FI255 - Tópicos de Óptica e Fotônica II

Óptica Não-Linear

5ª. aula

Prof. Cid B. de Araújo
UNICAMP - 06 de abril de 2018

Proposta de calendário

Listas de exercícios		Provas	
16 / 03	1ª. Lista	11 / 05	1ª. Prova
13 / 04	2ª. Lista	29 / 06	2ª. Prova
18 / 05	3ª. Lista		
15 / 06	4ª. Lista		

Breve revisão da 4ª. Aula

Óptica Não Linear

REVISÃO

Interação luz-matéria sob condições que violam o princípio de superposição linear

Polarização óptica ≡ momento de dipolo por unidade de volume

$$\vec{P} = \epsilon_0 \overleftrightarrow{\chi^{(1)}} \otimes \vec{E} + \epsilon_0 \overleftrightarrow{\chi^{(2)}} \otimes \vec{E}\vec{E} + \epsilon_0 \overleftrightarrow{\chi^{(3)}} \otimes \vec{E}\vec{E}\vec{E} + \ldots$$

$\overleftrightarrow{\chi^{(n)}} \equiv 0$, n = par (meios centro-simétricos)

$\vec{P}$ induz mudança na velocidade da luz no meio e novos comprimentos de onda podem ser gerados

Significado de cada parcela

REVISÃO

Vetor polarização

$$\overrightarrow{P^{(1)}} = \epsilon_0 \overleftrightarrow{\chi^{(1)}} \otimes \overrightarrow{E}$$

$$\overrightarrow{P^{(2)}} = \epsilon_0 \overleftrightarrow{\chi^{(2)}} \otimes \vec{E}\vec{E}$$

$$\overrightarrow{P^{(3)}} = \epsilon_0 \overleftrightarrow{\chi^{(3)}} \otimes \vec{E}\vec{E}\vec{E}$$

Componentes da polarização

$$P_i^{(1)} = \epsilon_0 \chi_{ij}^{(1)} E_j$$

$$P_i^{(2)} = \epsilon_0 \chi_{ijk}^{(2)} E_j E_k$$

$$P_i^{(3)} = \epsilon_0 \chi_{ijkl}^{(3)} E_j E_k E_l$$

analogamente para os demais têrmos ...

Oscilador anarmônico

REVISÃO

$$m\frac{d^2x}{dt^2} + m\gamma\frac{dx}{dt} + m\omega_0^2 x + mKx^2 = -e\varepsilon(t)$$

$$\varepsilon(t) = \varepsilon_0 \cos\omega t = \frac{1}{2}\,\varepsilon_0\,(e^{i\omega t} + e^{-i\omega t})$$

Solução tentativa

$$x(t) = \frac{1}{2}\,(X_1 e^{i\omega t} + X_2 e^{i2\omega t} + c.c.) \qquad X_1 \gg X_2$$

Polarização induzida

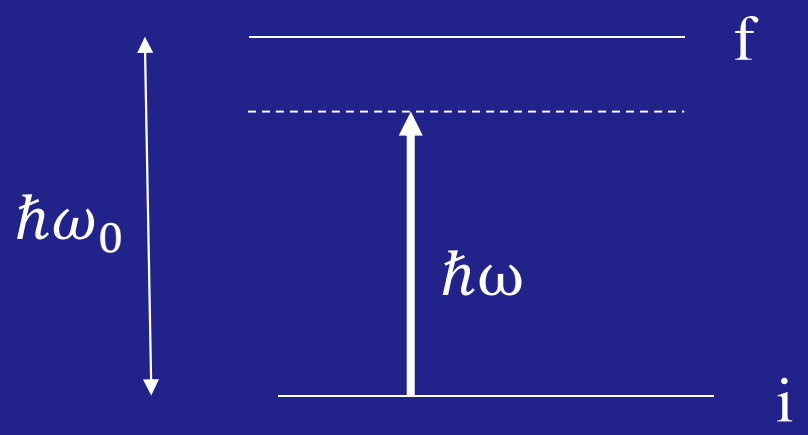
$$X_1 = -\frac{e\varepsilon_0}{m}\frac{1}{(\omega_0^2 - \omega^2) + i\gamma\omega}$$

$$P(\omega, t) = -Nex(\omega, t) = -\frac{Ne}{2}\left(X_1 e^{i\omega t} + c.c.\right)$$

$$= \epsilon_0\,\chi^{(1)}(\omega)\varepsilon(t)$$

$$\boxed{\chi^{(1)}(\omega;\omega) = \frac{Ne^2}{m\epsilon_0[(\omega_0^2 - \omega^2) + i\gamma\omega]}}$$

$$\chi^{(1)}(\omega;\omega) = \frac{Ne^2}{m\epsilon_0[(\omega_0^2 - \omega^2) + i\gamma\omega]}$$



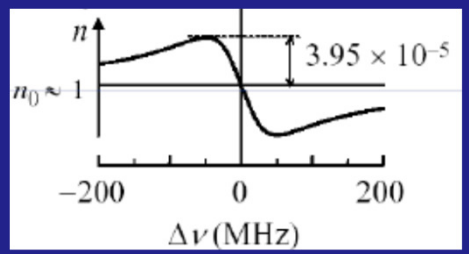
$n_0 \propto Re\,\chi^{(1)}(\omega;\omega)$

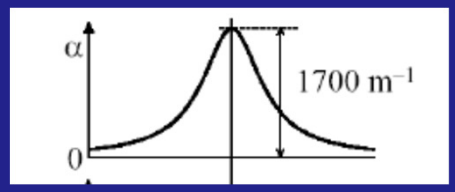
Índice de refração linear

$\alpha_0 \propto Im\,\chi^{(1)}(\omega;\omega)$

Coeficiente de absorção linear

Exemplo: sódio gasoso (2ª. Aula)



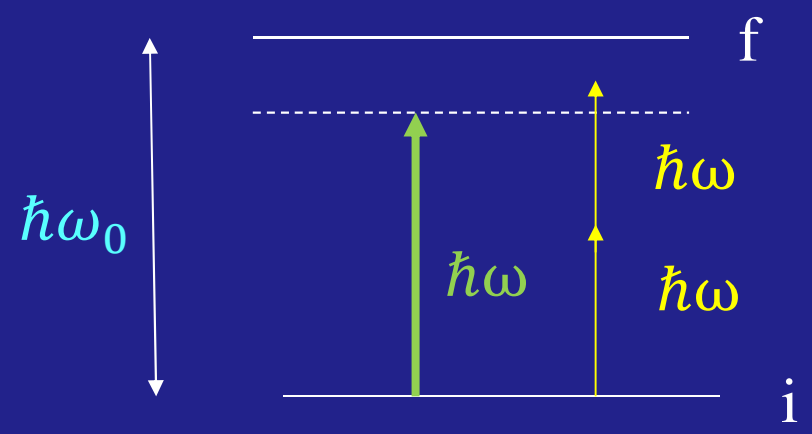


$$P(2\omega,t) = -Nex(2\omega,t) = -\frac{Ne}{2}\left(X_2 e^{i2\omega t} + c.c.\right)$$

$$= \epsilon_0 \chi^{(2)} \varepsilon(t)^2$$

$$\chi^{(2)}(2\omega,\omega,\omega) = \frac{Ne^3 K}{\epsilon_0 m^2 [(\omega_0^2 - \omega^2) + i\gamma\omega]^2 \, (\omega_0^2 - 4\omega^2 + i2\omega\gamma)}$$

ressonâncias



REVISÃO

$$\varepsilon(t) = \varepsilon_1 \cos \omega_1 t + \varepsilon_2 \cos \omega_2 t$$

$$P = -Ne\,x = P^{(1)} + P^{(2)} + P^{(3)} \ldots$$

Polarização de primeira ordem

$$P^{(1)}(\omega_1) \text{ and } P^{(1)}(\omega_2)$$

Polarização de segunda ordem

$$P^{(2)}(2\omega_1),\ P^{(2)}(2\omega_2),\ P^{(2)}(\omega_1 \pm \omega_2),\ P^{(2)}(0)$$

