Electro-optic effect

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Nonlinear polarisation

❑ Constitutive relations

$$\mathbf{D} = \varepsilon\mathbf{E} = \varepsilon_o\mathbf{E} + \mathbf{P},$$

$$\mathbf{P} = \varepsilon_o\chi\mathbf{E}$$

❑ Origin of nonlinear response

Related to anharmonic motion of bound electrons under the influence of an applied field.

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

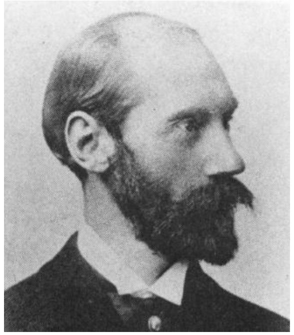
Note: $\chi^{(2)}$ is non-zero only for media that lack an inversion symmetry (centrosymmetry).

Linear electro-optic effect

Also called ***Pockels*** effect: Refractive index change linearly proportional to the external electric field, i.e. $\Delta n \propto E_{ext}$.

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

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



Friedrich Carl Alwin Pockels (1865 - 1913)

Quadratic electro-optic effect

Also called ***Kerr*** effect: Refractive index change quadratically proportional to the external electric field, i.e. $\Delta n \propto E_{ext}^2$.

John Kerr
(1824-1907)

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

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

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

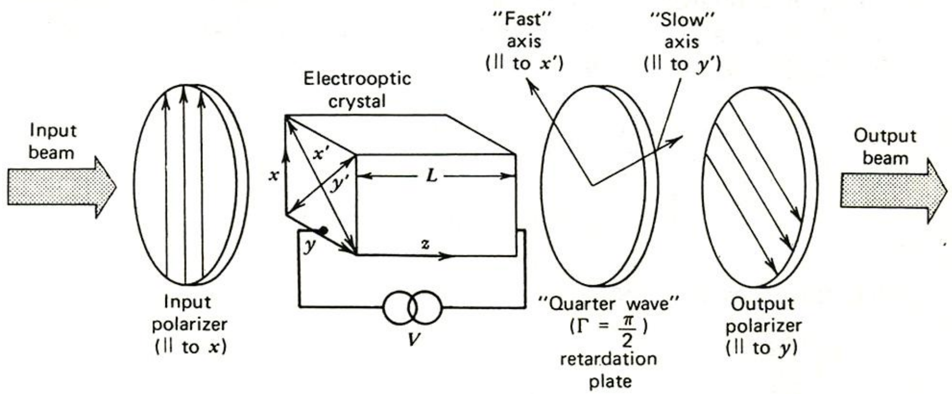
e.g. K = 5.1×10^{-14} m/V^2 for water

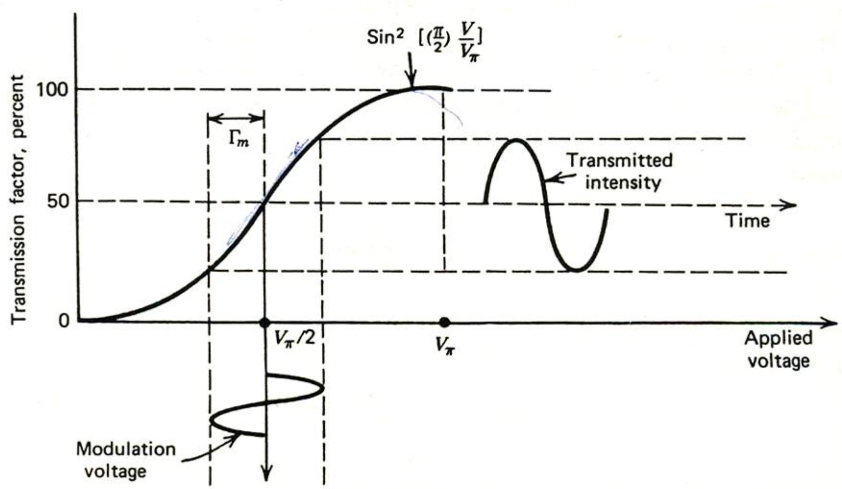
Intensity dependent refractive index: $\quad \Delta n = n_2 I, \text{ where } I = \frac{1}{2}\varepsilon_0 c n |E|^2$

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

Electro-optic amplitude modulator

Thorlabs



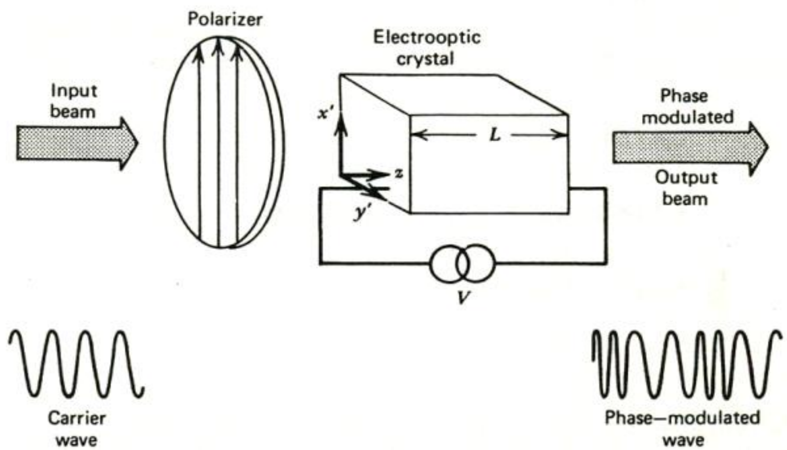


Source: Thorlabs

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

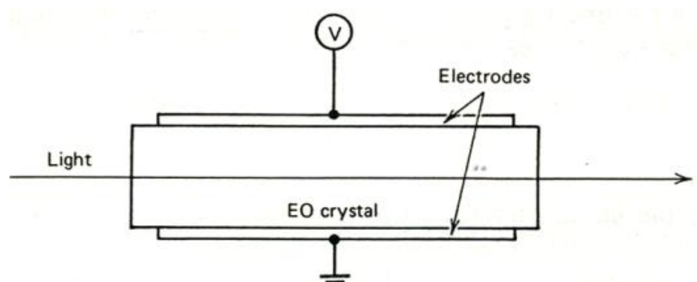
Source: *Optical Waves in Crystals*, A. Yariv and P. Yeh

