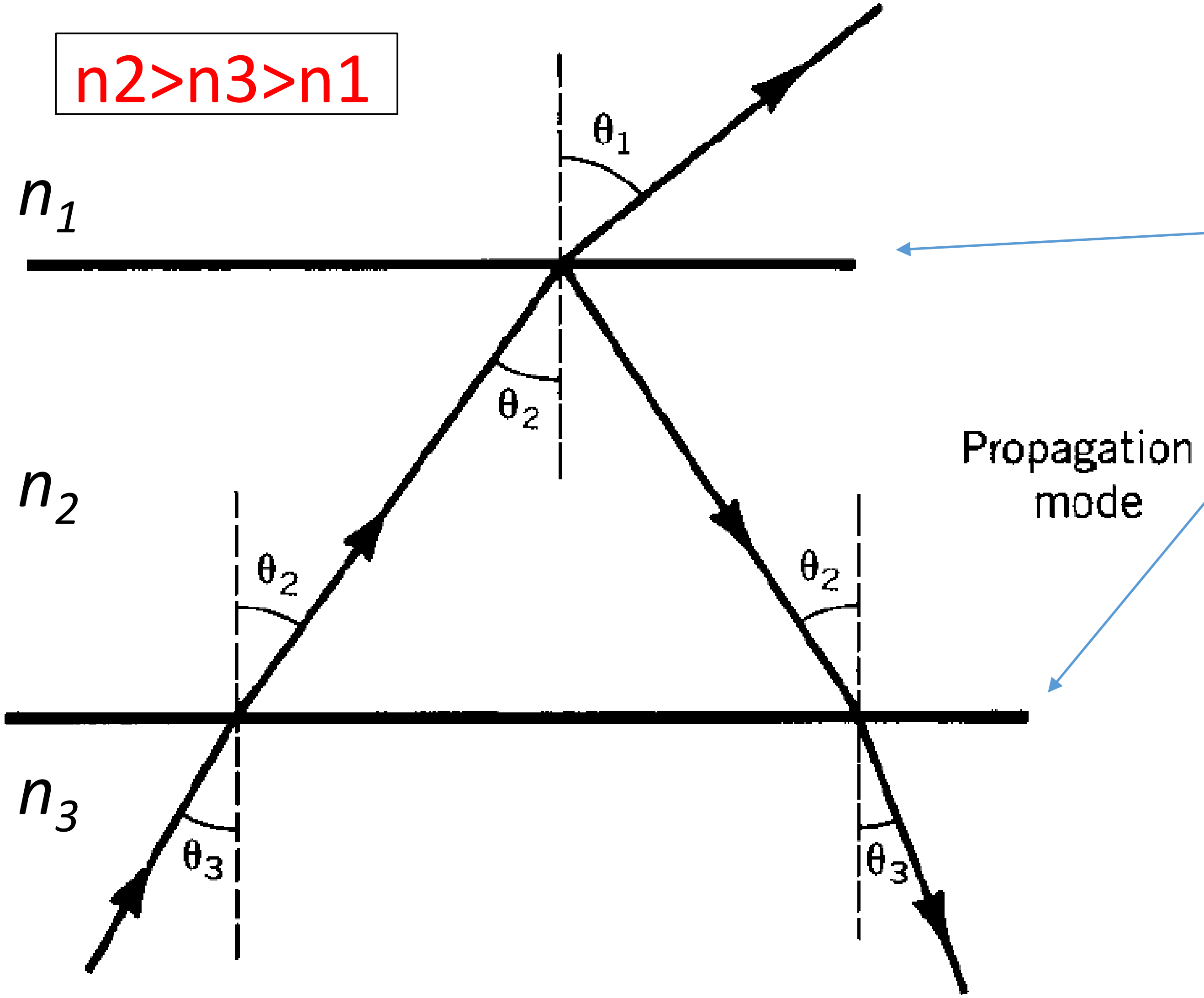


Riflessione totale interna

Propagazione guidata

- Guida d'onda planare – *propagation mode* -

n2>n3>n1



Per $0 \leq \theta_1 \leq \frac{\pi}{2}$ il raggio passa attraverso

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

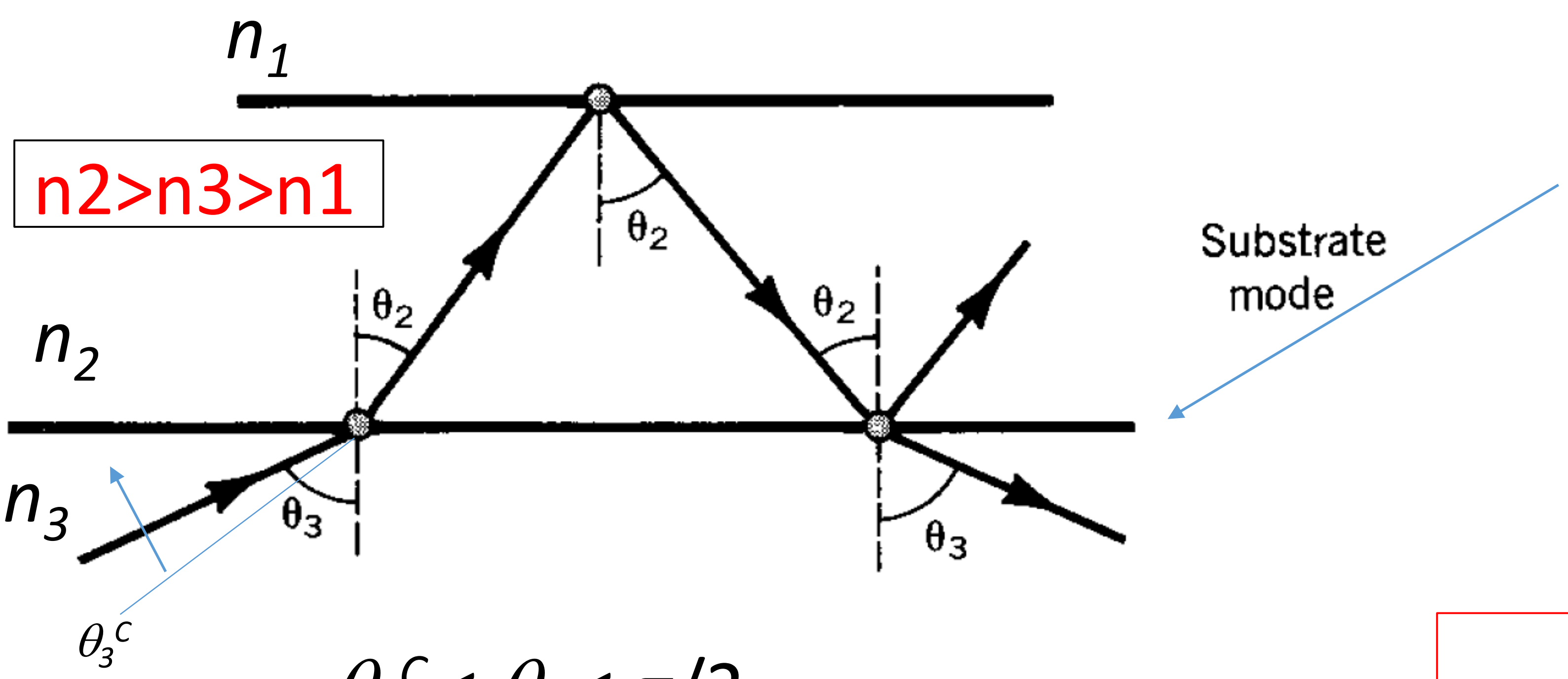
$$n_3 \sin\,\theta_3 = n_2 \sin\,\theta_2 = n_1$$

$$\theta_3 < \sin^{-1}\left(\frac{n_1}{n_3}\right) = \theta_3{}^C$$

$$\theta_2 < \sin^{-1}\left(\frac{n_1}{n_2}\right)$$

Propagazione guidata

- Guida d'onda planare – propagazione di substrato



$\theta_3^C < \theta_3 < \pi/2$

$$\sin^{-1}\left(\frac{n_1}{n_3}\right) < \theta_3 < \frac{\pi}{2}$$

Condizioni su angolo θ_2

$n_2 \sin\,\theta_2 = n_3 \sin\,\theta_3^C$

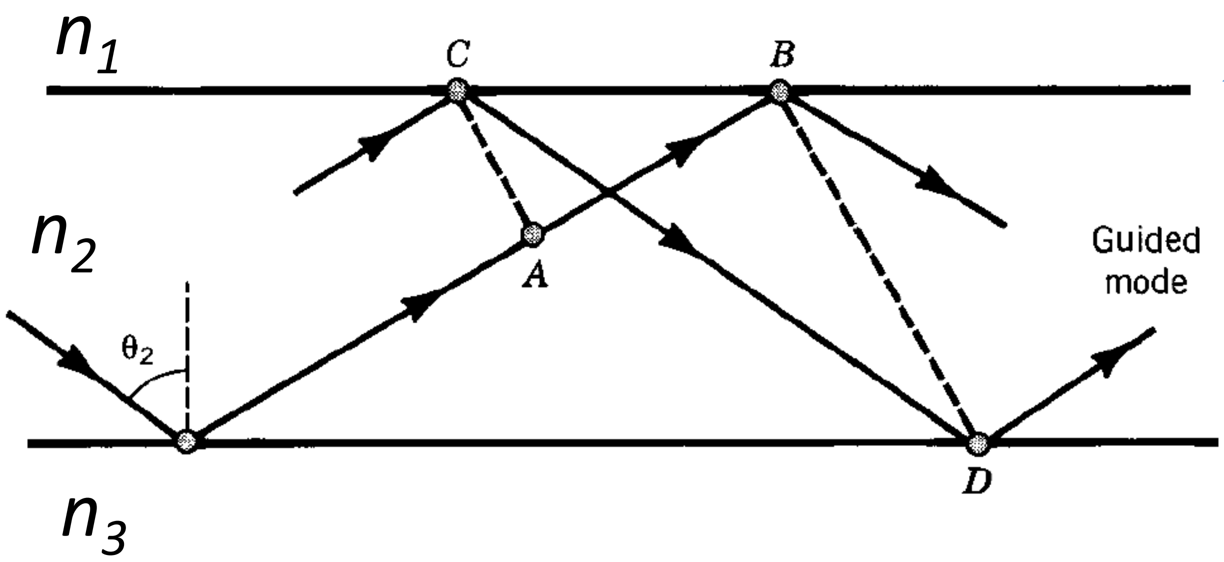
$n_2 \sin\,\theta_2 = n_3$

$$\sin^{-1}\left(\frac{n_1}{n_2}\right) < \theta_2 < \sin^{-1}\left(\frac{n_3}{n_2}\right)$$

