Nonlinear and Switchable Metamaterials for Optical Data Processing

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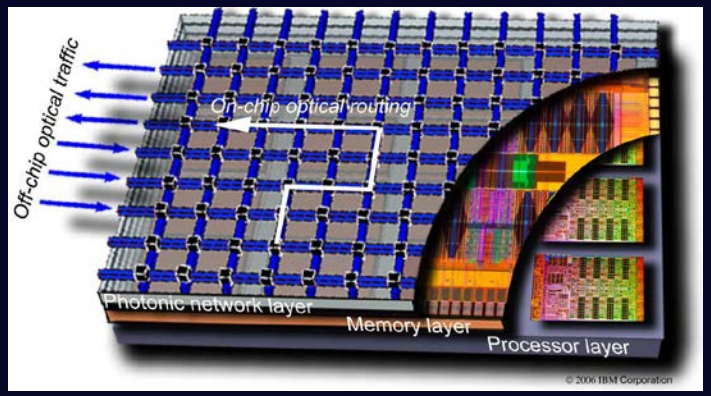
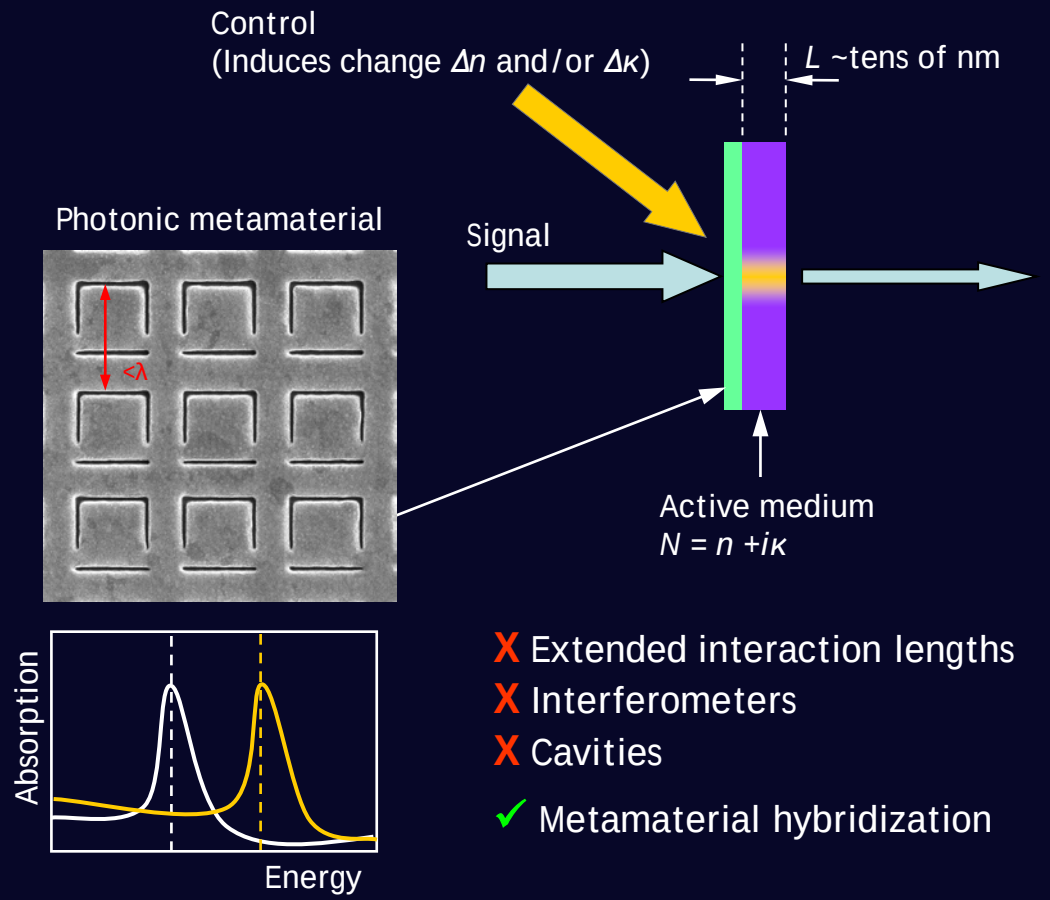
Solution: Photonic metamaterials

ICT progression:
Smaller, Faster, More efficient …



IBM concept: 3D processor
with on-chip nanophotonics



X Extended interaction lengths
X Interferometers
X Cavities
✓ Metamaterial hybridization

Small Δn or Δκ
⇒ Large change in resonant properties

Chalcogenide Phase-change Metamaterials:
Non-volatile, reversible, all-optical switching

B. Gholipour, J. Zhang, K. F. MacDonald,
D. W. Hewak, and N. I. Zheludev

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Chalcogenides: A material platform for future photonics

- Compounds of heavier Group 16 elements (S, Se, Te)
- Compositionally tuneable of properties

"amazingly flexible materials ..... perpetually underestimated in terms of their practical potential"

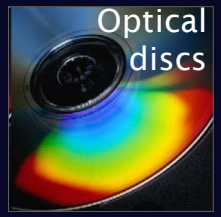
Yablonovitch (2004)

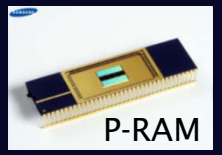
Optical nonlinearity: → ultrafast, low-power, all-optical signal processing, λ conversion

IR transparency: out to 20 μm → generation, guiding, modulation, detection of light

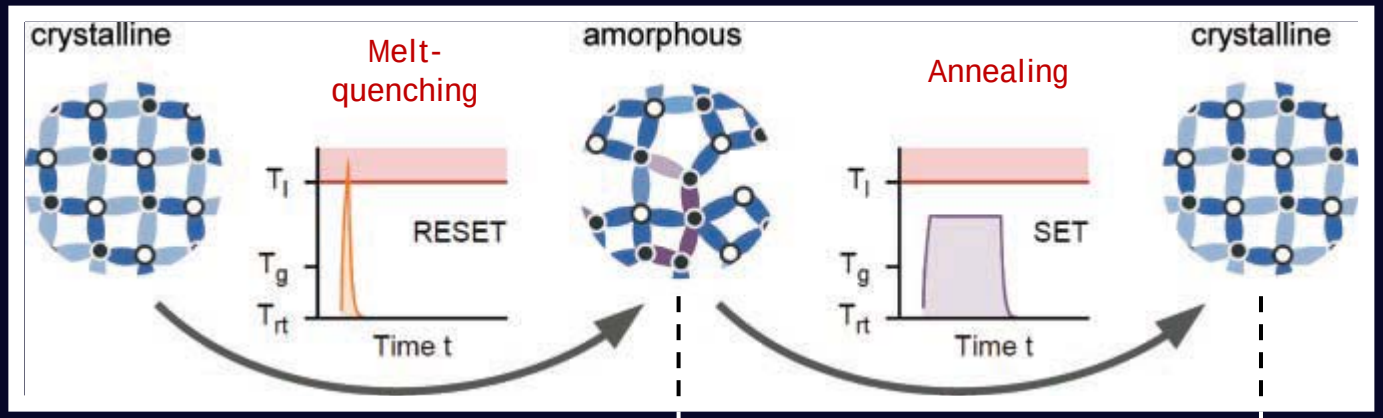
Phase-change functionality

- Optically/electrically-induced amorphous <-> crystalline transitions.
- Fast, low-power, non-volatile switching.