Electro-optic phase modulator



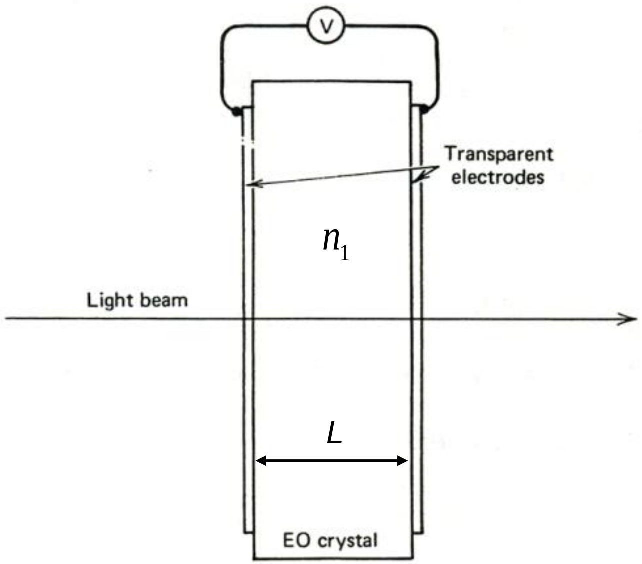
Source: Thorlabs

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



Source: *Optical Waves in Crystals*, A. Yariv and P. Yeh

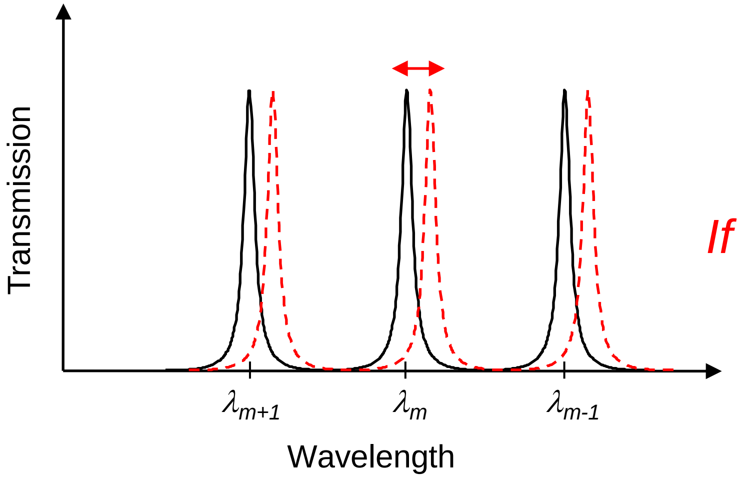
Electro-optic modulator (Fabry-Perot filter)



Source: *Optical Waves in Crystals*, A. Yariv and P. Yeh

Charles Fabry (1867-1945)

Alfred Perot (1863-1925)



For the maximum transmission:

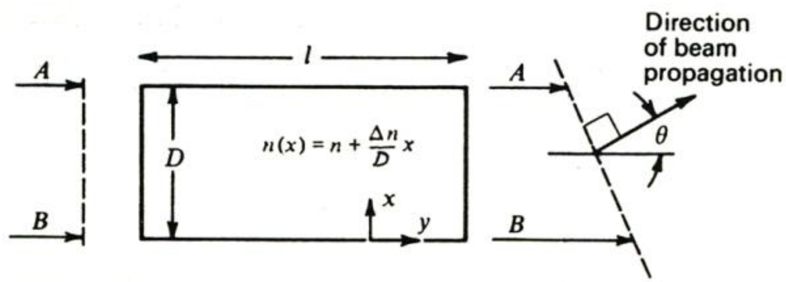
$$2kL = 2\frac{2\pi L}{\lambda}n_1 = 2m\pi, \quad m = 1, 2, 3, \cdots$$

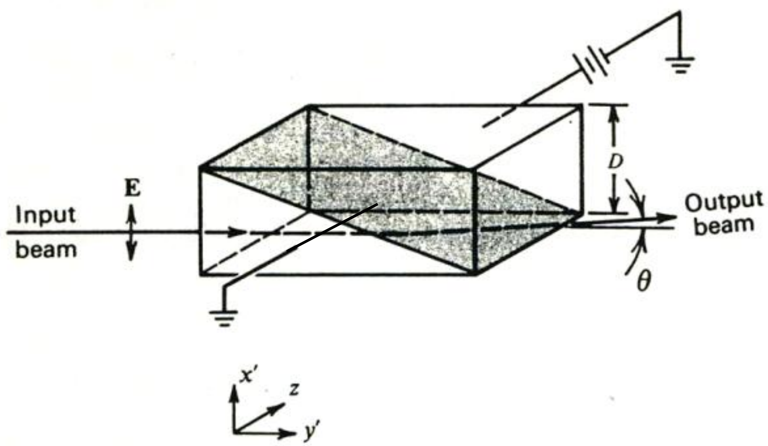
$$\lambda_m = \frac{2L}{m}n_1$$

If voltage applied:

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

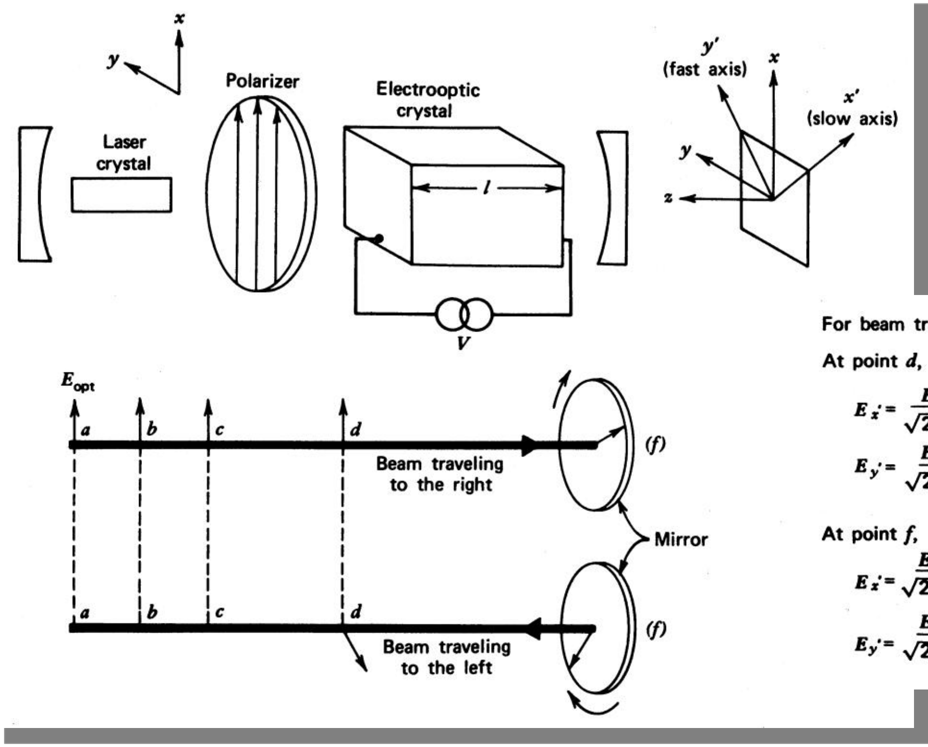
Electro-optic beam deflector





Source: *Optical Waves in Crystals*, A. Yariv and P. Yeh

Electro-optic Q-switch



For beam traveling to right:

At point d,

$$E_{x'} = \frac{E}{\sqrt{2}} \cos \omega t, \qquad E_{y'} = \frac{E}{\sqrt{2}} \cos \omega t$$

The optical field is linearly polarized with its electric field vector parallel to x

At point f,

$$E_{x'} = \frac{E}{\sqrt{2}} \cos \left(\omega t - kl - \frac{\pi}{2}\right), \qquad E_{y'} = \frac{E}{\sqrt{2}} \cos (\omega t - kl)$$

Circularly polarized

For beam traveling to left:

At point f,

$$E_{x'} = -\frac{E}{\sqrt{2}} \cos \left(\omega t - kl - \frac{\pi}{2}\right), \qquad E_{y'} = -\frac{E}{\sqrt{2}} \cos (\omega t - kl)$$