Polarização de terceira ordem… etc

$\chi^{(2)}$ Second order polarization

Non centro-symmetric materials

REVISÃO

$$P^{(2)} = \varepsilon_0 \chi^{(2)} \left(E_1 \cos\omega_1 t + E_2 \cos\omega_2 t\right)^2 =$$
$$P_0^{(2)} + P_{2\omega_1}^{(2)} + P_{2\omega_2}^{(2)} + P_{\omega_1+\omega_2}^{(2)} + P_{\omega_1-\omega_2}^{(2)}$$

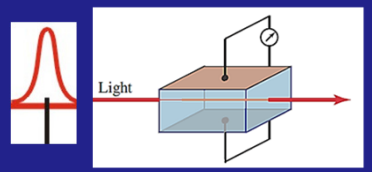
Optical retification

SHG

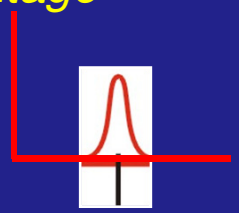
ω

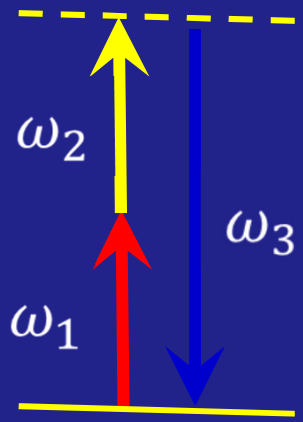
SFG

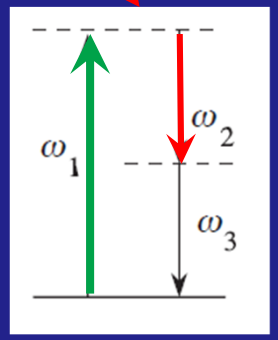
DFG



Light pulse



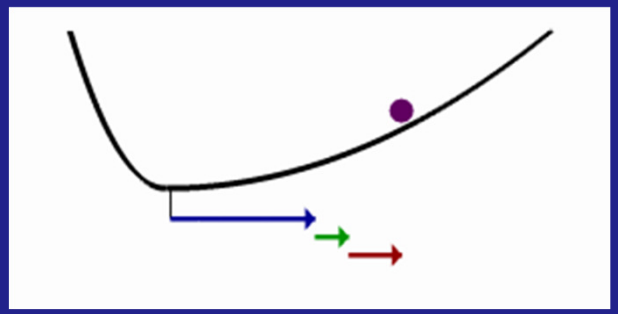


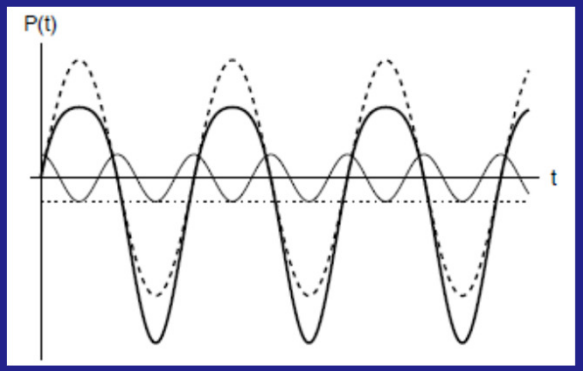


Estudaremos mais adiante alguns efeitos de mais alta ordem, porém, antes disso, veremos em detalhes como descrever matematicamente os efeitos de segunda e terceira ordem.

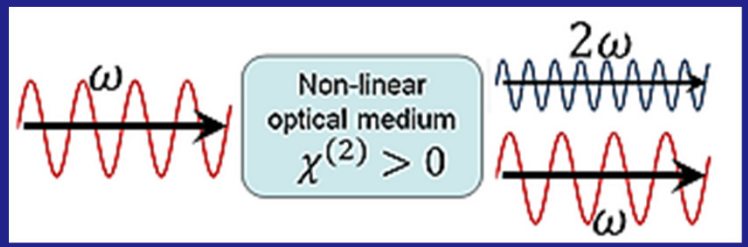
Nesta aula e na próxima vamos detalhar os cálculos para descrever a intensidade do sinal gerado devido à susceptibilidade $\chi^{(2)}$

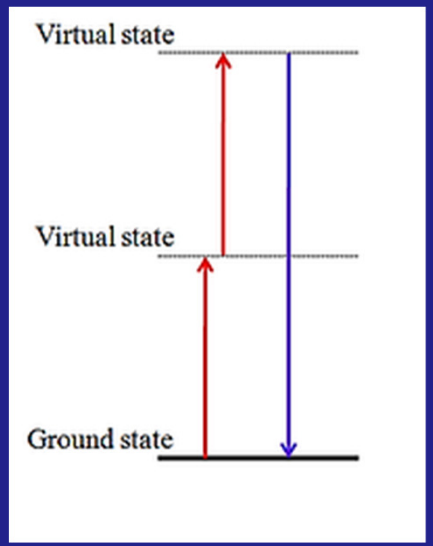
As aulas seguintes (7ª, 8ª, 9ª) serão dedicadas aos efeitos de terceira ordem (associados a $\chi^{(3)}$)





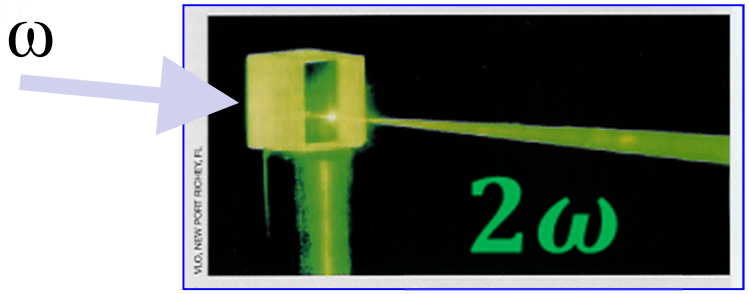
An electron (purple) is being pushed side-to-side by a sinusoidally-oscillating force, i.e. the light's electric field. But because the electron is in an anharmonic potential energy environment (black curve), the electron motion is *not* sinusoidal. The three arrows show the Fourier series of the motion: The blue arrow corresponds to ordinary (linear) susceptibility, the green arrow corresponds to second-harmonic generation, and the red arrow corresponds to optical rectification.