Propagazione guidata

- Guida d'onda planare – propagazione guidata

n2>n3>n1



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

$$n_2 \sin \theta_2 = n_3 \sin \theta_3$$

$$\sin \theta_2 > n_1/n_2$$

$$\sin \theta_2 > n_3/n_2$$

$$n_3 > n_1$$

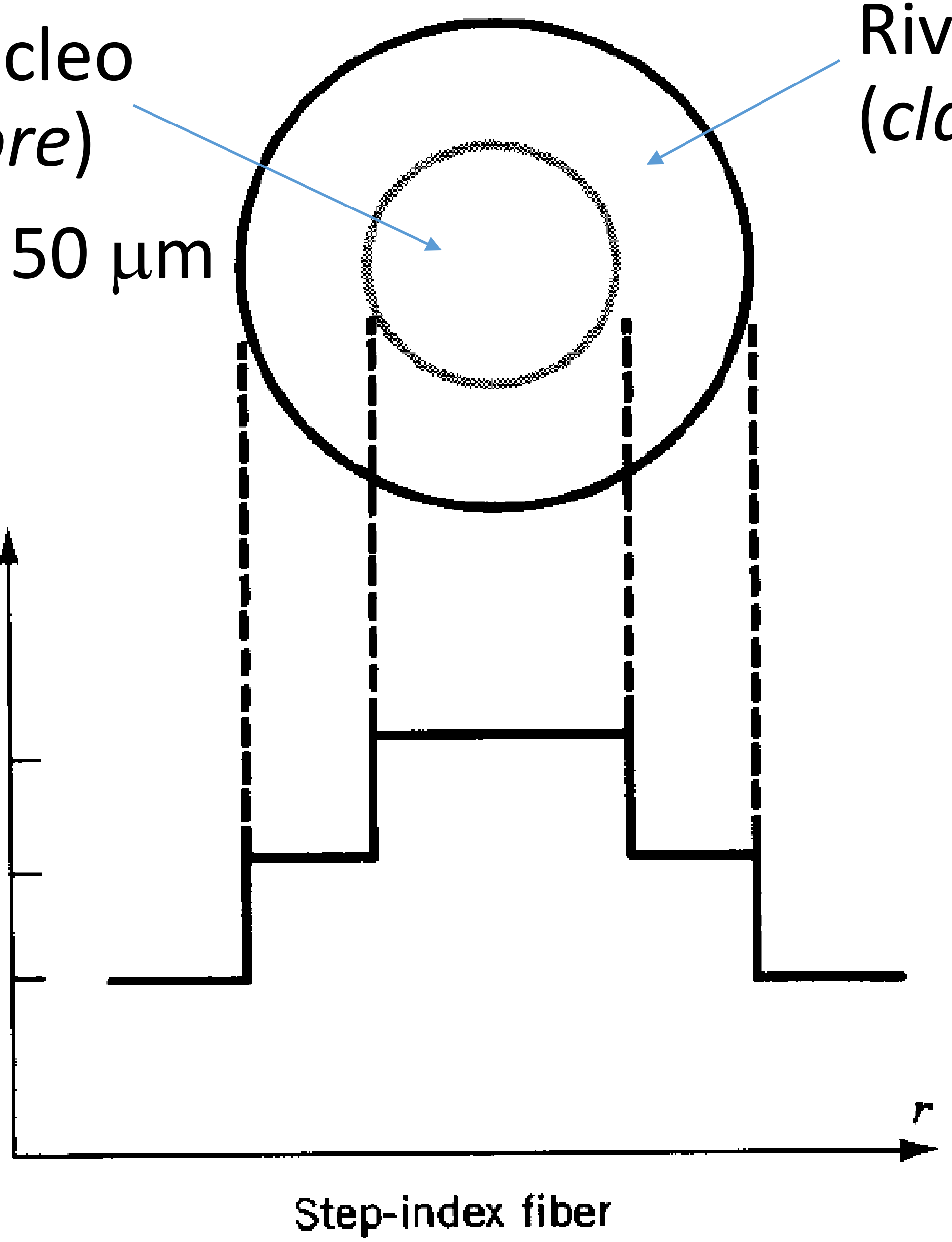
$$\sin^{-1}\left(\frac{n_3}{n_2}\right) < \theta_2 < \frac{\pi}{2}$$

Propagazione guidata

Nucleo
(*core*)

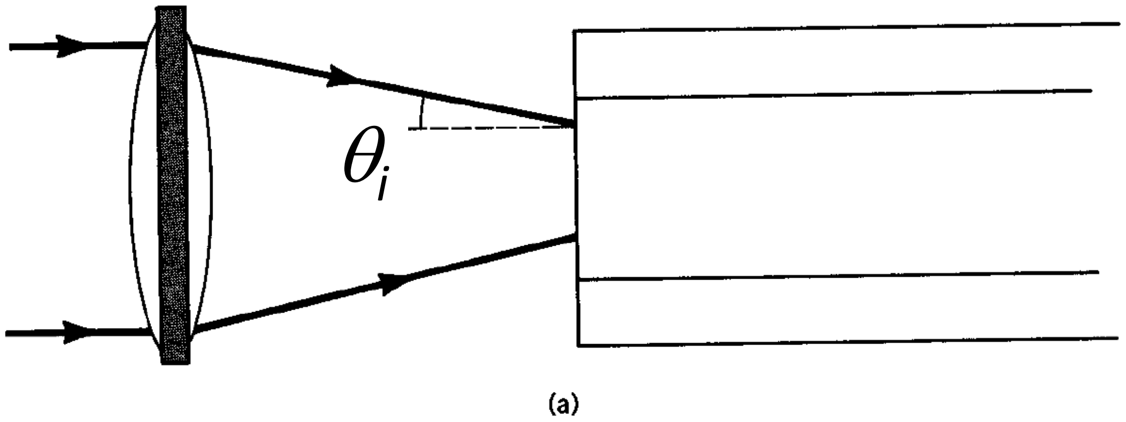
5 - 50 μm

Rivestimento
(*cladding*) >150 μm

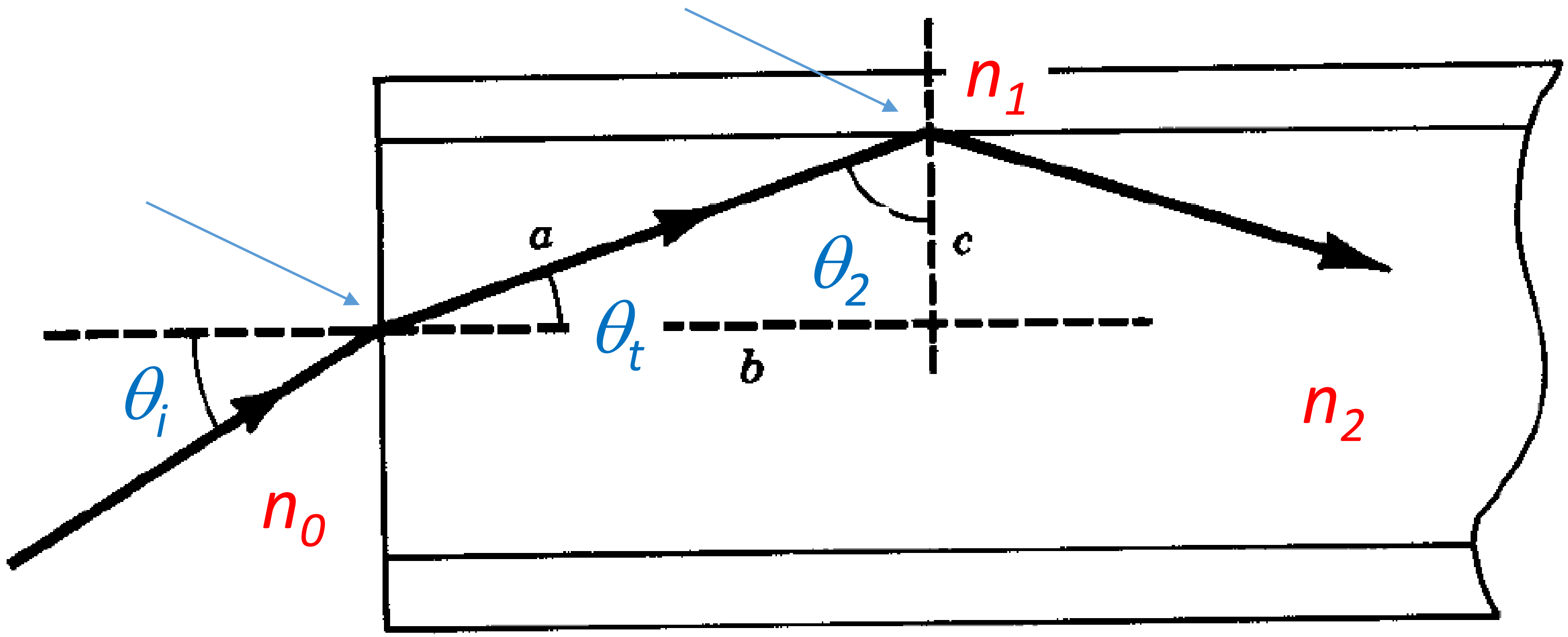


$$\theta_2 \geq \theta_c = \sin^{-1}\frac{n_1}{n_2}$$

Tutti i raggi con angolo $\theta_i < \theta_{NA}$ sono accoppiati



Propagazione guidata



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

$\theta_2 > \sin^{-1} (n_1/n_2)$

$\theta_2 > \theta_2^C$

$\theta_2 + \theta_t = \pi/2$

$n_0 \sin\, \theta_i = n_2 \cos\, \theta_2 = n_1$

$\theta_i < \theta_i^C = \theta_{NA}$

Propagazione guidata

$$n_0 \sin \theta_i = n_2 \cos \theta_2 = n_1$$

$$\theta_i < \theta_i^C = \theta_{NA}$$

$$n_0 \sin \theta_i < n_2 \sqrt{1 - \sin^2 \theta_2^C}$$

$$< n_2 \sqrt{1 - (n_1/n_2)^2}$$

$$< \sqrt{n_2^2 - n_1^2} = NA$$

Apertura numerica

$$NA = n_0 \sin \theta_{NA} = n_2 \sin \theta_t$$

$$= n_2 \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2}$$

$$= \sqrt{n_2^2 - n_1^2}$$

È proporzionale al massimo angolo di incidenza che la guida può accettare e trasmettere

