Structured Materials and Structured Light for Photonics

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Presented at META'15 New York, USA, August 4, 2015

Outline and Prospectus

Instead of a broad overview, I will concentrate on two topics

1. Development of a Plasmonic q-Plate (SAM to OAM Interface)

2. Huge NLO Response of ITO at its ENZ Wavelength

For other work of my group, I invite you to seven additional presentations.

Presentations from My Research Group

Tuesday Meta P8: **Building a better metasurface: high accuracy fabrication of plasmonic nano-structures,** Sebastian Andreas Schulz, Jeremy Upham, Frederic Bouchard, Israel De Leon, Ebrahim Karimi, Robert W. Boyd

Tuesday ICOAM 4:20 PM **Observation of optical polarization Möbius strips,** Ebrahim Karimi, Thomas Bauer, Peter Banzer, Sergej Orlov, Andrea Rubano, Lorenzo Marrucci, Enrico Santamato, Robert W. Boyd, Gerd Leuchs

Wed Poster ICOAM 6:00 to 7:30 **Quantum walks and tailored wave packet dynamics of orbital angular momentum states of light,** Filippo Cardano, Francesco Massa, Hammam Qassim, Ebrahim Karimi, Domenico Paparo, Corrado de Lisio, Sergei Slussarenko, Fabio Sciarrino, Enrico Santamato, Robert W. Boyd, Lorenzo Marrucci

Thursday ICOAM 1:50 PM **Quantum properties of orbital angular momentum of light**, Robert W. Boyd

Thursday ICOAM Poster 6:00 to 7:30 **Quantum coherence recovery of OAM reentangled states by spatial propagation,** Jeremie Harris, Frederic Bouchard, Harjaspreet Mand, Nicolas Bent, Robert W. Boyd, Ebrahim Karimi

Friday Meta 15:00 **: An improvement over the effective index method for photonic crystal simulations,** Sebastian Schulz, Anthony Park, Israel De Leon, Jeremy Upham, Robert W. Boyd

Friday ICOAM 10:10 AM – 10:25 AM **Holographic generation of highly twisted electron beams,** Vincenzo Grillo, Gian Carlo Gazzadi, Ebrahim Karimi, Roberto Balboni, Erfan Mafakheri, Stefano Frabboni, Robert W. Boyd

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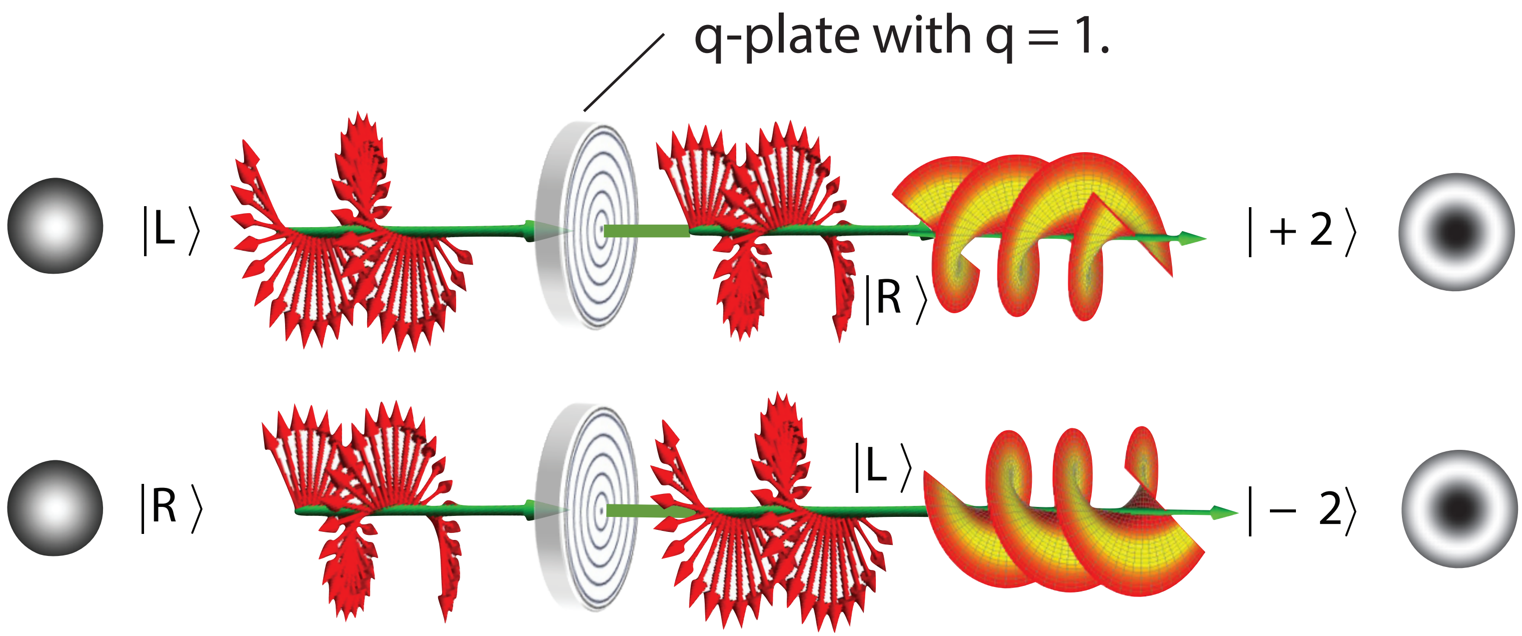
Photonic q-Plates: A Quantum Interface

Ability to change basis of encoding useful in quantum information studies

Spin angular momentum can be transferred to OAM by means of a q-plate

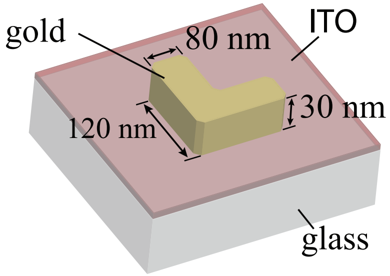
q-plates are usually carefully constructed liquid-crystal cells