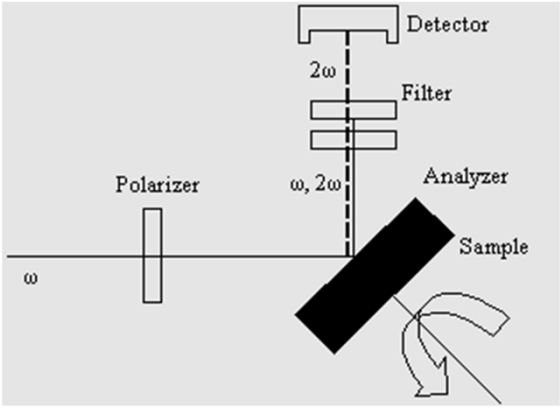


https://en.wikipedia.org/wiki/Second-harmonic_generation

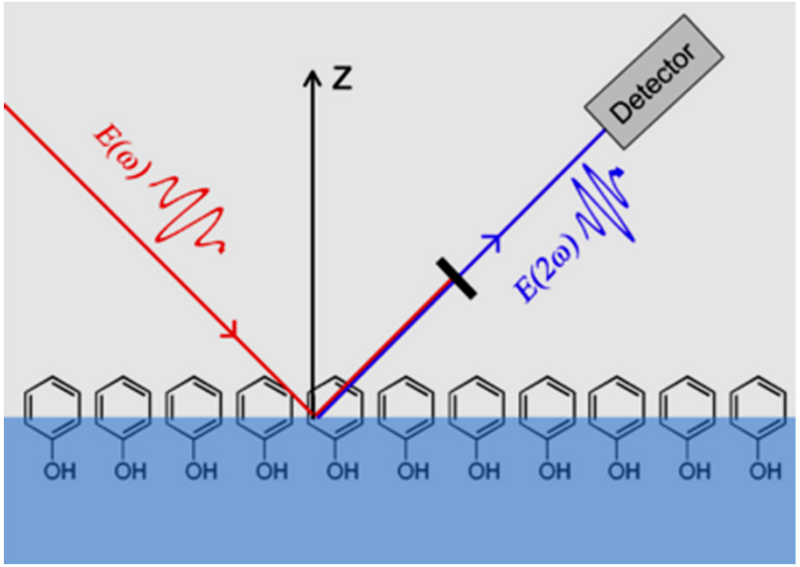
Bulk crystals (1961)



Crystal surface (1962)

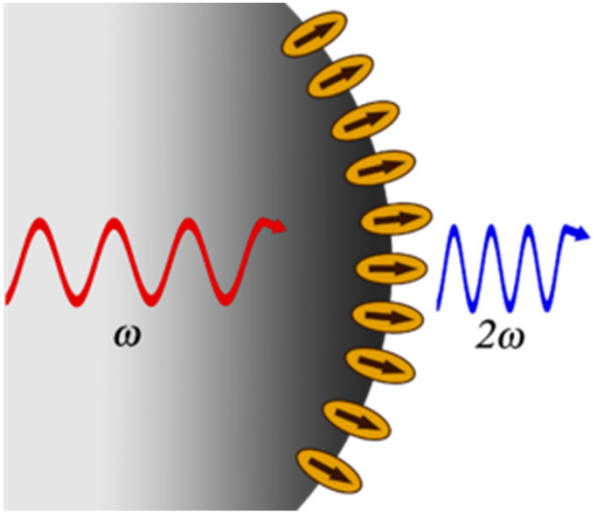


Phenol group at the air-water interface



Many analogous experiments starting in the 70's

Molecules on a curved surface



Many contemporary experiments with nanoparticles

Equação de onda para um meio não linear

$$\nabla^2 \vec{E}(\vec{r}, t) - \mu\epsilon \frac{\partial^2 \vec{E}(\vec{r}, t)}{\partial t^2} = \mu \frac{\partial^2 \vec{P}_{\mathrm{NL}}(\vec{r}, t)}{\partial t^2}$$

$\mu = \mu_0$ $\qquad$ $\epsilon = \epsilon(\omega)$

$$\nabla^2 \vec{E}(\vec{r}, t, \omega_i) - \mu\epsilon(\omega_i) \frac{\partial^2 \vec{E}(\vec{r}, t, \omega_i)}{\partial t^2} = \mu \frac{\partial^2 \vec{P}_{\mathrm{NL}}(\vec{r}, t, \omega_i)}{\partial t^2}$$

Processos não lineares de segunda ordem

Dois campos incidentes com frequências ω_1 e ω_2

$$\boxed{P_k^{(2)} = \epsilon_0 \chi_{kij}^{(2)} E_i E_j}$$

$$E_i(z,t,\omega_1) = \frac{1}{2}\left[E_i(z,\omega_1)\,\mathrm{e}^{\mathrm{i}(k_1 z - \omega_1 t)} + \mathrm{cc}\right],$$

$$E_j(z,t,\omega_2) = \frac{1}{2}\left[E_j(z,\omega_2)\,\mathrm{e}^{\mathrm{i}(k_2 z - \omega_2 t)} + \mathrm{cc}\right],$$

$$E_k(z,t,\omega) = \frac{1}{2}\left[E_k(z,\omega)\,\mathrm{e}^{\mathrm{i}(kz - \omega t)} + \mathrm{cc}\right],$$

Campo gerado devido a $\chi_{kij}^{(2)}(\omega, \omega_1, \omega_2)$

$$\frac{\partial^2 E_i(z,t,\omega_1)}{\partial z^2} - \mu\epsilon_1 \frac{\partial^2 E_i(z,t,\omega_1)}{\partial t^2} = \mu \frac{\partial^2 P_i^{(2)}(z,t,\omega_1)}{\partial t^2},$$

$$\frac{\partial^2 E_j(z,t,\omega_2)}{\partial z^2} - \mu\epsilon_2 \frac{\partial^2 E_j(z,t,\omega_2)}{\partial t^2} = \mu \frac{\partial^2 P_j^{(2)}(z,t,\omega_2)}{\partial t^2},$$

$$\frac{\partial^2 E_k(z,t,\omega)}{\partial z^2} - \mu\epsilon \frac{\partial^2 E_k(z,t,\omega)}{\partial t^2} = \mu \frac{\partial^2 P_k^{(2)}(z,t,\omega)}{\partial t^2},$$

$$P_i^{(2)}(z,t,\omega_1) = \frac{1}{2}\left[P_i^{(2)}(z,\omega_1)\,\mathrm{e}^{-\mathrm{i}\omega_1 t} + \mathrm{cc}\right],$$

$$P_j^{(2)}(z,t,\omega_2) = \frac{1}{2}\left[P_j^{(2)}(z,\omega_2)\,\mathrm{e}^{-\mathrm{i}\omega_2 t} + \mathrm{cc}\right],$$

$$P_k^{(2)}(z,t,\omega) = \frac{1}{2}\left[P_k^{(2)}(z,\omega)\,\mathrm{e}^{-\mathrm{i}\omega t} + \mathrm{cc}\right].$$