Circularly polarized

At point d,

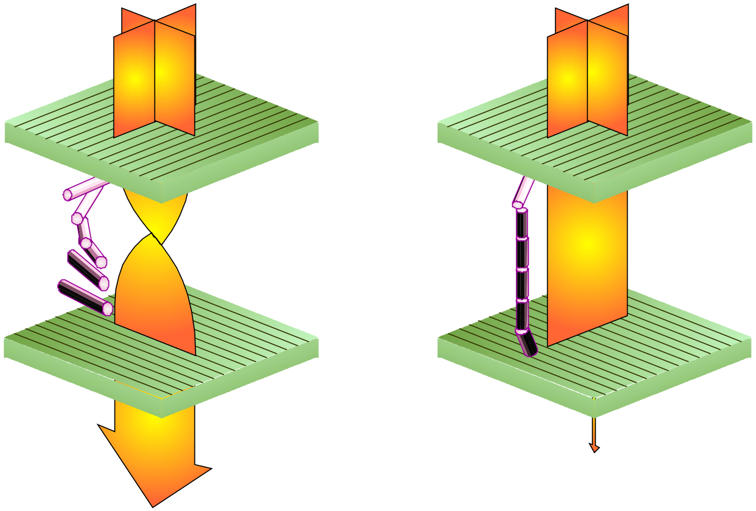
$$E_{x'} = -\frac{E}{\sqrt{2}} \cos (\omega t - 2kl - \pi), \qquad E_{y'} = -\frac{E}{\sqrt{2}} \cos (\omega t - 2kl)$$

Linearly polarized along y

Source: *Optical Waves in Crystals*, A. Yariv and P. Yeh

Electro-optic property of liquid crystal

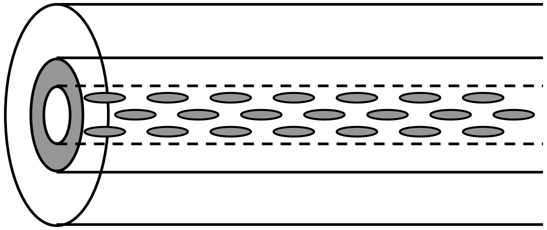
- ❑ **Liquid crystals**
  - Liquid crystal phases: smectic, <u>nematic</u>, and cholesteric
  - Nematic LC: uniaxial dipole moment
    ⇒ dynamic director alignment along the applied electric field
  - Switching time: ~msec
- ❑ **Twisted nematic LC in liquid crystal displays (LCD's)**



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

Applicable to fiber-optic devices?

LC-filled hollow fiber

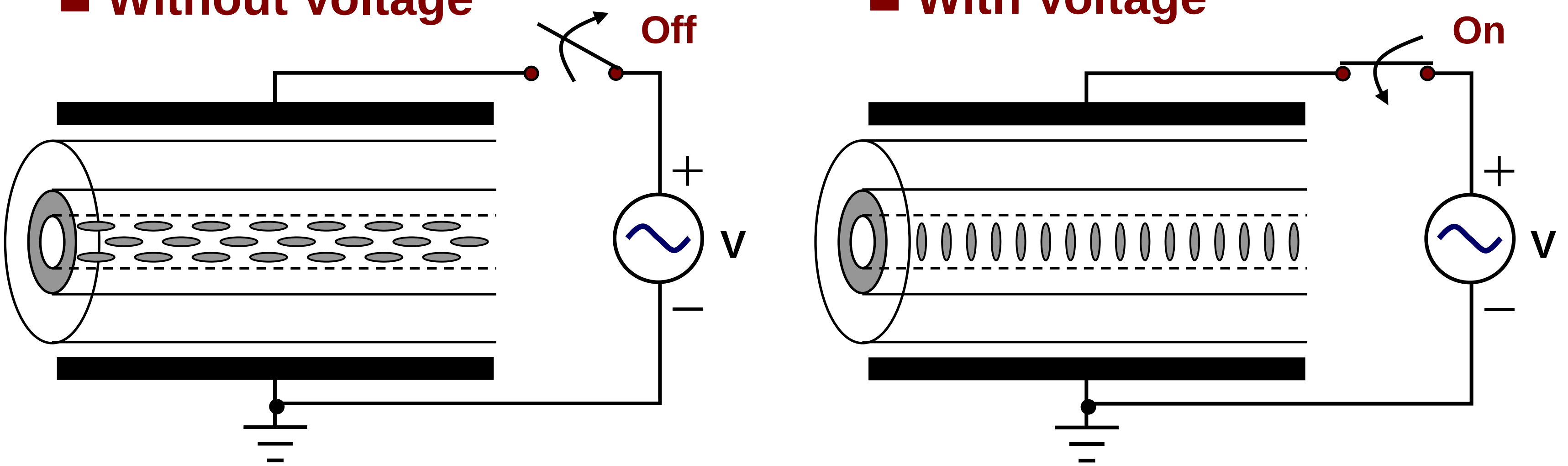


■ **Initial Alignment of nematic LC**

❑ **Director alignment of nematic LC**

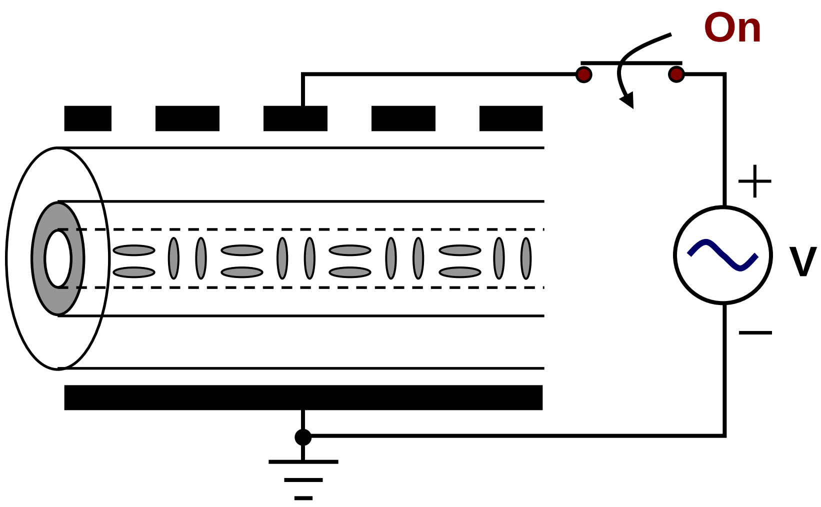
- Highly dependent on the liquid crystals-capillary interface interaction
- Silica: longitudinal direction, borosilicate capillaries: radial direction

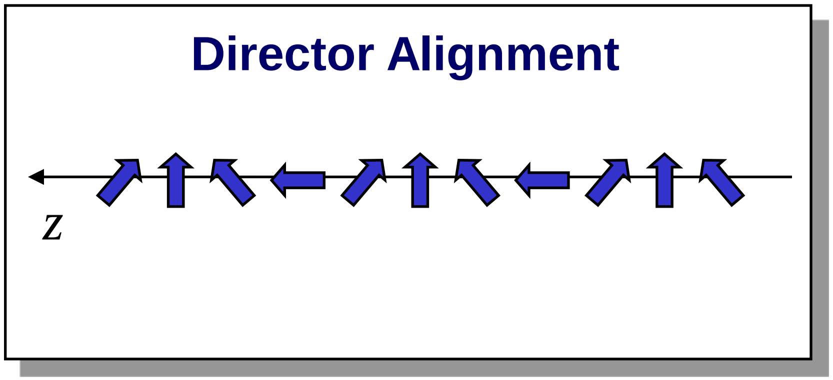
■ **Without Voltage** ■ **With Voltage**



