

# FI255 - Tópicos de Óptica e Fotônica II

## Óptica Não-Linear

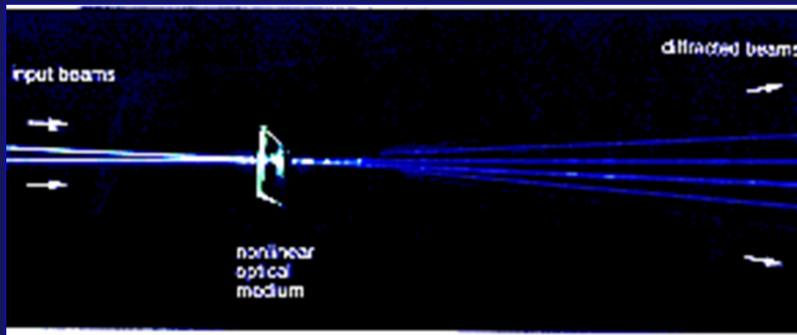
9<sup>a</sup>. aula

+ breve revisão da 8<sup>a</sup>. Aula

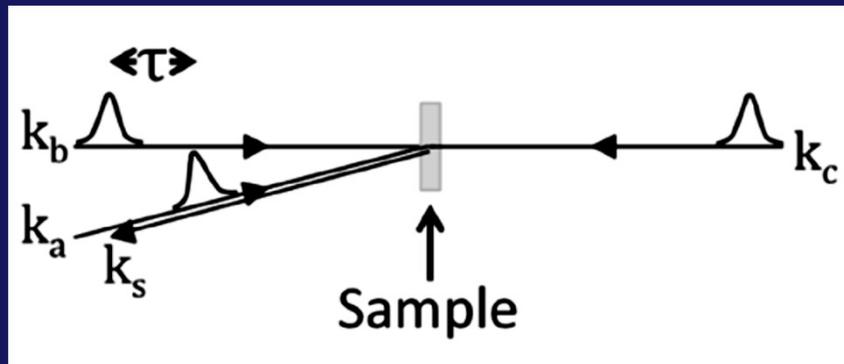
Prof. Cid B. de Araújo  
UNICAMP - 4 de maio de 2018

Na última aula vimos alguns efeitos não lineares e técnicas associadas a  $\chi^{(3)}$

