Nonlinear Optical Engineering

Electro-Optic Effect

Yoonchan Jeong

School of Electrical Engineering, Seoul National University

Tel: +82 (0)2 880 1623, Fax: +82 (0)2 873 9953

Email: yoonchan@snu.ac.kr

Linear Electro-Optic Effect

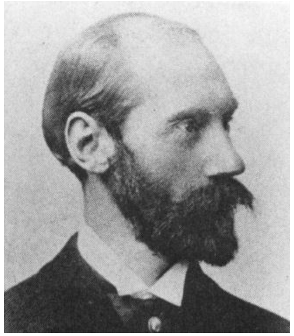
Also called ***Pockels*** effect:

$\rightarrow$ Refractive index change linearly proportional to the external electric field, i.e., $\Delta n \propto E_{ext}$

Recall:

$$\mathbf{P} = \varepsilon_o \chi \mathbf{E} = \varepsilon_o \left(\chi^{(1)} \mathbf{E} + \chi^{(2)} \mathbf{E}\mathbf{E} + \cancel{\chi^{(3)} \mathbf{E}\mathbf{E}\mathbf{E}} + \cdots \right)$$

$$\rightarrow \Delta n = C_L E_{ext}, \quad C_L \sim 10^{-12} \text{ m/V}$$



Friedrich Carl Alwin Pockels
(1865 - 1913)

Quadratic Electro-Optic Effect

Also called ***Kerr*** effect:

$\rightarrow$ Refractive index change quadratically proportional to the external electric field, i.e., $\Delta n \propto E^2_{ext}$

John Kerr
(1824-1907)

Recall:

$$\mathbf{P} = \varepsilon_o \chi \mathbf{E} = \varepsilon_o \left(\chi^{(1)}\mathbf{E} + \cancel{\chi^{(2)}\mathbf{EE}} + \chi^{(3)}\mathbf{EEE} + \cdots \right)$$

$$\rightarrow \ \Delta n = C_Q E_{ext}^2, \quad C_Q \sim 10^{-18} \ \mathrm{m^2/V^2}$$

Kerr constant: $\Delta n = K\lambda E^2$

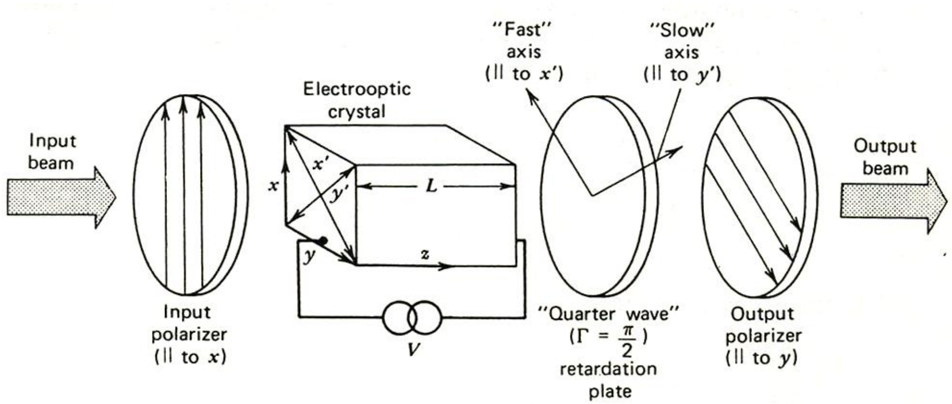
e.g. K = 5.1×10^{-14} m/V^2 for water

Intensity dependent refractive index: $\Delta n = n_2 I \ \leftarrow \ I = \dfrac{1}{2}\varepsilon_0 c n |E|^2$

e.g. n_2 ~ 3×10^{-20} m^2/W for silica glass

Electro-Optic Devices (1)

Electro-optic amplitude modulators:



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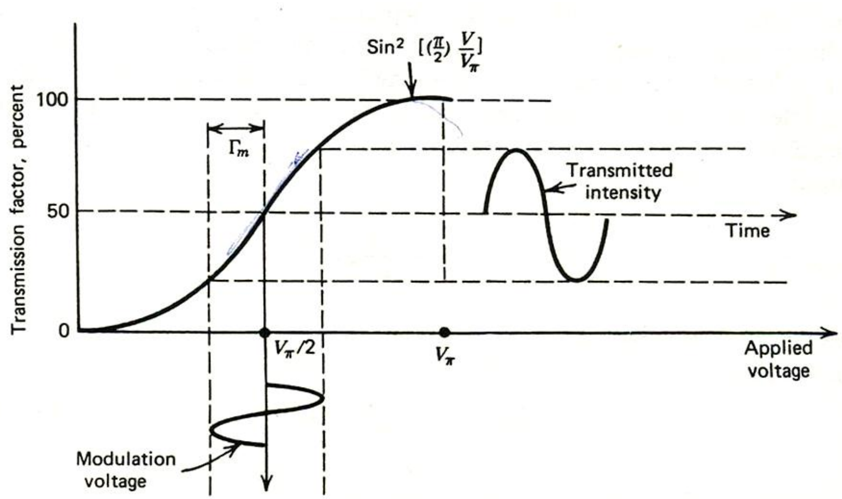