Chalcogenide phase-change functionality



Lencer, et al., *Adv. Mater.* 23, 2030 (2011)

Optical encoding/ readout

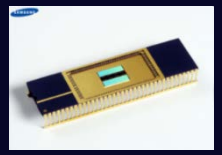
High reflectivity, *R*

Low *R*

Electronic encoding/ readout

High resistivity, *ρ*

Low *ρ*



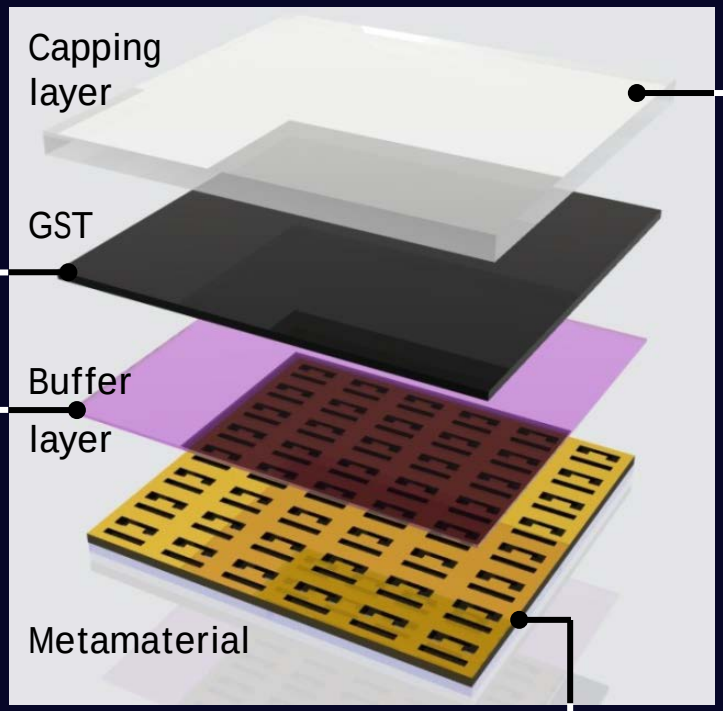
Chalcogenide metamaterial modulator structure

Chalcogenide phase-change layer:
15-40 nm Ge:Sb:Te (GST)

Thickness < λ/100

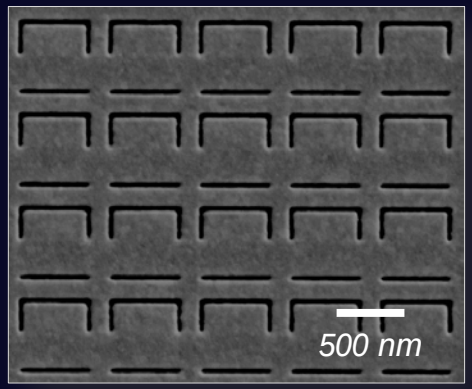
Inert buffer layer:
10-30 nm ZnS/SiO_2

Thickness < λ/150



Inert capping layer:
100 nm ZnS/SiO_2

Thickness < λ/15

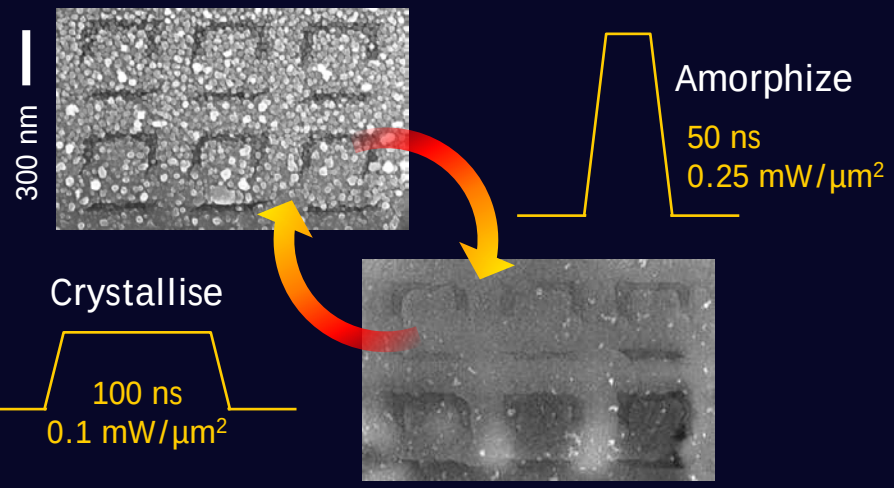


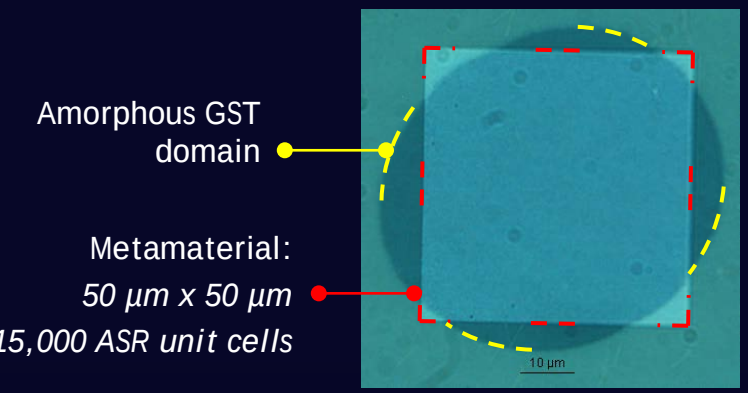
Plasmonic metamaterial:
50 nm Au on CaF/SiO_2
patterned by FIB / photolith.