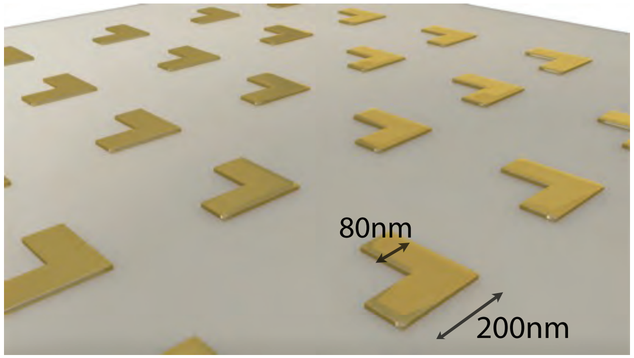


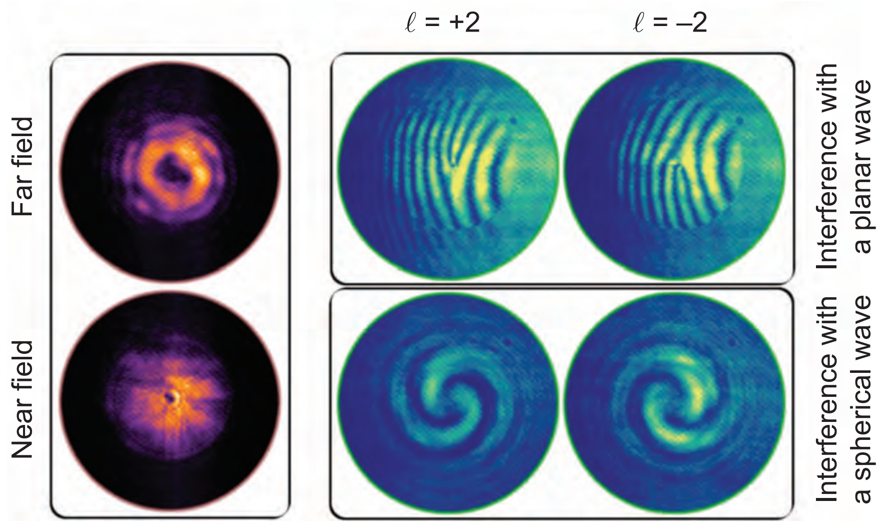
Marrucci et al., PRL 96, 163905 (2006)
Karimi et al., APL 98, 231124 (2009)

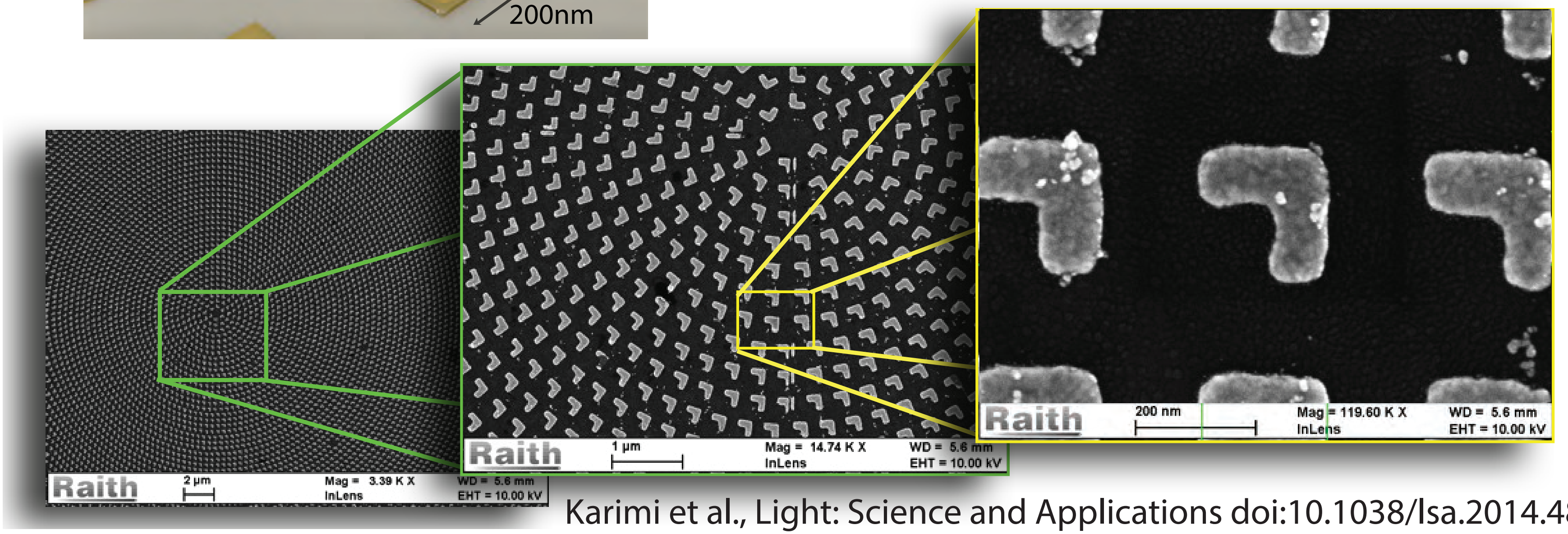
Fabrication of a Nano-Scale q-Plate

- A q-plate is a device that converts spin angular momentum into orbital angular momentum.
- It functions as a quantum interface.
- Fabricated device is only 30-nm thick and thus suitable for use in integrated quantum circuits.