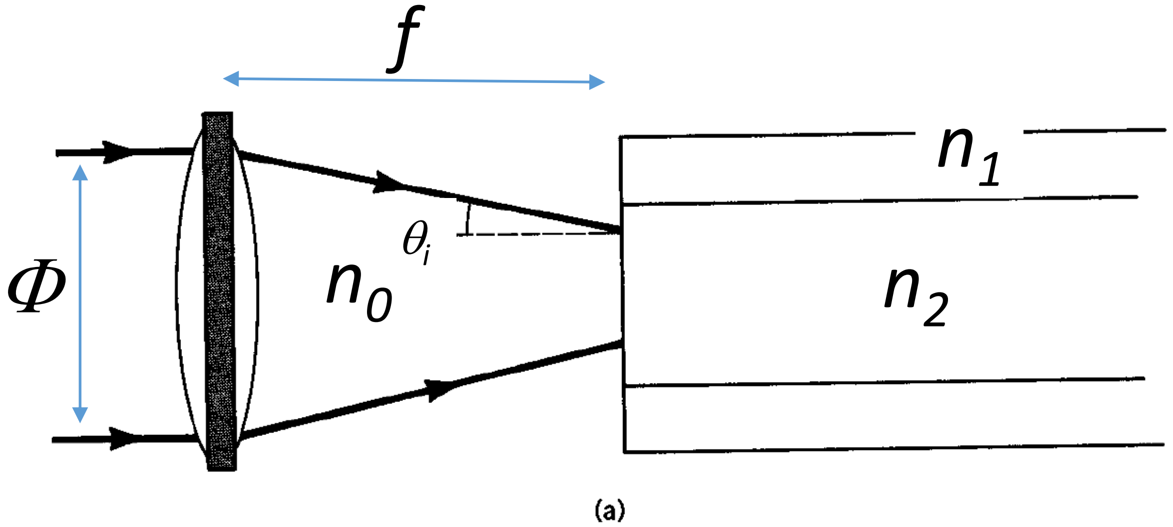
raggi *meridiani* = incrociano l'asse ottico della guida

Propagazione guidata

$n_0 = 1$

$n_1 = 1.5$

$n_2 = 1.53$



$\theta_2^C > \sin^{-1}(n_1/n_2) = 79°$

$NA = n_0 \sin\, \theta_{NA} = \sqrt{n_2^2 - n_1^2} = 0.3$

$\theta_{NA} = 18°$

$\theta_i < \theta_{NA} = 18°$

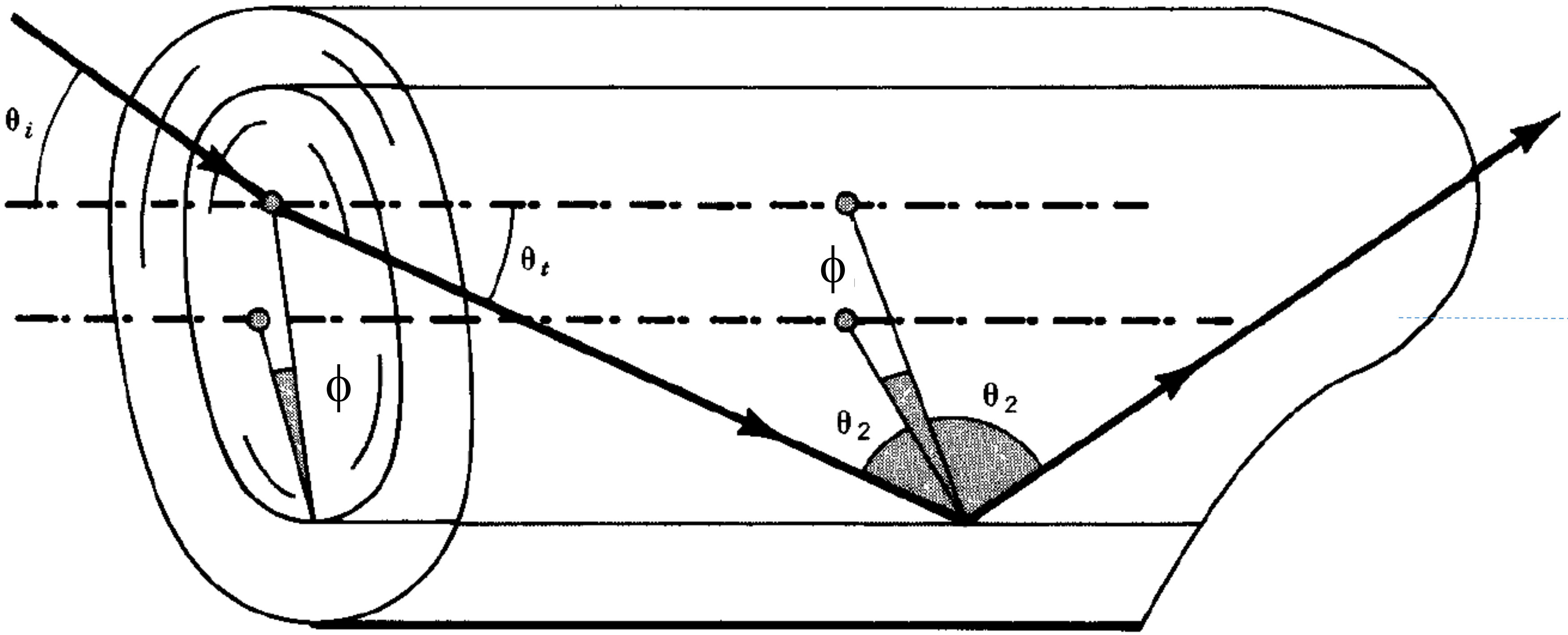
Per accoppiare luce in fibra o collimare un fascio in uscita da una fibra scegliere un collimatore con $NA_{\text{coll}} \geq NA_{fibra}$

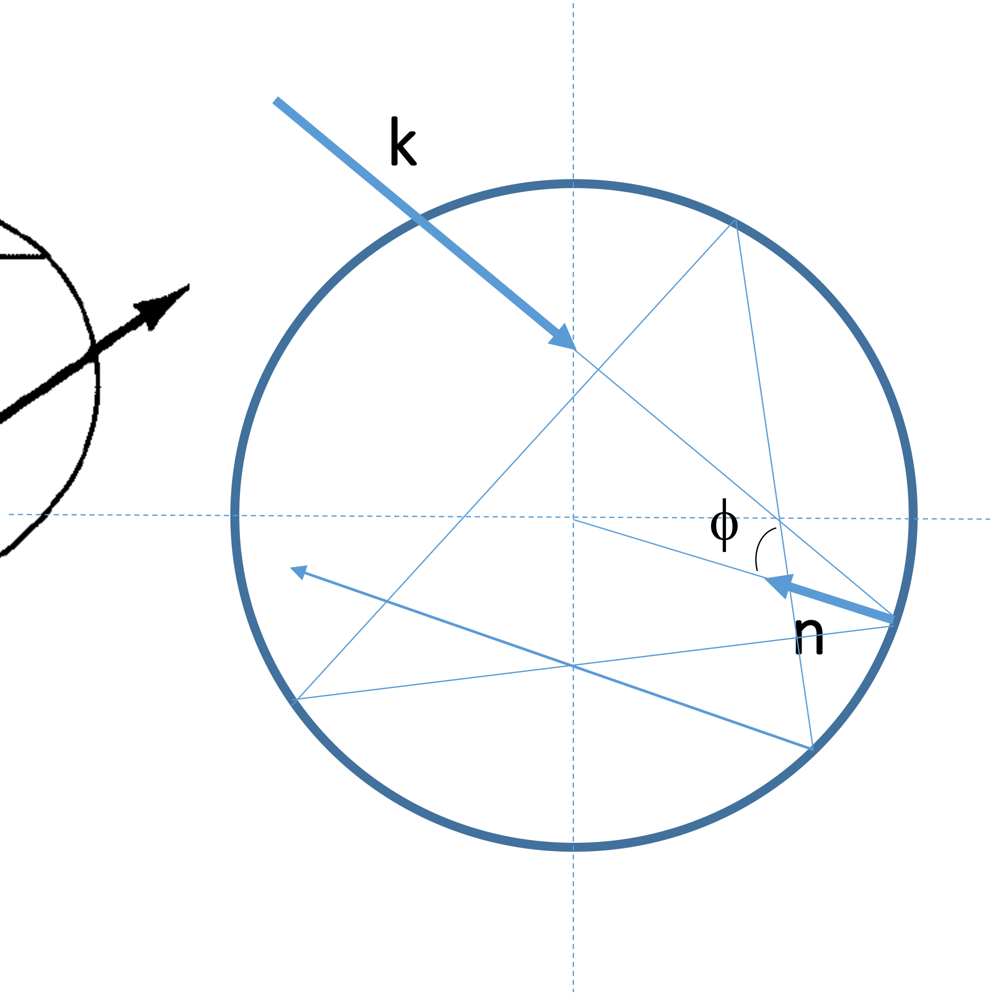
$f = 0.5\ \Phi_{(1/e^{\wedge}2)} / NA$

Beam diameter:	$Ø_{beam}$ = 1.0 mm
Effective numerical aperture of fiber:	NA=0.08
Focal length:	f'= 0.5 · 1.0 mm/ 0.08 = 6.25 mm
-> select lens with	f' = 6.2 mm

https://www.sukhamburg.com/download/fiberopt-cat_e.pdf

Raggi sghembi (*skew rays*)