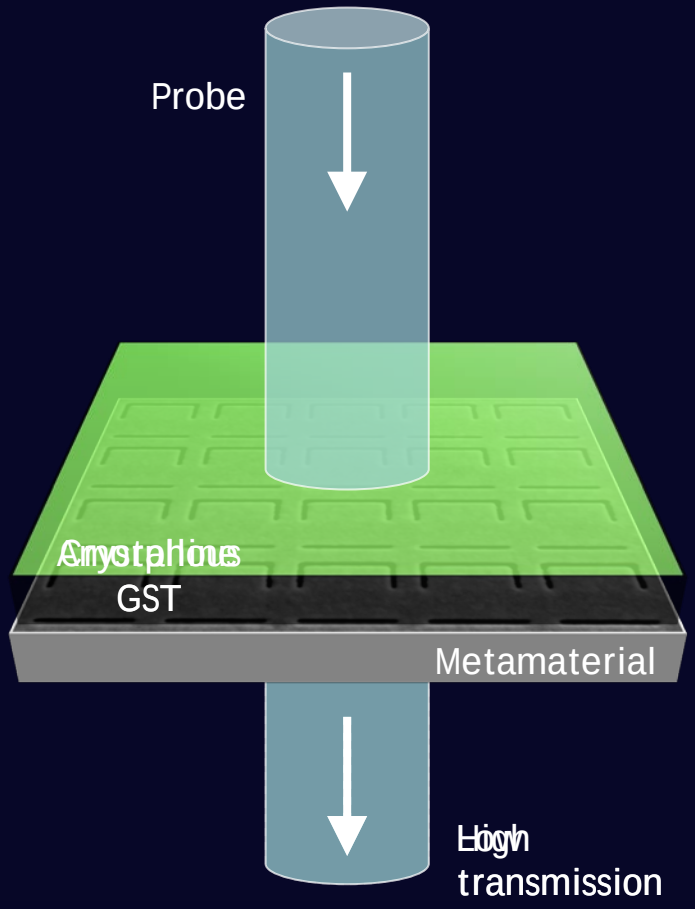
Thickness = λ/100 - λ/30

Large area, single-pulse, reversible optical phase switching

- Single 660 nm diode pulses → uniform switching over 2000 μm²



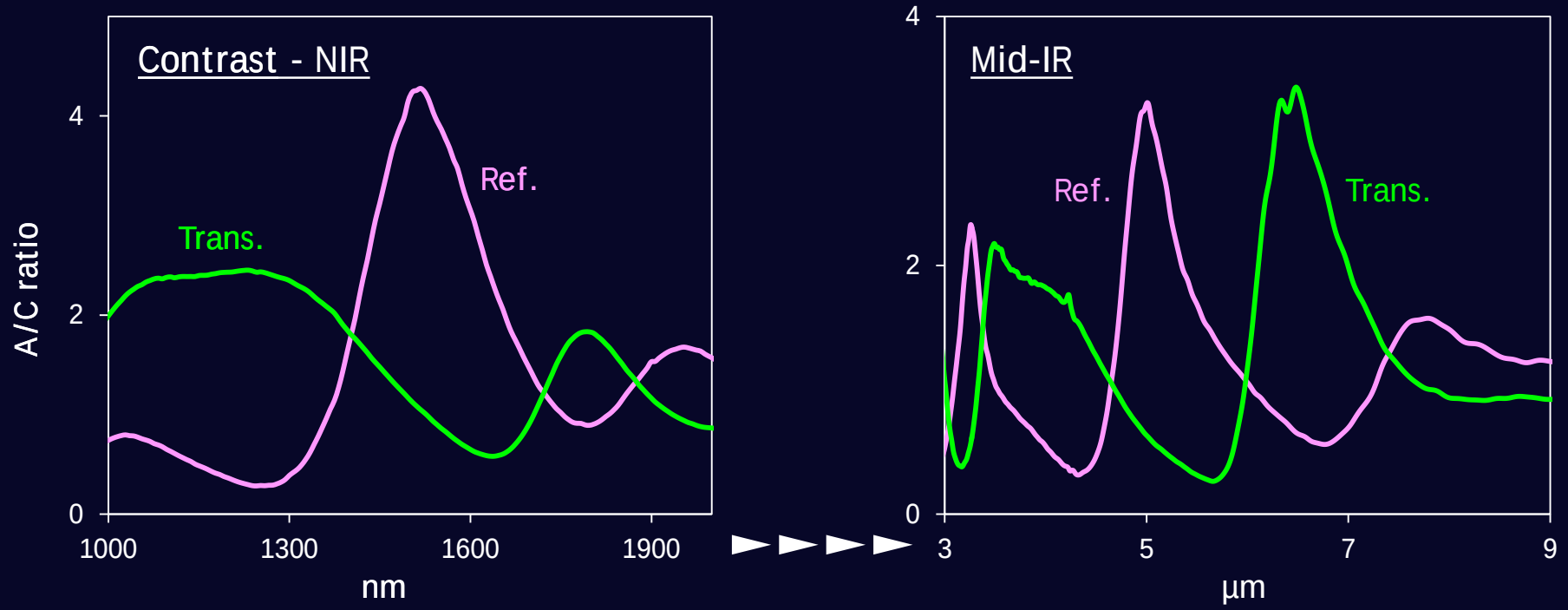




Non-volatile, near/mid-IR, all-optical metamaterial modulators

- 400 nm metamaterial unit cell
- Device thickness 175 nm (~λ/9)

- 600 nm
- 220 nm (~λ/27)



Chalcogenide non-volatile, metamaterial switches

- Functional material platform with proven technological pedigree
  - *Robust switching performance beyond that of other phase-change media*
- Metamaterial hybridization opens new exploitation horizons
  - *Nanoscale all-optical switching [4:1 contrast at λ/27 thickness]*
  - *Memory 'meta-devices'; IR spatial light modulation*
  - *Operational band adjustable across broad chalcogenide VIS-IR transparency range*

Engineering Gold's Nonlinearity:
Metamaterial framework as a functional medium

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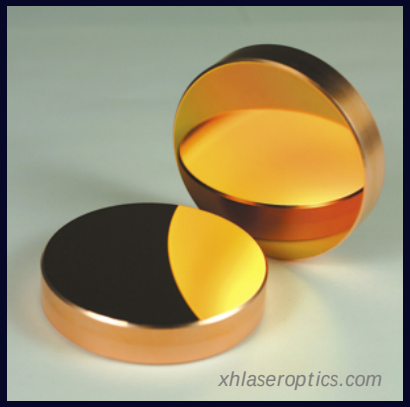
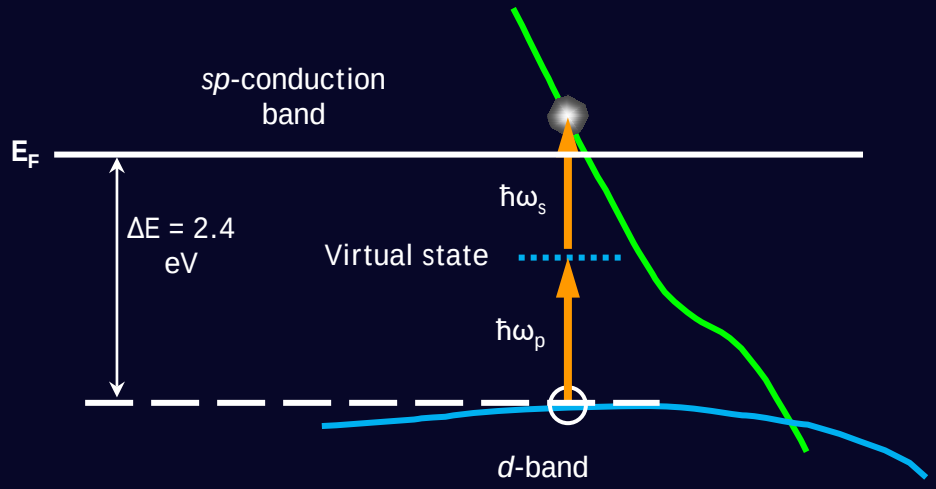
Gold nonlinearity



Nonlinear?