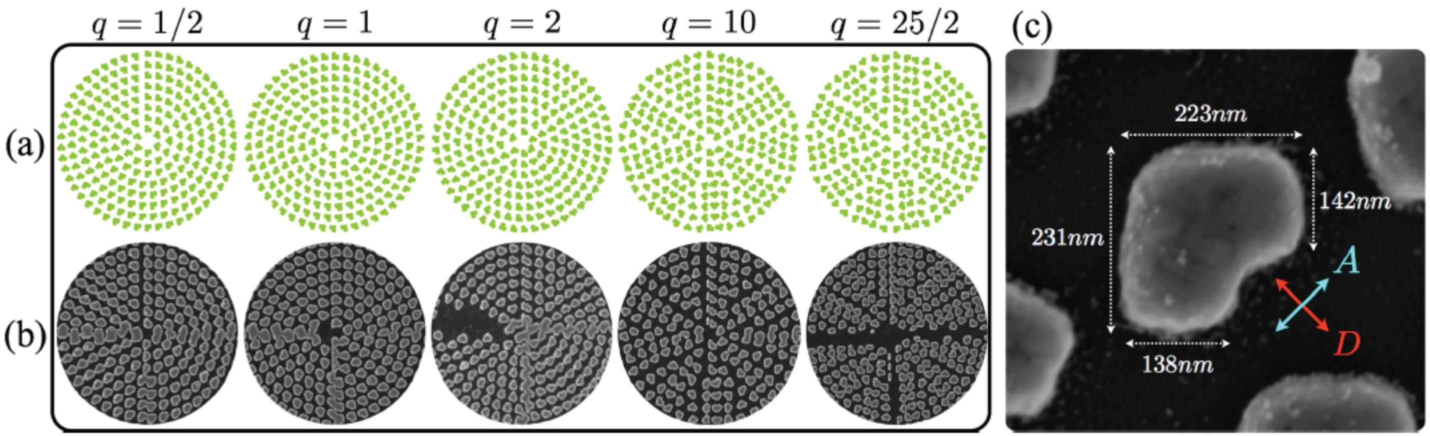




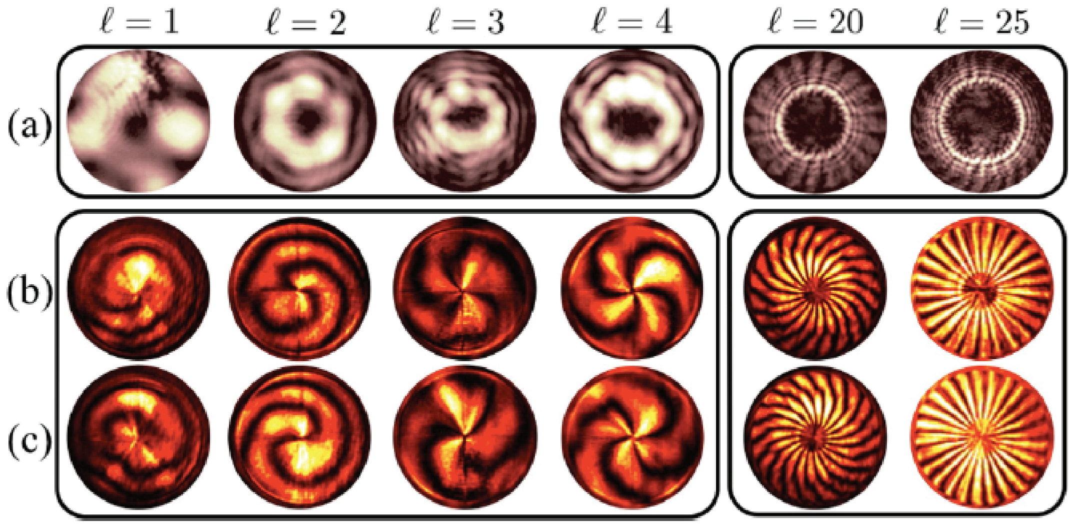
Karimi et al., Light: Science and Applications doi:10.1038/lsa.2014.48 (2014)

q-Plates for Producing Arbitrary ℓ

- Design of plasmonic metasurfaces for arbitray q



- Performance of the structures
  - Excite with right- or left-hand-circular light
  - ℓ value changes by $\pm 2q$



Bouchard, De Leon, Schulz, Upham, Karimi, and Boyd, Appl. Phys. Lett. 105, 101905 (2014).

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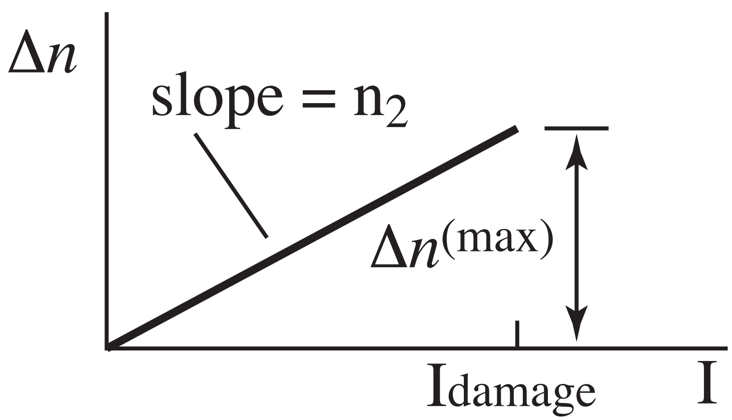
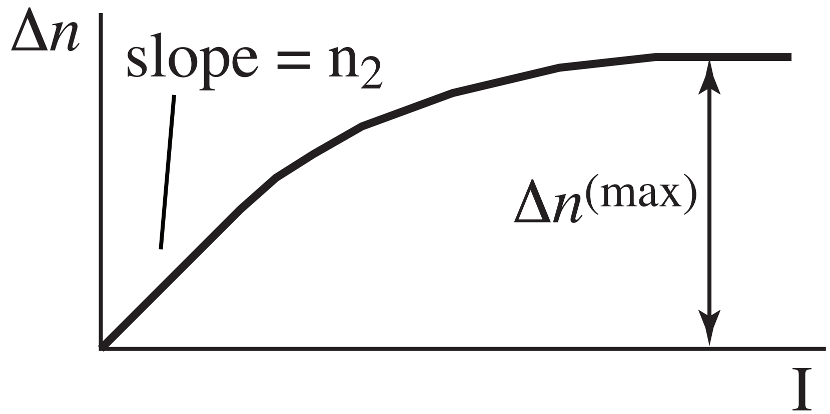
What Makes a Good (Kerr-Effect) Nonlinear Optical Material?

Want n_2 large; and also want $\Delta n^{(max)}$ large.

These are distinct concepts! Damage and saturation can limit $\Delta n^{(max)}$





We report a material for which both n_2 and $\Delta n^{(max)}$ are extremely large!

For ITO at ENZ wavelength, $n_2 = 8 \times 10^{-11}$ cm^2/W and $\Delta n^{(max)} = 0.8$

(For silica glass $n_2 = 3.2 \times 10^{-16}$ cm^2/W, $I_{damage} = 1$ TW/cm^2, and thus $\Delta n^{(max)} = 3 \times 10^{-4}$)

Nonlinear Optical Properties of Indium Tin Oxide (ITO)

ITO is a degenerate semiconductor (so highly doped as to be metal-like).

It has a very large density of free electrons, and a bulk plasma frequency corresponding to a wavelength of approximately 1.24 μm.

Recall the Drude formula

$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}$$

Note that $\mathrm{Re}\,\epsilon = 0$ for $\omega = \omega_p/\sqrt{\epsilon_\infty} \equiv \omega_0$.

The region near ω_0 is known as the epsilon-near-zero (ENZ) region.