LC fiber grating with a comb electrode

- ❑ **Comb electrode**
  - Periodically patterned electrode with openings

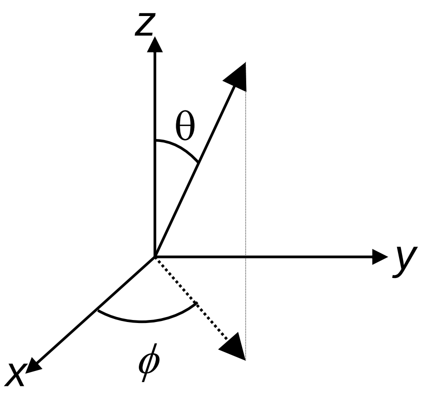




- ❑ **Electrically controllable director alignment**
  - Periodical modulation of director alignment
  - Controllable long-period gratings

Anisotropic mode couplings in the LC core

❑ **Permittivity tensor according to director alignment**



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

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

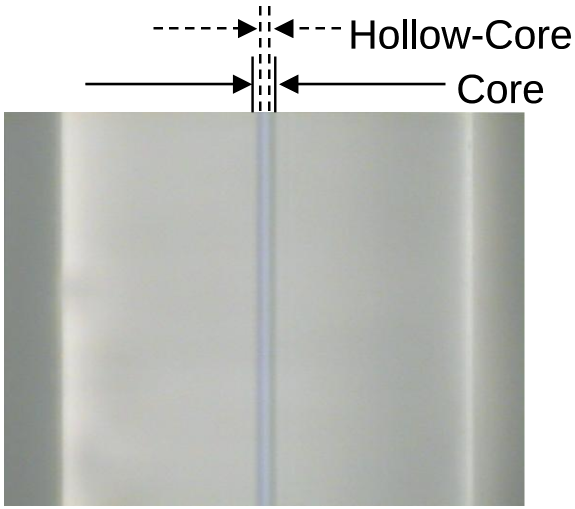
Permittivity perturbation $\Rightarrow$ $\Delta\varepsilon_{r\phi z}(\theta,\phi)=\varepsilon_{r\phi z}(\theta,\phi)-\varepsilon_{r\phi z}(0,0)$

❑ **Mode couplings**

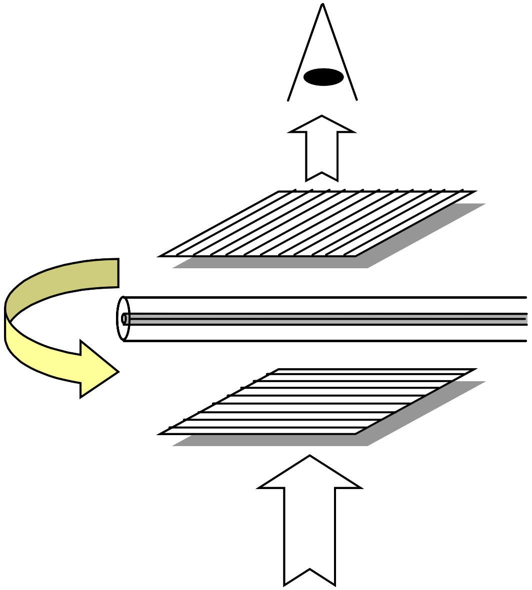
- Long-period regime: a fundamental HE_{11} core mode $\Leftrightarrow$ cladding modes
- Cladding modes to be coupled: $TM_{0m}^{cl}, TE_{0m}^{cl}, HE_{1m}^{cl}, HE_{2m}^{cl}, HE_{3m}^{cl}$

$\Leftarrow$ Non-symmetric azimuthal ϕ-variation in $\Delta\varepsilon_{r\phi z}(\theta,\phi)$