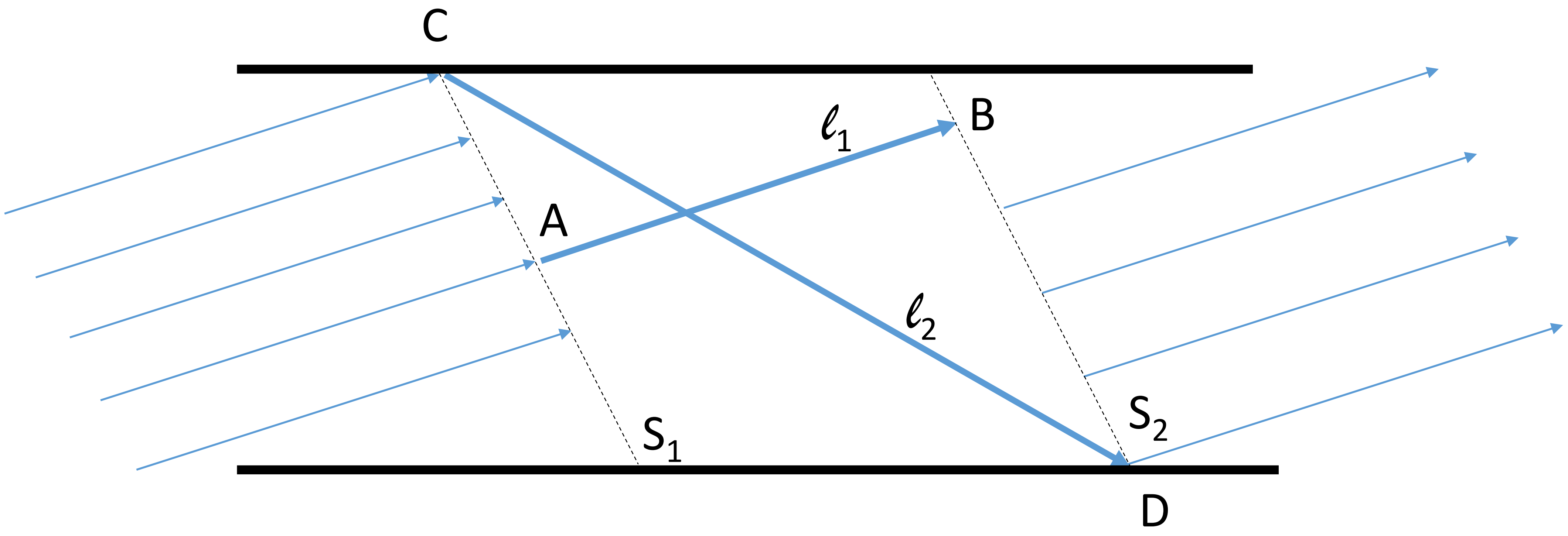




Raggi che non incrociano l'asse ottico della guida

$$(NA)_s = \frac{NA}{\cos \phi}$$

Relazione di dispersione



Impongo che le due superfici S_1 ed S_2 siano equifase

δ_C ed δ_D shift di fase per rifl. totale

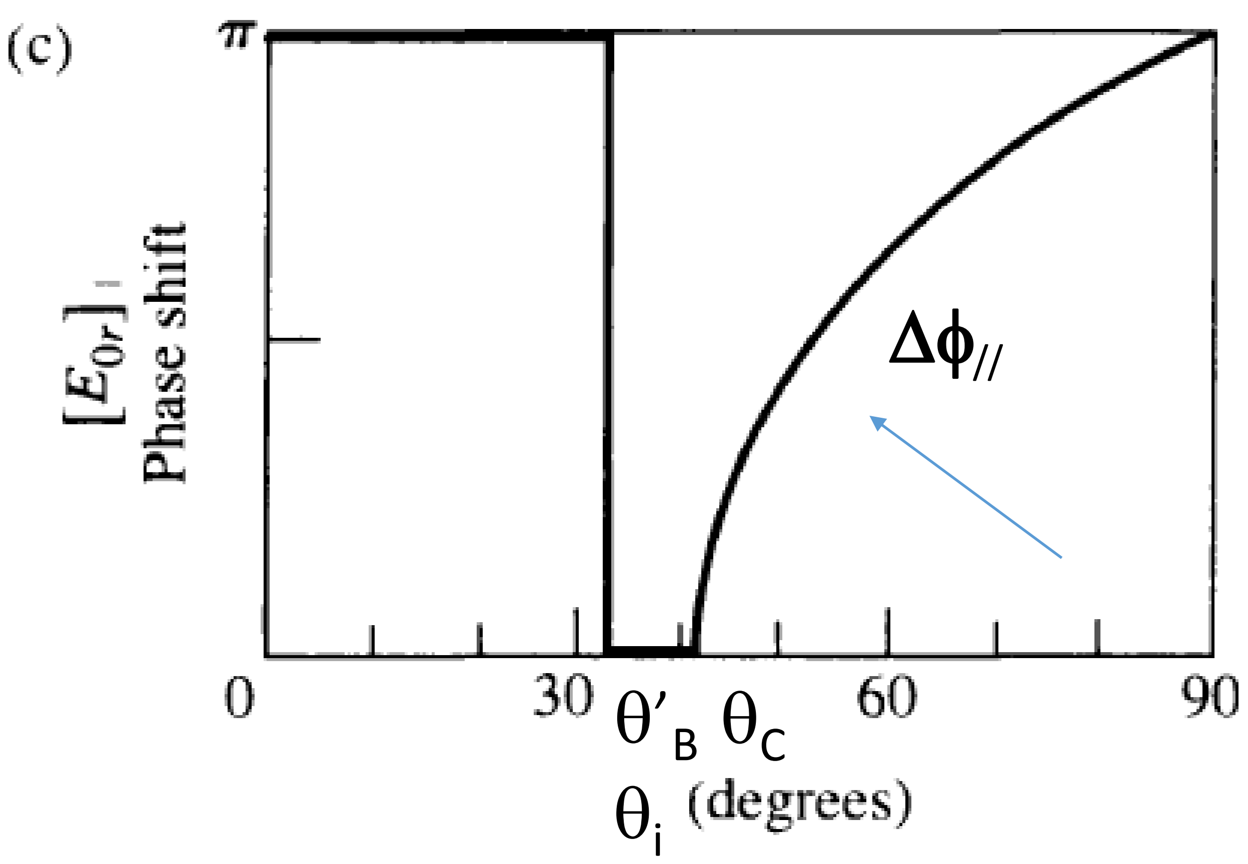
$$k\,(\ell_2 - \ell_1) + \delta_C + \delta_D = 2\,m\,\pi$$