$$\frac{\mathrm{d}^2\left[E_i\left(z,\omega_1\right)\mathrm{e}^{\mathrm{i}k_1 z}\right]}{\mathrm{d}z^2}+\mu\epsilon_1\omega_1^2 E_i\left(z,\omega_1\right)\mathrm{e}^{\mathrm{i}k_1 z}=-\mu\,\omega_1^2 P_i^{(2)}\left(z,\omega_1\right),$$

$$\frac{\mathrm{d}^2\left[E_j\left(z,\omega_2\right)\mathrm{e}^{\mathrm{i}k_2 z}\right]}{\mathrm{d}z^2}+\mu\epsilon_2\omega_2^2 E_j\left(z,\omega_2\right)\mathrm{e}^{\mathrm{i}k_2 z}=-\mu\,\omega_2^2 P_j^{(2)}\left(z,\omega_2\right),$$

$$\frac{\mathrm{d}^2\left[E_k\left(z,\omega\right)\mathrm{e}^{\mathrm{i}kz}\right]}{\mathrm{d}z^2}+\mu\epsilon\omega^2 E_k\left(z,\omega\right)\mathrm{e}^{\mathrm{i}kz}=-\mu\,\omega^2 P_k^{(2)}\left(z,\omega\right).$$

Sum frequency generation

$$\omega = \omega_1 + \omega_2 \qquad \vec{k} = \overrightarrow{k_1} + \overrightarrow{k_2}$$

$$P_i^{(2)}(z,\omega_1) = \frac{\epsilon_0}{2}\sum_{jk}\chi_{ijk}^{(2)}(\omega_1,-\omega_2,\omega)E_j^*(z,\omega_2)\,E_k(z,\omega)\,\mathrm{e}^{\mathrm{i}(k-k_2)z},$$

$$P_j^{(2)}(z,\omega_2) = \frac{\epsilon_0}{2}\sum_{ki}\chi_{jki}^{(2)}(\omega_2,\omega,-\omega_1)E_k(z,\omega)\,E_i^*(z,\omega_1)\,\mathrm{e}^{\mathrm{i}(k-k_1)z},$$

$$P_k^{(2)}(z,\omega) = \frac{\epsilon_0}{2}\sum_{ij}\chi_{kij}^{(2)}(\omega,\omega_1,\omega_2)E_i(z,\omega_1)\,E_j(z,\omega_2)\,\mathrm{e}^{\mathrm{i}(k_1+k_2)z},$$

$$\frac{\mathrm{d}^2}{\mathrm{d}z^2}\left[E_i(z,\omega_1)\mathrm{e}^{\mathrm{i}k_1 z}\right]+\mu\epsilon_1\omega_1^2 E_i(z,\omega_1)\mathrm{e}^{\mathrm{i}k_1 z}$$

$$=\left[\frac{\mathrm{d}^2 E_i(z,\omega_1)}{\mathrm{d}z^2}+2\mathrm{i}k_1\frac{\mathrm{d}E_i(z,\omega_1)}{\mathrm{d}z}+\left(\mu\epsilon_1\omega_1^2-k_1^2\right)E_i(z,\omega_1)\right]\mathrm{e}^{\mathrm{i}k_1 z}$$

$$\approx 2\mathrm{i}k_1\mathrm{e}^{\mathrm{i}k_1 z}\frac{\mathrm{d}E_i(z,\omega_1)}{\mathrm{d}z}.$$

$$\frac{\mathrm{d}^2}{\mathrm{d}z^2}\left[E_j(z,\omega_2)\mathrm{e}^{\mathrm{i}k_2 z}\right]+\mu\epsilon_2\omega_2^2 E_j(z,\omega_2)\mathrm{e}^{\mathrm{i}k_2 z}=2\mathrm{i}k_2\mathrm{e}^{\mathrm{i}k_2 z}\frac{\mathrm{d}E_j(z,\omega_2)}{\mathrm{d}z},$$

$$\frac{\mathrm{d}^2}{\mathrm{d}z^2}\left[E_k(z,\omega)\mathrm{e}^{\mathrm{i}kz}\right]+\mu\epsilon\omega^2 E_k(z,\omega)\mathrm{e}^{\mathrm{i}kz}=2\mathrm{i}k\mathrm{e}^{\mathrm{i}kz}\frac{\mathrm{d}E_k(z,\omega)}{\mathrm{d}z}.$$

SVEA $$\frac{\mathrm{d}^2 E(z,\omega)}{\mathrm{d}z^2}\ll k\frac{\mathrm{d}E(z,\omega)}{\mathrm{d}z}$$

$$k_1^2=\mu\epsilon_1\omega_1^2,\quad k_2^2=\mu\epsilon_2\omega_2^2,\quad k^2=\mu\epsilon\omega^2$$

$$\Delta k = k - k_1 - k_2$$

$$\frac{\mathrm{d}E_i(z,\omega_1)}{\mathrm{d}z} = \frac{\mathrm{i}\omega_1}{4cn_1}\sum_{jk}\chi^{(2)}_{ijk}(\omega_1,-\omega_2,\omega)E^*_j(z,\omega_2)E_k(z,\omega)\mathrm{e}^{\mathrm{i}\Delta kz},$$

$$\frac{\mathrm{d}E_j(z,\omega_2)}{\mathrm{d}z} = \frac{\mathrm{i}\omega_2}{4cn_2}\sum_{ki}\chi^{(2)}_{jki}(\omega_2,\omega,-\omega_1)E_k(z,\omega)E^*_i(z,\omega_1)\mathrm{e}^{\mathrm{i}\Delta kz},$$

$$\frac{\mathrm{d}E_k(z,\omega)}{\mathrm{d}z} = \frac{\mathrm{i}\omega}{4cn}\sum_{ij}\chi^{(2)}_{kij}(\omega,\omega_1,\omega_2)E_i(z,\omega_1)E_j(z,\omega_2)\mathrm{e}^{-\mathrm{i}\Delta kz},$$

$$\frac{\mathrm{d}E_i(\omega_1)}{\mathrm{d}z} = \mathrm{i}\alpha\frac{\omega_1}{n_1}E^*_j(\omega_2)E_k(\omega)\mathrm{e}^{\mathrm{i}\Delta kz},$$

$$\frac{\mathrm{d}E_j(\omega_2)}{\mathrm{d}z} = \mathrm{i}\alpha\frac{\omega_2}{n_2}E_k(\omega)E^*_i(\omega_1)\mathrm{e}^{\mathrm{i}\Delta kz},$$

$$\frac{\mathrm{d}E_k(\omega)}{\mathrm{d}z} = \mathrm{i}\alpha\frac{\omega}{n}E_i(\omega_1)E_j(\omega_2)\mathrm{e}^{-\mathrm{i}\Delta kz},$$

Transparent crystal

$$\alpha = \frac{1}{4c}\chi^{(2)}_{\mathrm{eff}} = \frac{1}{2c}d^{(2)}_{\mathrm{eff}}$$

Intensidades dos feixes incidentes e feixe gerado

$$I(\omega_1) = \frac{1}{2}\epsilon_0 n_1 c E_i(\omega_1) E_i^*(\omega_1)$$

$$\frac{\mathrm{d}I(\omega_1)}{\mathrm{d}z} = \frac{1}{2}\epsilon_0 n_1 c \left[E_i(\omega_1)\frac{\mathrm{d}E_i^*(\omega_1)}{\mathrm{d}z} + E_i^*(\omega_1)\frac{\mathrm{d}E_i(\omega_1)}{\mathrm{d}z} \right]$$