LC-filled hollow fiber

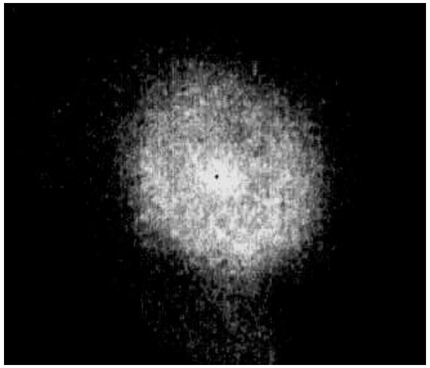


Fiber image



Director check

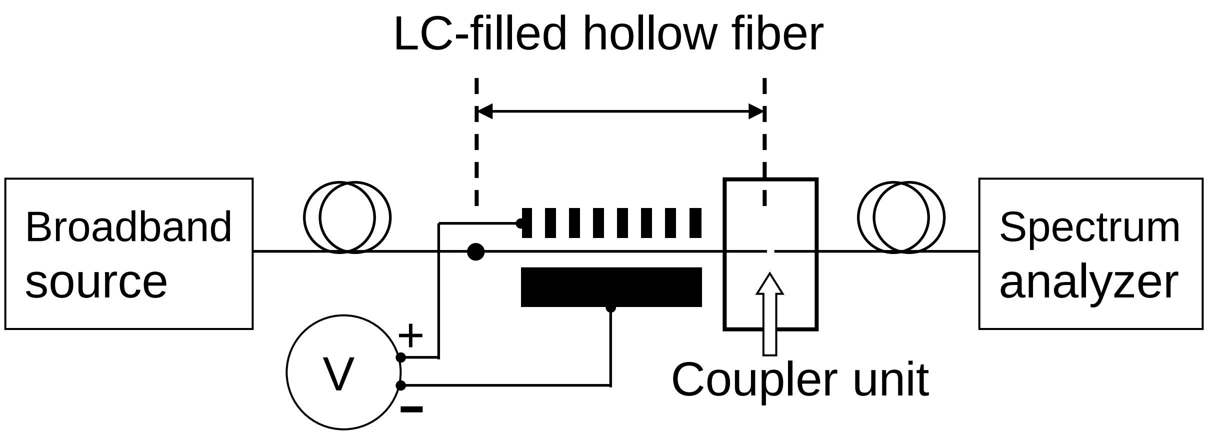
LC-filling: **MLC-6295**



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 fiber axis

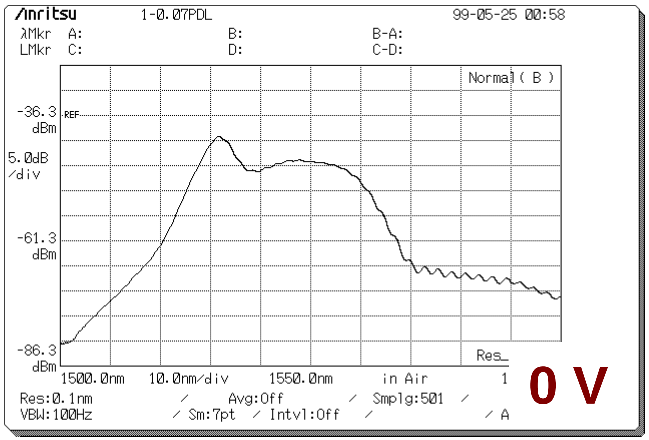
Experimental layout

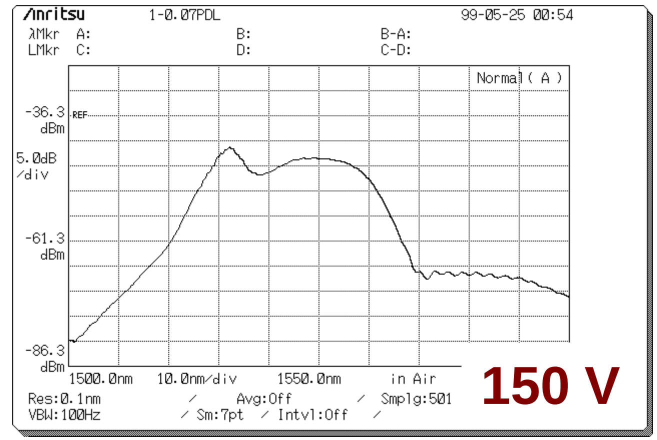


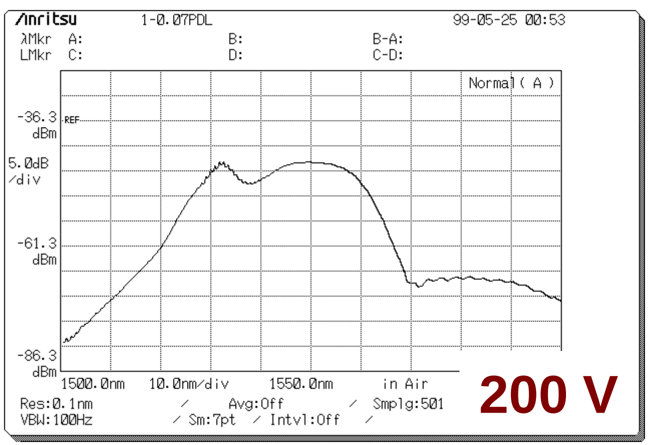
- **Experimental apparatus**
  - Broadband source: EDFA ASE
  - Comb electrode
    Period of openings: 483 μm, effective grating length: 15.5 mm
  - Applied voltage: 0 ~ 250 V

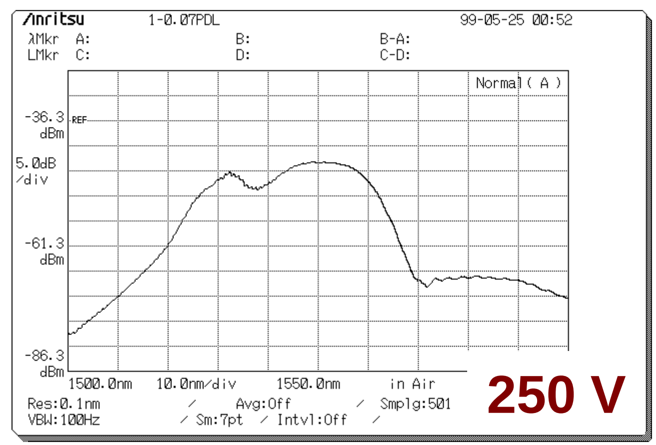
Long-period LC fiber grating

- ❑ **Spectral responses according to applied voltages**





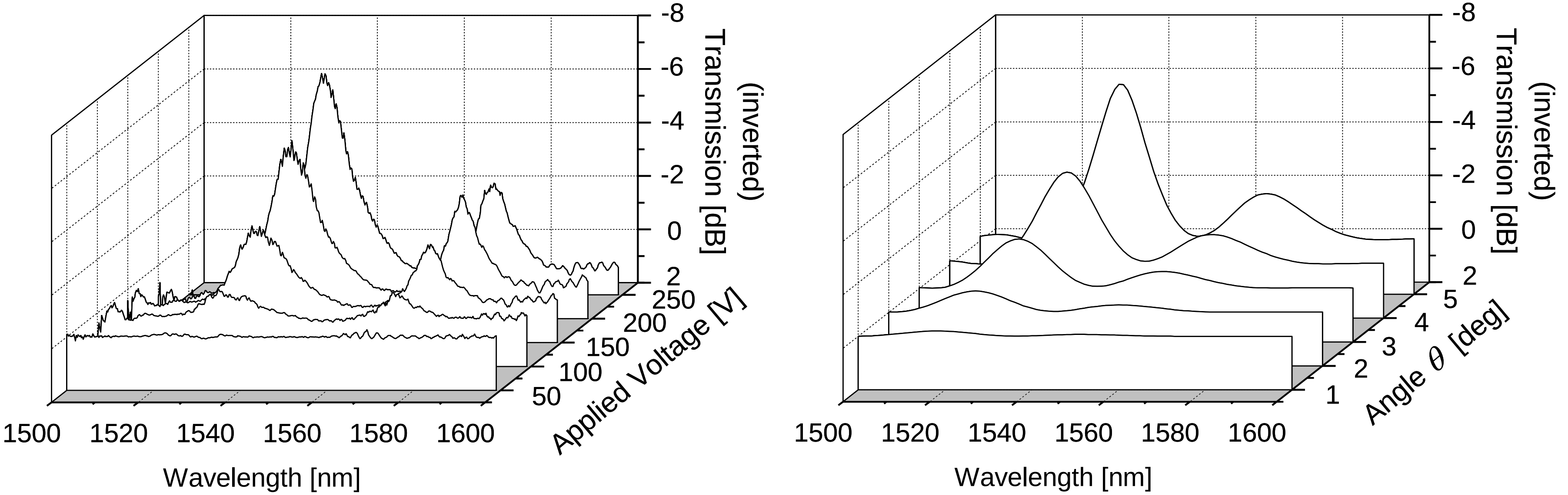




Long-period LC fiber grating

❑ Normalized spectral responses

Experiments | **Simulations**



❑ Simulations

- Based on the discretized coupled-mode theory in anisotropic media
- Resonant couplings to the 3rd and 4th TM cladding modes

Nonlinear response of fiber gratings

■ Nonlinear Coupled-Mode Theory

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

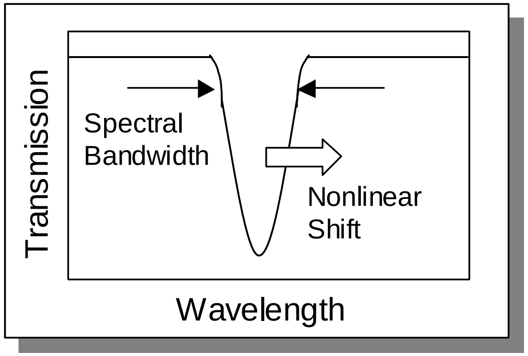
$$\Delta\varepsilon_{NL(q)} = \varepsilon_o \frac{3}{4}\chi^{(3)}(r,\phi,z)\cdot\sum_s \alpha_{(q,s)}\left|E_s(t,z)\right|^2\left|\hat{e}_s\right|^2,\ \alpha_{(q,s)} = \begin{cases} 1 & (q=s), \\ 2 & (q\neq s). \end{cases}$$

■ Efficiency of All-Optical Switching in Fiber Gratings

- Conditions for high efficiency:

Large nonlinear spectral shift &
Rapid spectral modulation band

- Nonlinear spectral shift: $\dfrac{\Delta\lambda_s}{\lambda} \approx \dfrac{n_{2,eff} I_{eff}}{\Delta n_g}$