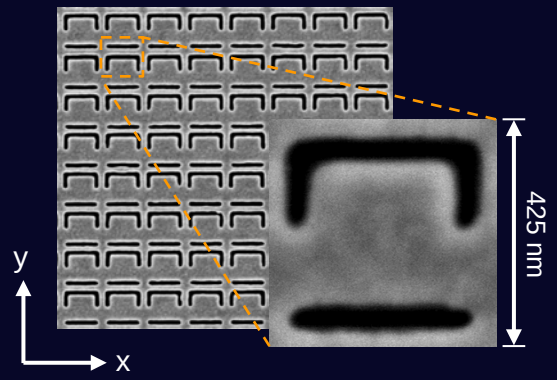


Two Photon Absorption (2PA)

- Absorption between *d*- and *sp*-states via virtual intermediate state (lifetime < 1 fs)
- Ultrafast pump-probe response (photons must coincide in time)
- β ~10^{-8} m/W

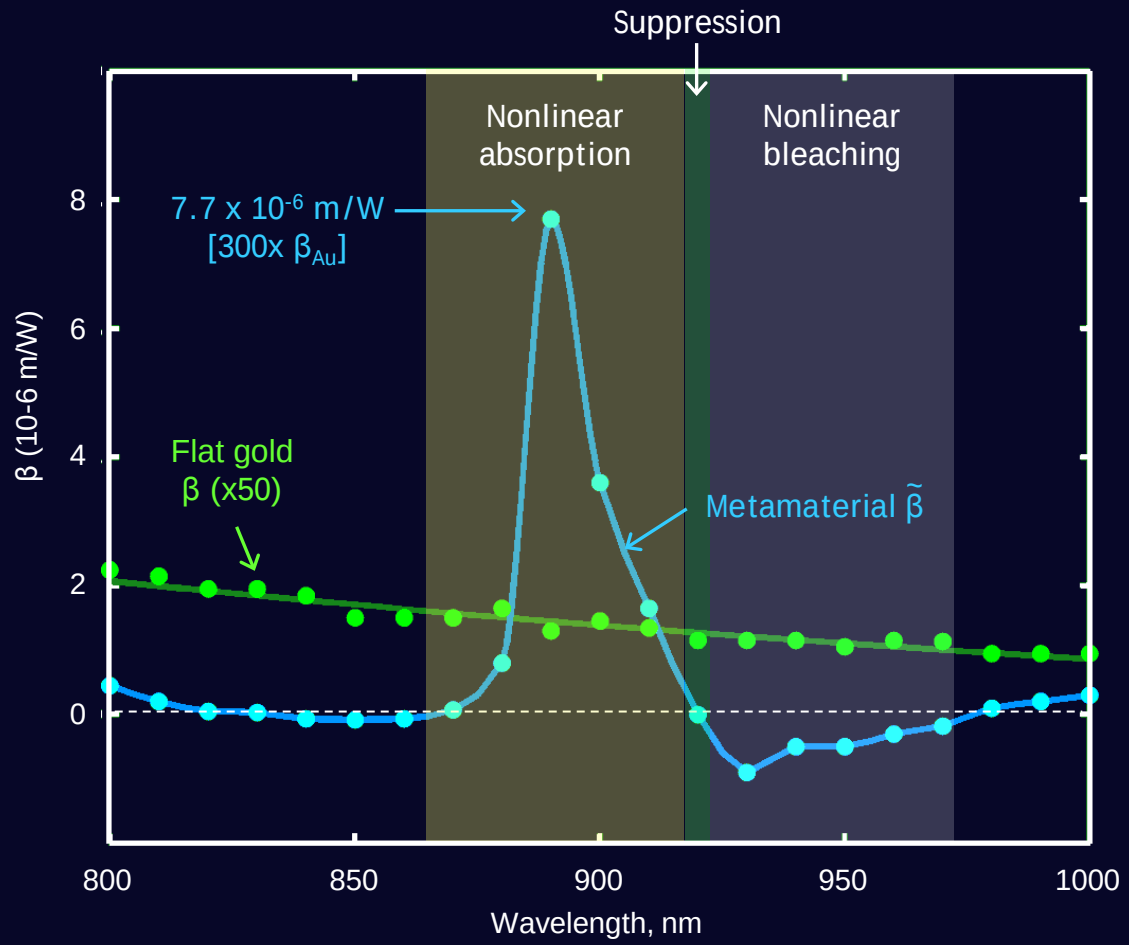
Metamaterial structuring enables enhancement
and control over dispersion and sign of nonlinearity!

Gold nonlinearity enhancement



50 nm Au on SiO_2 patterned by FIB

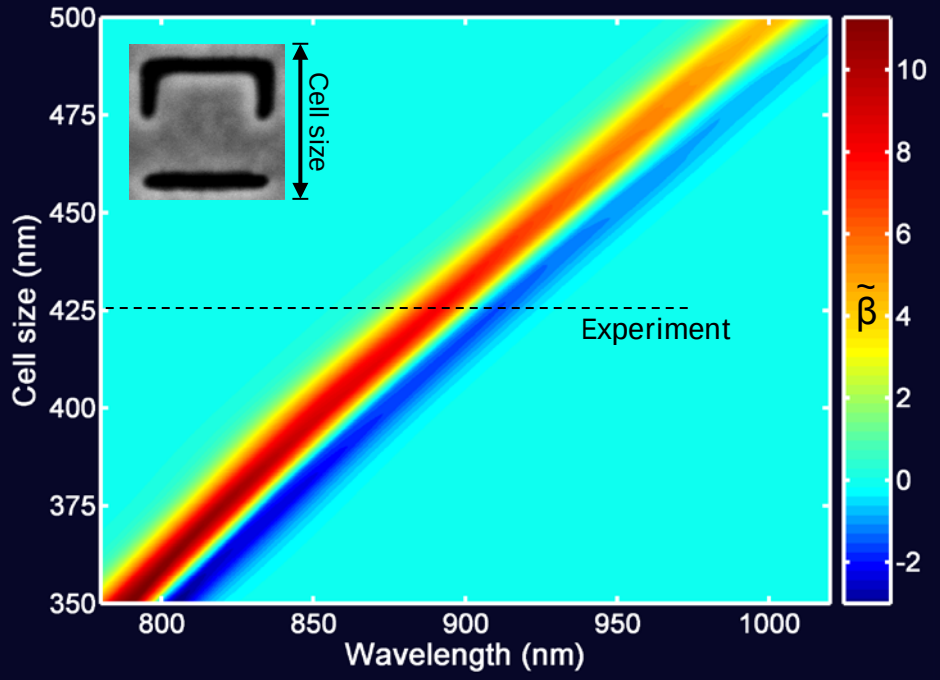
Ti:Sapphire z-scan; 115 fs pulses; 6 μm focus

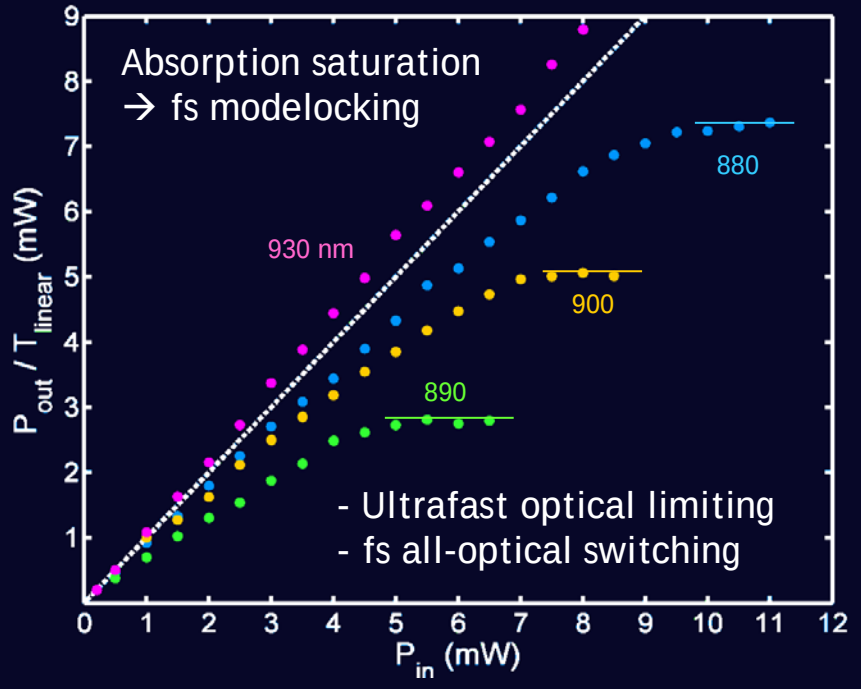


- Structuring
  → 300x RESONANT ENHANCEMENT of gold's nonlinear absorption
- Nonlinearity clear at ~3 mW avg. (peak I ~ few GW/cm^2)
- Ultrafast <100 fs response