Parte imaginária

$$\begin{aligned}\frac{\mathrm{d}I(\omega_1)}{\mathrm{d}z} &= \frac{1}{2}\epsilon_0 c\alpha\omega_1 \left[-\mathrm{i}E_i(\omega_1)E_j(\omega_2)E_k^*(\omega)\,\mathrm{e}^{-\mathrm{i}\Delta kz} \right. \\ &\quad \left. +\mathrm{i}E_i^*(\omega_1)E_j^*(\omega_2)E_k(\omega)\,\mathrm{e}^{\mathrm{i}\Delta kz} \right] \\ &= \epsilon_0 c\alpha\omega_1 I_{\mathrm{im}} \left[\mathrm{i}E_i^*(\omega_1)E_j^*(\omega_2)E_k(\omega)\,\mathrm{e}^{\mathrm{i}\Delta kz} \right].\end{aligned}$$

$$\frac{\mathrm{d}I(\omega_2)}{\mathrm{d}z} = \epsilon_0 c\alpha\omega_2 I_{\mathrm{im}} \left[\mathrm{i}E_i^*(\omega_1)E_j^*(\omega_2)E_k(\omega)\,\mathrm{e}^{\mathrm{i}\Delta kz} \right],$$

$$\frac{\mathrm{d}I(\omega = \omega_1 + \omega_2)}{\mathrm{d}z} = -\epsilon_0 c\alpha\omega I_{\mathrm{im}} \left[\mathrm{i}E_i^*(\omega_1)E_j^*(\omega_2)E_k(\omega)\,\mathrm{e}^{\mathrm{i}\Delta kz} \right]$$

$$\frac{\mathrm{d}}{\mathrm{d}z}\left[I(\omega_1)+I(\omega_2)+I(\omega=\omega_1+\omega_2)\right]=0$$

$$\frac{1}{\omega}\frac{\mathrm{d}I(\omega)}{\mathrm{d}z}=-\frac{1}{\omega_1}\frac{\mathrm{d}I(\omega_1)}{\mathrm{d}z}=-\frac{1}{\omega_2}\frac{\mathrm{d}I(\omega_2)}{\mathrm{d}z}$$

Campo gerado

$$\frac{\mathrm{d}E_k(\omega)}{\mathrm{d}z}=\mathrm{i}\alpha\frac{\omega}{n}E_i(\omega_1)E_j(\omega_2)\mathrm{e}^{-\mathrm{i}\Delta kz}$$

Saida da amostra

$$E_k(\omega_1+\omega_2,z=L)=\mathrm{i}(\omega_1+\omega_2)\frac{\alpha}{n}E_i(\omega_1)E_j(\omega_2)\int_0^L \mathrm{e}^{-\mathrm{i}\Delta kz}\,\mathrm{d}z$$

$$=\mathrm{i}(\omega_1+\omega_2)\frac{\alpha}{n}L\,\mathrm{e}^{-\mathrm{i}\frac{\Delta k}{2}L}E_i(\omega_1)E_j(\omega_2)\mathrm{sinc}\left(\frac{\Delta kL}{2}\right),$$

Intensidade gerada

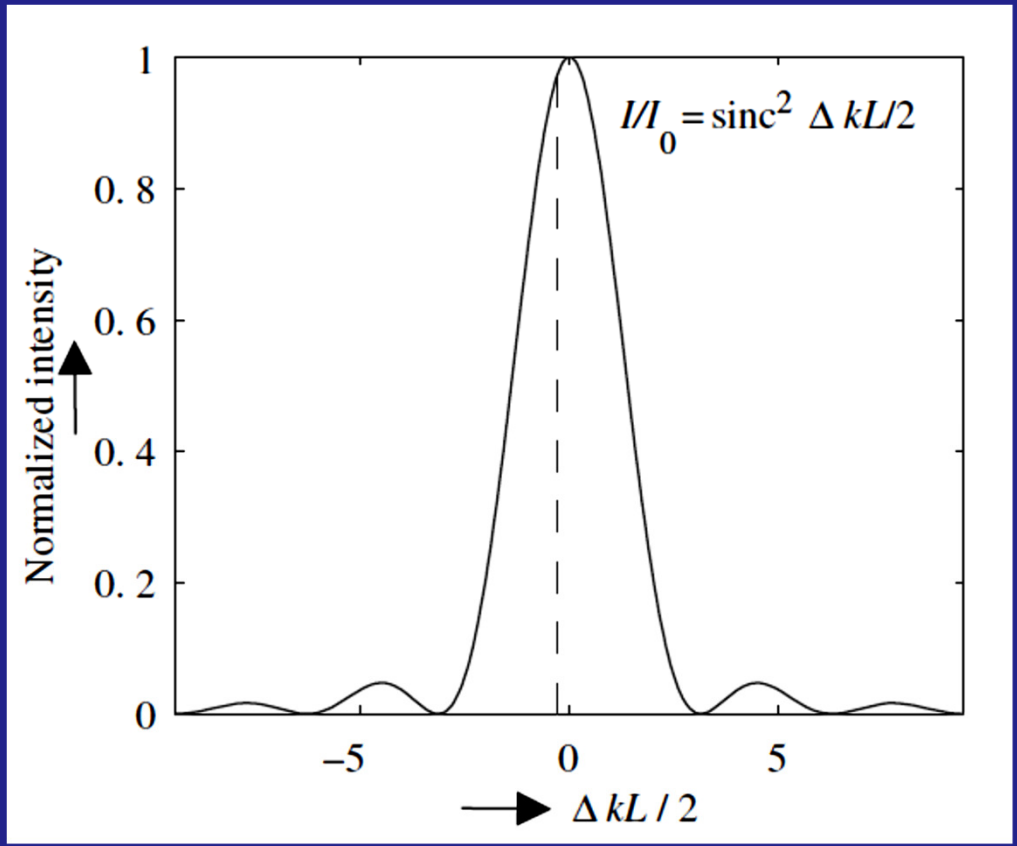
$$I(\omega_1+\omega_2, z=L) = I_0 \,\mathrm{sinc}^2\left(\frac{\Delta k L}{2}\right)$$

$$I_0 = \frac{(\omega_1+\omega_2)^2 L^2 I(\omega_1) I(\omega_2)}{2 n_1 n_2 n \epsilon_0 c^3} (d_{\mathrm{eff}}^{(2)})^2$$

$$I(\omega_1) = \frac{1}{2}\epsilon_0 n_1 c \left|E_i(\omega_1)\right|^2$$

$$I(\omega_2) = \frac{1}{2}\epsilon_0 n_2 c \left|E_j(\omega_2)\right|^2$$

$$\mathrm{sinc}\left(\frac{\Delta k L}{2}\right) = \frac{\sin(\Delta k L/2)}{\Delta k L/2}$$



$$\theta \approx \frac{\Delta k}{k} = \frac{2\pi/L}{2\pi/\lambda} = \frac{\lambda}{L}$$