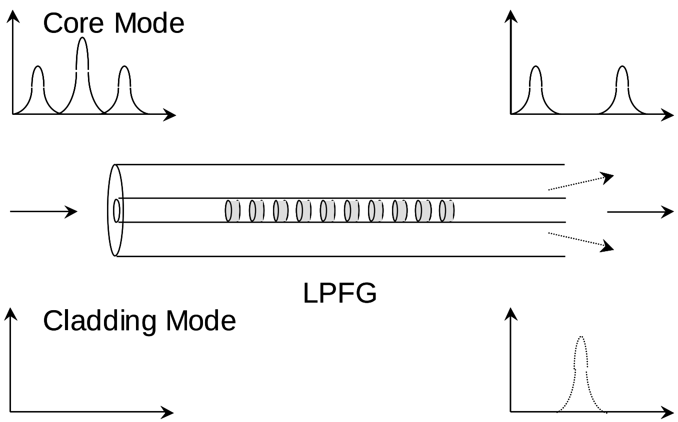
FBG: Steep spectral modulation slope but small spectral shift

LPFG: Large spectral shift but slow spectral modulation slope

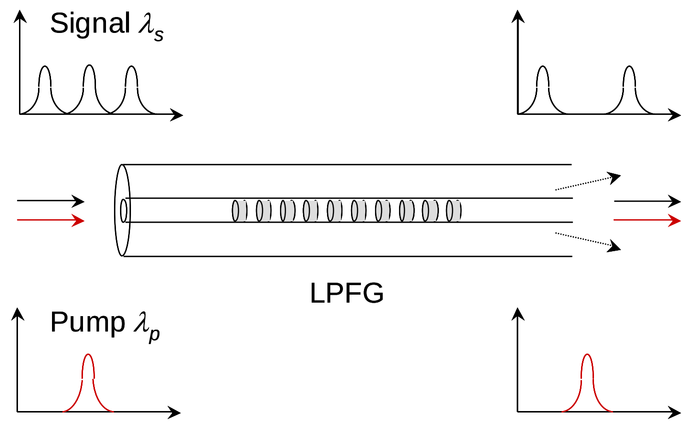
$\Rightarrow$ Cascaded LPFG's

Nonlinear response of LPFGs

■ SPM Regime

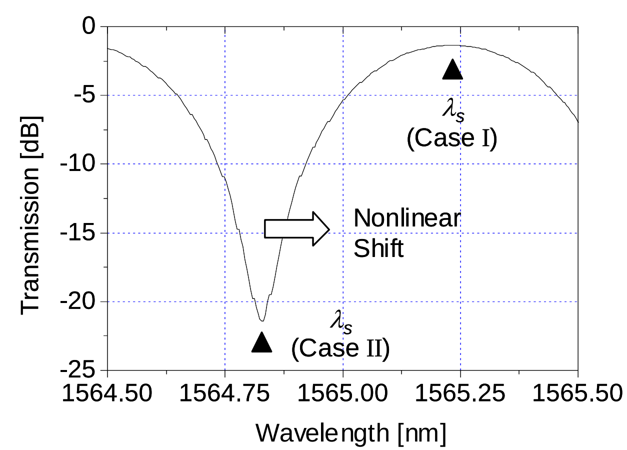


■ XPM Regime



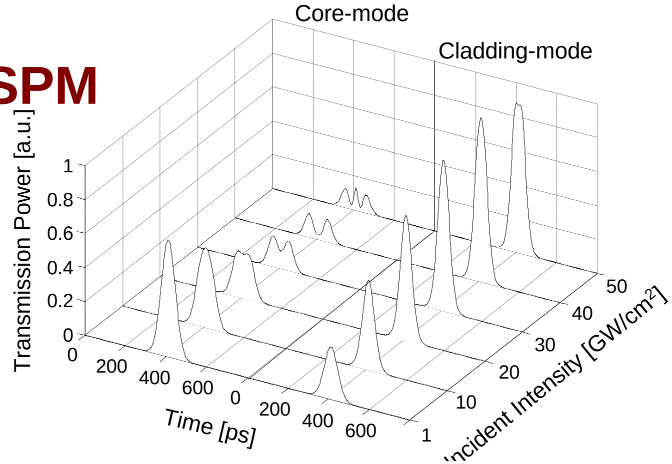
■ All-Optical Gating Mode

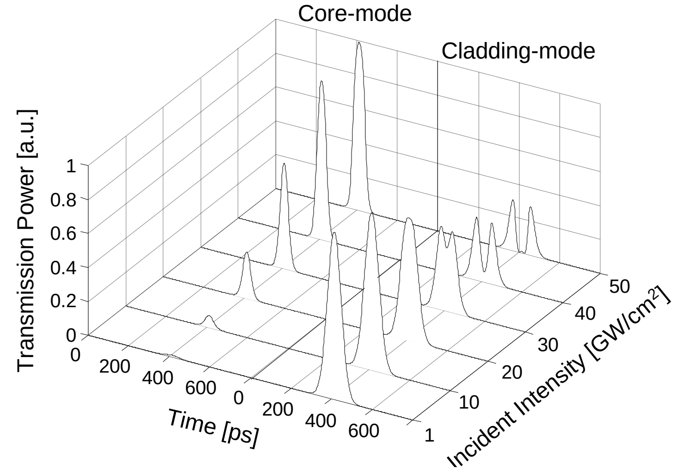
- Normally white mode (Case I)
- Normally black mode (Case II)