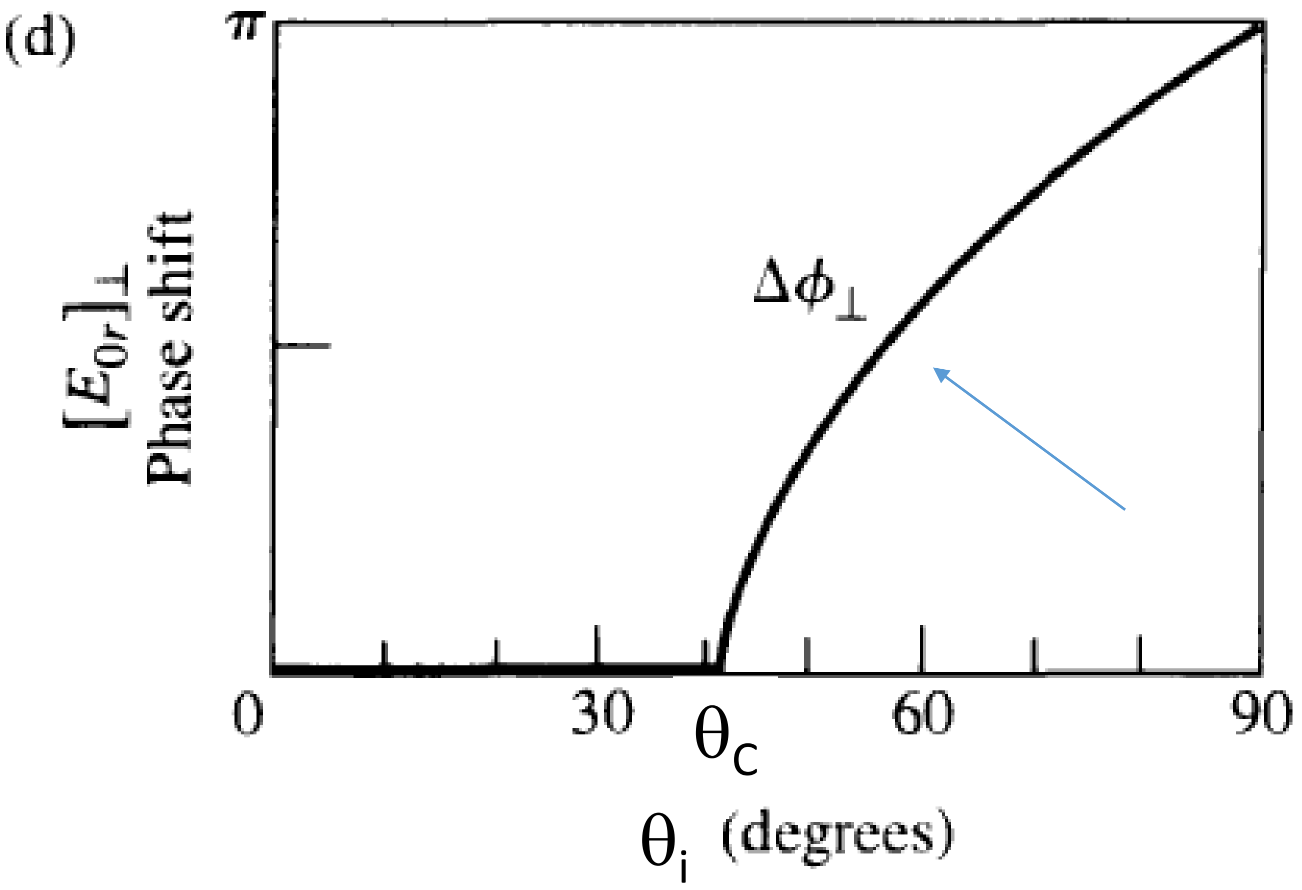
Riflessione Rifrazione

- shift di fase

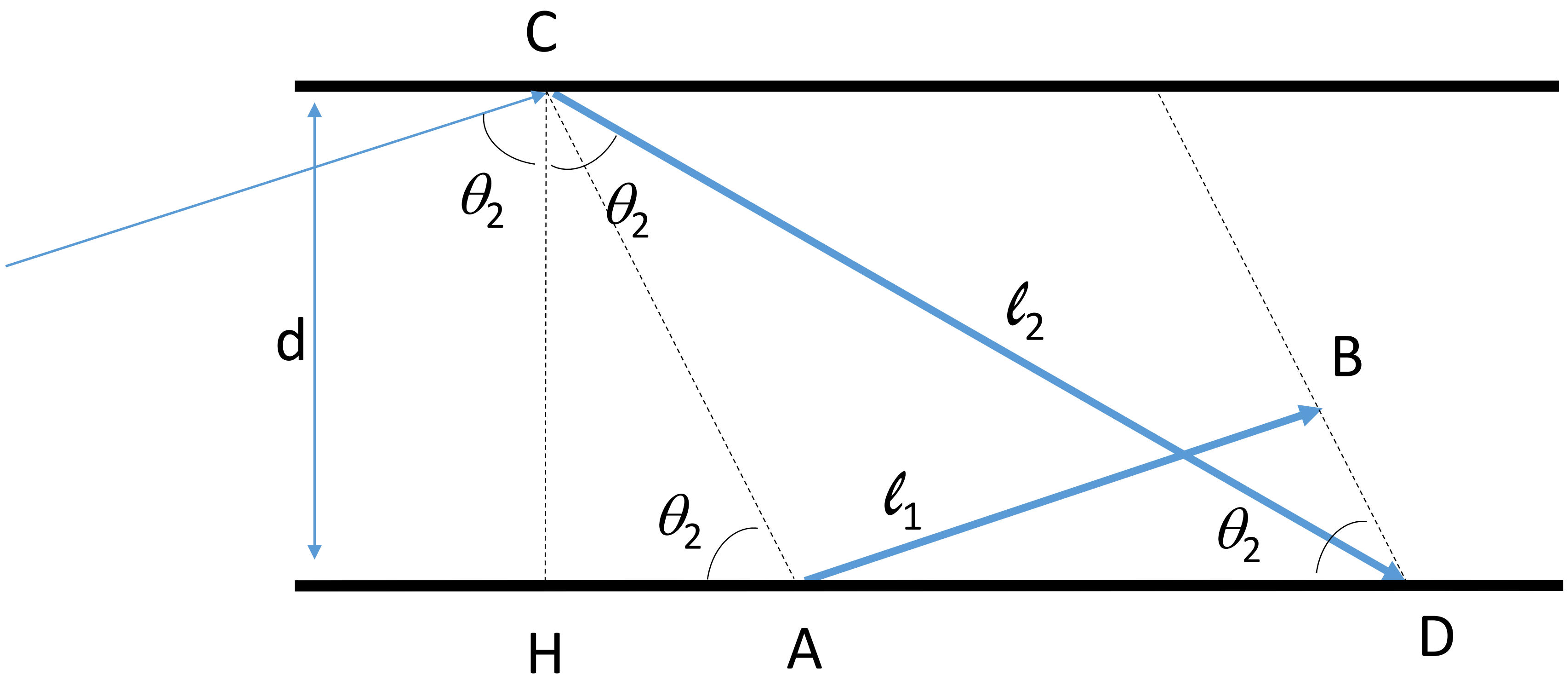
n_i=1.5
n_t=1

Riflessione interna





Relazione di dispersione



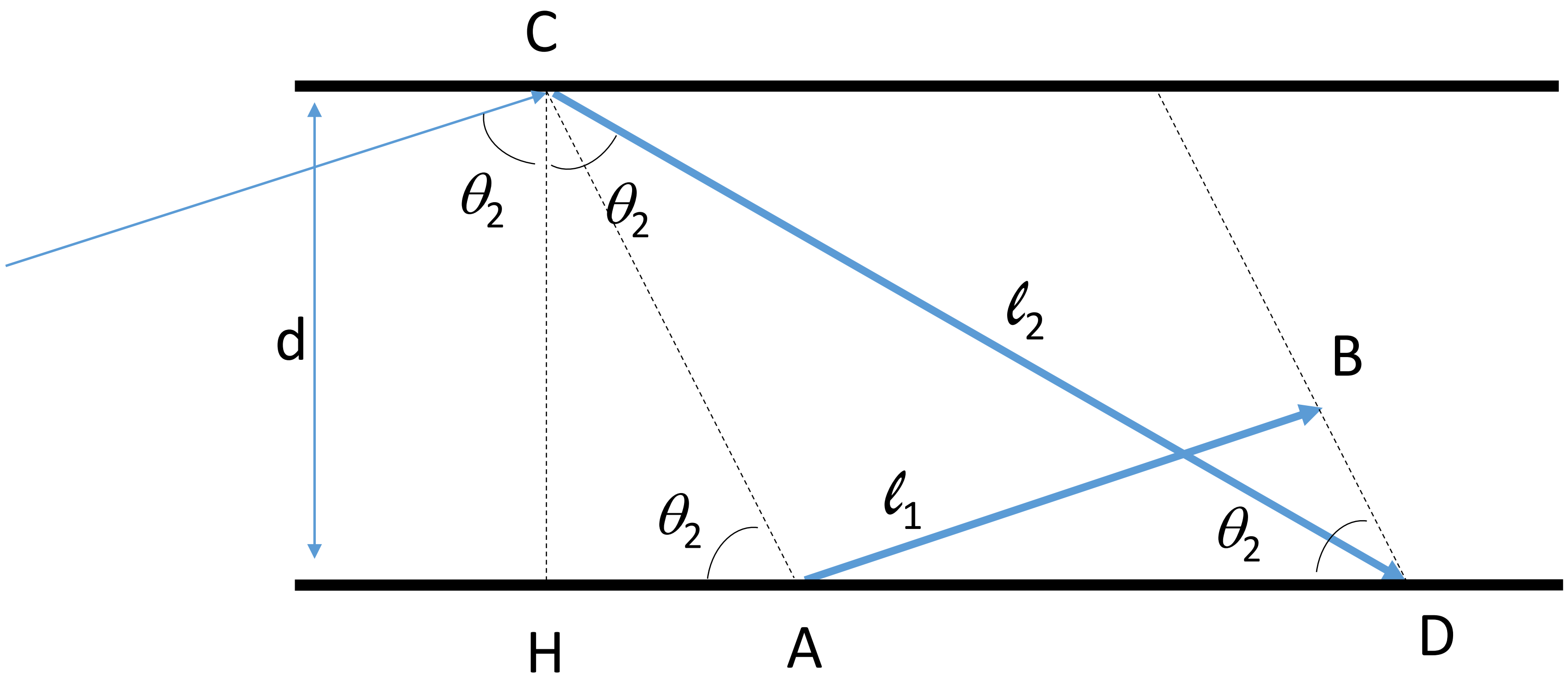
$\ell_2 \cos\,\theta_2 = d$

$\ell_1 = AD \sin\,\theta_2$

$AD + HA = \ell_2 \sin\,\theta_2$

$d = HA \tan\,\theta_2$

Relazione di dispersione



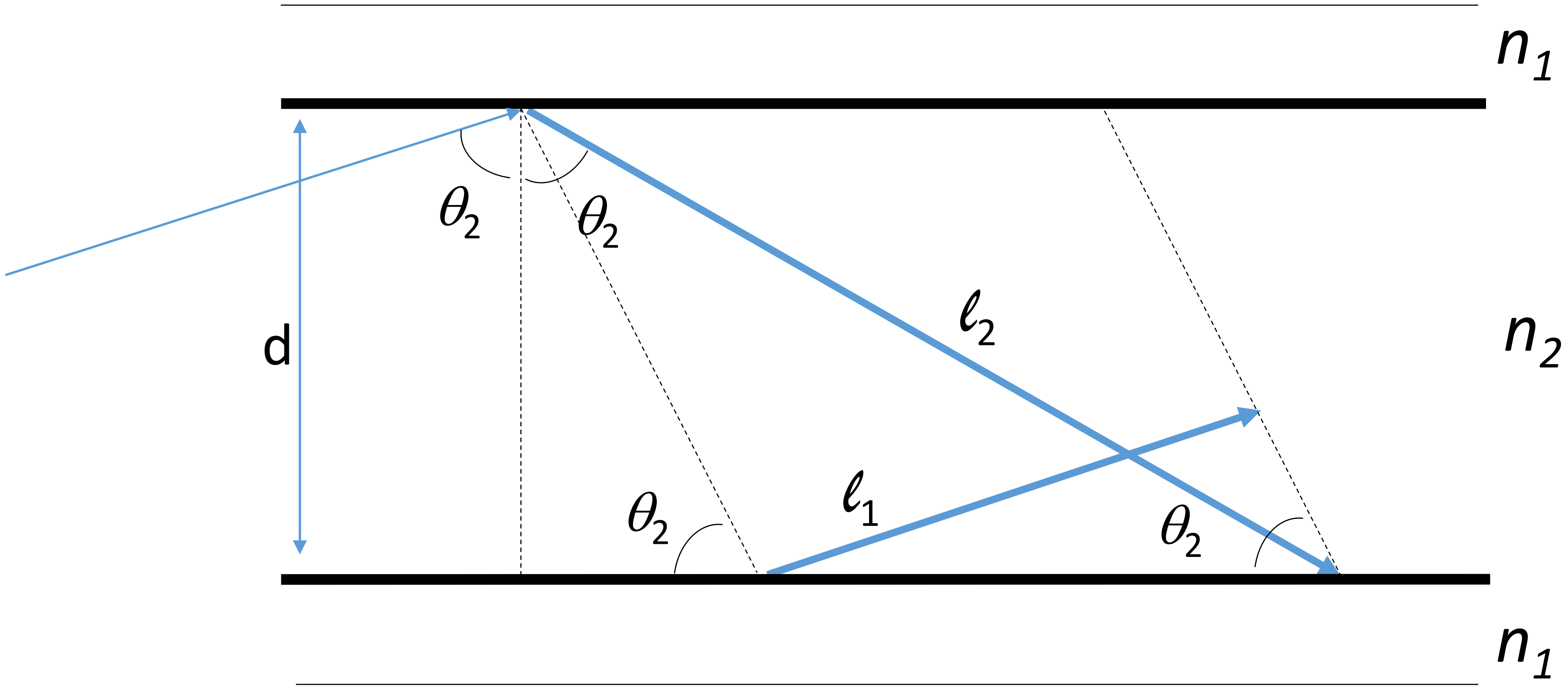
$$\ell_2 = d\,/\cos\,\theta_2$$

$$\ell_2 - \ell_1 = 2\,d\,\cos\,\theta_2$$

$$\ell_1 = \ell_2 \sin^2\theta_2 \text{ - } d\,\cos\,\theta_2$$

$$2\,k\,d\,\cos\,\theta_2 + \delta_C(\theta_2) + \delta_D(\theta_2) = 2\,m\,\pi$$

Relazione di dispersione



$$2\,k\,d\cos\theta_2 + \delta_C(\theta_2) + \delta_D(\theta_2) = 2\,m\,\pi$$

Per modi guidati $\quad \sin\theta_2 > n_1/n_2 \;\Rightarrow\; \cos\theta_2 < \sqrt{1-(n_1/n_2)^2}$

Relazione di dispersione

$$m_{MAX} = 2d/\lambda_0 \sqrt{n_2^2 - n_1^2} + (\delta_C + \delta_D)/2\pi$$

Numero di modi nella fibra

$$2\, k_0\, d \sqrt{n_2^2 - n_1^2} + \delta_C(\theta_2) + \delta_D(\theta_2) = 2\, m\, \pi$$

$$2\, k\, d \cos \theta_2 + \delta_C(\theta_2) + \delta_D(\theta_2) = 2\, m\, \pi$$

Per modi guidati $\sin \theta_2 > n_1/n_2$ ⟹ $\cos \theta_2 < \sqrt{1 - (n_1/n_2)^2}$