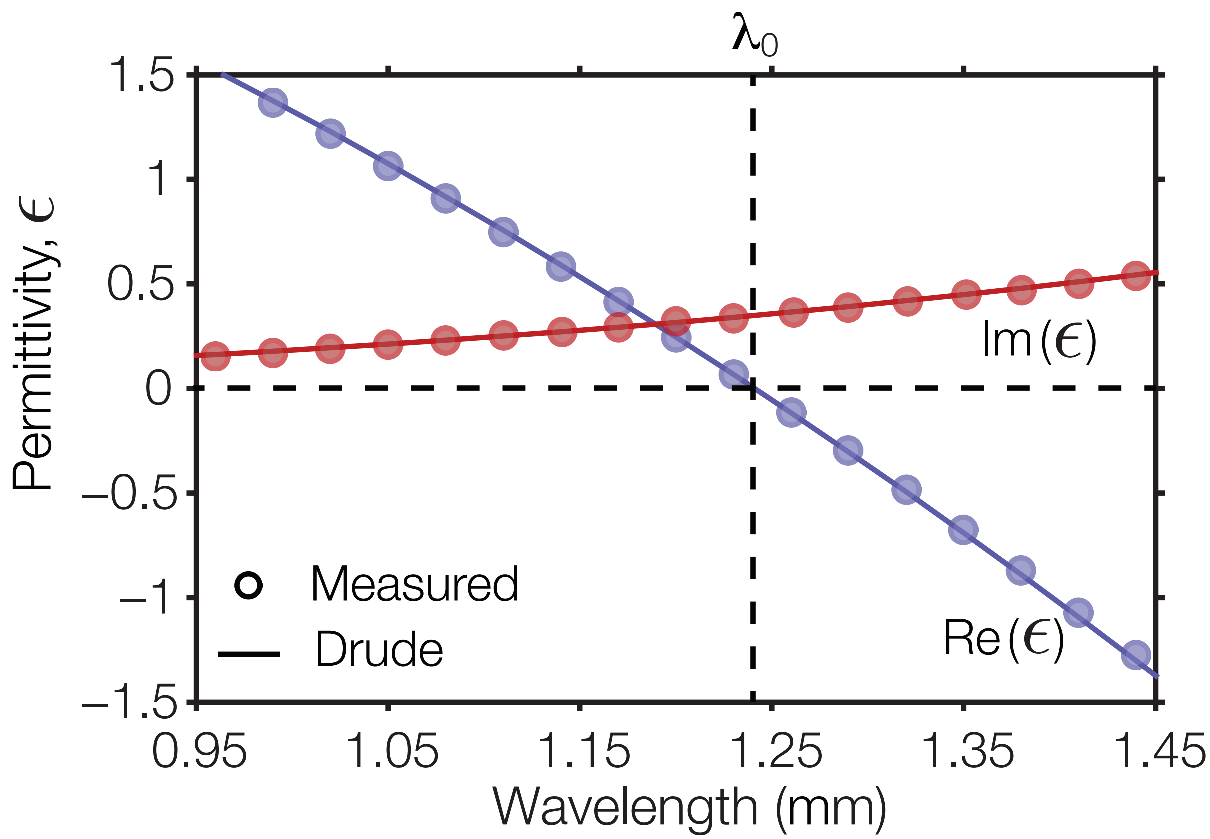
There has been great recent interest in studies of ENZ phenomena:

H. Suchowski, K. O'Brien, Z. J. Wong, A. Salandrino, X. Yin, and X. Zhang, Science 342, 1223 (2013).
C. Argyropoulos, P.-Y. Chen, G. D'Aguanno, N. Engheta, and A. Alu, Phys. Rev. B 85, 045129 (2012).
S. Campione, D. de Ceglia, M. A. Vincenti, M. Scalora, and F. Capolino, Phys. Rev. B 87, 035120 (2013).
A. Ciattoni, C. Rizza, and E. Palange, Phys. Rev. A 81,043839 (2010).

The Epsilon-Near-Zero (ENZ) region of Indium Tin Oxide (ITO)

Measured real and imaginary parts of the dielectric permittivity.

Commercial ITO sample, 310 nm thick on a glass substrate



Drude fit

$\epsilon_\infty = 3.77$

$\gamma = 0.0468\ \omega_p$

$\omega_p/2\pi = 473\ \mathrm{THz}$

Note that $\mathrm{Re}(\epsilon)$ vanishes at 1.24 mm, but that the loss-part $\mathrm{Im}(\epsilon)$ is non-zero.

Implications of ENZ Behavior for Nonlinear Optics

Here is the intuition for why the ENZ conditions are of interest in NLO

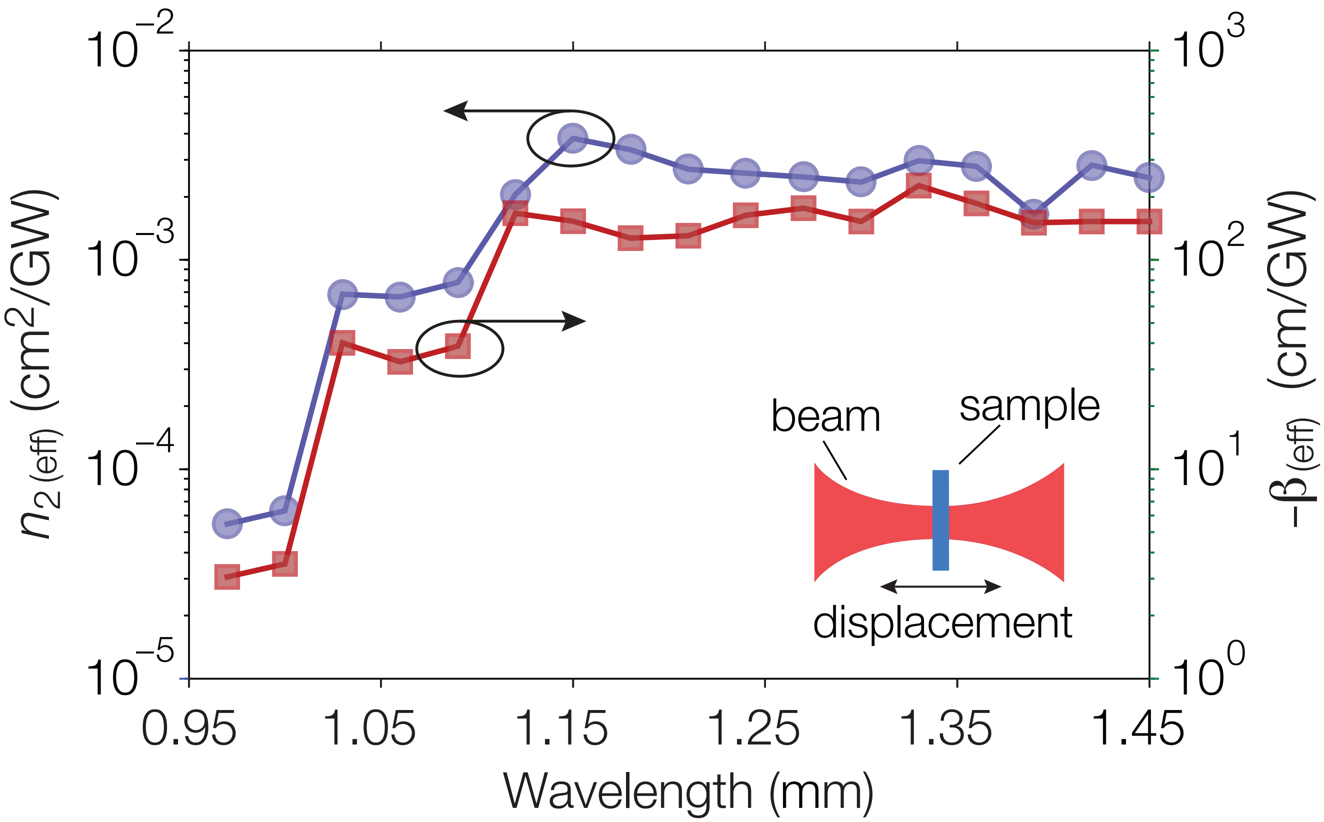
Recall the standard relation between n_2 and $\chi^{(3)}$

$$n_2 = \frac{3\chi^{(3)}}{4\epsilon_0 c\, n_0\, \mathrm{Re}(n_0)}$$

Note that for ENZ conditions the denominator becomes very small, leading to a very large value of n_2

