Electro-Optics:

Electro-Optics (2)

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Quadratic Electro-Optic Effect

$$\rightarrow s_{ij} = \begin{pmatrix} s_{11} & s_{12} & s_{13} & s_{14} & s_{15} & s_{16} \\ s_{21} & s_{22} & s_{23} & s_{24} & s_{25} & s_{26} \\ s_{31} & s_{22} & s_{33} & s_{34} & s_{35} & s_{36} \\ s_{41} & s_{22} & s_{43} & s_{44} & s_{45} & s_{46} \\ s_{51} & s_{22} & s_{53} & s_{54} & s_{55} & s_{56} \\ s_{61} & s_{22} & s_{53} & s_{64} & s_{65} & s_{66} \end{pmatrix}$$

Permutation symmetries:

$$\rightarrow s_{ijkl} = s_{jikl}$$

$$\rightarrow s_{ijkl} = s_{ijlk} \qquad \rightarrow 1 = (11),\ 2 = (22),\ 3 = (33),$$

$$4 = (23) = (32),\ 5 = (13) = (31),\ 6 = (12) = (21)$$

Index ellipsoid: $\rightarrow \eta_{ij}(\mathbf{E}) = \eta_{ij}(0) + r_{ijk}E_k + s_{ijkl}E_kE_l$

$$\rightarrow x^2\left(\frac{1}{n_x^2} + s_{11}E_x^2 + s_{12}E_y^2 + s_{13}E_z^2 + 2s_{14}E_yE_z + 2s_{15}E_zE_x + 2s_{16}E_xE_y\right)$$

$$+ y^2\left(\frac{1}{n_y^2} + s_{21}E_x^2 + s_{22}E_y^2 + s_{23}E_z^2 + 2s_{24}E_yE_z + 2s_{25}E_zE_x + 2s_{26}E_xE_y\right)$$

$$+ z^2\left(\frac{1}{n_z^2} + s_{31}E_x^2 + s_{32}E_y^2 + s_{33}E_z^2 + 2s_{34}E_yE_z + 2s_{35}E_zE_x + 2s_{36}E_xE_y\right)$$

$$+ 2yz\left(s_{41}E_x^2 + s_{42}E_y^2 + s_{43}E_z^2 + 2s_{44}E_yE_z + 2s_{45}E_zE_x + 2s_{46}E_xE_y\right)$$

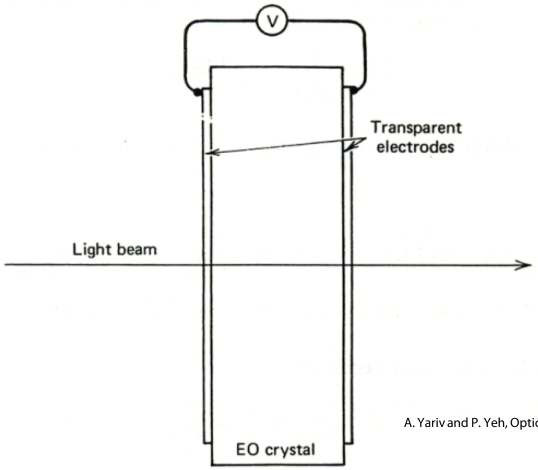
$$+ 2zx\left(s_{51}E_x^2 + s_{52}E_y^2 + s_{53}E_z^2 + 2s_{54}E_yE_z + 2s_{55}E_zE_x + 2s_{56}E_xE_y\right)$$

$$+ 2xy\left(s_{61}E_x^2 + s_{62}E_y^2 + s_{63}E_z^2 + 2s_{64}E_yE_z + 2s_{65}E_zE_x + 2s_{66}E_xE_y\right) = 1$$

Electro-Optic Light Modulators

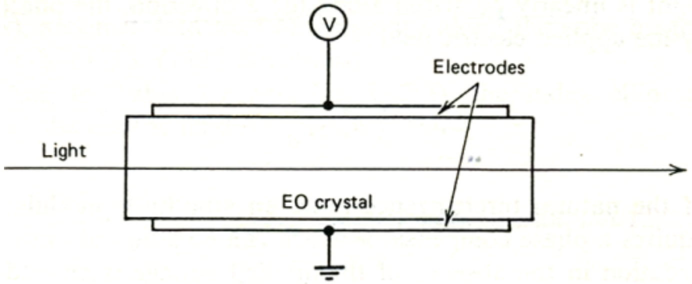
Longitudinal electro-optic modulation:

→ Large acceptance area with a thin EO crystal plate



A. Yariv and P. Yeh, Optical Waves in Crystals, John Wiley & Sons, 1984.

Transverse electro-optic modulation:

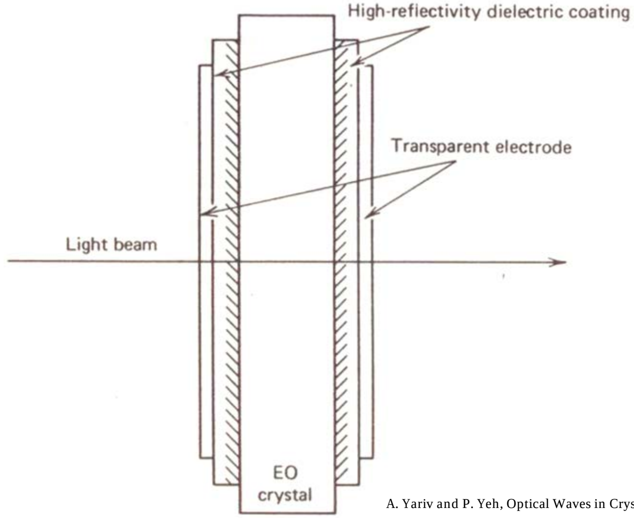


A. Yariv and P. Yeh, Optical Waves in Crystals, John Wiley & Sons, 1984.

→ Long interaction length at a given field strength

Electro-Optic Fabry-Perot Modulators

Electro-optic amplitude modulator:

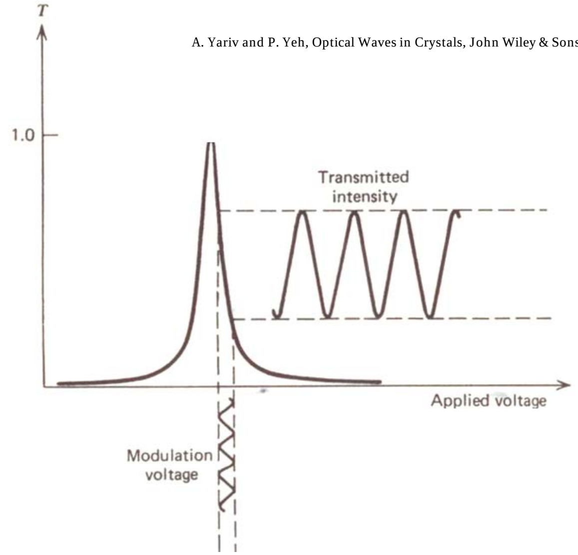


A. Yariv and P. Yeh, Optical Waves in Crystals, John Wiley & Sons, 1984.

Charles Fabry
(1867-1945)

Alfred Perot
(1863-1925)

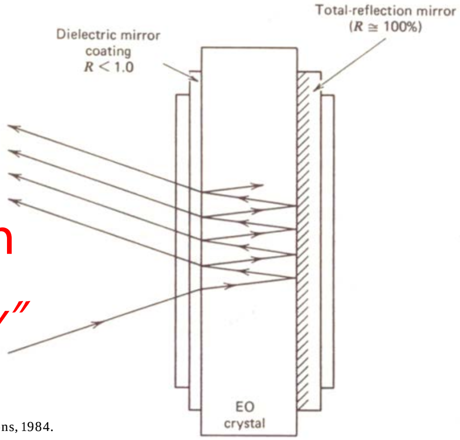
Transmission as a function of applied voltage:



A. Yariv and P. Yeh, Optical Waves in Crystals, John Wiley & Sons, 1984.

→ Gires-Tournois eltalon

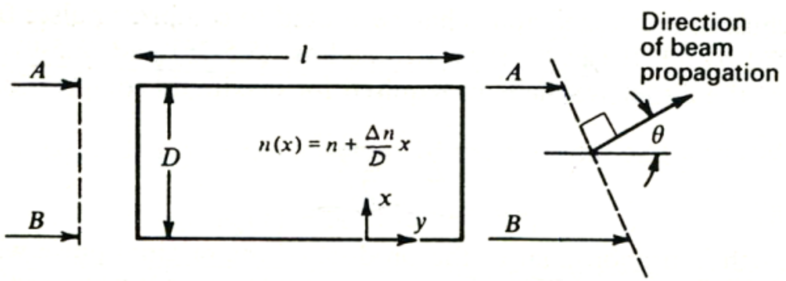
"Phase modulation only"

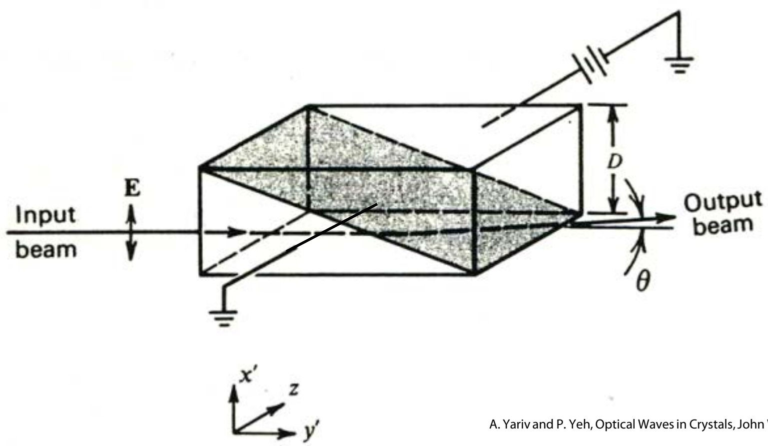


A. Yariv and P. Yeh, Optical Waves in Crystals, John Wiley & Sons, 1984.

Electro-Optic Beam Deflectors

Double-prism KDP beam deflectors:





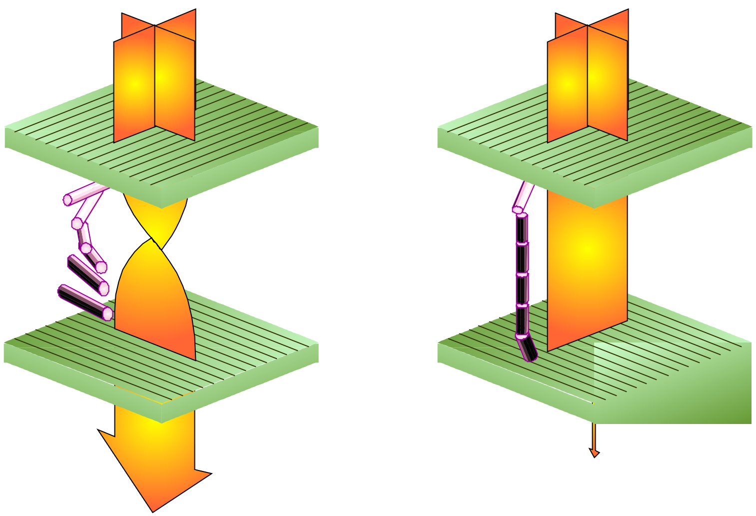
A. Yariv and P. Yeh, Optical Waves in Crystals, John Wiley & Sons, 1984.

Electro-Optic Property of Liquid Crystal

Liquid crystals:

Liquid crystal phases: smectic, nematic, and cholesteric
Nematic LC: uniaxial dipole moment
→ Dynamic director alignment along the applied electric field
→ Switching time: ~msec

Twisted nematic LC in liquid crystal displays (LCDs):



V_{LC} = 0V (off) V_{LC} = 5V (on)

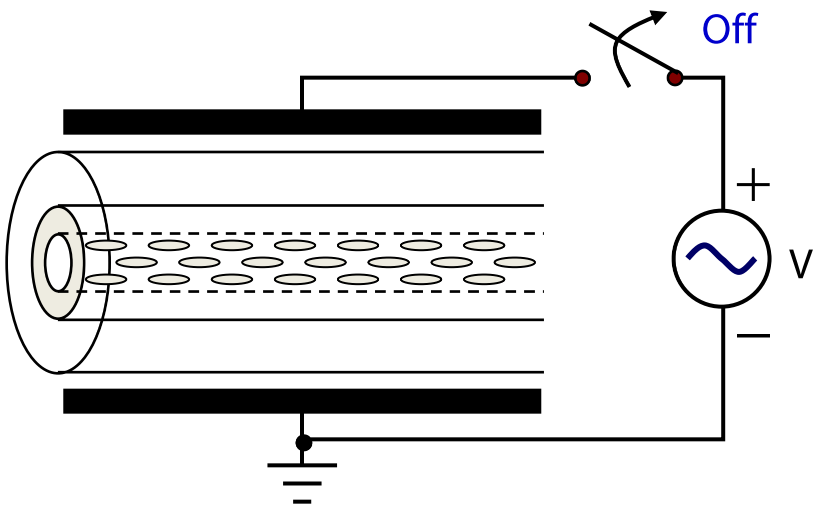
Applicable to fiber-optic devices?

LC-Filled Hollow Optical Fiber (1)

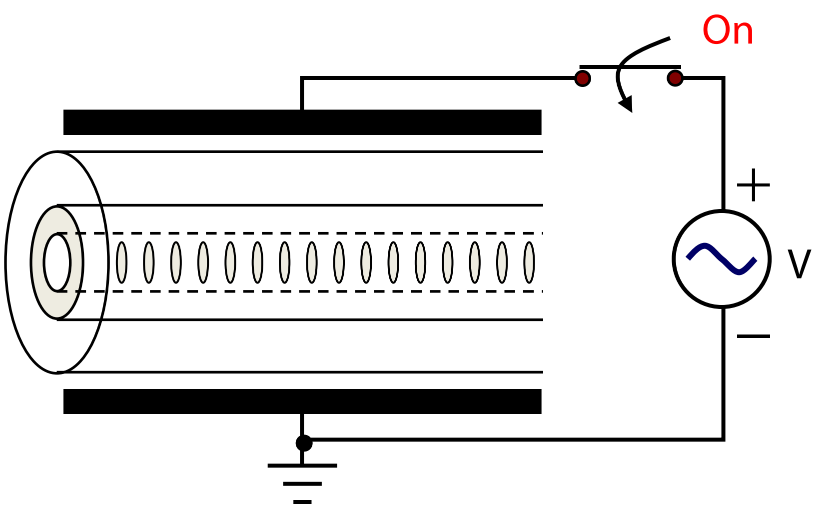
Director alignment of nematic LC:

- Highly dependent on the liquid crystals-capillary interface interaction
  - Silica: longitudinal direction
  - borosilicate capillaries: radial direction

Voltage off:

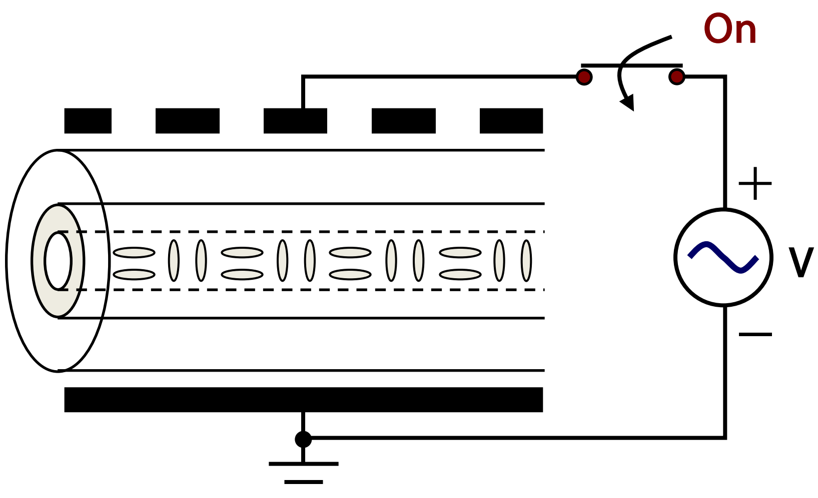


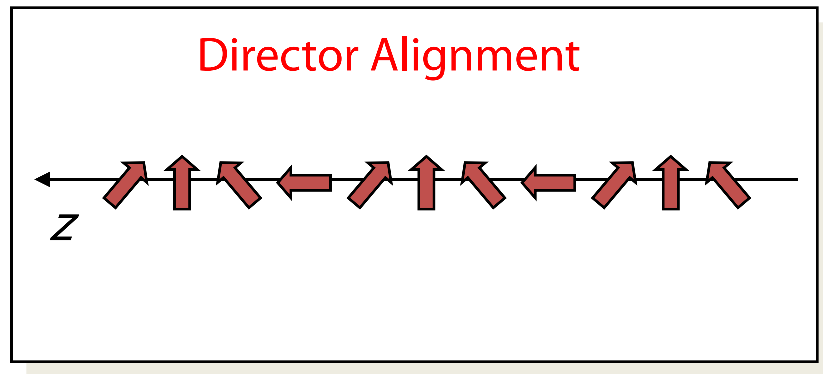
Voltage on:



LC-Filled Hollow Optical Fiber (2)

Comb electrode:





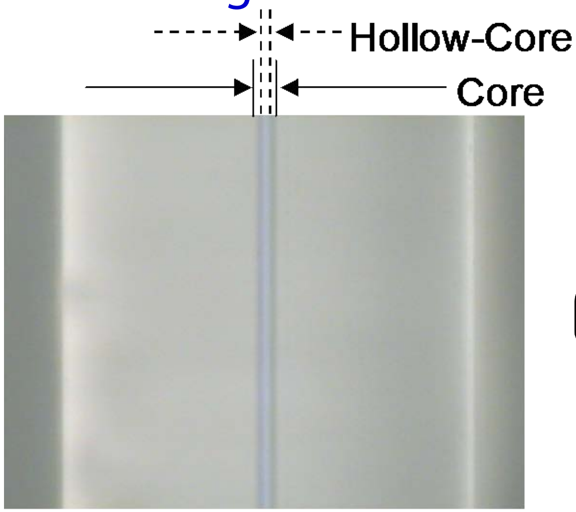
Electrically controllable director alignment:

Periodical modulation of director alignment

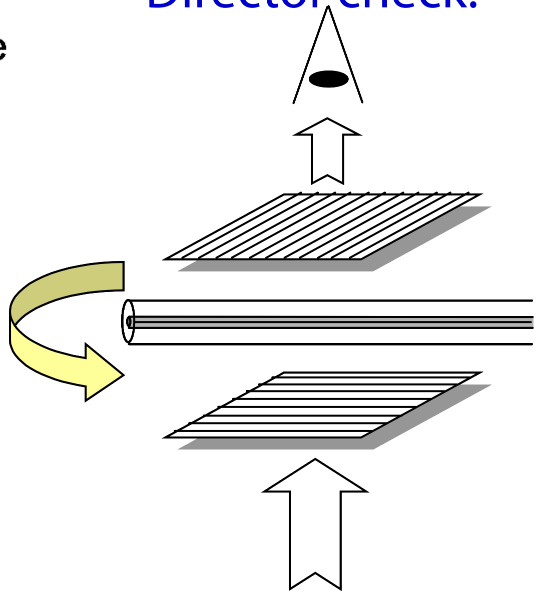
→ Controllable long-period gratings

LC-Filled Hollow Optical Fiber (3)

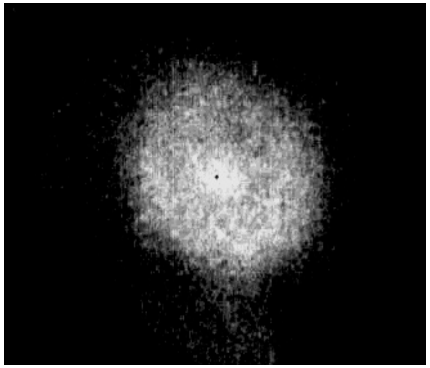
Fiber image:



Director check:



Far-field image:



Properties of MLC-6295:

Smectic/Nematic turning point: –30 °C, clearing point +101 °C

n_o: 1.4772, n_e: 1.5472 @20 °C, 589 nm

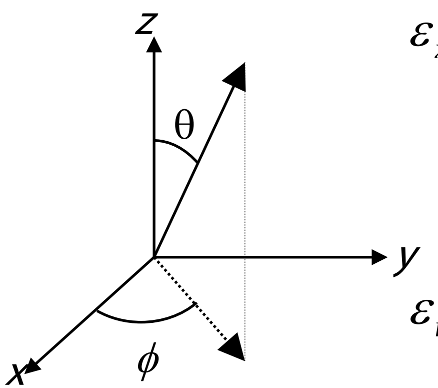
Director alignment check:

Visibility detection under a microscope between crossed polarizers

Uniform director alignment to the direction of the fiber axis

Anisotropic Mode Couplings in the LC Core

Permittivity tensor dependent on the director alignment:



$$\varepsilon_{xyz}(\theta) = \varepsilon_o \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} n_o^2 & 0 & 0 \\ 0 & n_o^2 & 0 \\ 0 & 0 & n_e^2 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix}$$

$$\varepsilon_{r\phi z}(\theta,\phi) = \varepsilon_o \begin{pmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \varepsilon_{xyz}(\theta) \cdot \begin{pmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Permittivity perturbation:

$$\Delta\varepsilon_{r\phi z}(\theta,\phi) = \varepsilon_{r\phi z}(\theta,\phi) - \varepsilon_{r\phi z}(0,0)$$

Mode couplings:

Long-period regime: a fundamental core mode (HE_{11}) $\leftrightarrow$ cladding modes

Cladding modes to be coupled:

$$TM_{0m}^{cl}, TE_{0m}^{cl}, HE_{1m}^{cl}, HE_{2m}^{cl}, HE_{3m}^{cl} \quad \leftarrow \quad \Delta\varepsilon_{r\phi z}(\theta,\phi)$$

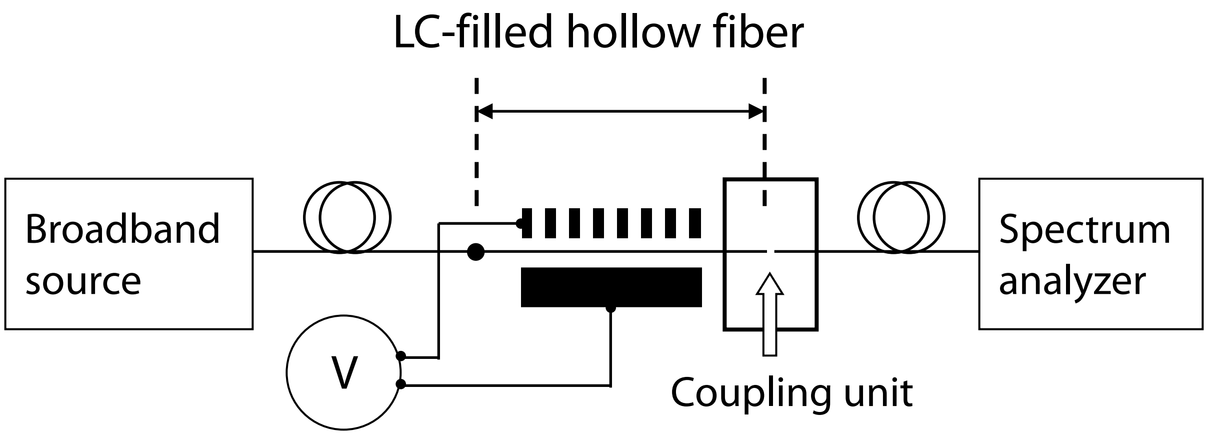
Experimental Arrangement

Experimental setup:

Broadband source: EDFA ASE

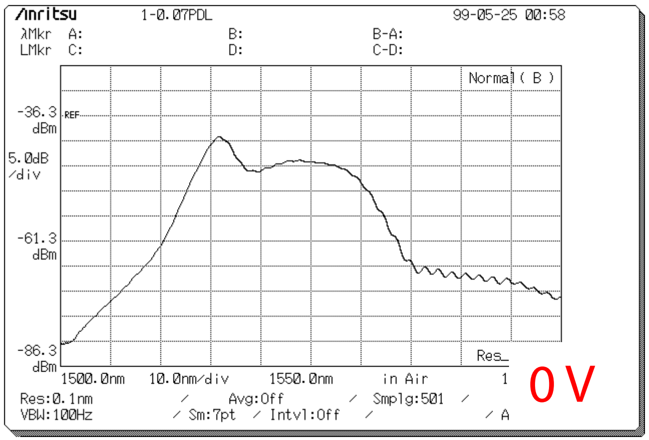
Comb electrode: Period of 483 μm, length of 15.5 mm