REVISÃO -2ª. aula

ANISOTROPIA ÓPTICA

ÁTOMOS NUM GAZ OU LÍQUIDO NÃO TÊM DIREÇÕES PREFERENCIAS SE NÃO HOUVER UMA PERTURBAÇÃO EXTERNA

DEVIDO À SIMETRIA DA REDE CRISTALINA OS SÓLIDOS PODEM APRESENTAR ANISOTROPIA ÓPTICA DANDO ORIGEM AO FENÔMENO DE BIRREFRINGÊNCIA

CONSEQUÊNCIA

OS ÍNDICES DE REFRAÇÃO DEPENDEM DA DIREÇÃO DE PROPAGAÇÃO DA LUZ

$$\frac{1}{n_e^2(\theta)} = \frac{cos^2\theta}{n_0^2} + \frac{sen^2\theta}{n_e^2}$$

YARIV – Cap. 16

Optical anisotropy

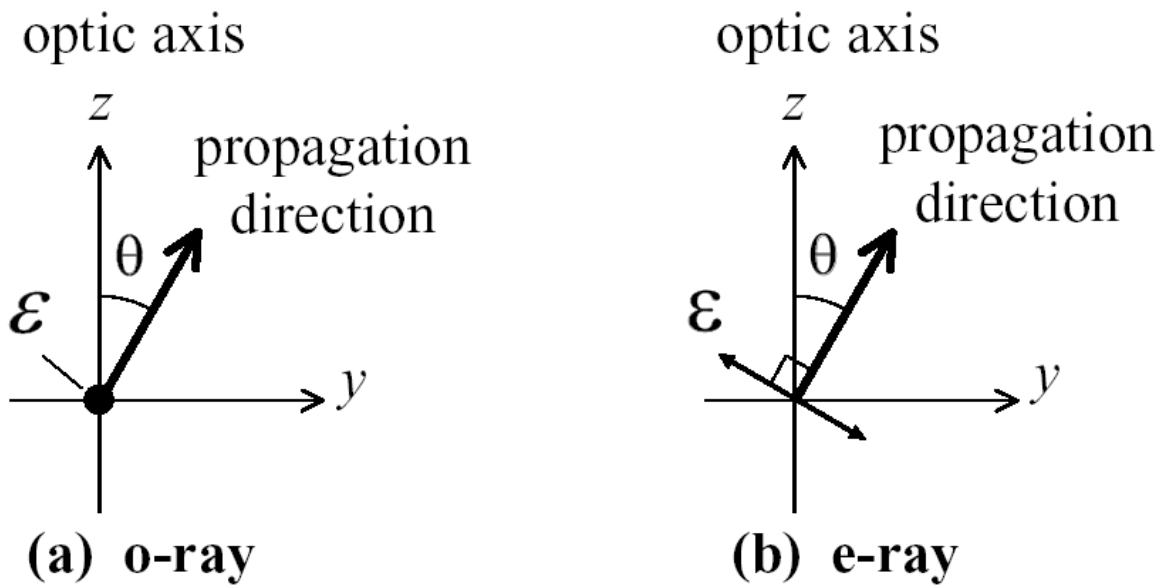
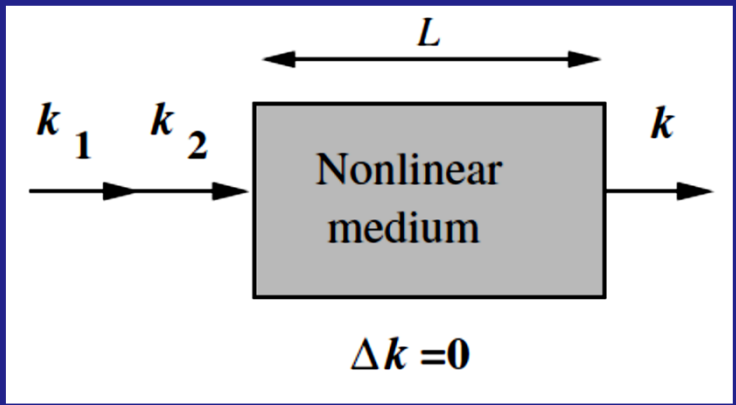


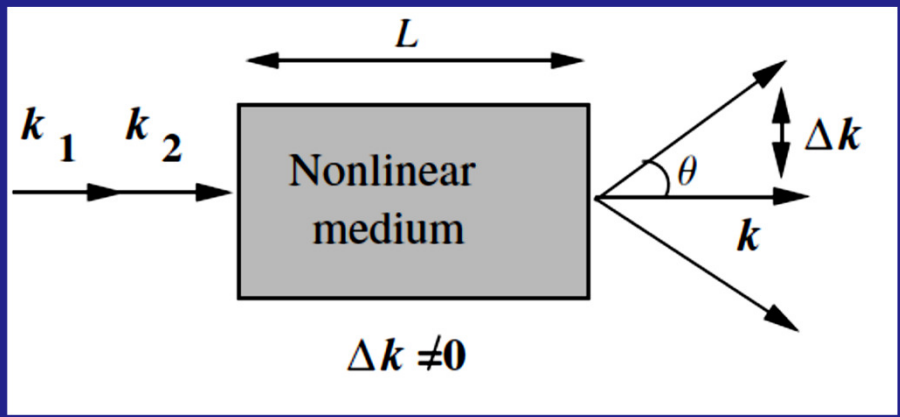
Figure 2.12
Birefringence caused by difference of dielectric constants (and hence refractive index) along the different crystal axes.

$$\begin{pmatrix} D_x \\ D_y \\ D_z \end{pmatrix} = \varepsilon_0 \begin{pmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}$$

Phase Matching

$$(\omega_1+\omega_2)n(\omega_1+\omega_2)=\omega_1 n(\omega_1)+\omega_2 n(\omega_2)$$





Type I Phase Matching

$$n_o(\omega_1+\omega_2)=\frac{\omega_1}{\omega_1+\omega_2}n_e(\omega_1)+\frac{\omega_2}{\omega_1+\omega_2}n_e(\omega_2)$$

Type II Phase Matching

$$n_o(\omega_1+\omega_2)=\frac{\omega_1}{\omega_1+\omega_2}n_o(\omega_1)+\frac{\omega_2}{\omega_1+\omega_2}n_e(\omega_2)$$

Applications

Interface structure

Adsorption measurements

Molecular orientation

Confocal Microscopy:
monolayers, single molecule, single nanoparticles

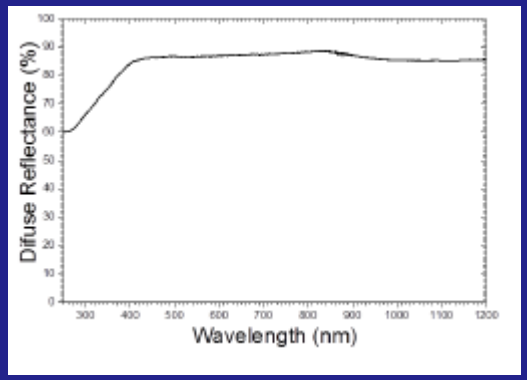
Many applications in biology and medical physics