Z-Scan Measurements of the NLO Response

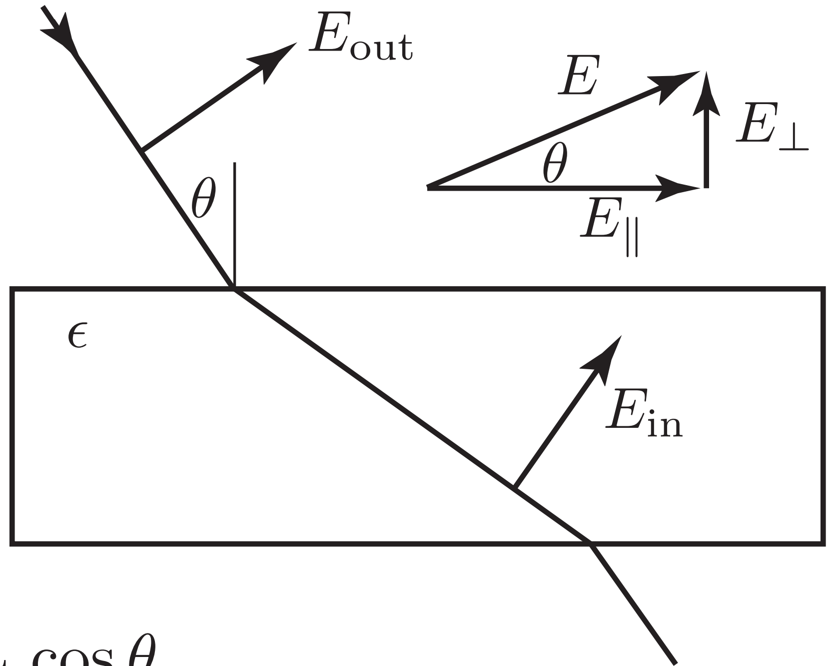
NLO response at *normal incidence*



Maximum measured value of n_2 is 3×10^{-3} cm^2/GW = 3×10^{-12} cm^2/W

Note that n_2 is positive (self focusing) and β is negative (saturable absorption).

The NLO Response Is Even Larger at Oblique Incidence



Standard boundary conditions show that:

$$E_{\text{in},\parallel} = E_{\text{out},\parallel} = E_{\text{out}} \cos\theta$$

$$D_{\text{in},\perp} = D_{\text{out},\perp} \quad \Rightarrow \quad E_{\text{in},\perp} = E_{\text{out},\perp}/\epsilon = E_{\text{out}} \cos\theta/\epsilon$$

Thus the total field inside of the medium is given by

$$E_{\text{in}} = E_{\text{out}} \sqrt{\cos^2\theta + \frac{\sin^2\theta}{\epsilon}}$$

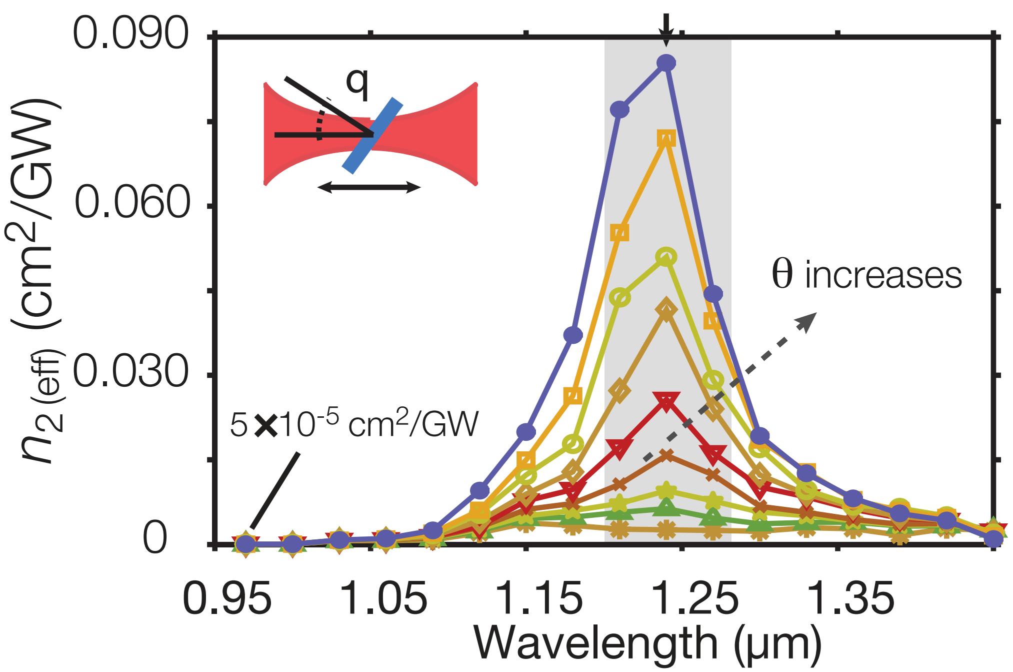
Note that, for $\epsilon < 1$, E_{in} exceeds E_{out} for $\theta \neq 0$.

Note also that, for $\epsilon < 1$, E_{in} increases as θ increases.

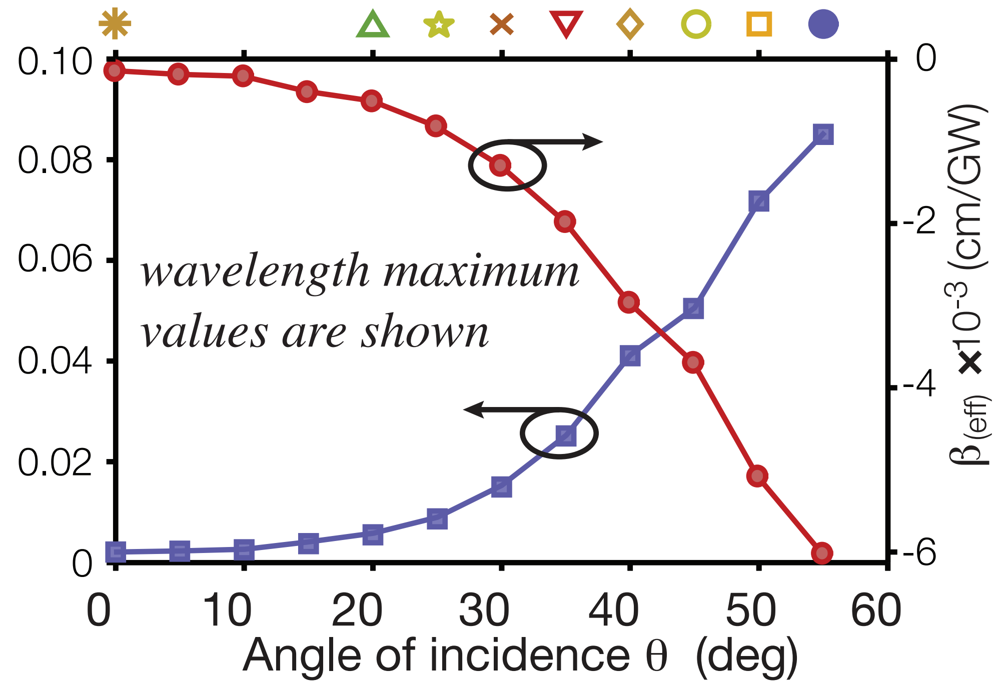
Nonlinear Optical Response at Oblique Incidence