Relazione di dispersione

$$m_{MAX} = 2d/\lambda_0 \sqrt{n_2^2 - n_1^2} + (\delta_C + \delta_D)/2\pi$$

Numero di modi nella fibra

$$V = k_0\, d \sqrt{n_2^2 - n_1^2}$$

Spessore normalizzato della fibra

<u>Es.</u>

$n_0 = 1$

$n_1 = 1.5$

$n_2 = 1.53$

$\lambda_0 = 1\ \mu m$

$d = 100\ \mu m$

$$V = 2\pi/\lambda_0\, d \sqrt{1.53^2 - 1.5^2} = 190 \text{ rad}$$

$$m_{MAX} = V/\pi + (2\pi)/2\pi = 61 \text{ modi}$$

Relazione di dispersione

$$m_{MAX} = 2d/\lambda_0 \sqrt{n_2^2 - n_1^2} + (\delta_C + \delta_D)/2\pi$$

Numero di modi nella fibra

$$V = k_0\, d \sqrt{n_2^2 - n_1^2}$$

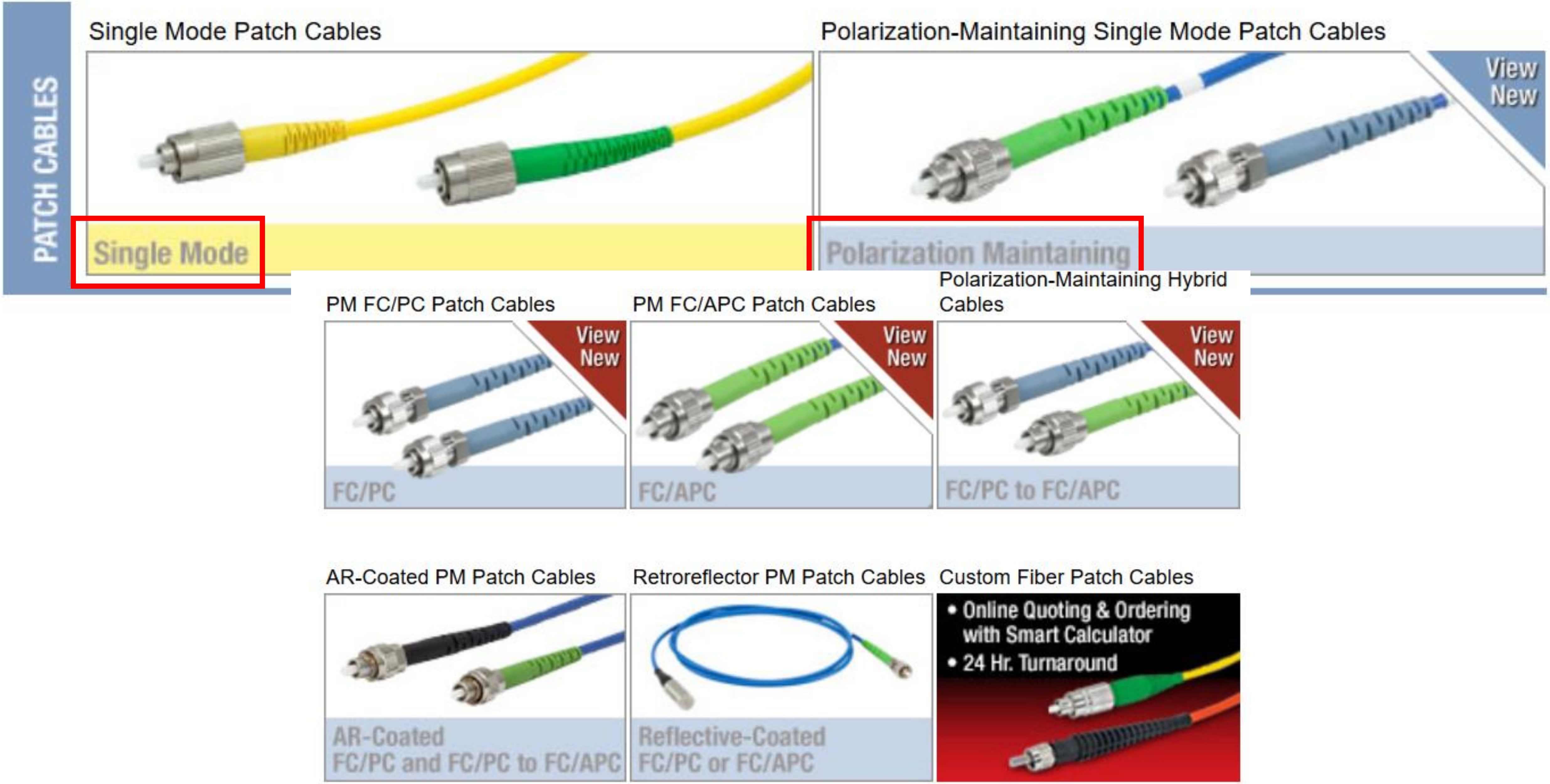
Spessore normalizzato della fibra

Condizione per singolo modo

$$0 < V < 2.405$$

→ soluz. eq. Maxwell

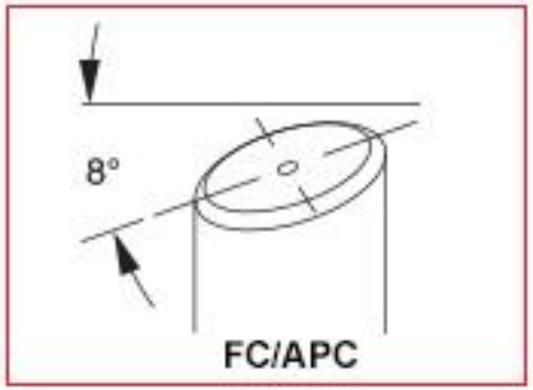
Fibre ottiche

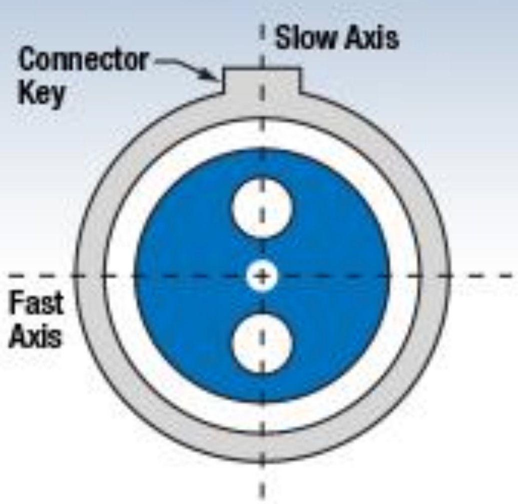


Fibre ottiche

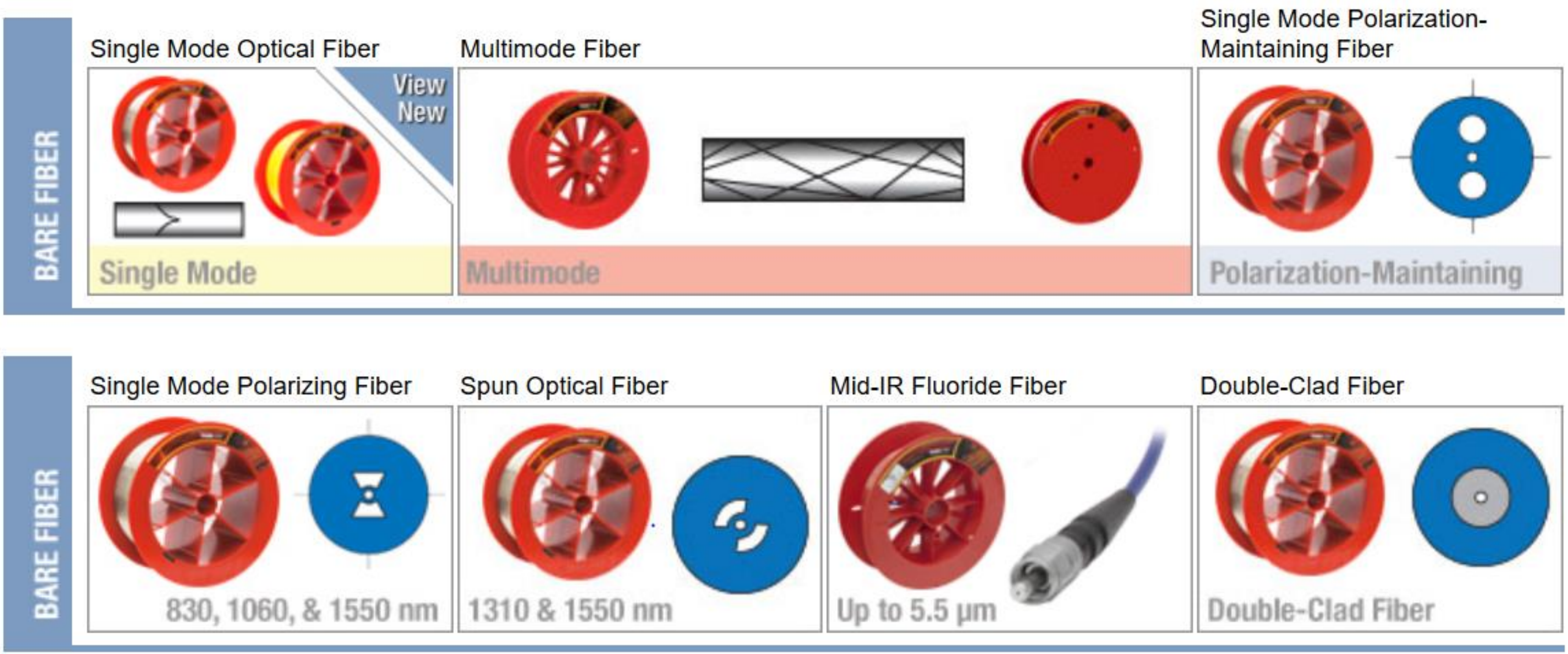
- FC/APC (Fiber connector Angled Physical Contact)