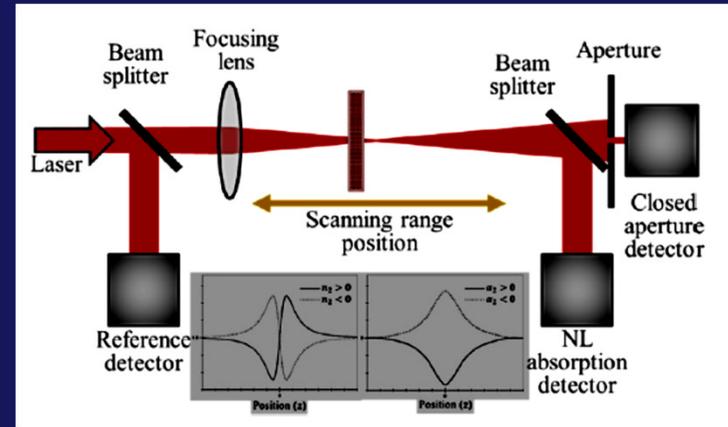
### Degenerate four wave-mixing



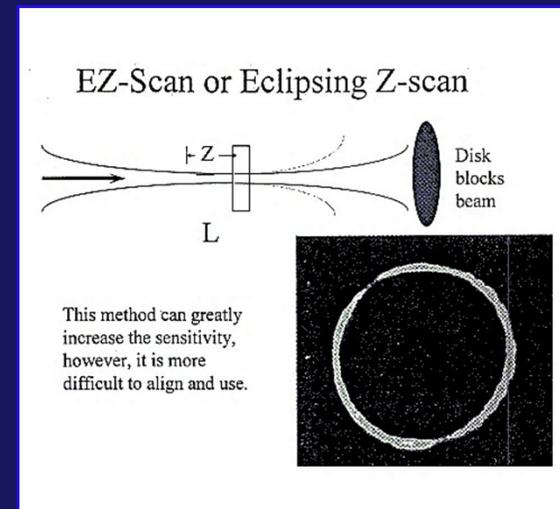
### Phase conjugation



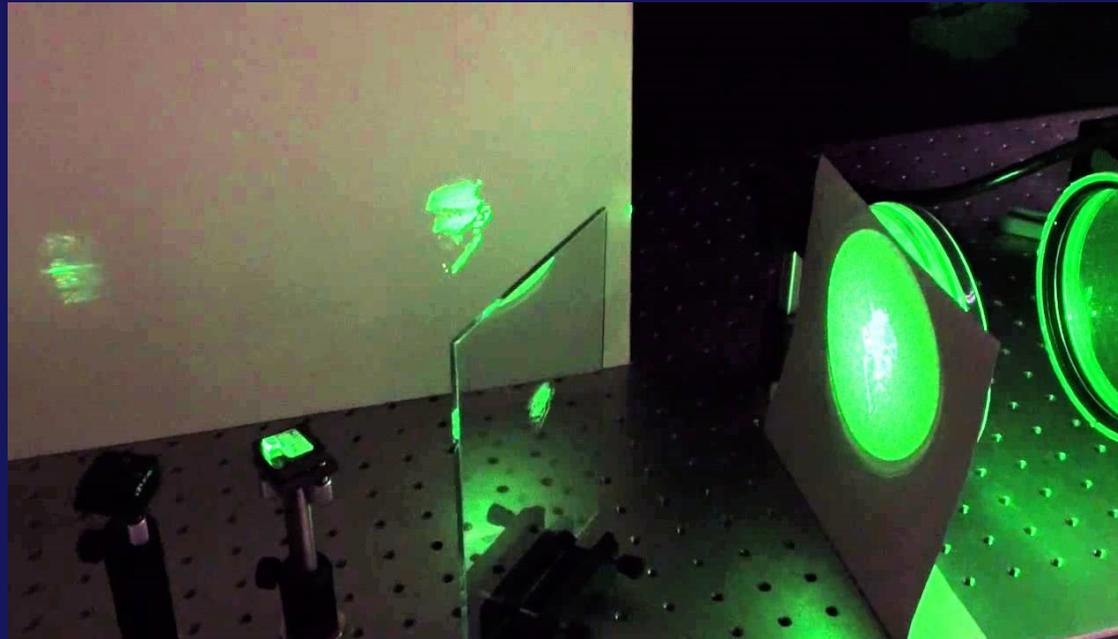
### Z-scan



### EZ-scan

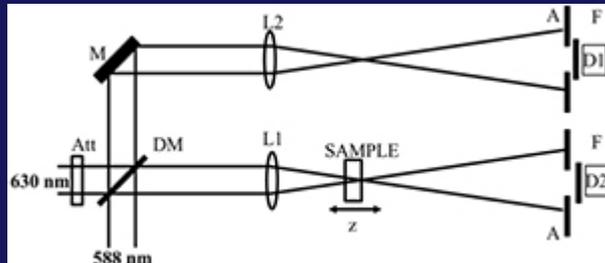


# Filme sobre conjugação de fase

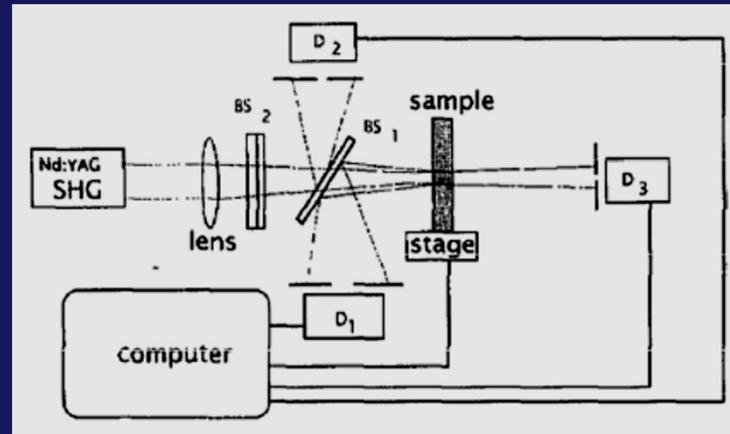


<https://www.youtube.com/watch?v=gAy39ErqV34>

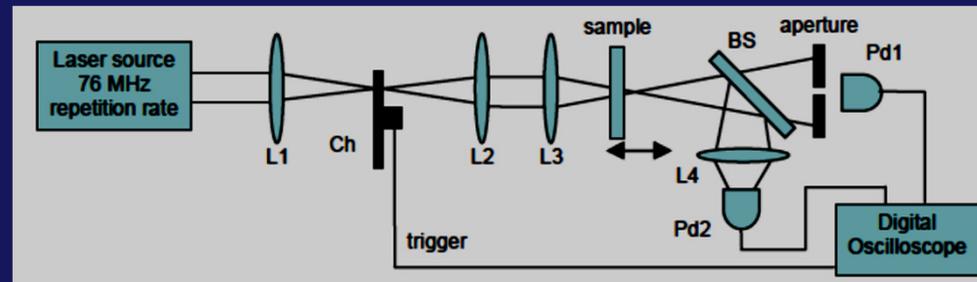
## Two-color Z-scan



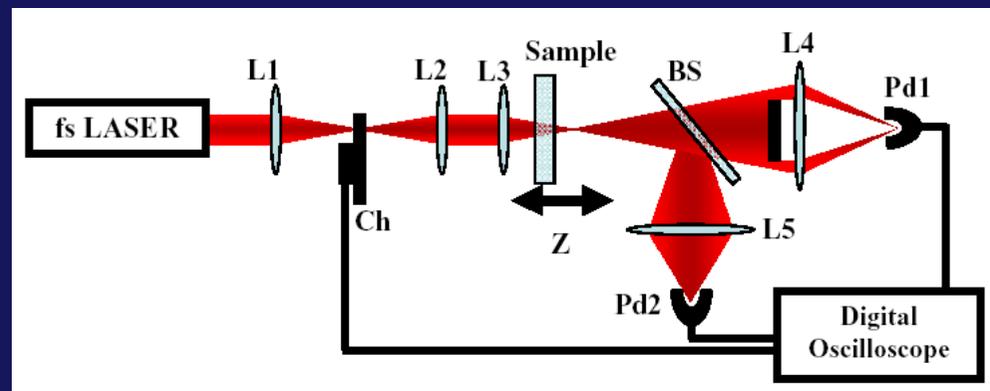
## RZ-scan



## TM Z-scan



## TM- EZ scan



Hoje para complementar a discussão sobre os efeitos paramétricos vamos discutir três tópicos:

- (1) Técnica de “beam deflector”
- (2) Como relacionar a densidade de energia no campo eletromagnético com as suscetibilidades não lineares
- (3) Como conectar a descrição da polarização não linear nos domínios temporal e espectral

# “Beam deflection”

O efeito de curvamento da trajetória da luz está relacionado diretamente com o efeito de auto-focalização (self-focusing)

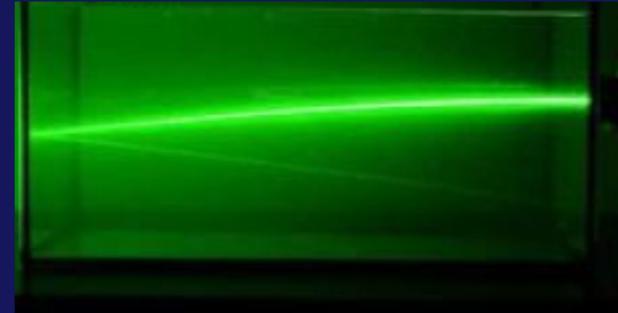
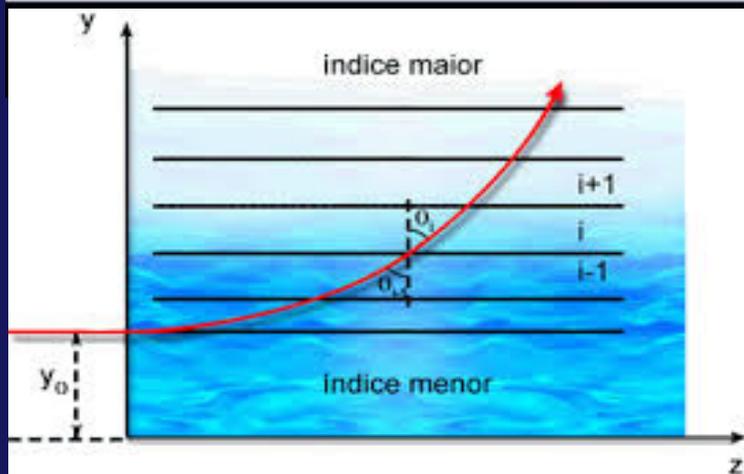
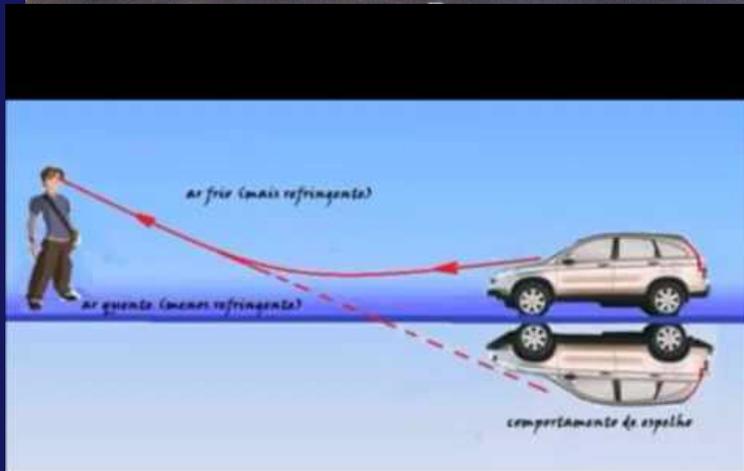
Para visualizarmos a auto-focalização fizemos analogia com o efeito de uma lente convergente