Z-scan measurements for non-normal incidence

Wavelength dependence of n_2



Variation with incidence angle



- Both n_2 and nonlinear absorption increase with angle of incidence
- n_2 achieves a maximum value of 0.08 cm^2/GW = 8×10^{-11} cm^2/W at 1.25 μm and 60 deg.

Why is n_2 so large?

The short-wavelength value of n_2 of ITO is 5×10^{-5} cm^2/GW, which is 150 times larger that of fused silica (3.2×10^{-7} cm^2/GW).

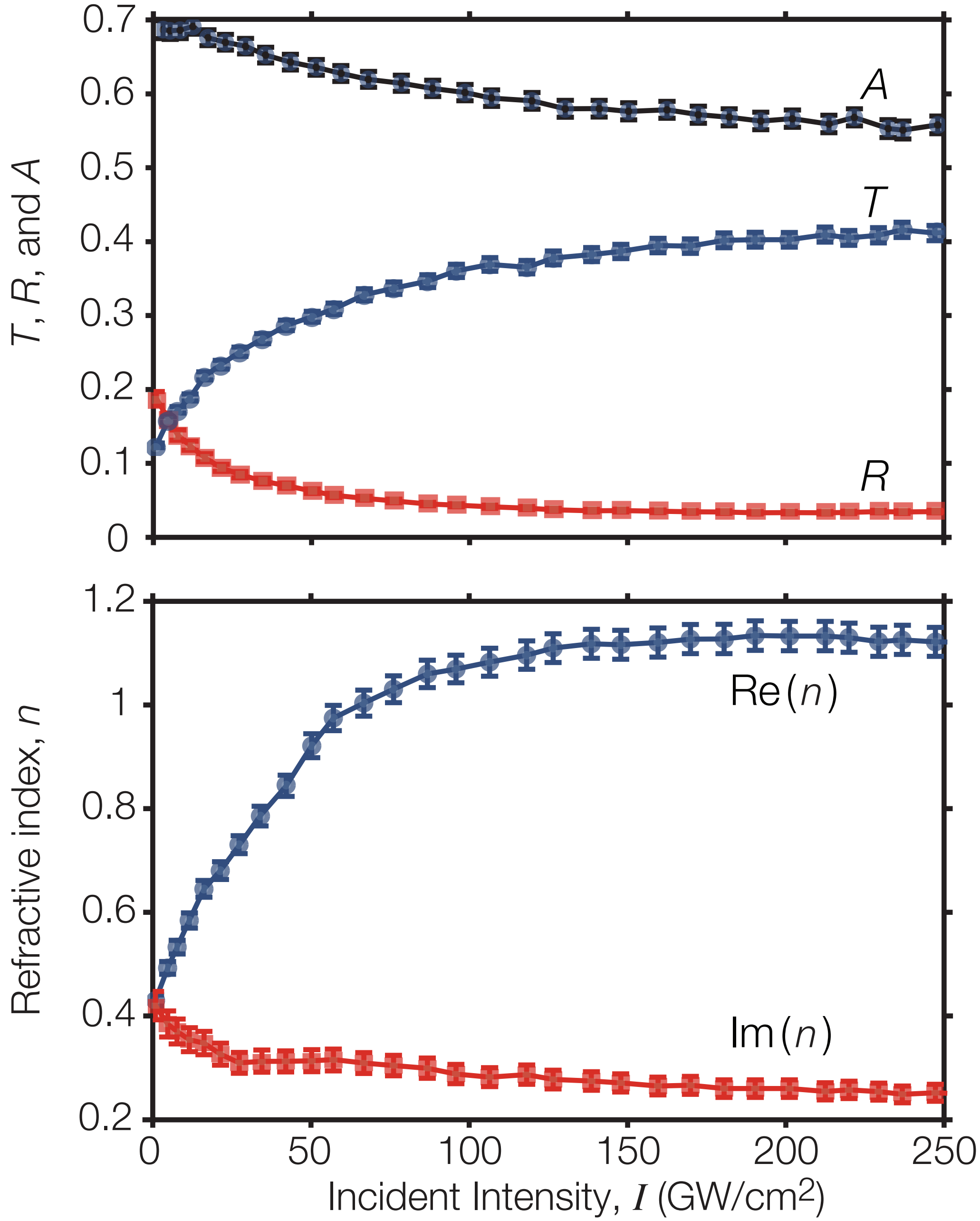
There is a 50x enhancement from working at the ENZ wavelength and an additional 30x enhancement from using non-normal incidence.

Thus $n_2 = 8 \times 10^{-2}$ cm^2/GW, which is 2.5×10^5 times that of fused silica.

Incidentally, for arsenic trisulfide glass, $n_2 = 2.4 \times 10^{-4}$ cm^2/GW. which is 800 times larger than that of fused silica.

R.E. Slusher et al., J. Opt. Soc. Am. B 21, 1146 (2004).

Beyond the $\chi^{(3)}$ limit



The nonlinear change in refractive index is so large as to change the transmission, absorption, and reflection!

Note that transmission is increased at high intensity.

Here is the refractive index extracted from the above data.

Note that the total nonlinear change in refractive index is $\Delta n = 0.8$.