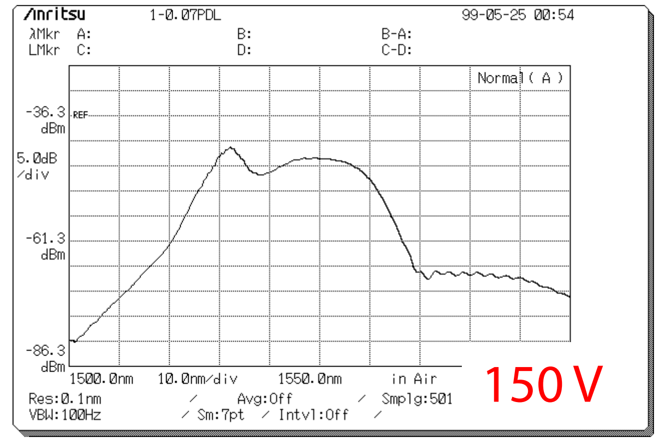
Applied voltage: 0 ~ 250 V

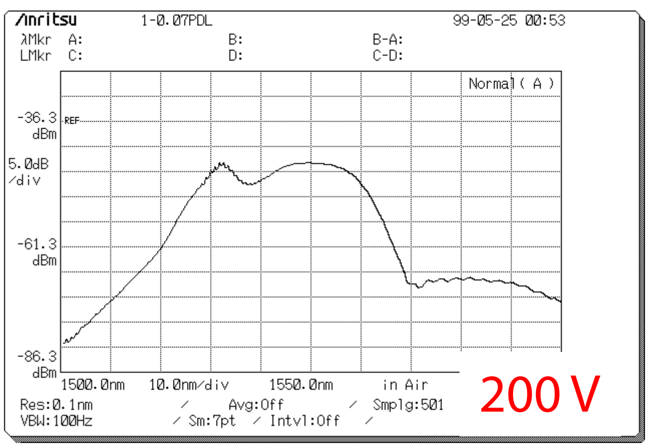


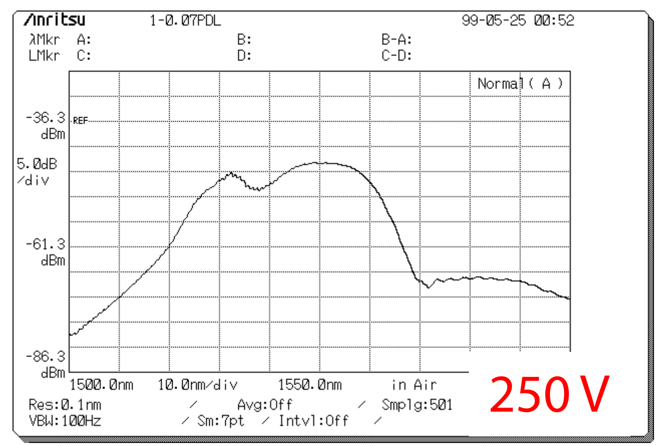
Long-Period LC Fiber Grating (1)

Spectral responses with respect to applied voltages:





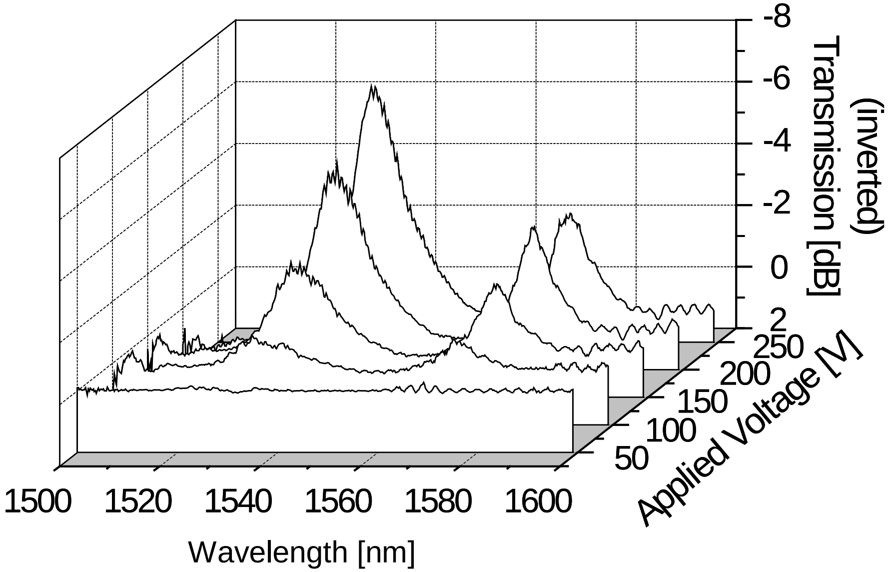




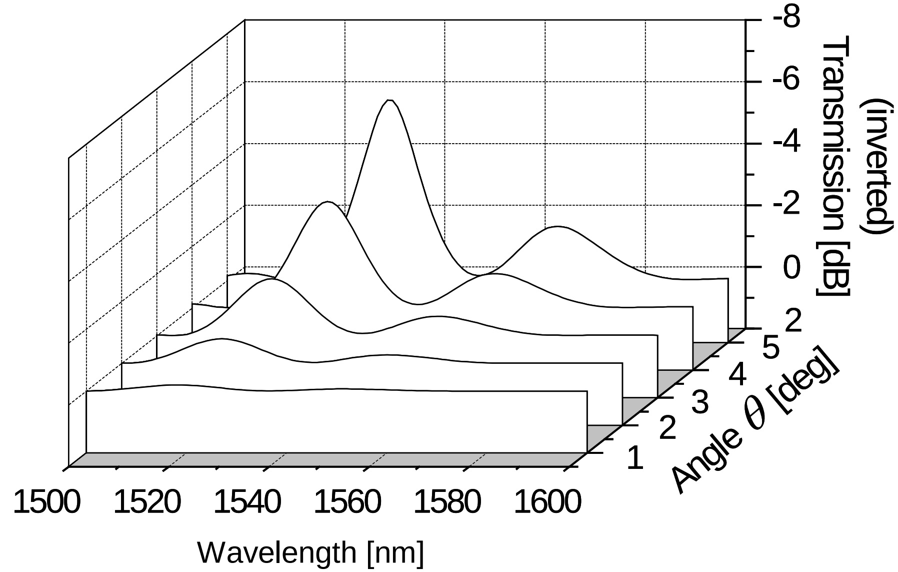
Long-Period LC Fiber Grating (2)