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Self-bending: também é devido à variação não linear induzida sobre o índice de refração

Neste caso a analogia é com o efeito de um prisma induzido

# Óptica linear



$$n_0(r)$$

Luz - trajetória curva

self - focusing

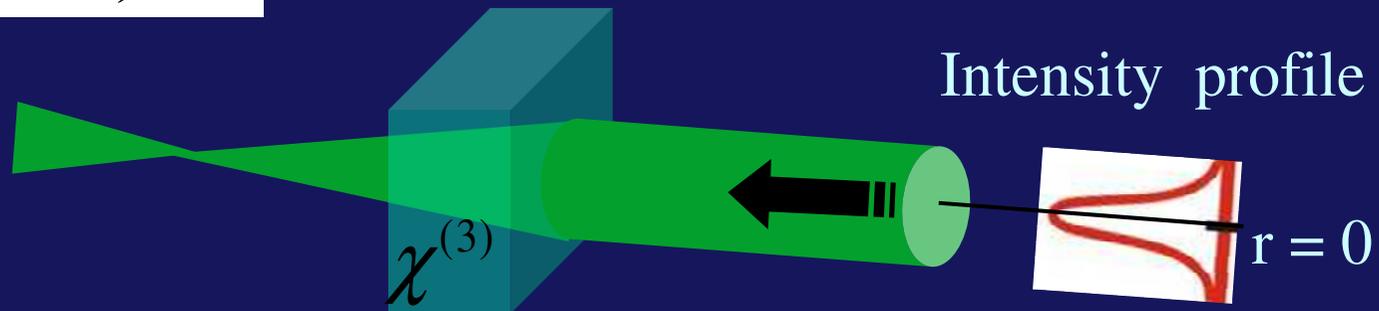
$$n_2 \propto \text{Re } \chi^{(3)}$$

A laser beam with Gaussian intensity profile will induce a Gaussian refractive index profile inside the NL sample.