Per evitare riflessioni all'interfaccia fibra-aria



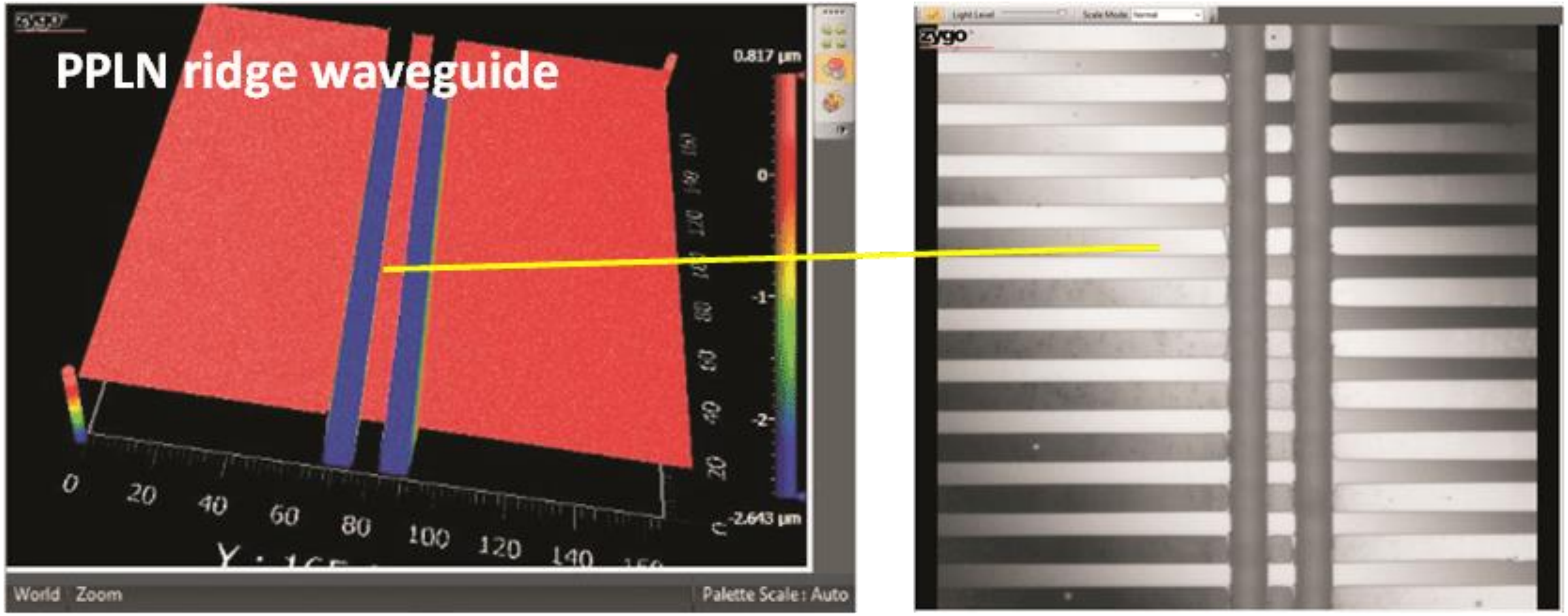


Fibre ottiche

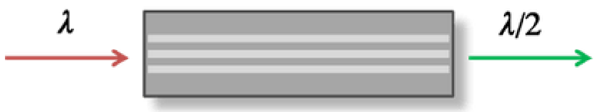


Fibre ottiche

Guide d’onda

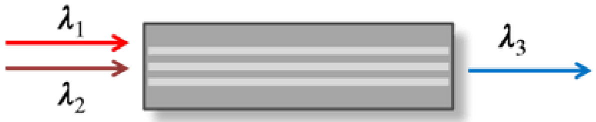


SHG



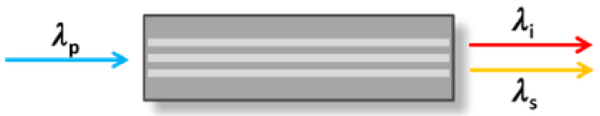
5 mol.% MgO doped PPLN for Second Harmonic Generation (SHG) of blue to red light from a laser source between 950-2200nm infrared wavelength.

SFG



5 mol.% MgO doped PPLN for sum-frequency generation (SFG) of blue to red light from the conventional laser sources such as Yb/Er fiber laser, YAG laser or Ti:Sapphire lasers.

Down Conversion

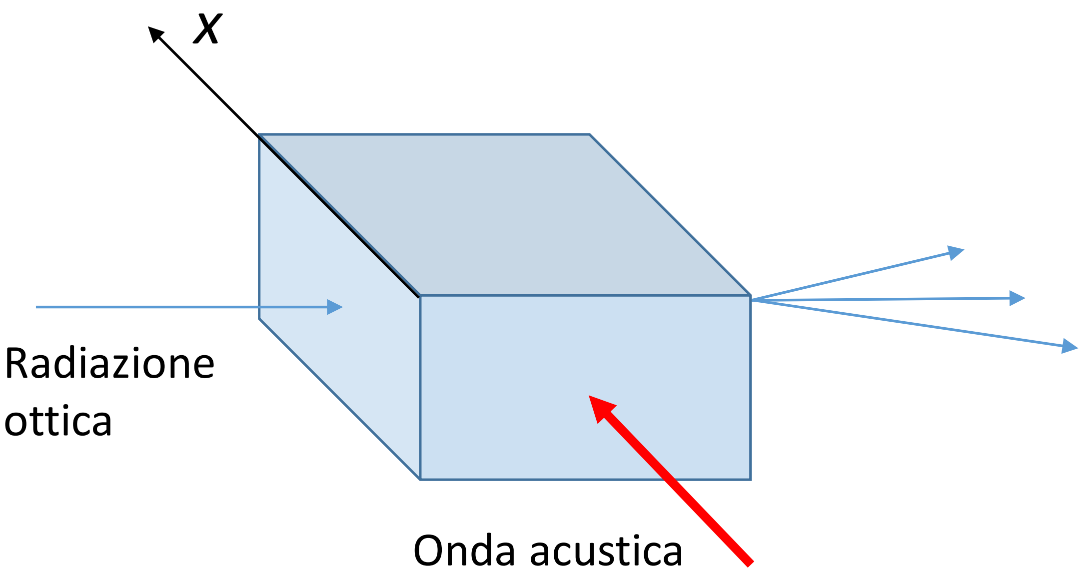


5 mol.% MgO doped PPLN for laser wavelength downconversion (e.g. optical parametric generation, difference frequency generation) of the conventional pump laser such as Yb fiber lasers, YAG laser, and Ti: Sapphire lasers.

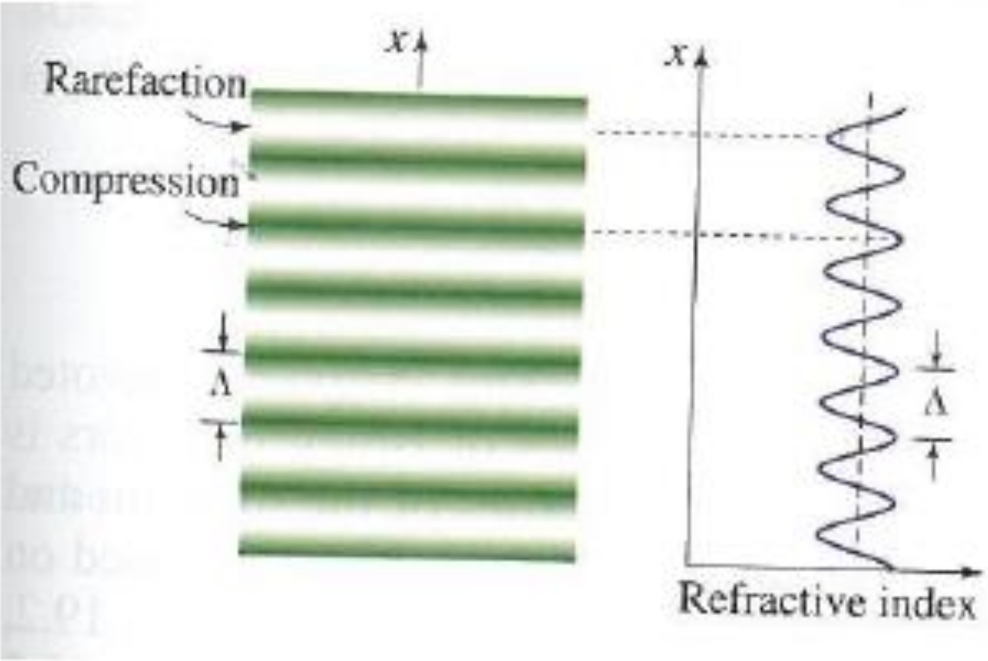
Modulatori Acusto-Ottici (AOM)

- Usati per controllare *intensità*, *frequenza* e *direzione* di un fascio laser

- Effetto *foto-acustico:* Variazione dell'*indice di rifrazione* di un mezzo trasparente in presenza di variazioni di *pressione*



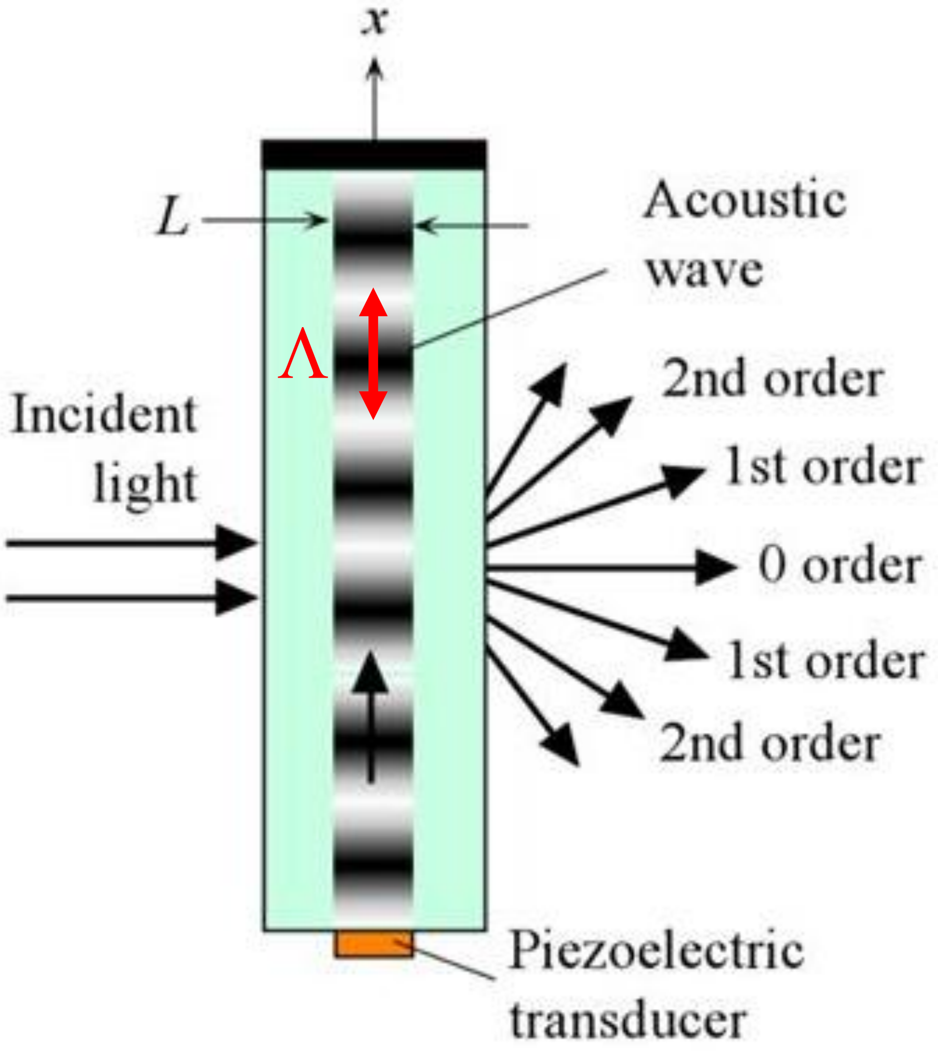
$$n = n_0 + \Delta n \cos(\omega t - k_a x)$$