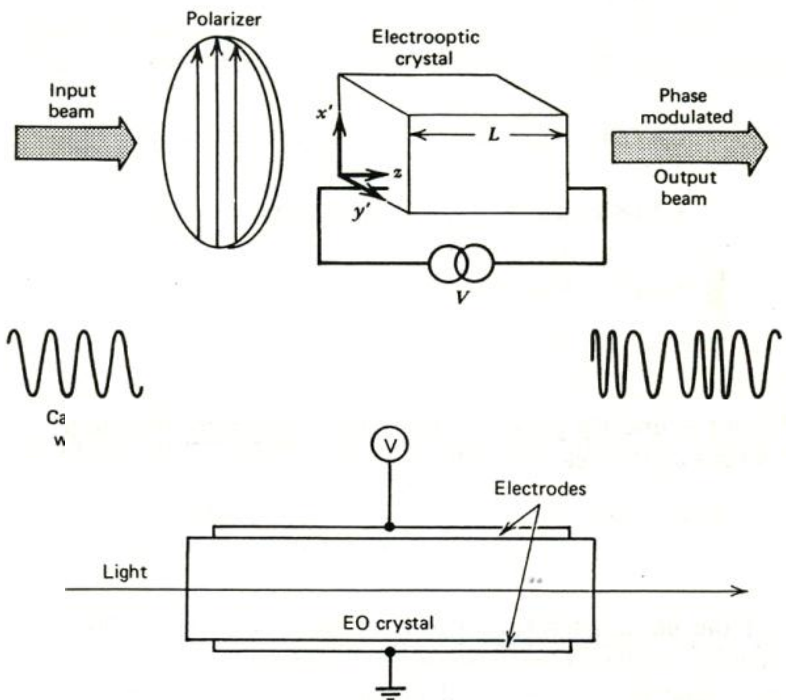
$$\Gamma = \frac{\pi}{2} + \Gamma_m \sin \omega_m t$$

$$\rightarrow\ T = \sin^2 \frac{\Gamma}{2}$$

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

Electro-Optic Devices (2)

Electro-optic phase modulators:



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

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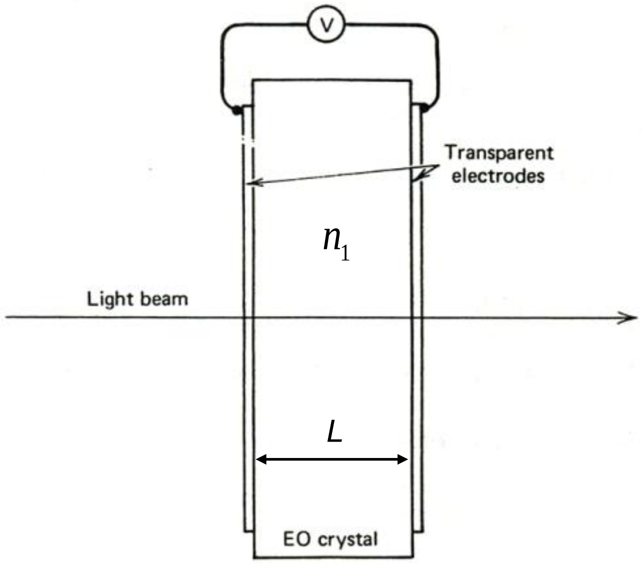
$$\rightarrow\ E_{out} = A\cos\left[\omega t - \frac{\omega}{c}\left(n_o + C_L E_m \sin\omega_{mt} t\right)L\right]$$

Electro-Optic Devices (3)

Electro-optic Fabry-Perot filters:



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

Charles Fabry (1867-1945)

Alfred Perot (1863-1925)

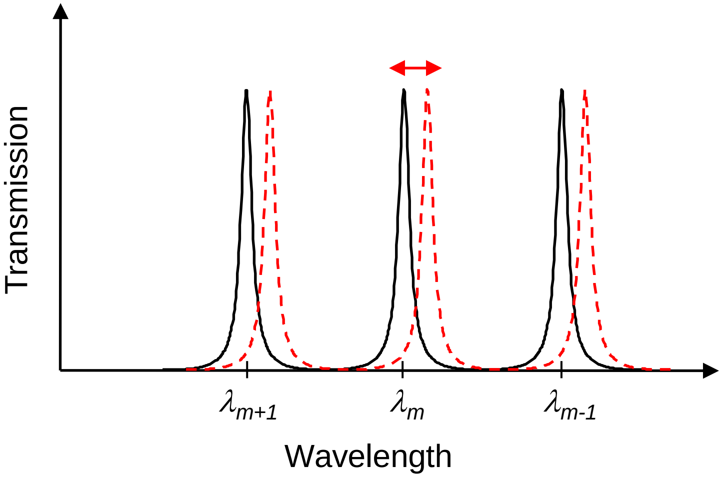
For the maximum transmission:

$$2kL = 2\frac{2\pi L}{\lambda}n_1 = 2m\pi,\ \ m = 1, 2, 3, \cdots$$

$$\lambda_m = \frac{2L}{m}n_1$$

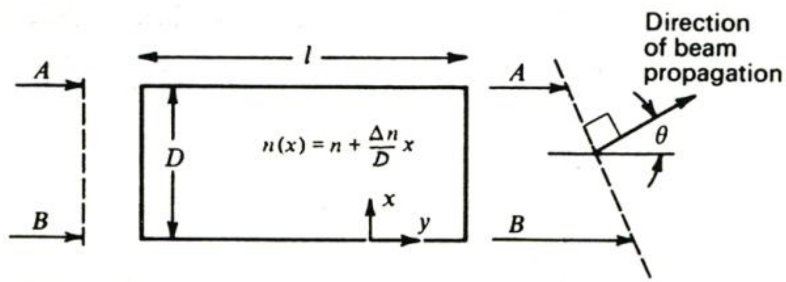
If voltage applied:

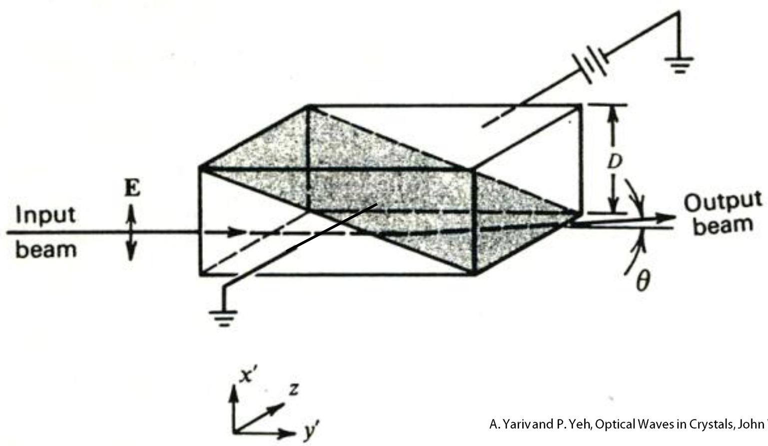
$$\rightarrow\ \lambda_m = \frac{2L}{m}(n_1 + C_L E_{ext})$$



Electro-Optic Devices (4)

Electro-optic beam deflectors:





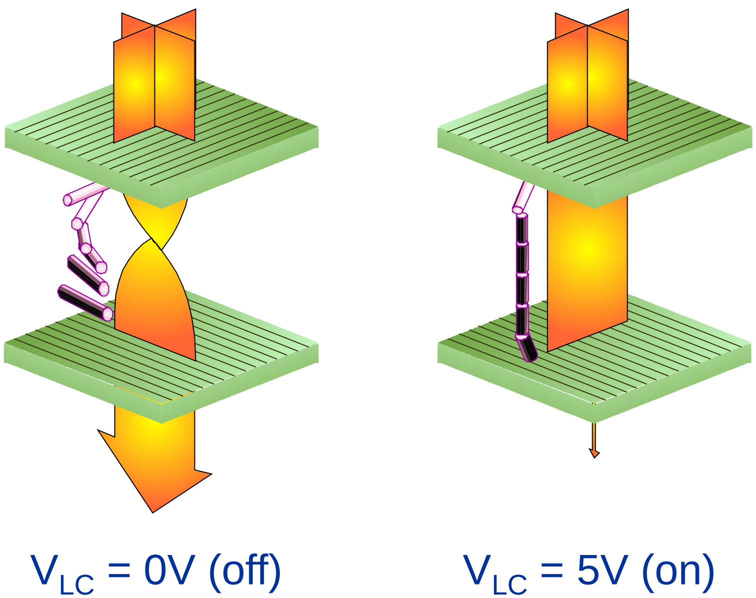
A. Yariv and P. Yeh, Optical Waves in Crystals, John Wiley & Sons, 1984.

Electro-Optic Property of Liquid Crystal

Liquid crystals:

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

Twisted nematic LC in liquid crystal displays (LCDs):



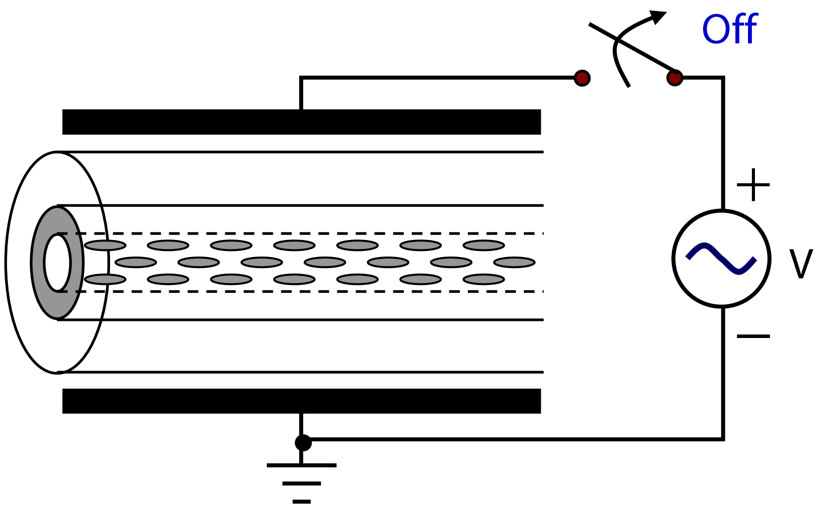
Applicable to fiber-optic devices?