$$E(\omega) \exp\left(\frac{-r^2}{\Delta^2}\right) e^{-i\omega t}$$

$$n_2 > 0$$

$$I(r) = I_0 \exp\{-r^2/w^2\}$$

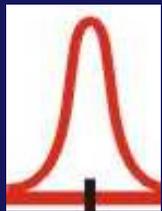


$$n = n_0 + n_2 I_0 \exp\{-r^2/w^2\}$$

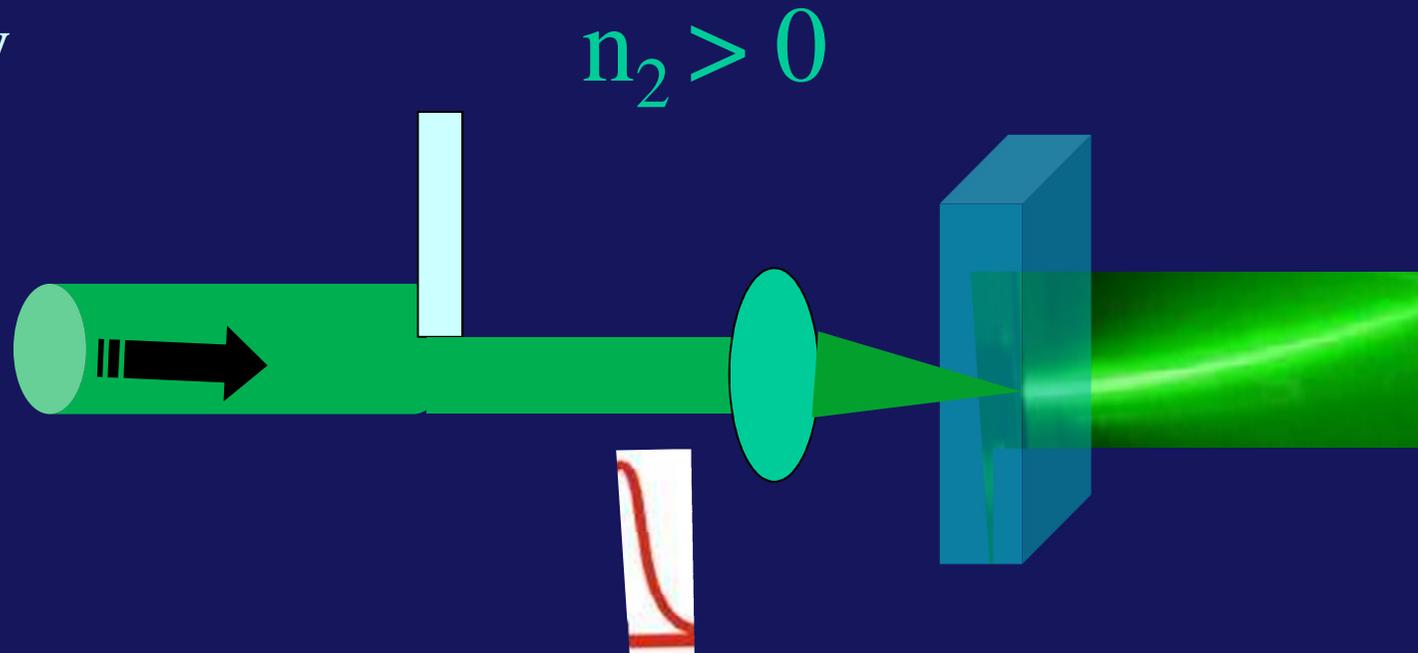
Sample behaves as a convergent lens

# Self-bending-Nonlinear analogue of mirage

Intensity  
profile



$r = 0$



A. E. Kaplan, JETP Lett. **9**, 33 (1969).

M. S. Brodin and A. M. Kamuz, JETP Lett. **9**, 352 (1969).

## Beam deflection– short history

A. E. Kaplan, Bending of trajectories of asymmetrical light beam in nonlinear media, JETP Lett. **9**, 33 (1969).

M. S. Brodin and A. M. Kamuz, Observation of self-bending of a nonuniform intense laser beam in an NaCl crystal, JETP Lett. **9**, 352 (1969).

W. B. Jackson et al., Photothermal deflection spectroscopy and detection , Appl. Opt. **20**, 1333 (1981).

H. Ma and C. B. de Araújo, Light-controlled beam deflector in semiconductor doped glasses Appl. Phys. Lett. **63**, 3553 (1993) .

H. Ma and C. B. de Araújo, Time shortening of laser pulses as an application of dynamical light-bending effects, Opt. Commun. **110**, 615 (1994).

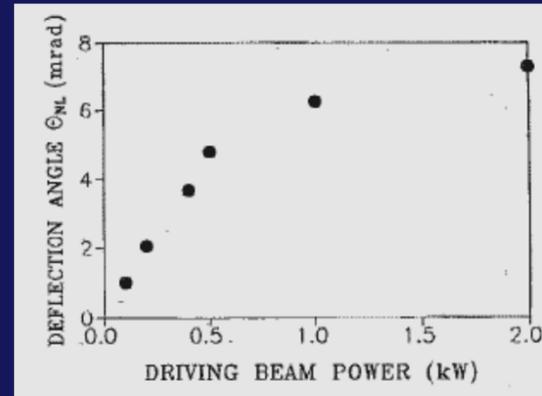
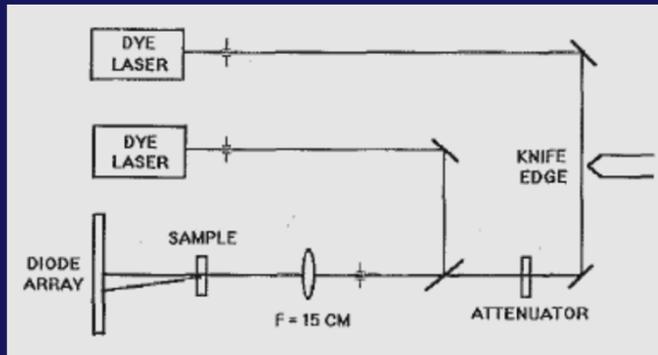
M. R. Ferdinandus et al., Beam deflection measurement of time and polarization resolved ultrafast nonlinear refraction , Opt. Lett. **38**, 3518 (2013).