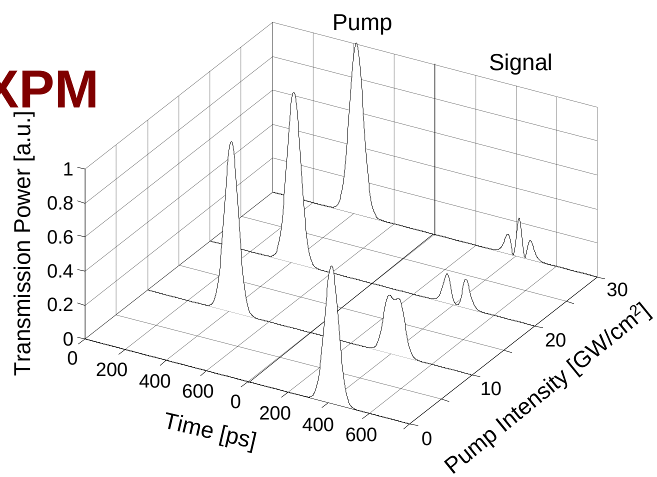
Nonlinear transmission of wave packets

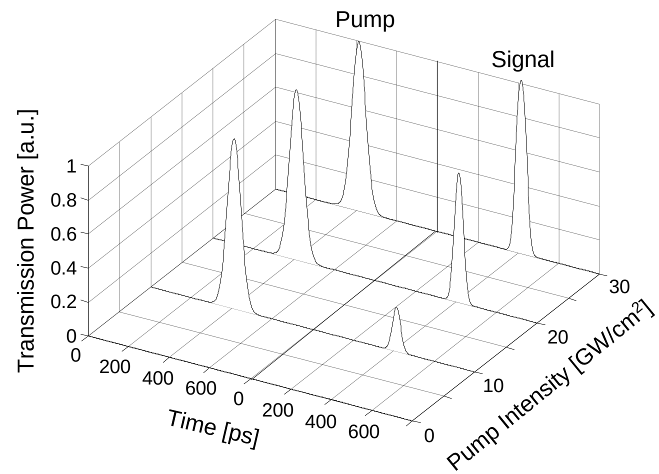
■ **SPM**





■ **XPM**





Y. Jeong and B. Lee, *IEEE J. Quantum Electron.*, 35(9),1284 (1999).

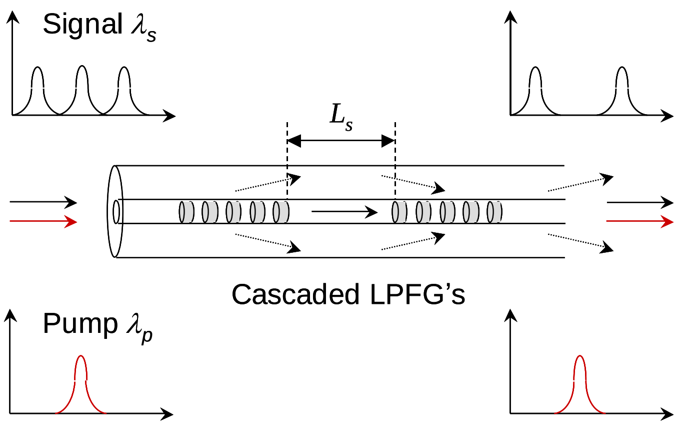
Cascaded LPFGs

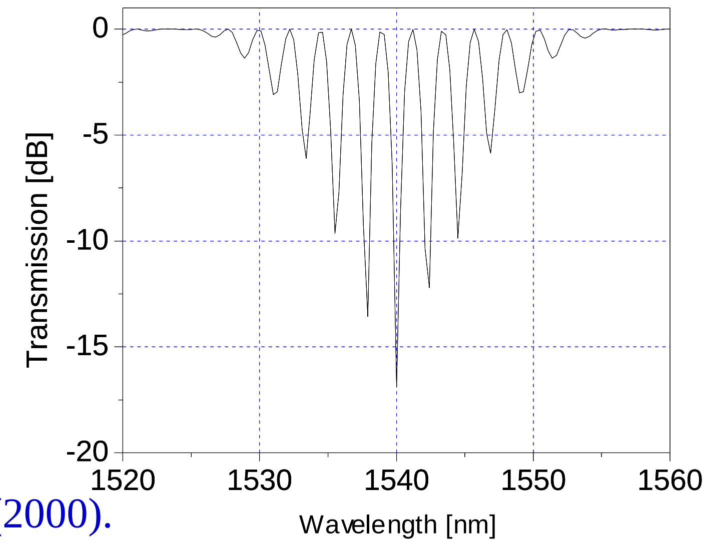
■ Spectral Response of Cascaded LPFG's

- Transmission of cladding mode: $|t_{cl}|^2 \propto f_{cl}\left\{1+\cos\left(\frac{2\pi}{\lambda}\Delta n_g L_s + 2\phi_{co}\right)\right\}$
- Spectral fringe spacing: $\Delta\lambda_{fringe} \approx \frac{\lambda^2}{\Delta n_g L_s}$
- Nonlinear spectral shift: $\frac{\Delta\lambda_s}{\lambda} \approx \frac{n_{2,eff} I_{eff}}{\Delta n_g}$

cf: E. M. Dianov *et al*., *ECOC*, Gent, Belgium, 1997, pp. 65-68.