Ren, *et al.*, Adv. Mater. 23, 5540 (2011)

Tuneability & application





System	% T modulation	Fluence, μJ/cm²	Response time, fs
Gold metamaterial	40	270	<100
Metamaterial + α-silicon	30	300	>750
Metamaterial + CNTs	15	13	<400
Plasmonic nanorods	80	7000	~1000

Perfect Absorption and Transparency:
Controlling light-with-light *without* nonlinearity

J. Zhang, K. F. MacDonald, and N. I. Zheludev

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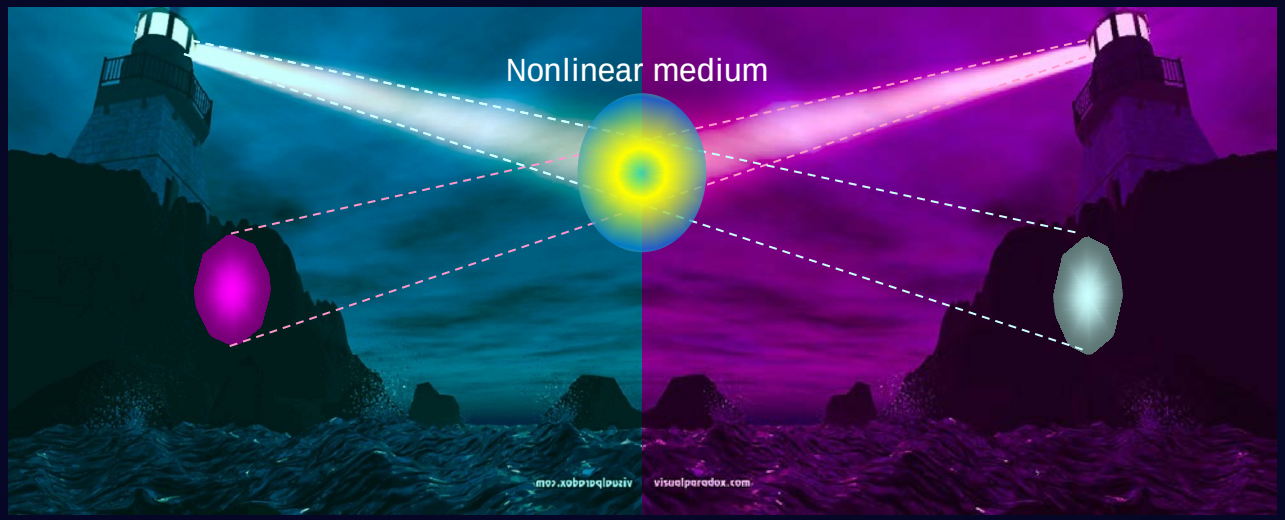
Superposition principle

Eine andere, und mit die wunderbarste Eigenschaft des Lichtes besteht darin, dass die von verschiedenen oder selbst entgegengesetzten Richtungen kommenden Lichtstrahlen einander durchdringen und ohne irgend eine Behinderung ihre Wirkung ausüben. Daher kommt es auch, dass mehrere Beob-

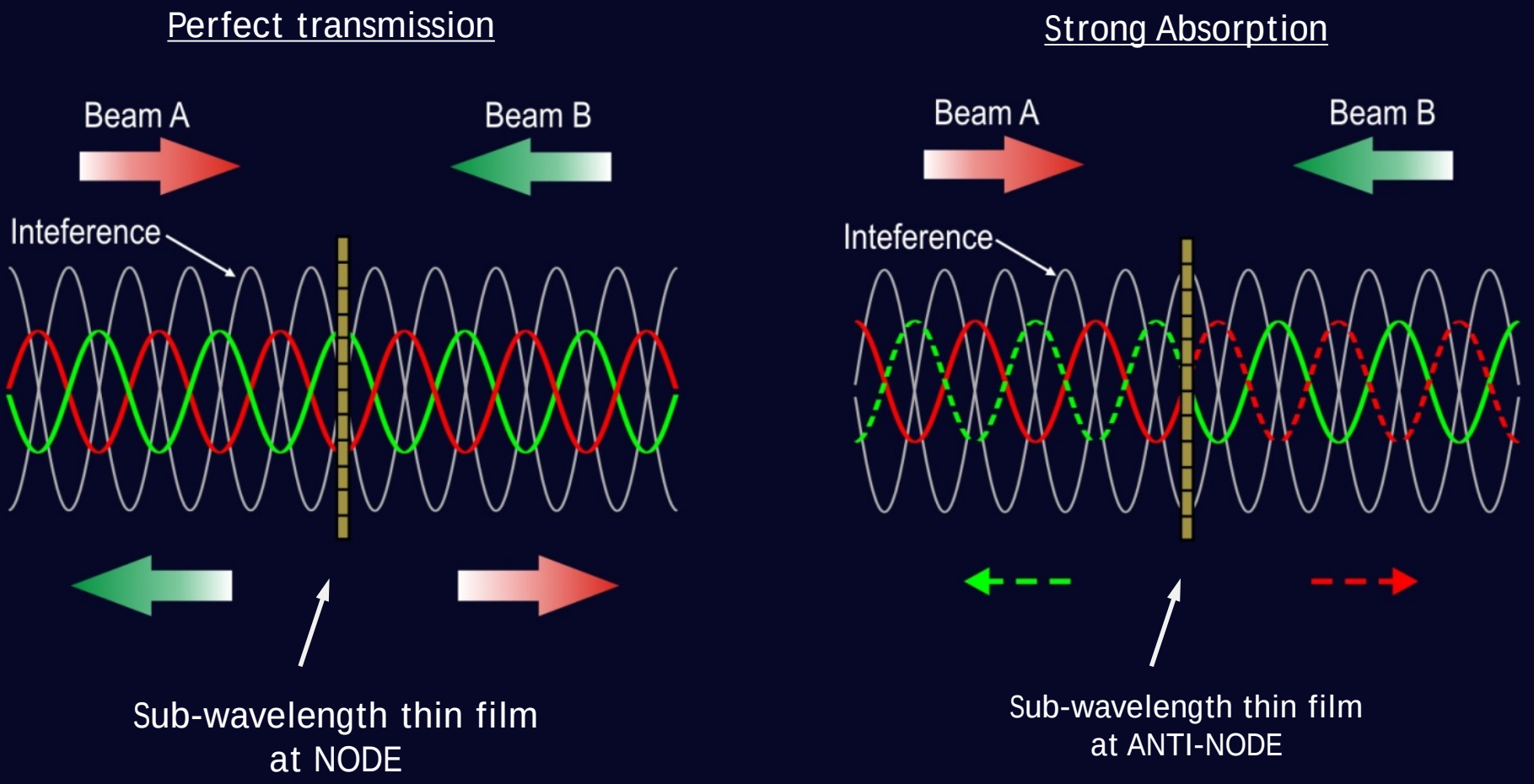
"……light beams travelling in different and even opposite directions pass though one another without mutual disturbance."