LC-Filled Hollow Optical Fiber (1)

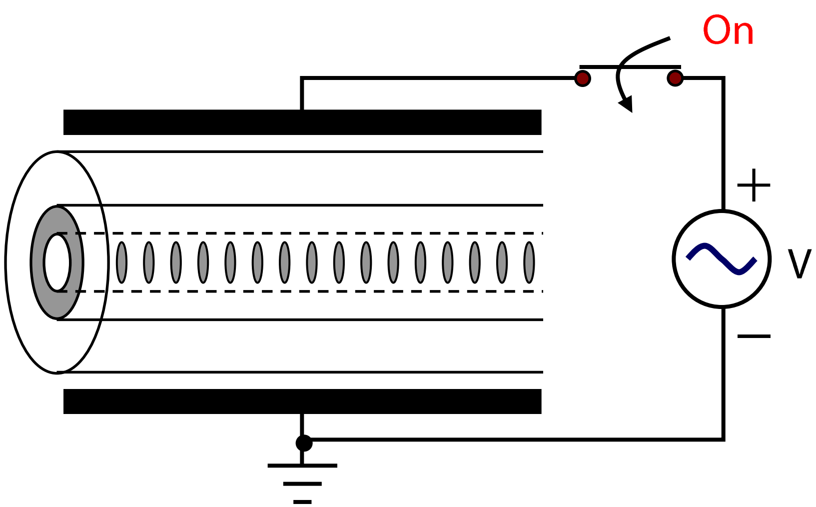
Director alignment of nematic LC:

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

Voltage off:

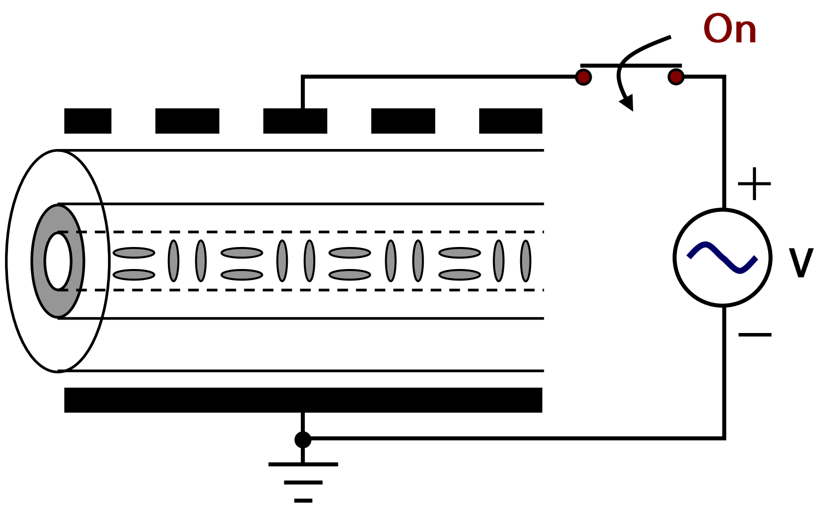


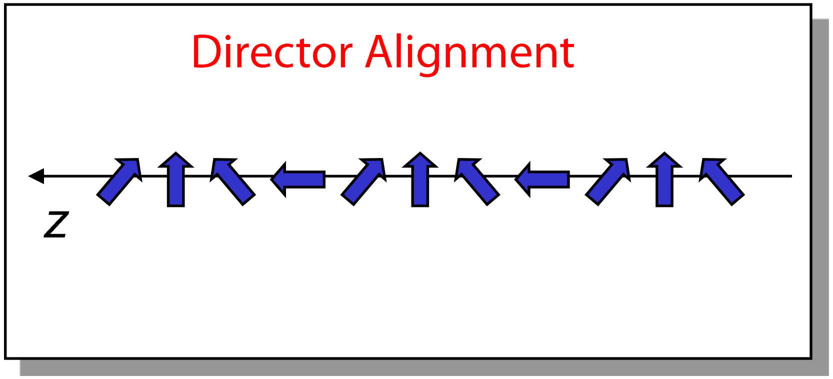
Voltage on:



LC-Filled Hollow Optical Fiber (2)

Comb electrode:





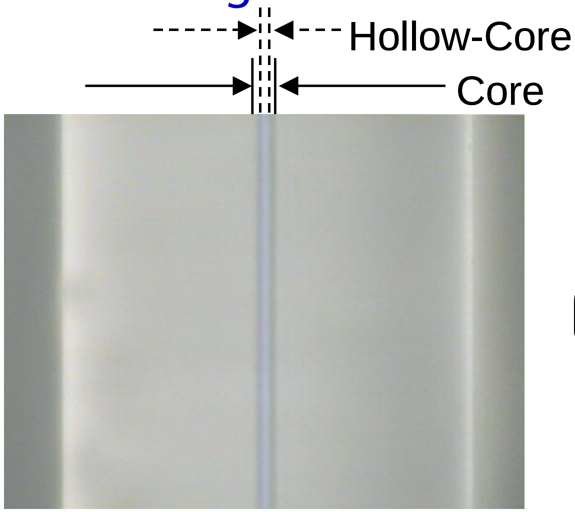
Electrically controllable director alignment:

Periodical modulation of director alignment

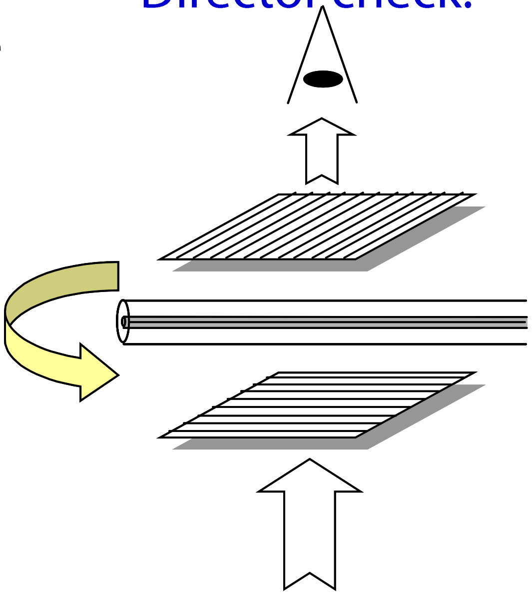
→ Controllable long-period gratings

LC-Filled Hollow Optical Fiber (3)

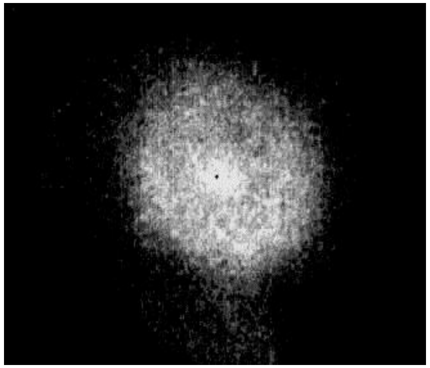
Fiber image:



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

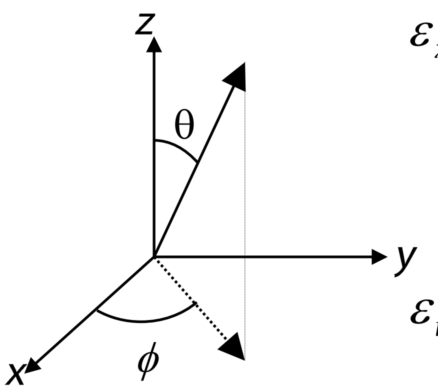
Director alignment check:

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

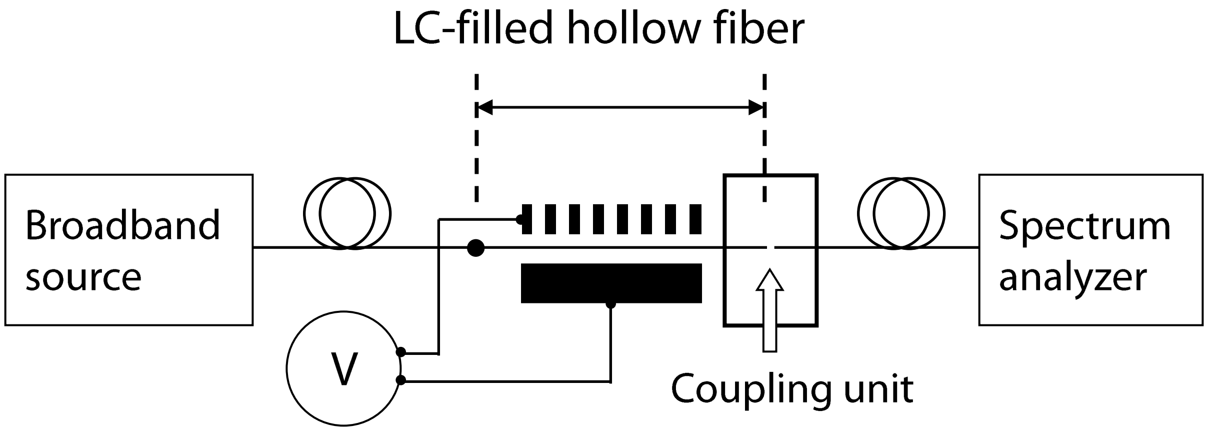
Cladding modes to be coupled:

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

Experimental Arrangement

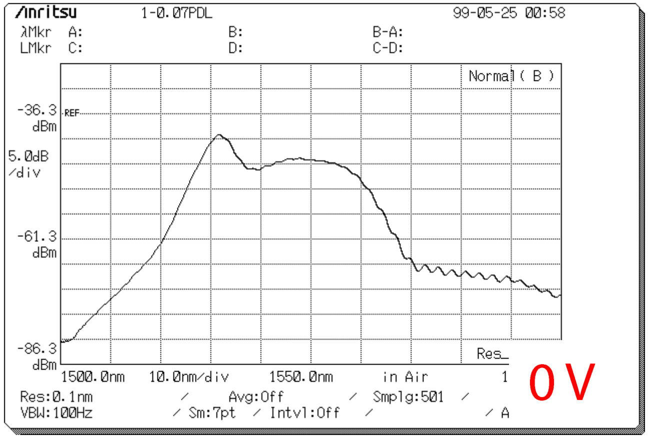
Experimental setup:

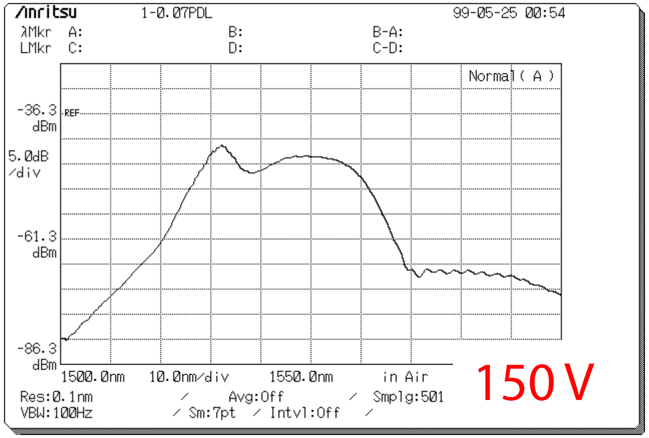
- Broadband source: EDFA ASE
- Comb electrode: Period of 483 μm, length of 15.5 mm
- Applied voltage: 0 ~ 250 V

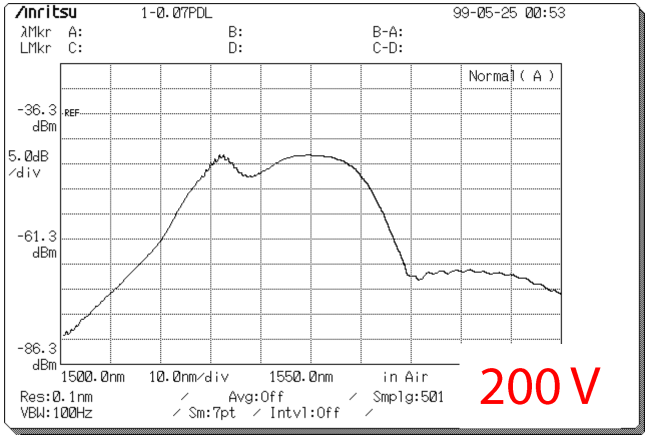


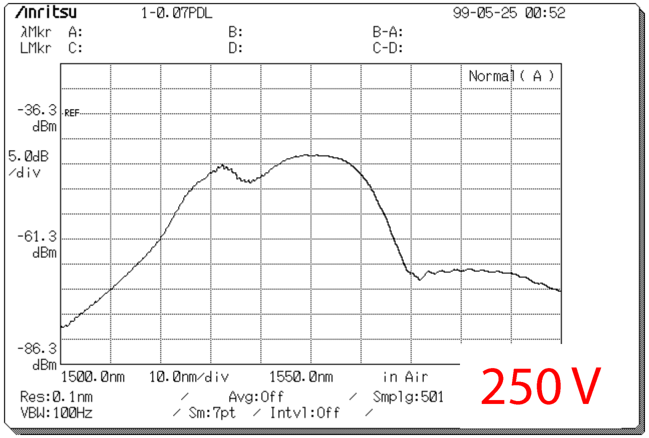
Long-Period LC Fiber Grating (1)

Spectral responses with respect to applied voltages:





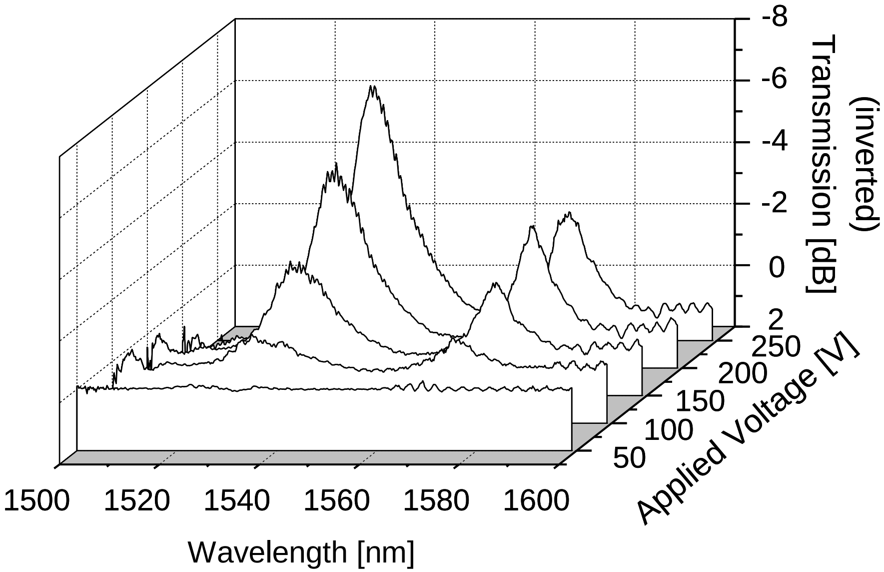




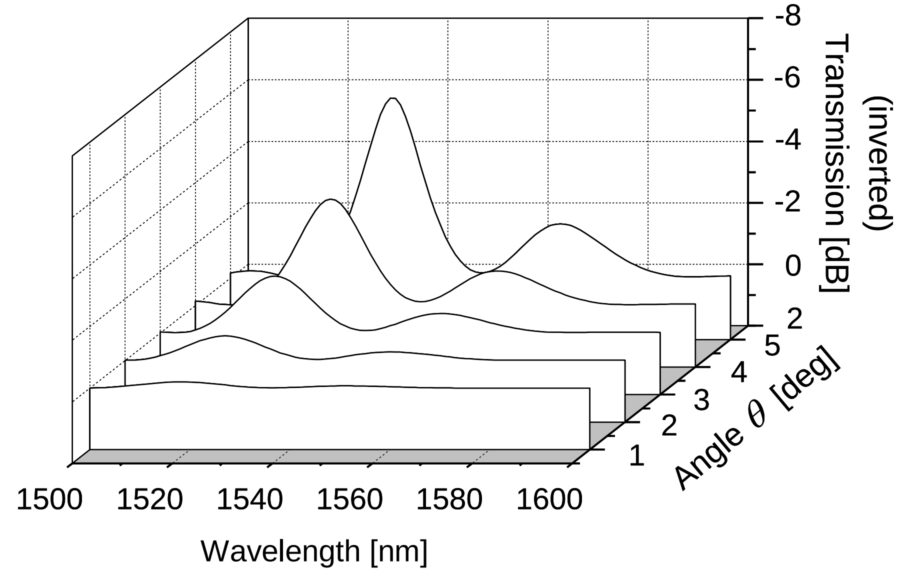
Long-Period LC Fiber Grating (2)

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)

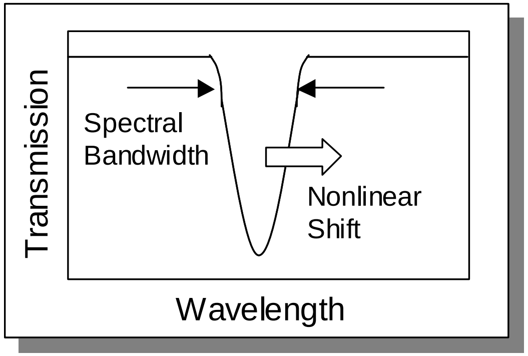
Coupled-mode theory with nonlinear perturbation:

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

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

Nonlinear spectral shift:

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

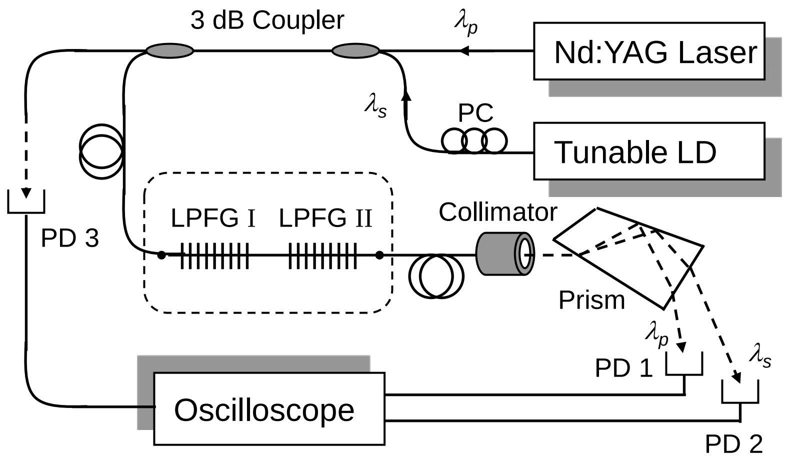


Nonlinear Response of Fiber Gratings (2)

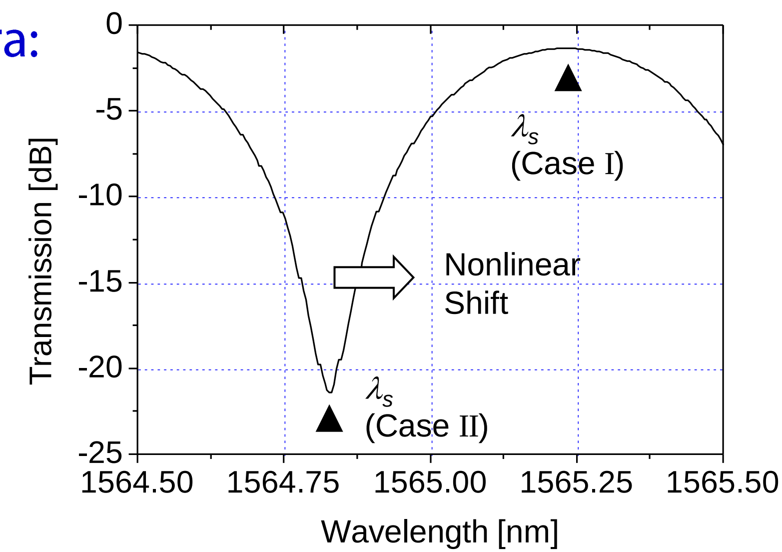
Experimental setup:

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

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

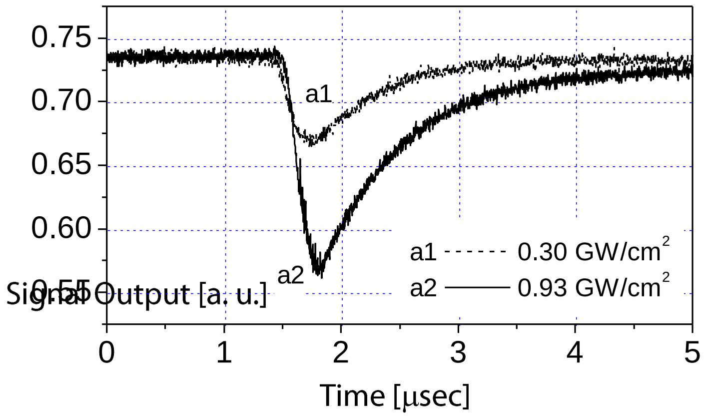


Initial transmission spectra:

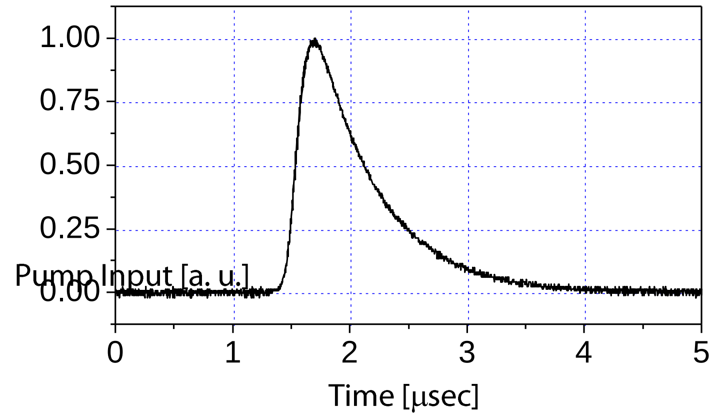


Nonlinear Response of Fiber Gratings (3)

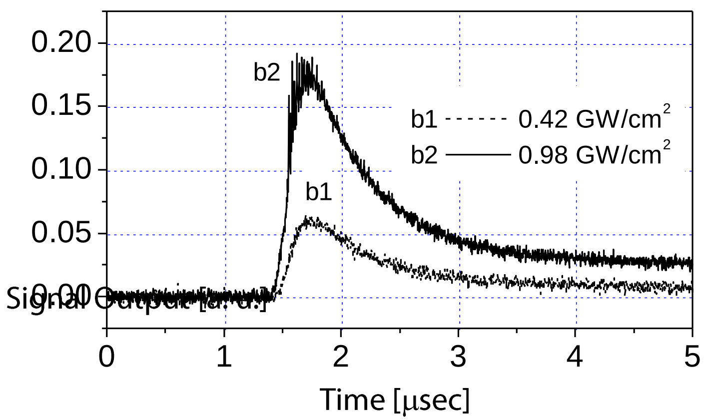
Signal (Case I):

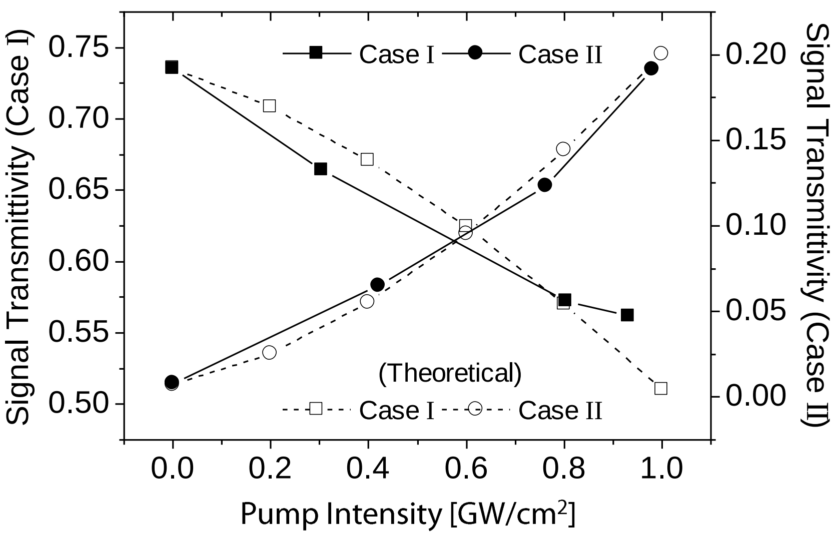


Pump:



Signal (Case II):





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