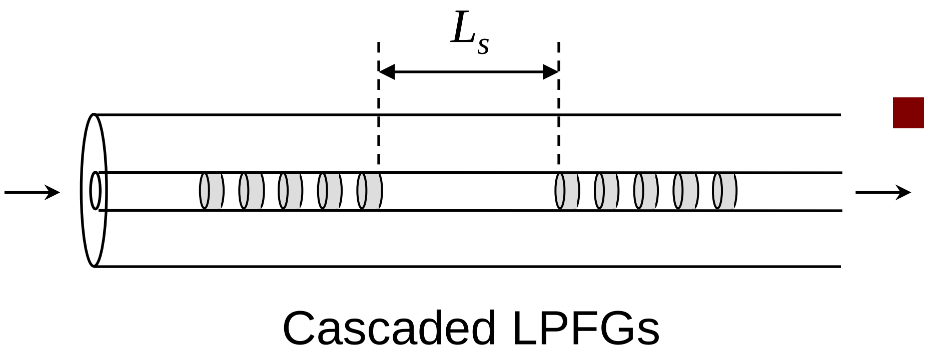
■ XPM Regime





Y. Jeong, S. Baek, and B. Lee, *IEEE PTL*, 12(9), 1216 (2000).

Linear spectra of cascaded LPFGs

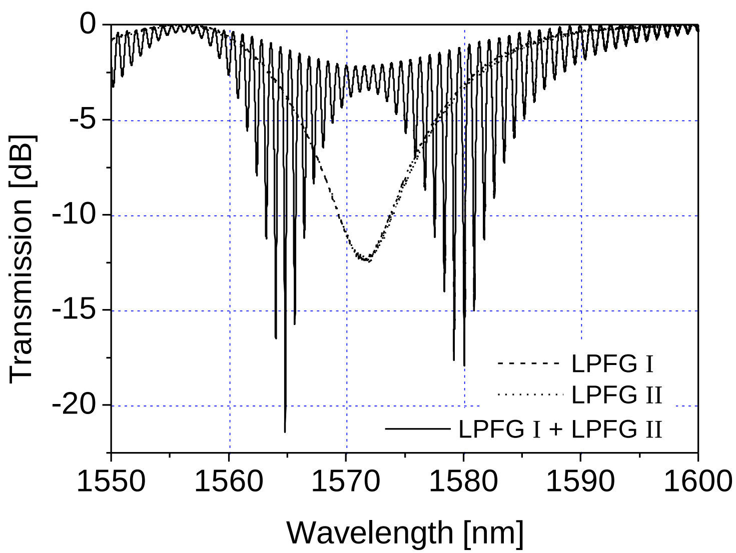


Grating Lengths and Separation

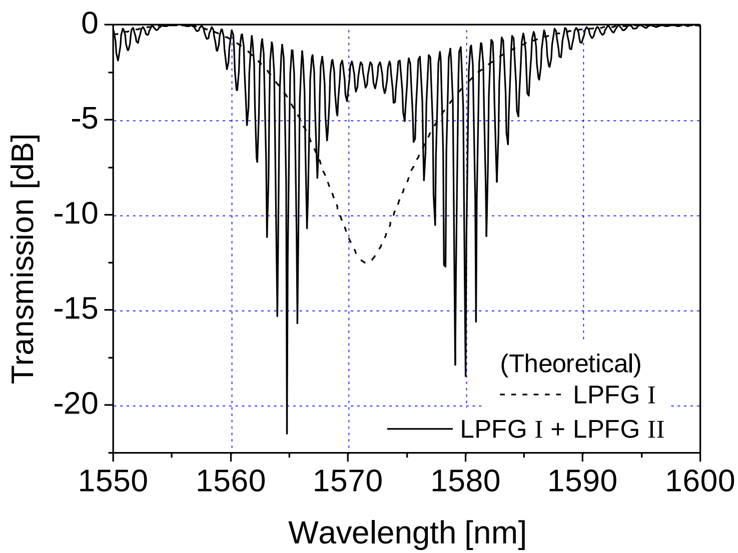
$\Lambda = 500\ \mu m$

$L_I = 3$ cm, $L_{II} = 3$ cm, $L_s = 60$ cm

Experimental

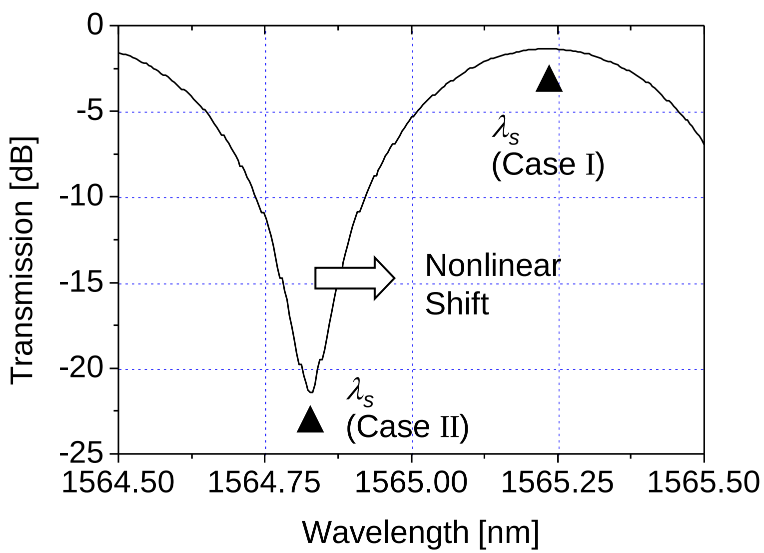


Theoretical

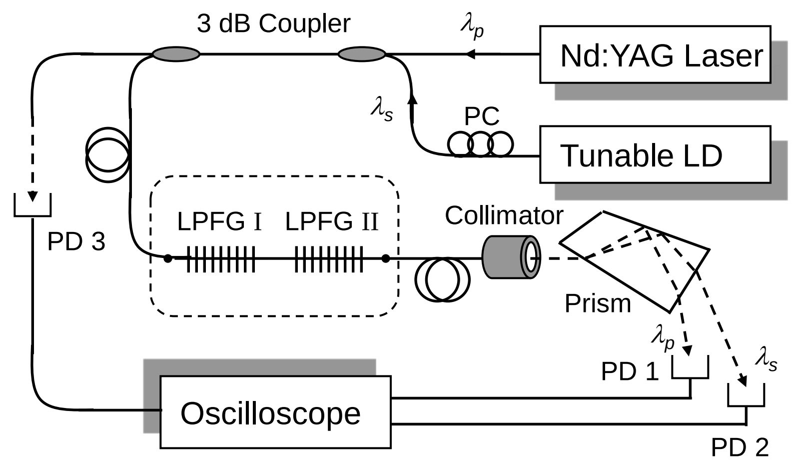


Experimental arrangement

■ Transmission Dip



■ Arramgement

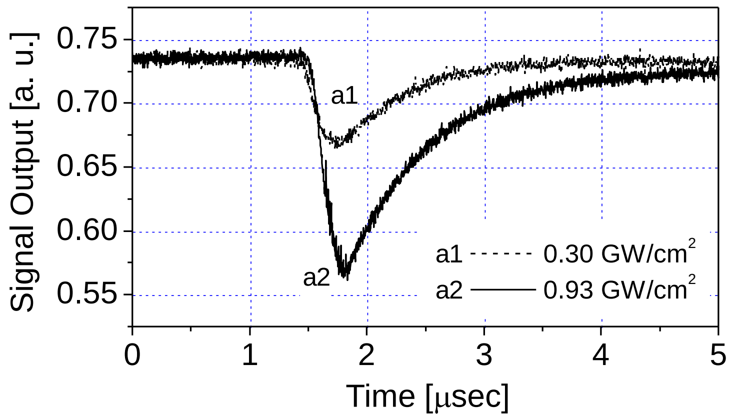


■ Experiments

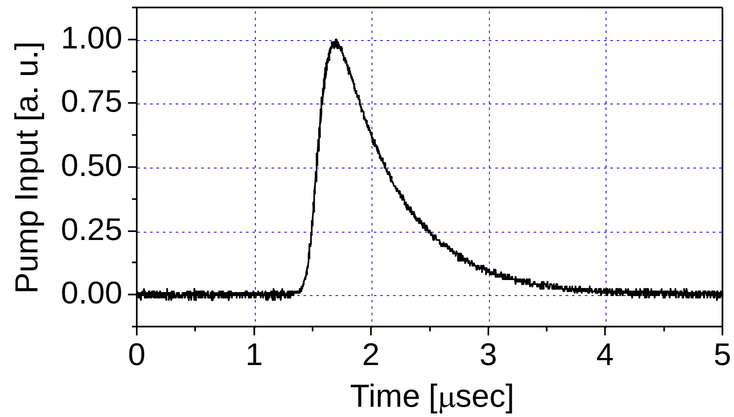
- Signal wave: Tunable LD @1565.2 nm (Case I), @1564.8 nm (Case II)
- Pump wave: Q-switched Nd:YAG laser (1 kHz)

Experimental results

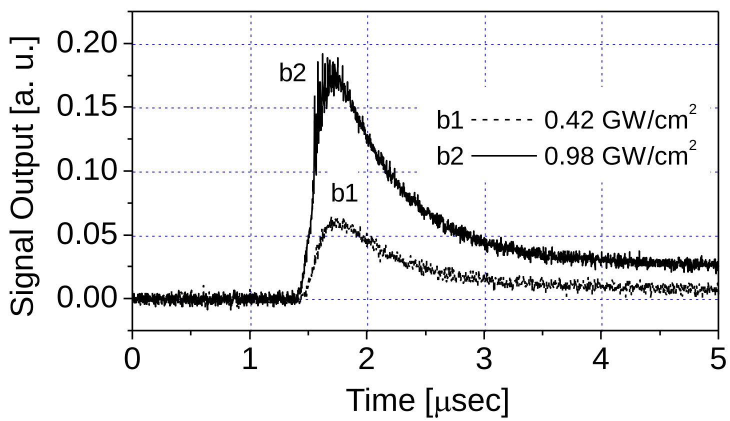
■ Case I

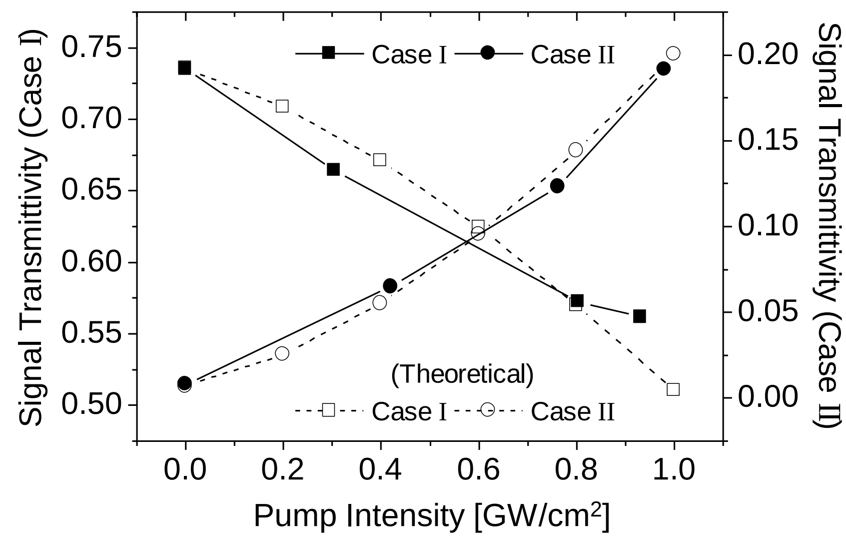


■ Pump



■ Case II





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