[Christian Huygens, "Abhandlung über das Licht" 1678]

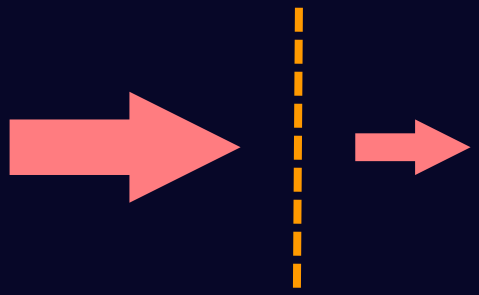
Action of 'light-on-light' requires a nonlinear medium……



Metamaterial perfect absorption and *transparency*

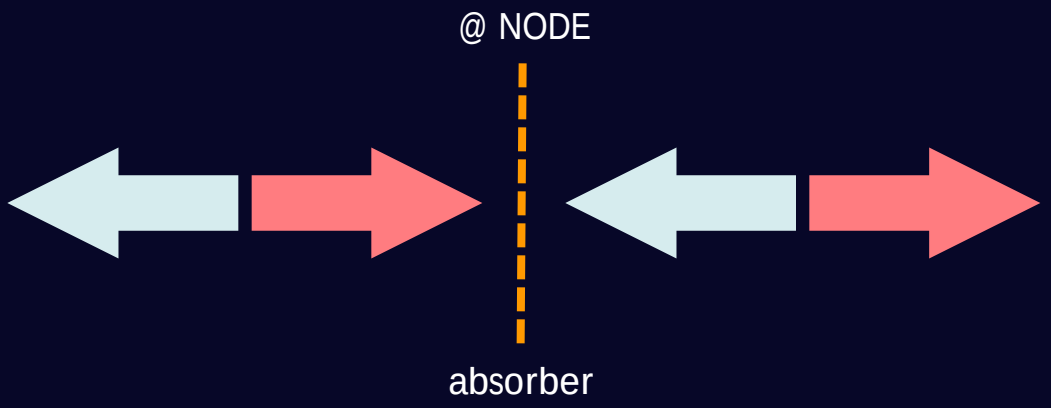


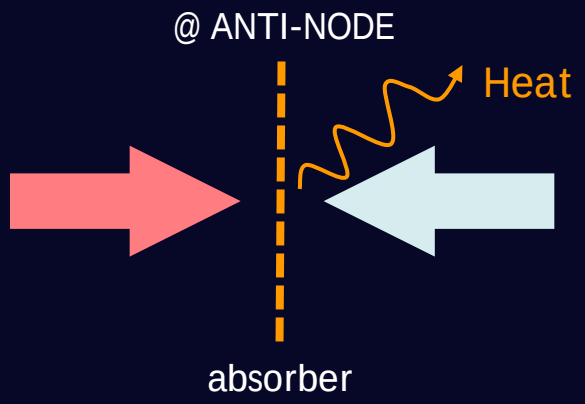
Modulating light with light



‘zero’ thickness absorber

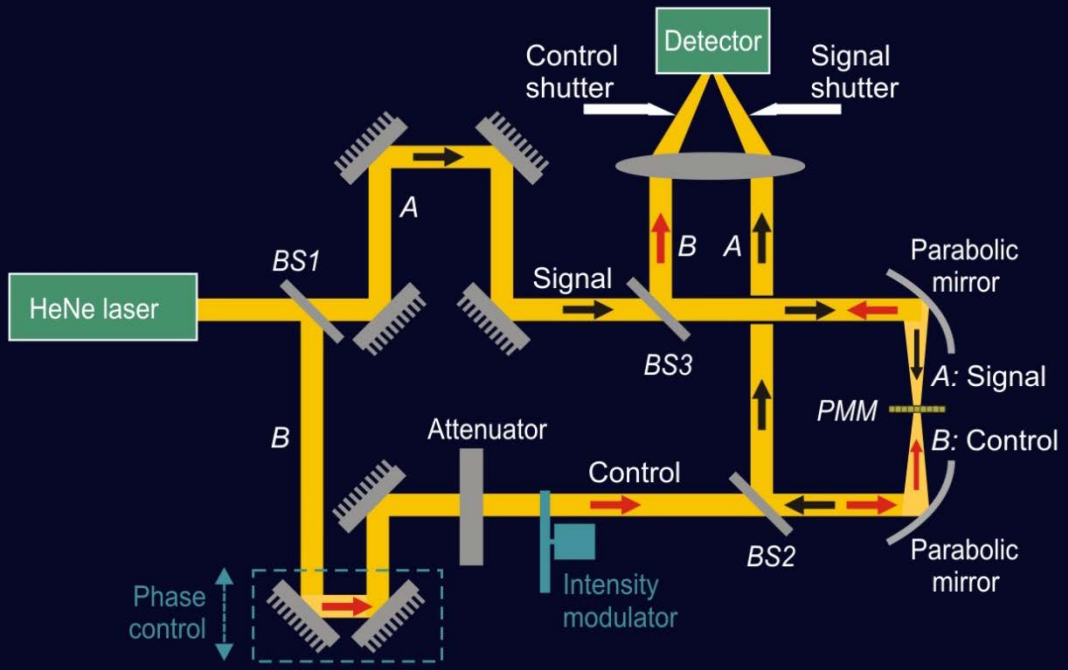
[Single-beam A_{max} = 50%]



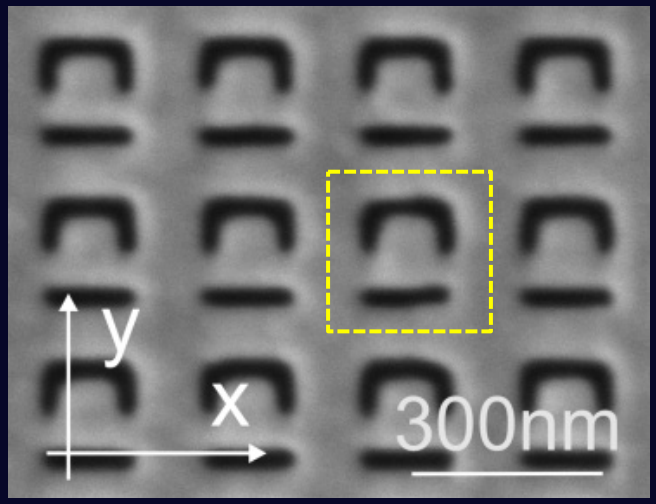


Changing phase/intensity of one beam
changes absorption (and so transmission) of the other