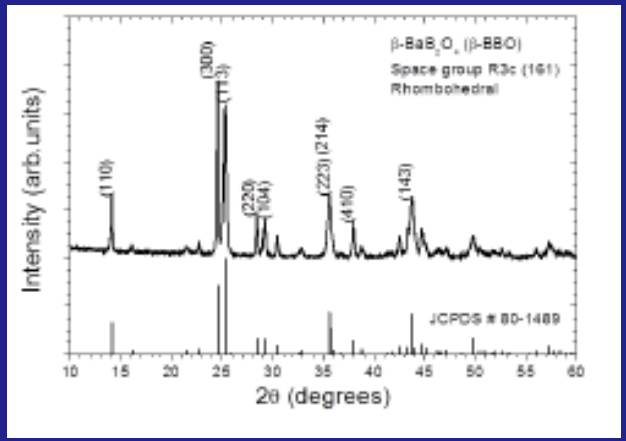
UNIVERSIDADE FEDERAL DE PERNAMBUCO
DEPARTAMENTO DE FÍSICA – CCEN
PROGRAMA DE PÓS-GRADUAÇÃO EM FÍSICA

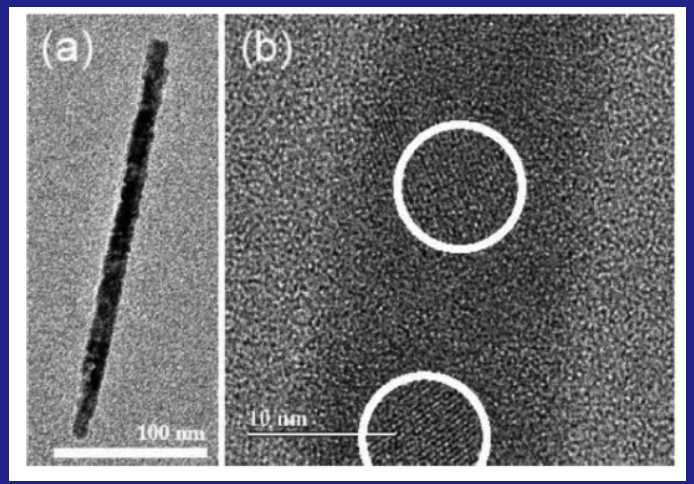
SECOND-HARMONIC CONFOCAL MICROSCOPY OF SINGLE β-BBO NANOCRYSTALS

RODRIGO GALVÃO DOS SANTOS

2017

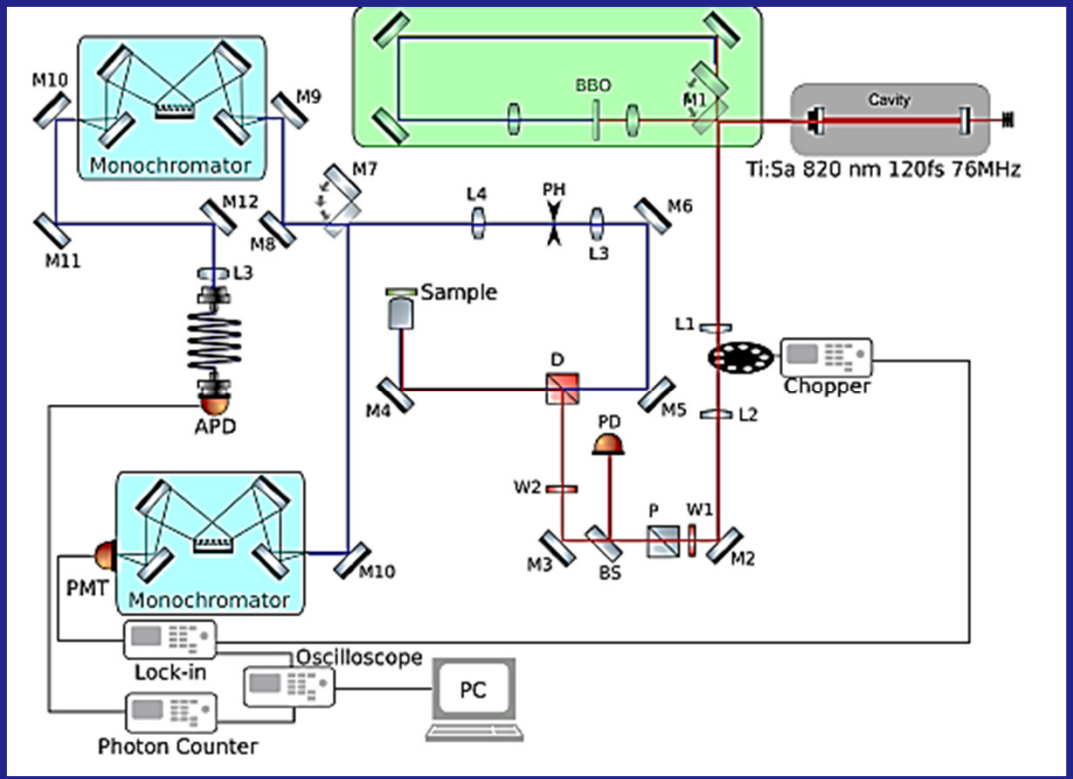




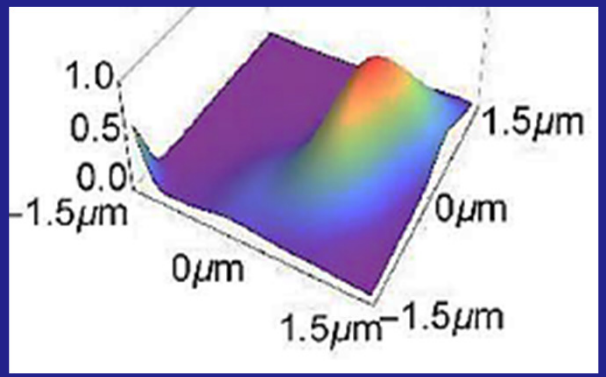


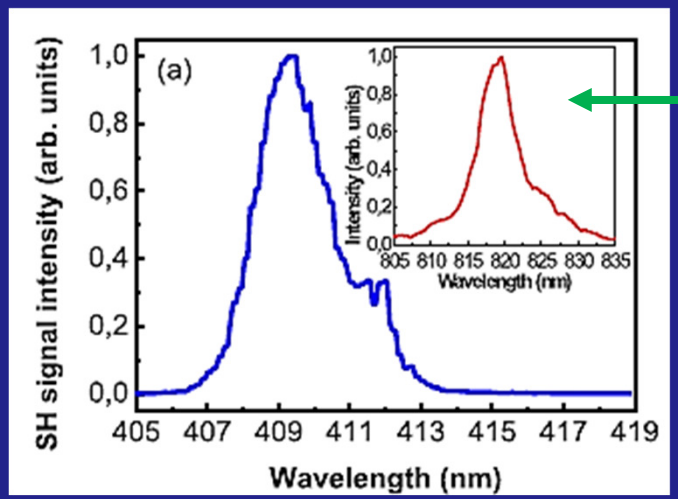
β – BBO nanocrystals

(BaB_2O_4) Beta Barium Borate

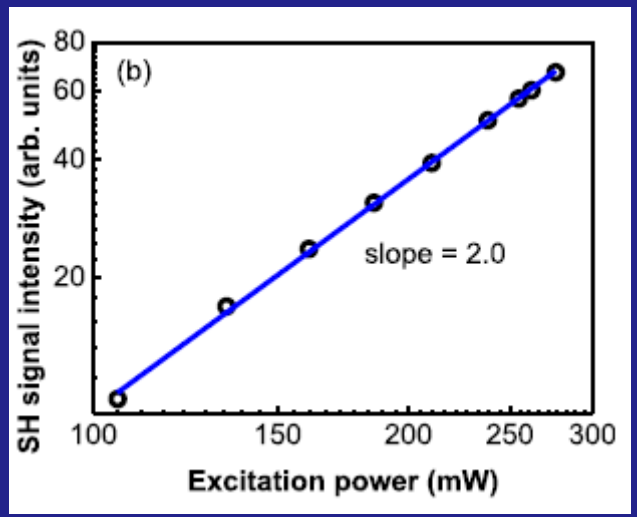


Single nanocrystal



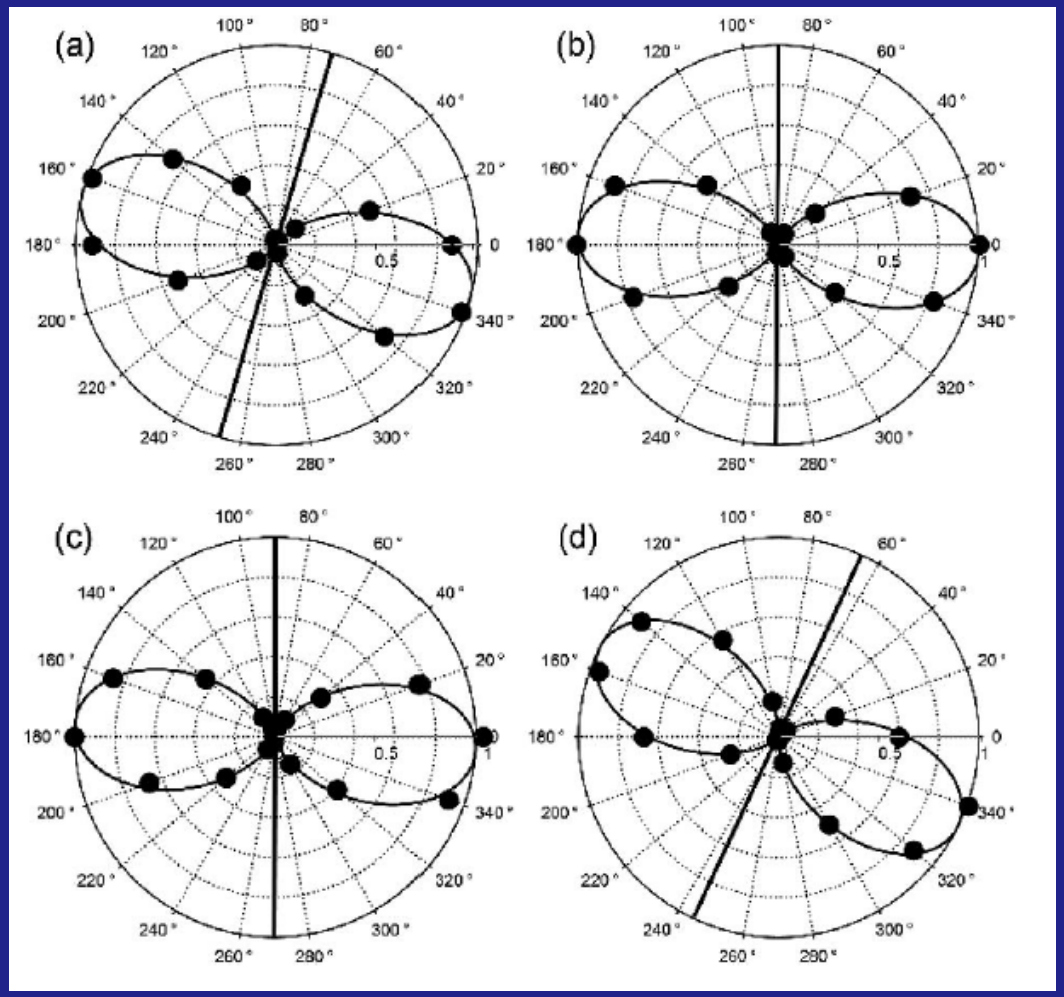


Laser spectrum



Orientação dos nanocristais

A linha reta indica o eixo do NC



References for applications in biology, medical physics, biophotonics

[1] KADOUCH, D. et al. Diagnostic accuracy of confocal microscopy imaging versus punch biopsy for diagnosing and subtyping basal cell carcinoma. *Journal of the European Academy of Dermatology and Venereology*, p. 1–21, 2017.

[2] KYMIONIS, G. D. et al. Correlation of the Corneal Collagen Cross-Linking Demarcation Line Using Confocal Microscopy and Anterior Segment Optical Coherence Tomography in Keratoconic Patients. *American Journal of Ophthalmology*, v. 157, n. 1, p. 110–115.e1, 2014.

[3] VILLANI, E. et al. In Vivo Confocal Microscopy of the Ocular Surface: From Bench to Bedside. *Current Eye Research*, v. 39, n. 3, p. 213–231, 2014.