# Appl. Phys. Lett. 63 (1993) 3553

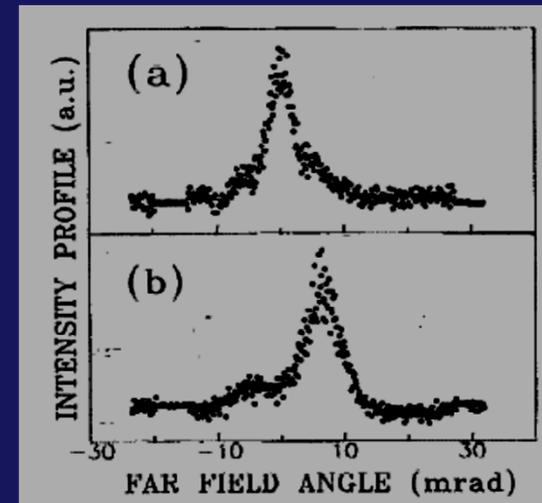
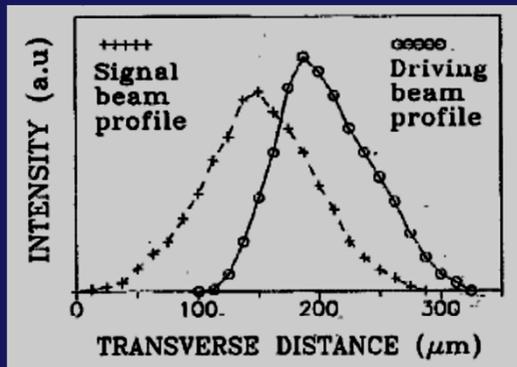
## Light-controlled beam deflector in semiconductor doped glasses

H. Ma and Cid B. de Araújo

*Departamento de Física, Universidade Federal de Pernambuco, 50732-910 Recife, PE, Brazil*



Signal  
beam  
1.5 kW

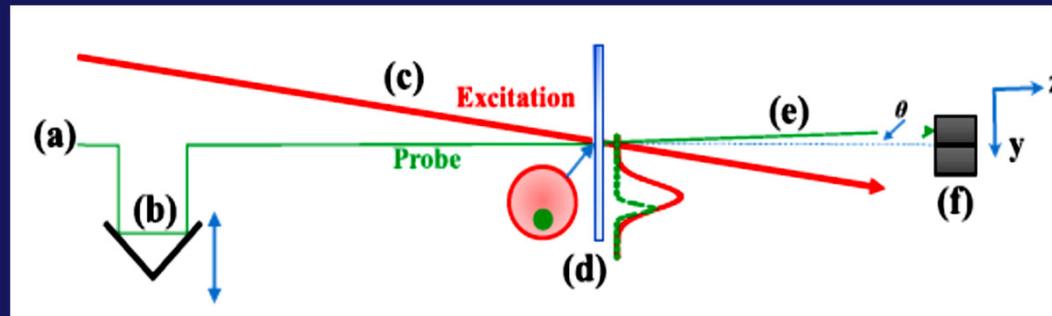


Driving  
beam  
peak power  
1.5 kW

Opt. Lett. 38 (2013) 3518

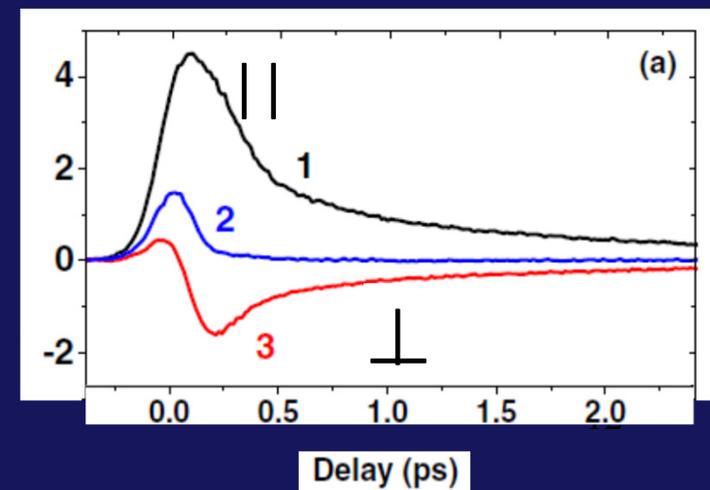
# Beam deflection measurement of time and polarization resolved ultrafast nonlinear refraction