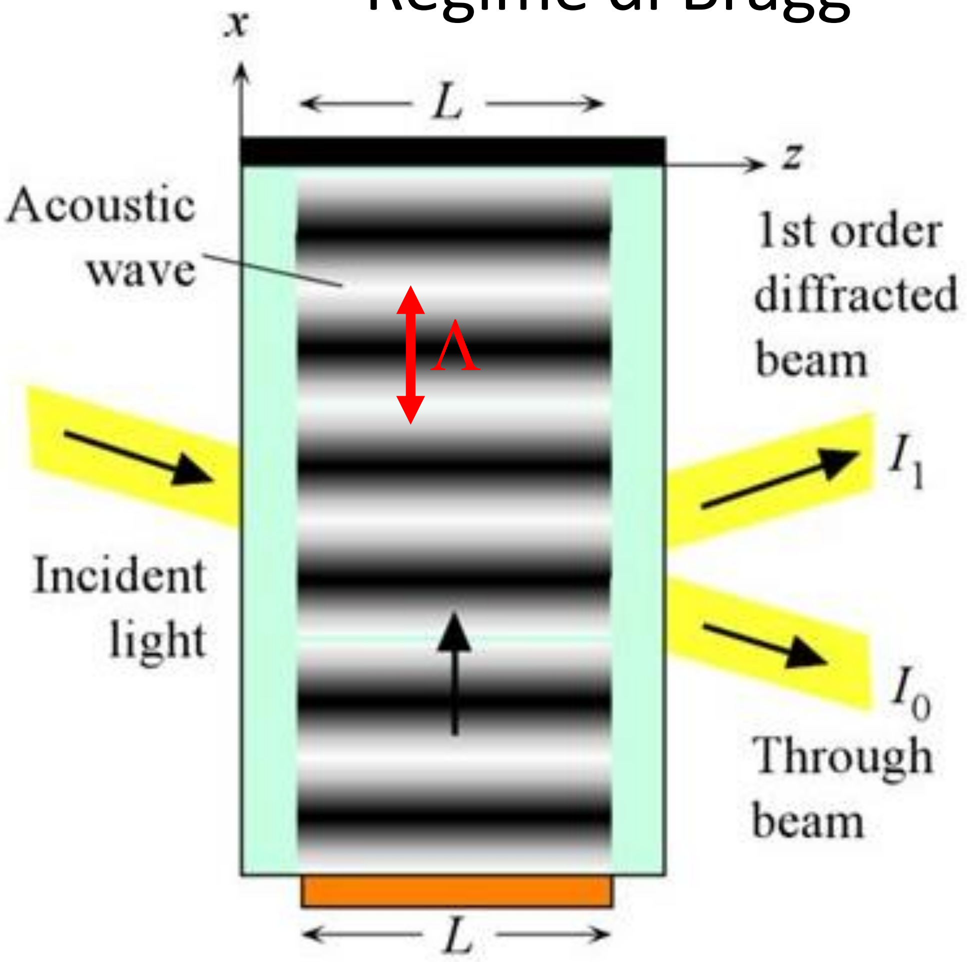
Diffrazione

Modulatori Acusto-Ottici (AOM)

- Regime di Raman-Nath

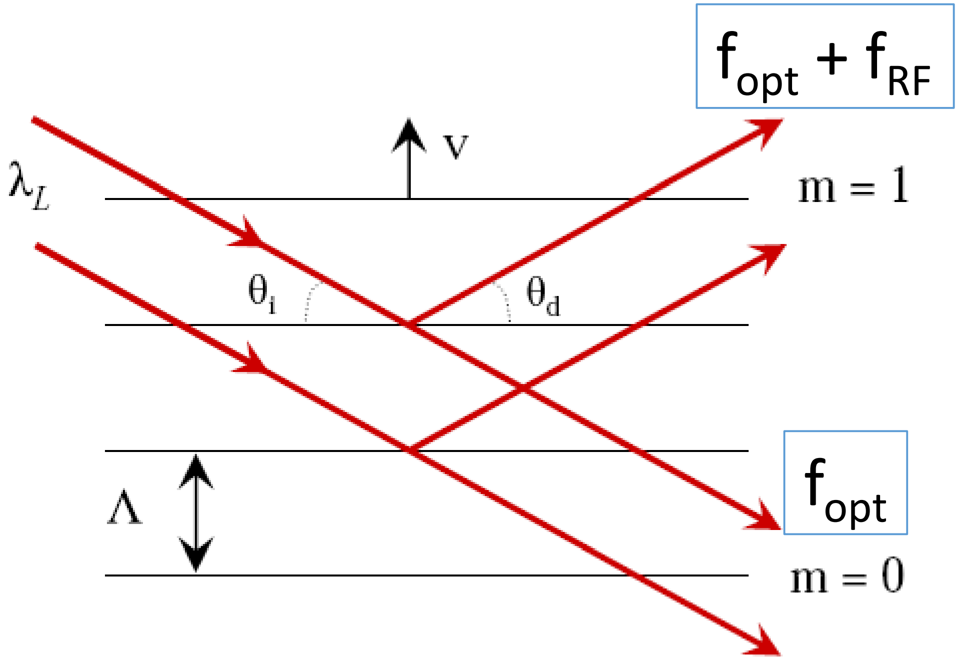


- Regime di Bragg



Modulatori Acusto-Ottici (AOM)

- Controllo di *intensità*, *frequenza* e *direzione* del fascio laser



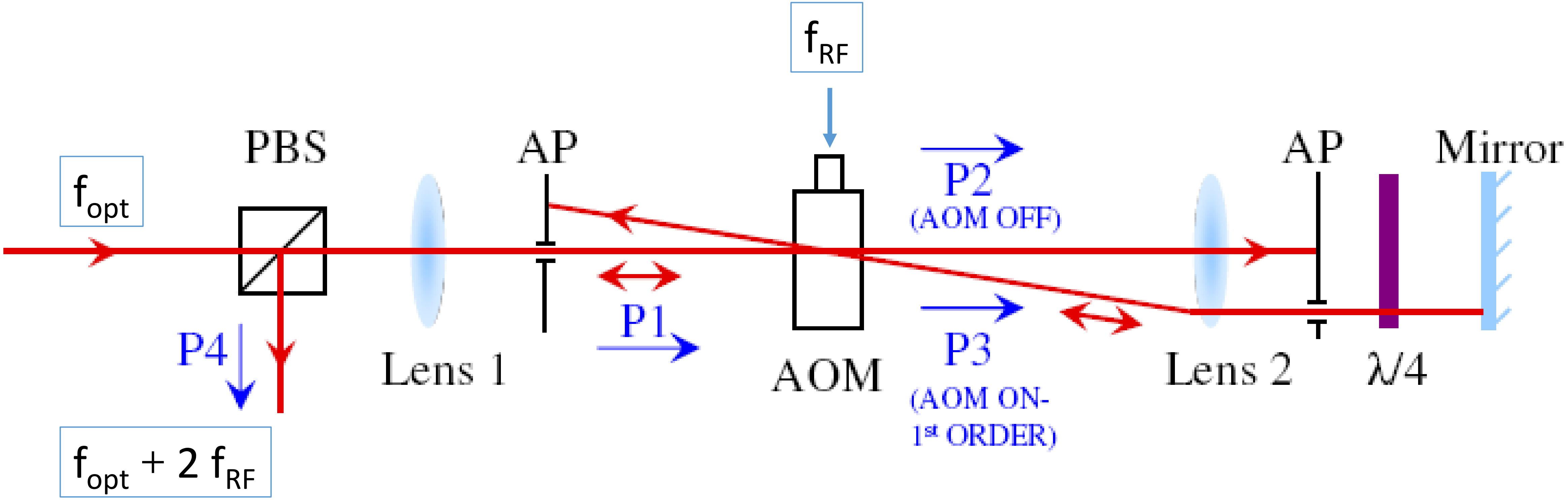
$$n\lambda_L = 2\Lambda \sin\theta_d$$

$\theta_i = \theta_d$

$$\Delta f = \frac{m\, E_{phonon}}{h}$$

Modulatori Acusto-Ottici (AOM)

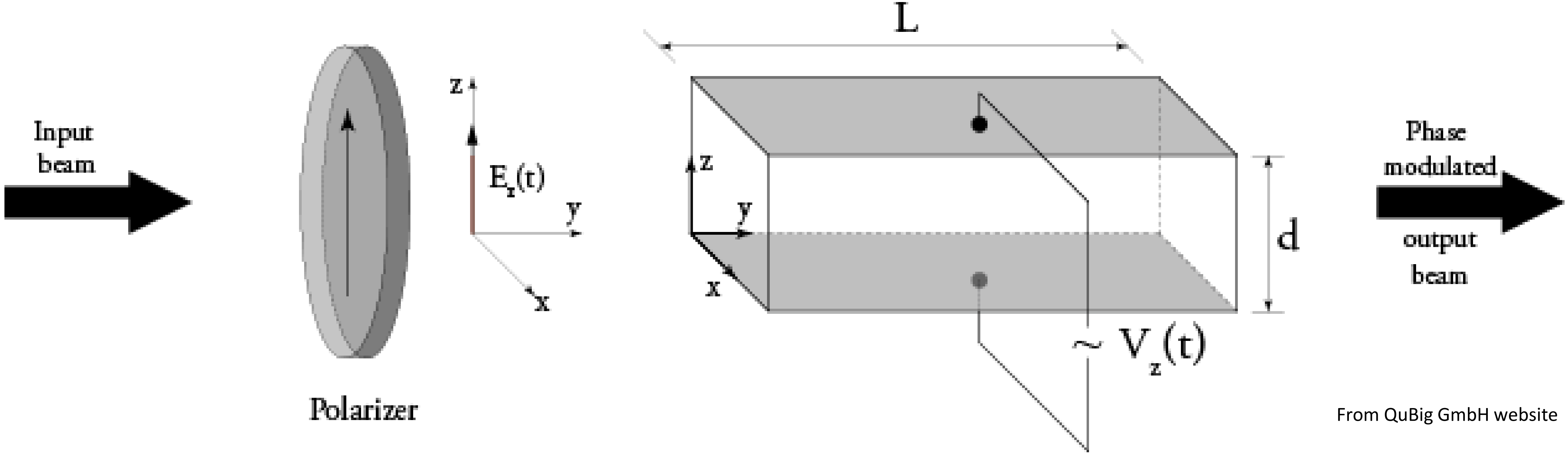
- AOM in doppio passaggio



Electro-Optical Modulators (EOM)

Effetto Pockels: esiste nei cristalli non centrosimmetrici (birifrangenti)

variazione lineare dell' indice di rifrazione con E esterno $\Delta n \propto E$



From QuBig GmbH website

- Modulatore di <u>fase</u> (V_π è il voltaggio richiesto per sfasare di 180° all'uscita)
- In combinazione a polarizzatori in uscita posso creare un modulatore di <u>intensità</u>