[4] HOOVER, E. E.; SQUIER, J. A. Advances in multiphoton microscopy technology. *Nat Photon*, v. 7, n. 2, p. 93–101, 2013.

[5] RAJADHYAKSHA, M. et al. Reflectance confocal microscopy of skin in vivo: From bench to bedside. *Lasers in Surgery and Medicine*, v. 49, n. 1, p. 7–19, 2017.

[6] THEODOSSIOU, T. A. et al. Second harmonic generation confocal microscopy of collagen type i from rat tendon cryosections. *Biophysical Journal*, v. 91, n. 12, p. 4665–4677, 2006.

[7] ADUR, J. et al. Second harmonic generation microscopy as a powerful diagnostic imaging modality for human ovarian cancer. *Journal of Biophotonics*, v. 7, n. 1-2, p. 37–48, 2014.

[8] LIU, J. et al. Second Harmonic Super-resolution Microscopy for Quantification of mRNA at Single Copy Sensitivity. *ACS Nano*, v. 8, n. 12, p. 12418–12427, 2014.

[9] LIU, J. et al. Single-cell screening and quantification of transcripts in cancer tissues by second-harmonic generation microscopy. *Journal of Biomedical Optics*, v. 20, n. 9, p. 096016–1–7, 2015.

[10] WOLF, J.-P. Ultrafast nano-biophotonics. In: *Nano-Optics: Principles Enabling Basic Research and Applications*. Dordrecht: Springer Netherlands, 2017. p. 191–212.

Proposta de calendário

Listas de exercícios		Provas	
16 / 03	1ª. Lista	11 / 05	1ª. Prova
13 / 04	2ª. Lista	29 / 06	2ª. Prova
18 / 05	3ª. Lista		
15 / 06	4ª. Lista		