Manuel R. Ferdinandus,<sup>1</sup> Honghua Hu,<sup>1</sup> Matthew Reichert,<sup>1</sup> David J. Hagan,<sup>1,2</sup> and Eric W. Van Stryland<sup>1,2,\*</sup>



$$\Delta n_p(x, y, t) = \Delta n_p(t) \exp\left(\frac{-2(x^2 + y^2)}{w_e^2}\right)$$

$\langle \Delta n_p \rangle (\times 10^{-5})$



## Densidade de energia

$$E_i(t) = \sum_n E_i(\omega_n) e^{-i\omega t}$$

## Teorema de Poynting

$$U = \frac{1}{2} \langle \vec{D} \cdot \vec{E} \rangle = \frac{1}{2} \sum_i \langle D_i E_i \rangle$$

$$D_i(t) = \epsilon_0 \sum_j \epsilon_{ij} E_j(t) = \epsilon_0 \sum_j \sum_n \epsilon_{ij}(\omega_n) E_j(\omega_n) e^{-i\omega_n t}$$

$$\epsilon_{ij}(\omega_n) = \delta_{ij} + \chi_{ij}^{(1)}(\omega_n)$$

Densidade no vácuo

No meio dielétrico

$$U = \frac{\epsilon_0}{2} \sum_i \sum_n E_i^*(\omega_n) E_i(\omega_n) + \frac{\epsilon_0}{2} \sum_{ij} \sum_n E_i^*(\omega_n) \chi_{ij}^{(1)}(\omega_n) E_j(\omega_n)$$

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No meio não linear – (Boyd Seção 1.5)

$$U = \frac{\epsilon_0}{2} \sum_i \sum_n \chi_{ij}^{(1)}(\omega_n) E_i^*(\omega_n) E_j(\omega_n) \\ + \frac{\epsilon_0}{3} \sum_{ijk} \sum_{mn} \chi_{ijk}^{(2)'}(-\omega_n - \omega_m, \omega_m, \omega_n) E_i^*(\omega_m + \omega_n) E_j(\omega_m) E_k(\omega_n) \\ \frac{\epsilon_0}{4} \sum_{ijkl} \sum_{mno} \chi_{ijkl}^{(3)'}(-\omega_0 - \omega_n - \omega_m, \omega_m, \omega_n, \omega_0) E_i^*(\omega_m + \omega_n \\ + \omega_0) E_j(\omega_m) E_k(\omega_n) E_l(\omega_0) + \dots$$

$$P_i(\omega_n) = \frac{\partial U}{\partial E_i^*(\omega_n)}$$

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

$$P_i^{(2)}(\omega_m + \omega_n) = \epsilon_0 \sum_{jk} \sum_{mn} \chi_{ij}^{(2)'}(-\omega_m - \omega_n, \omega_m, \omega_n) E_j(\omega_m) E_k(\omega_n)$$

$$P_i^{(3)}(\omega_m + \omega_n + \omega_o) =$$

$$\epsilon_0 \sum_{jkl} \sum_{mno} \chi_{ijkl}^{(3)'}(-\omega_m - \omega_n - \omega_o, \omega_m, \omega_n, \omega_o) \times E_j(\omega_m) E_k(\omega_n) E_l(\omega_o)$$