Modulating light-with-light without nonlinearity

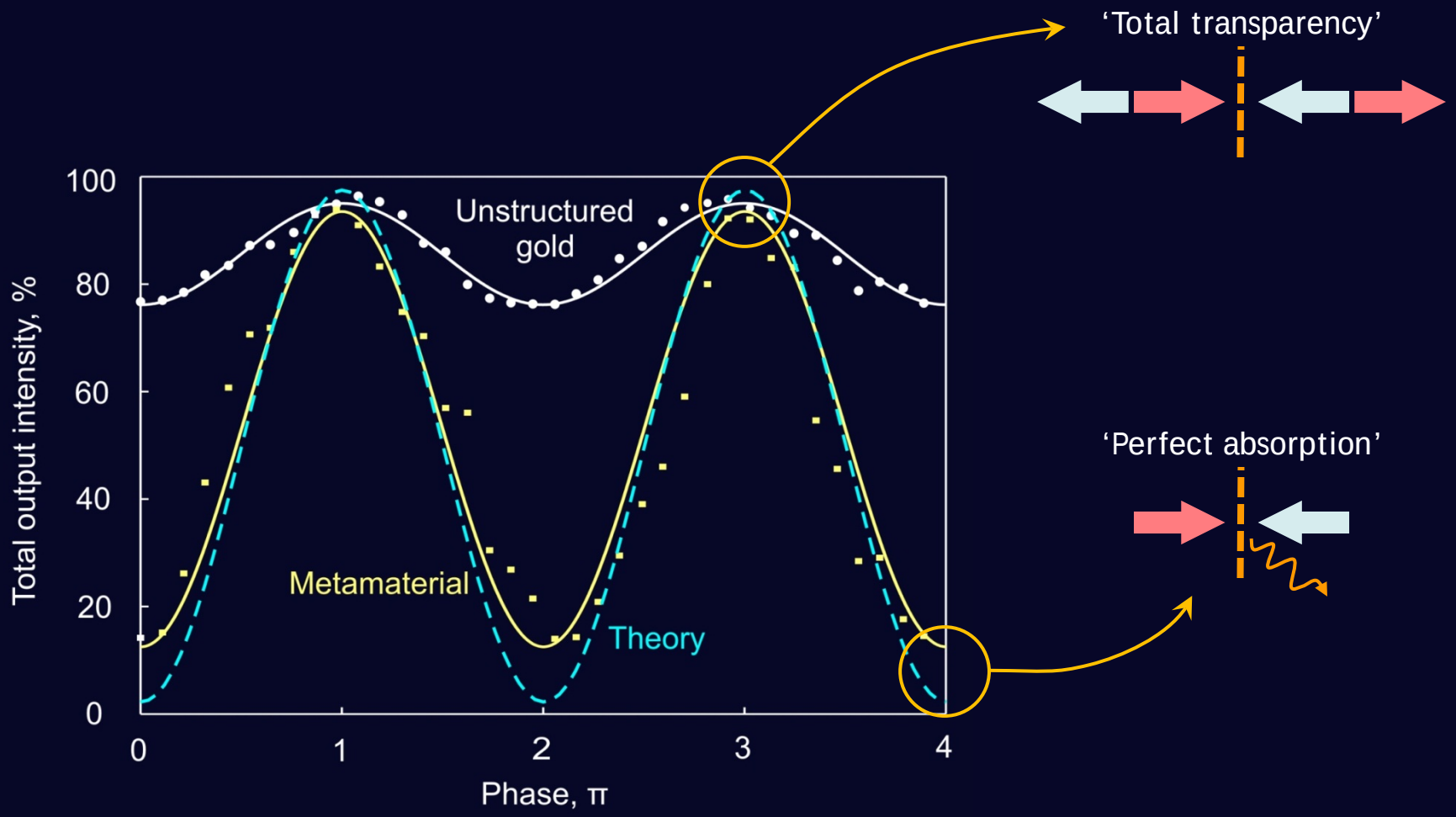


Metamaterial nano-absorber:
50 nm gold (~λ/13) on silica

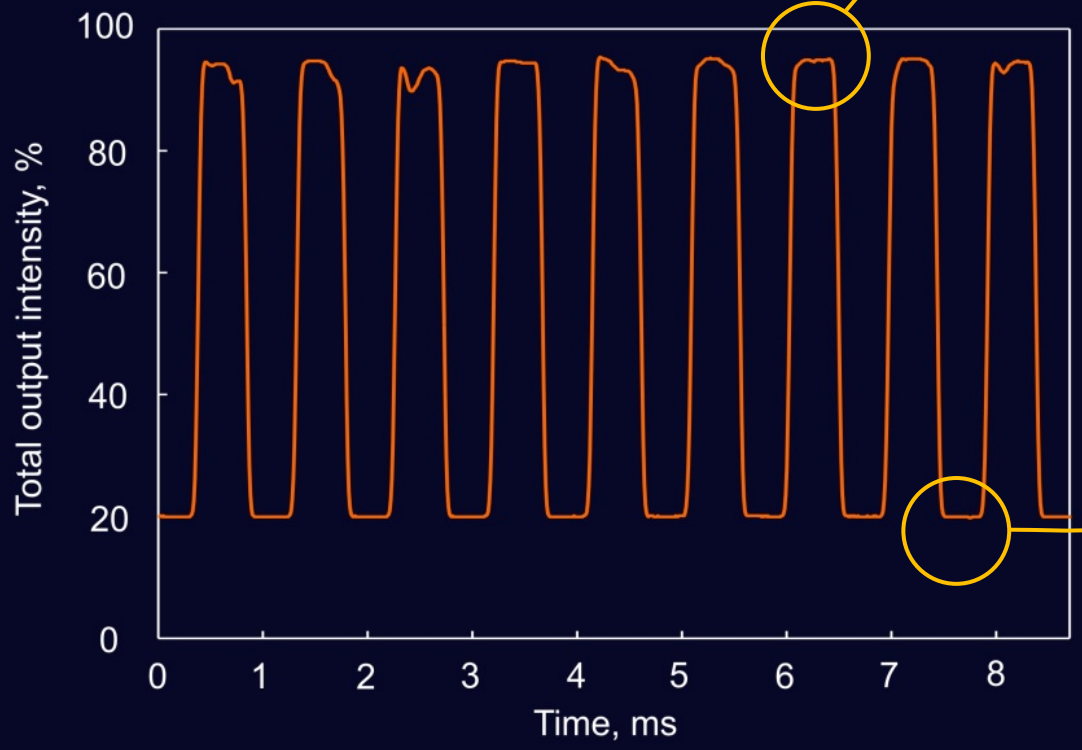


- Single laser source provides coherent signal & control beams
- Control beam phase and/or intensity can be modulated

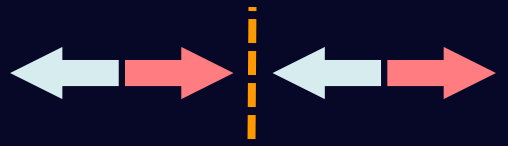
Modulating light-with-light without nonlinearity