Normalized spectral responses:

Experiments:



Simulations:



Simulations:

Based on the coupled-mode theory in anisotropic media

Resonant couplings to the 3rd and 4th TM cladding modes

Nonlinear Response of Fiber Gratings (1)

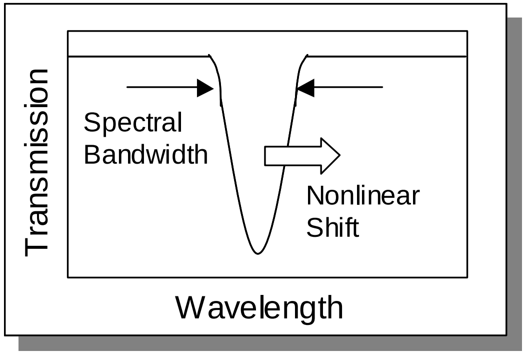
Coupled-mode theory with nonlinear perturbation:

$$\nabla \cdot (E' \times H_p^* + E_p^* \times H') = -i\omega E_p^* \cdot (\Delta\varepsilon_L + \Delta\varepsilon_{NL}) E', \quad (p = 1,2,\ldots)$$

$$\Delta\varepsilon_{NL(q)} = \varepsilon_o \frac{3}{4} \chi^{(3)}(r,\phi,z) \cdot \sum_s \alpha_{(q,s)} \left| E_s(t,z) \right|^2 \left| \hat{e}_s \right|^2, \; \alpha_{(q,s)} = \begin{cases} 1 & (q = s), \\ 2 & (q \neq s). \end{cases}$$

Nonlinear spectral shift:

$$\rightarrow \frac{\Delta\lambda_s}{\lambda} \approx \frac{n_{2,eff} I_{eff}}{\Delta n_g}$$

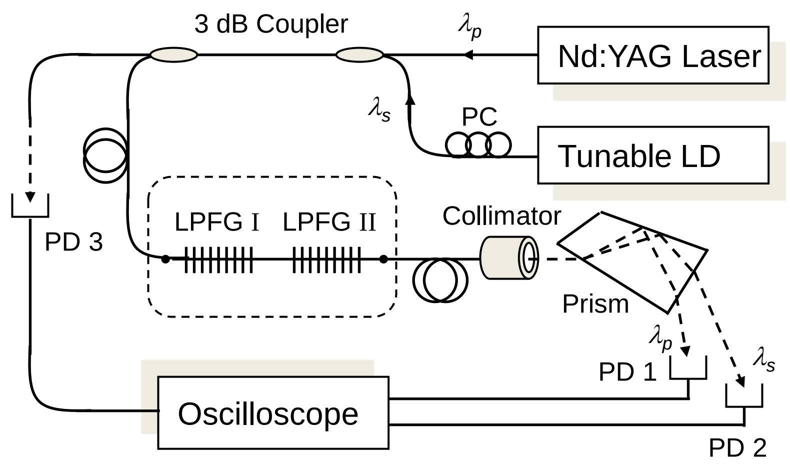


Nonlinear Response of Fiber Gratings (2)

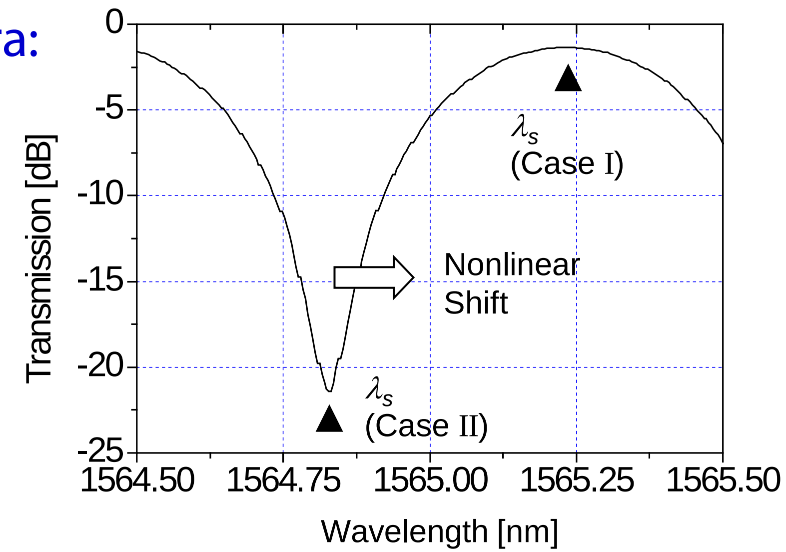
Experimental setup:

Signal wave: Tunable LD @1565.2 nm (Case I), @1564.8 nm (Case II)

Pump wave: Q-switched Nd:YAG laser (1 kHz)

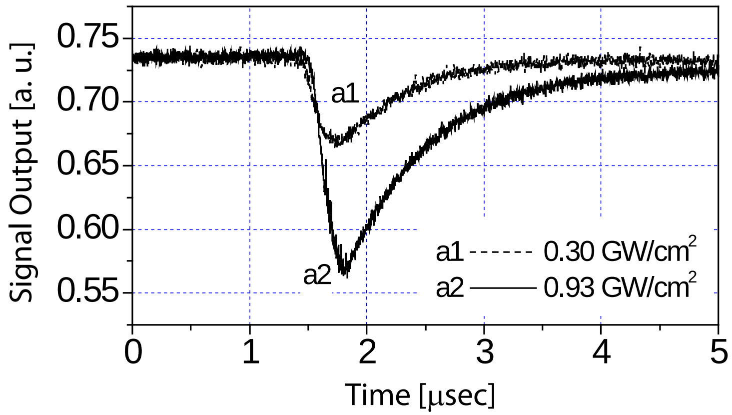


Initial transmission spectra:

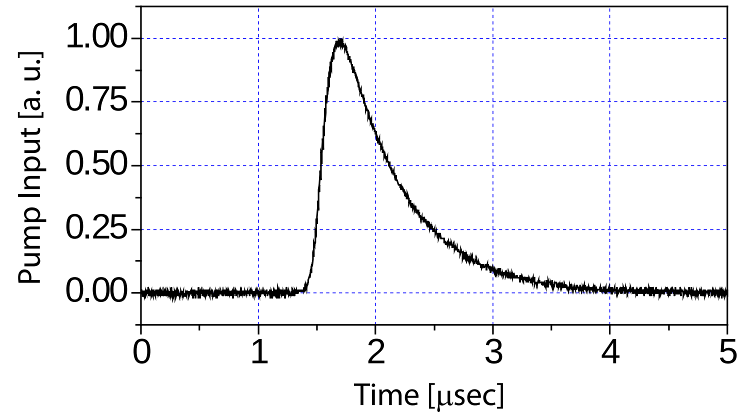


Nonlinear Response of Fiber Gratings (3)

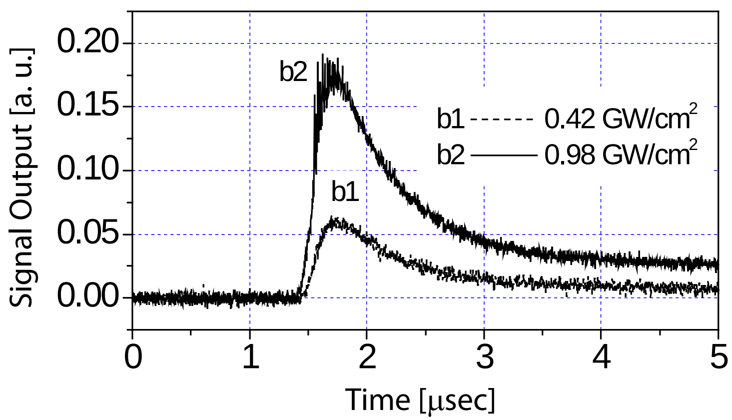
Signal (Case I):

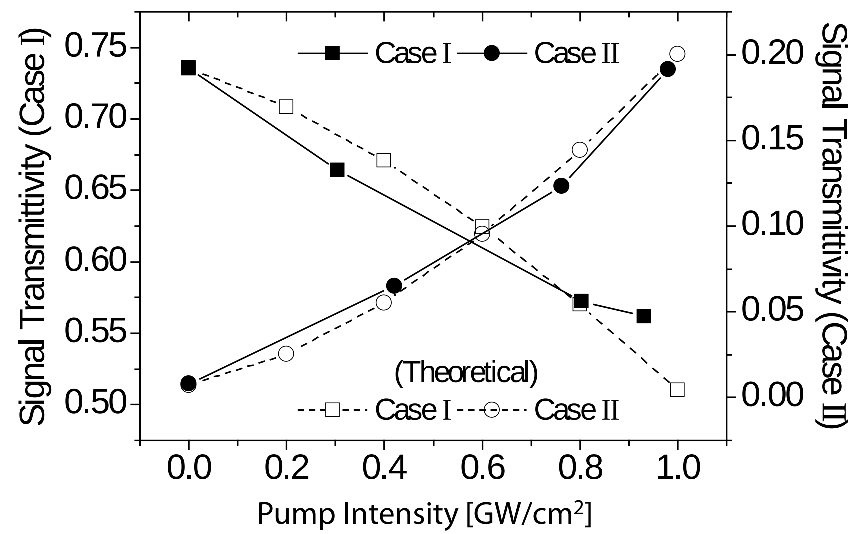


Pump:



Signal (Case II):





$\rightarrow \Delta\lambda_s \sim 0.12$ nm/(GW/cm^2)