A demonstração só vale para meios transparentes

# Descrição da não linearidade óptica no domínio temporal

As descrições nos domínios espectral e temporal são equivalentes. A descrição temporal é mais conveniente quando são envolvidos pulsos curtos

$$P^{(1)}(t) = \epsilon_0 \int_0^{\infty} R^{(1)}(\tau) E(t - \tau) d\tau$$

$R^{(1)}(\tau)$  - resposta linear no instante  $t$  a um campo aplicado no instante  $(t - \tau)$

$$R^{(1)}(\tau) = 0 \quad \text{se} \quad \tau < 0$$

A polarização depende do campo passado e não dos valores do campo no futuro

A equação pode ser transformada para o domínio espectral introduzindo uma transformada de Fourier

$$E(\omega) = \int_{-\infty}^{\infty} E(t) e^{i\omega t} dt \quad E(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E(\omega) e^{-i\omega t} d\omega$$

$$P^{(1)}(t) = \epsilon_0 \int_0^{\infty} R^{(1)}(\tau) E(t - \tau) d\tau$$

$$P^{(1)}(t) = \epsilon_0 \int_0^{\infty} d\tau \frac{1}{2\pi} \int_{-\infty}^{\infty} R^{(1)}(\tau) E(\omega) e^{-i\omega(t-\tau)} d\omega$$

$$P^{(1)}(t) = \epsilon_0 \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \int_0^{\infty} d\tau R^{(1)}(\tau) E(\omega) e^{i\omega\tau} e^{-i\omega t}$$

$$P^{(1)}(t) = \epsilon_0 \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \chi^{(1)}(\omega, \omega) E(\omega) e^{-i\omega t}$$

$$\chi^{(1)}(\omega, \omega) = \int_0^{\infty} d\tau R^{(1)}(\tau) e^{i\omega\tau}$$

$$P^{(1)}(t) = \epsilon_0 \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} P^{(1)}(\omega) e^{-i\omega t}$$

$$P^{(1)}(\omega) = \epsilon_0 \chi^{(1)}(\omega, \omega) E(\omega)$$

$$P^{(2)}(t) = \epsilon_0 \int_0^{\infty} d\tau_1 \int_0^{\infty} d\tau_2 R^{(2)}(\tau_1, \tau_2) E(t - \tau_1) E(t - \tau_2)$$

$$R^{(2)}(\tau_1, \tau_2) = 0 \quad \tau_1, \tau_2 < 0$$

$$P^{(2)}(t) = \epsilon_0 \times \int_{-\infty}^{\infty} \frac{d\omega_1}{2\pi} \int_{-\infty}^{\infty} \frac{d\omega_2}{2\pi} \int_0^{\infty} d\tau_1 \int_0^{\infty} d\tau_2 R^{(2)}$$

$$P^{(2)}(t) = \epsilon_0 \int_{-\infty}^{\infty} \frac{d\omega_1}{2\pi} \int_{-\infty}^{\infty} \frac{d\omega_2}{2\pi} \chi^{(2)}(\omega_\sigma, \omega_1, \omega_2) E(\omega_1) E(\omega_2) e^{-i\omega_\sigma t}$$

$$\chi^{(2)}(\omega_\sigma, \omega_1, \omega_2) = \int_0^\infty d\tau_1 \int_0^\infty d\tau_2 R^{(2)}(\tau_1, \tau_2) e^{i(\omega_1\tau_1 + \omega_2\tau_2)}$$

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De modo análogo podemos obter

$$\begin{aligned} & \chi^{(3)}(\omega_\sigma, \omega_1, \omega_2, \omega_3) \\ &= \int_0^\infty d\tau_1 \int_0^\infty d\tau_2 \int_0^\infty d\tau_3 R^{(3)}(\tau_1, \tau_2, \tau_3) e^{i(\omega_1\tau_1 + \omega_2\tau_2 + \omega_3\tau_3)} \end{aligned}$$

$$\omega_\sigma = \omega_1 + \omega_2 + \omega_3$$

Para mais detalhes e referências sobre as técnicas discutidas nas aulas e mais algumas sugiro consultar o artigo:

**IOP** Publishing

Rep. Prog. Phys. **79** (2016) 036401 (30pp)

Review

## Techniques for nonlinear optical characterization of materials: a review

Cid B de Araújo<sup>1</sup>, Anderson S L Gomes<sup>1</sup> and Georges Boudebs<sup>2</sup>

Four wave-mixing

Phase conjugation

Kerr gate

Scattered Light

Imaging Method –SLIM

Pump-and-probe

Beam deflection  
techniques

Single beam Z-scan

Two-color Z-scan

Reflection Z-scan

Eclipsing Z-scan

Thermally managed

TM-Z scan

TM-EZ scan

Hartmann

- Schack Z-scan

White-light continuum  
Z-scan

Intensity scan (I-scan)

## Na próxima aula:

- (1) Propriedades de simetria das susceptibilidades
- (2) Efeitos não paramétricos