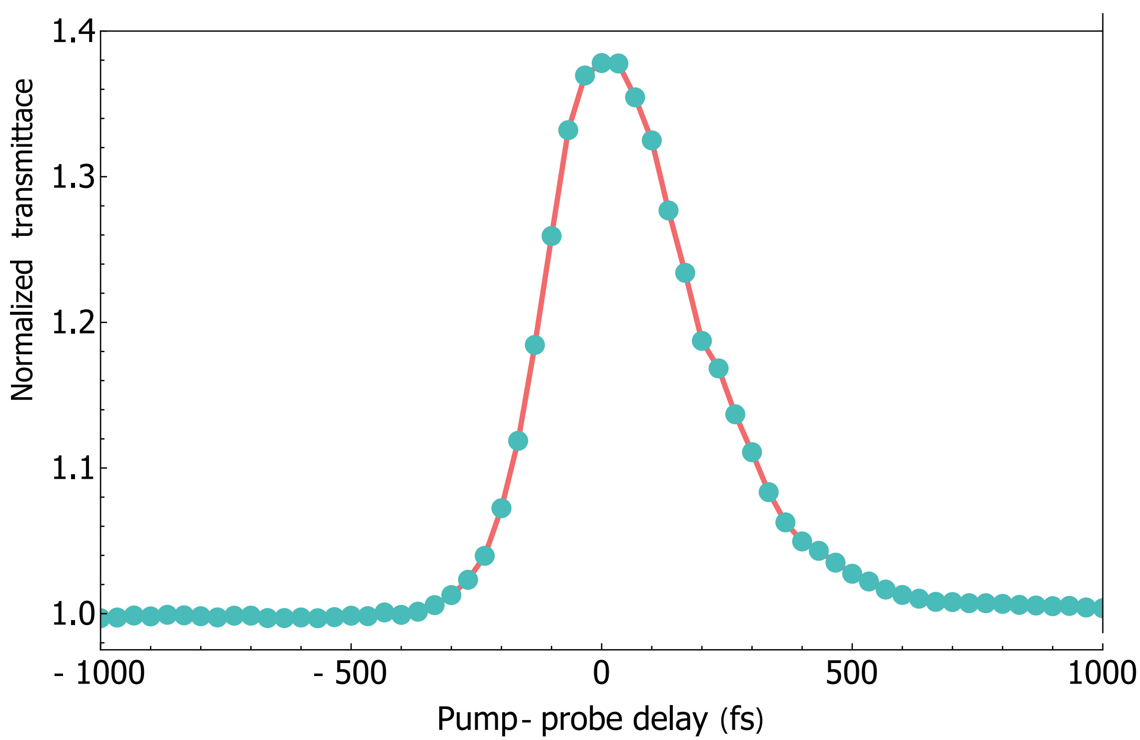
The absorption decreases at high intensity, allowing a predicted NL phase shift of 0.5 radians.

Measurement of Response Time of ITO

We have performed a pump-probe measurement of the response time. Both pump and probe are 100 fs pulses at 1.2 μm.

Data suggests a response time of 270 fs.

ITO will support THz switching speeds



Implications of the Large NLO Response of ITO

Indium Tin Oxide at its ENZ wavelength displays enormously strong NLO properties:

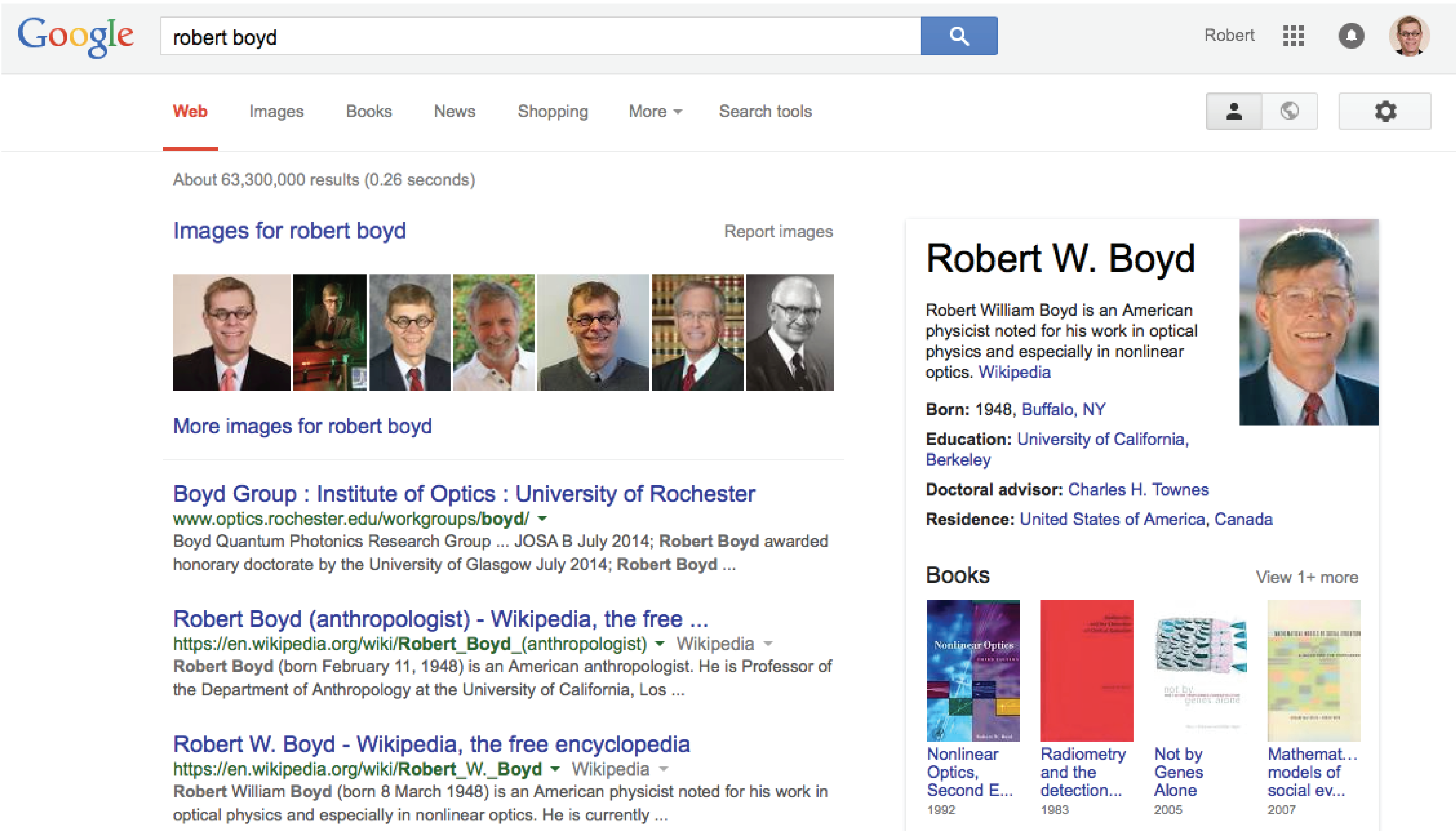
n_2 is 2.5 x 10^5 times that of fused silica
nonlinear change in refractive index as large as 0.8

Note that the usual "power-series" description of NLO is not adequate for describing this material. (We can have fun reformulating the laws of NLO!)