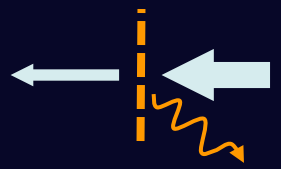
Time-domain intensity modulation



Control beam ON
--> 'Total transparency' for both



Control beam OFF
--> signal absorption



kHz demonstration; THz modulation possible

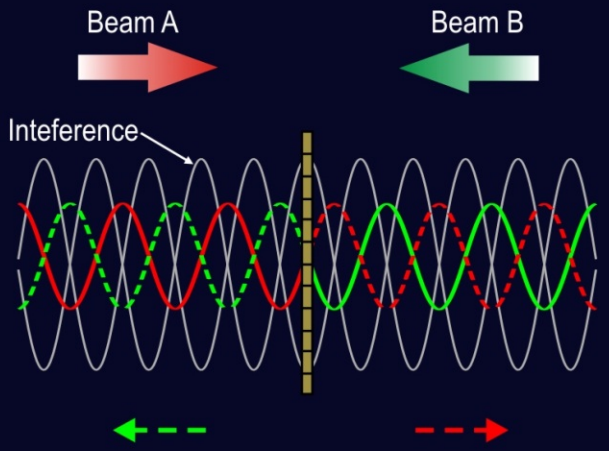
Light-by-light control without nonlinearity

Perfect absorption AND transparency in a planar (<<λ) metamaterial

- 0 – 100% absorption controlled by phase/intensity
- Operational wavelength selected by design anywhere in VIS/NIR range
- THz modulation bandwidth

Potential applications:

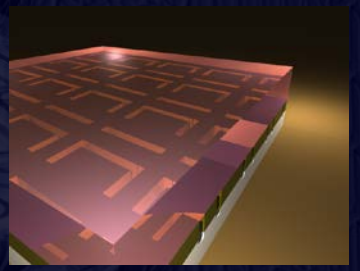
- All-optical modulation
- Pulse restoration
- Coherence filtering



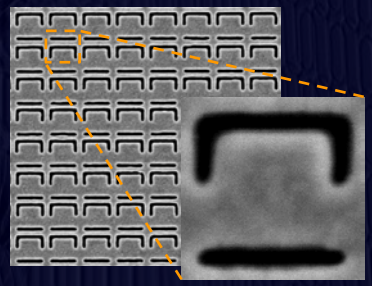
Nature - Light: Science & Applications ***1****, e18 (2012)*

Photonic metamaterials: Nanoscale switching & modulation technologies

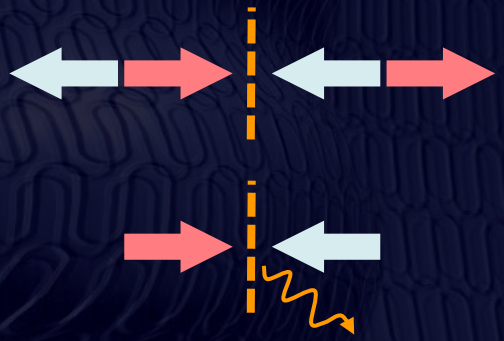
1. Chalcogenide hybrid metamaterials
   - *Proven material platform for electro/all-optical, non-volatile switching/memory devices*
   - *Resonant contrast enhancement in sub-wavelength structures*



2. Nonlinear nanostructured metal
   - *Resonant nonlinear absorption enhancement/suppression/inversion*
   - *Femtosecond modelocking, optical limiting, switching*



3. Perfect absorption and transparency
   - *Ultra-thin absorbers by design*
   - *Light-by-light control at arbitrarily low intensity*



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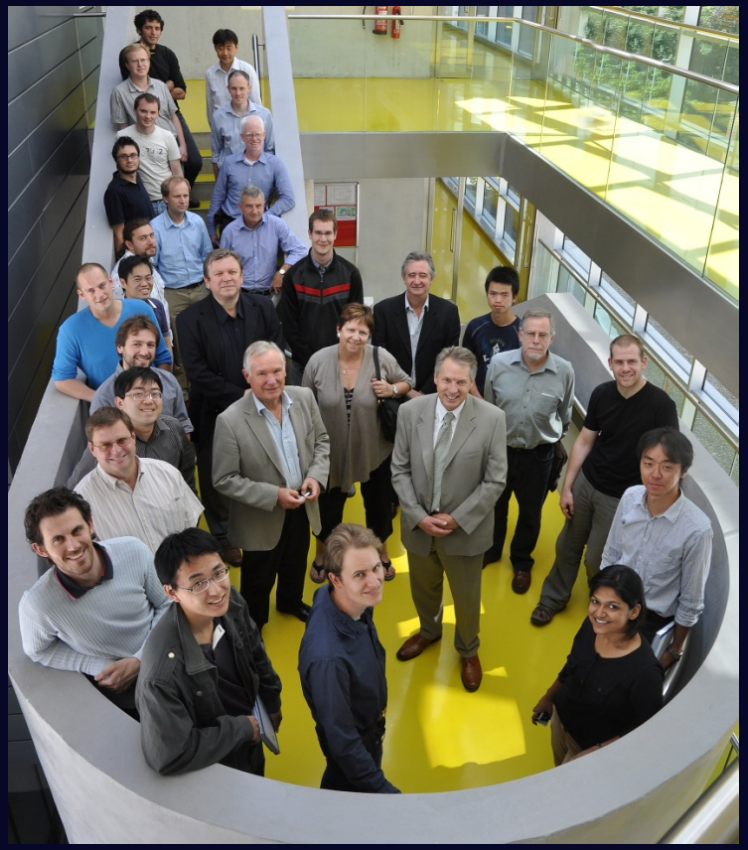

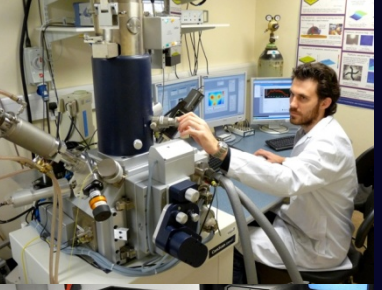
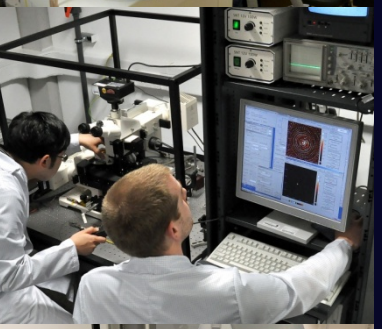
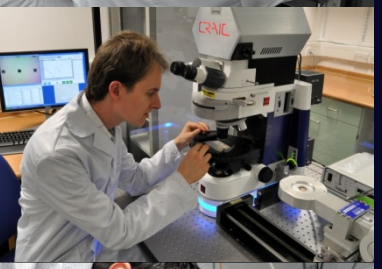

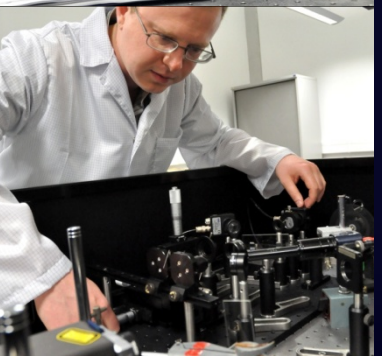




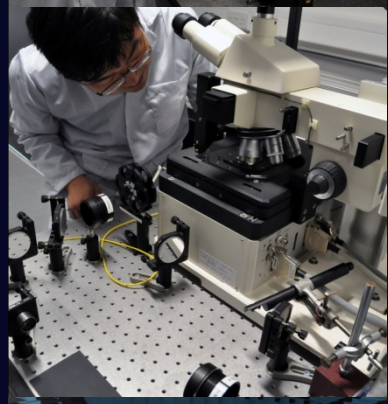


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