Some possible new effects

Waveguiding outside the "weakly-guiding" regime
Efficient all-optical switching
No need for phase-matching

Why We Shouldn't Always Trust Google

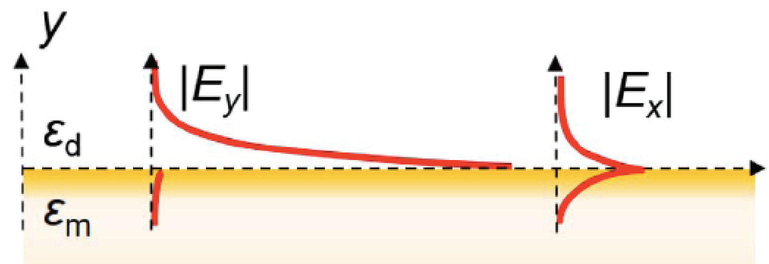


An Additional Topic (If Time Permits)

What are the nonlinear optical properties of surface plasmon polaritons?

What are the NLO properties of Surface Plasmon Polaritons?

- Surface plasmon polaritons (SPPs) are surface excitations at the interface between a metal and a dielectric.

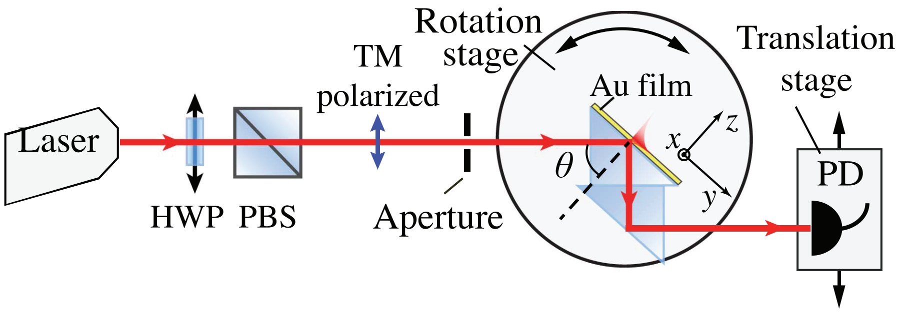


Baron et al., JOSA B (2014)

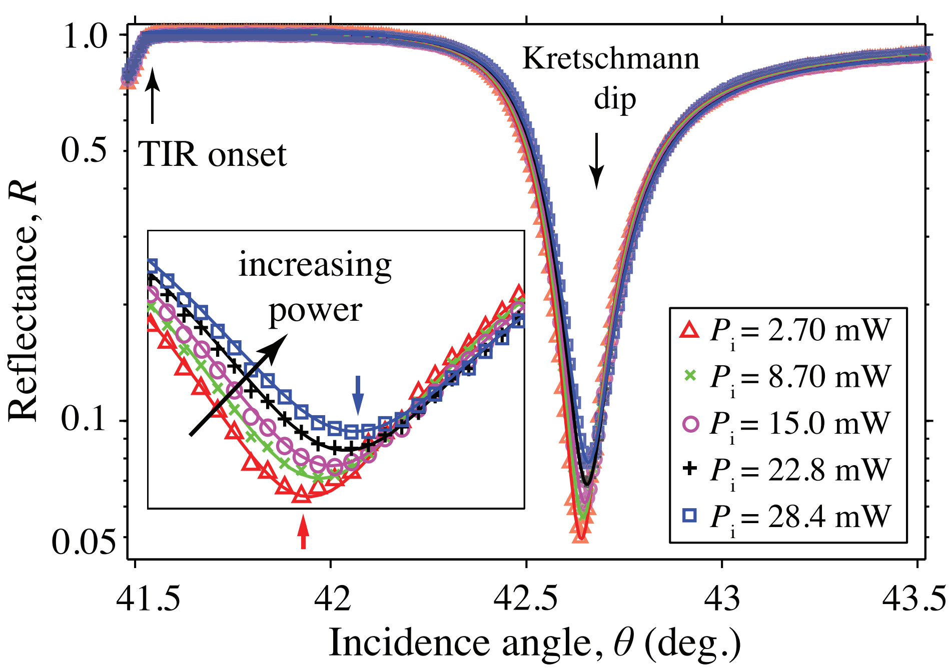
- Light is tightly confined in transverse direction.
- Permits high packing density of photonic circuits.
- Also leads to strong NLO response.
  (Metals are highly nonlinear and the light is tightly confined).
- But SPPs are highly lossy
- How much nonlinear phase shift does an SPP acquire (in one absorption length)? (Can it be as large as π radians?)

What are the NLO properties of Surface Plasmon Polaritons?

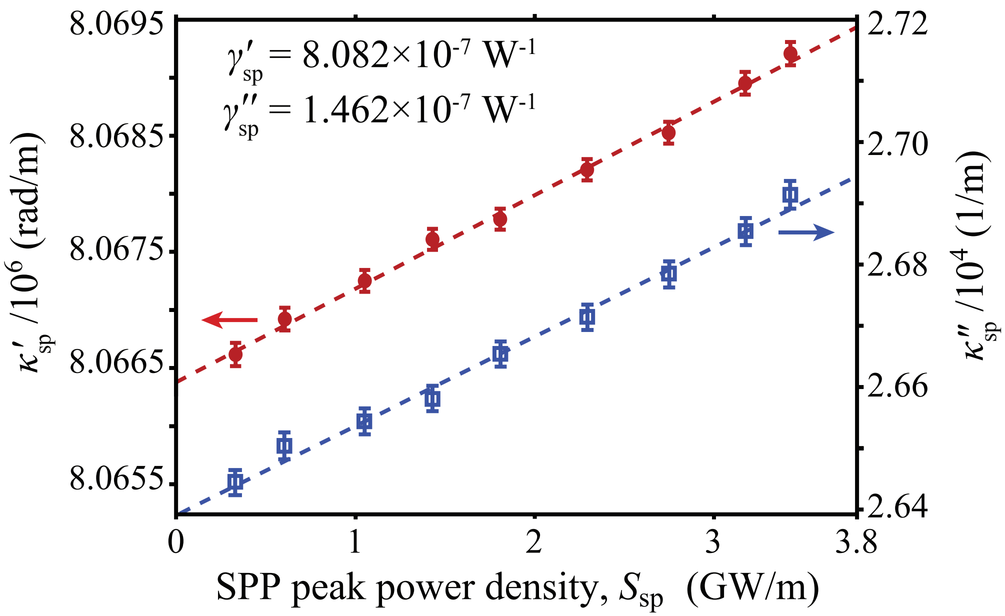
- Kretschmann setup



- Measure intensity dependence of the Kretschmann angle
  - power varies from 2.7 to 28 mW
  - intensity varies from 2 to 22 GW/cm
  - laser wavelength is 796.5 nm



- We can extract the value of $\chi^{(3)}$ of gold



$$\tilde{\chi}^{(3)}_{\mathrm{Au}} = (4.67 + i3.03) \times 10^{-19}\ \mathrm{m}^2/\mathrm{V}^2$$

- But the predicted maximum NL phase shift in one absorption length is only π/60

I. De Leon, Z. Shi, A. Liapis and R.W.Boyd, Optics Letters 39, 2274 (2014)