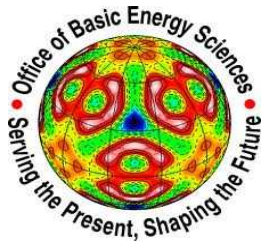
SAND2017-7608C

Nonlinear optics of epsilon near zero material using CdO

Ting S. (Willie) Luk
Sandia National Laboratories

Invited Presentation at Meta 2017
July 27, 2017



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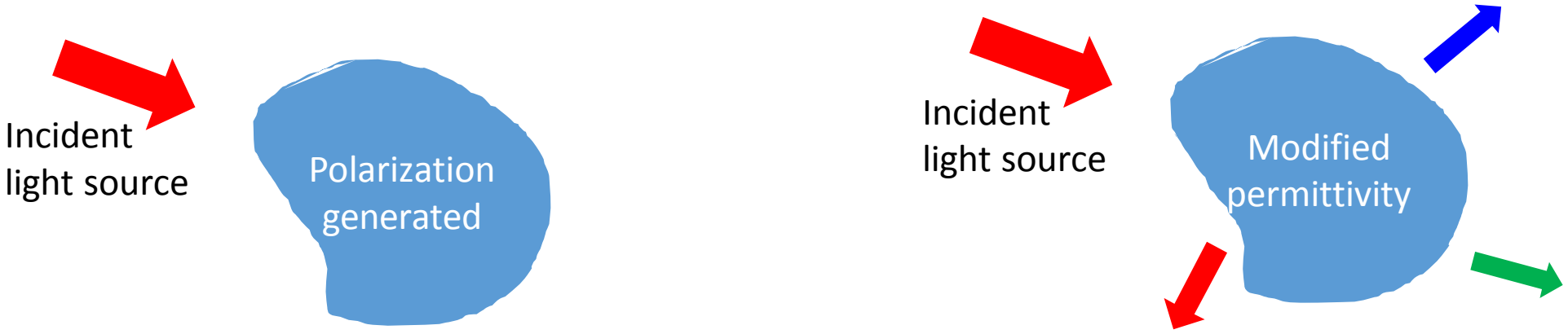
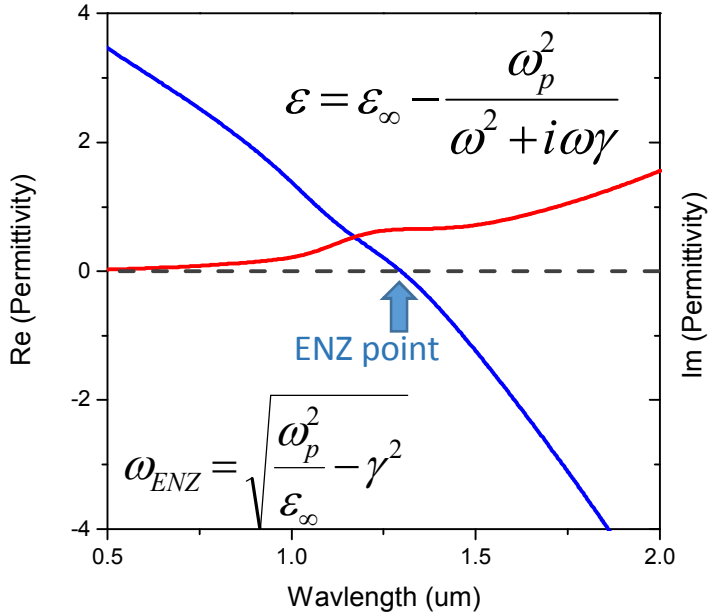
Kyle Kelley *(North Carolina State University)*
Jon-Paul Maria *(North Carolina State University)*
Gordon Keeler *(SNL)*

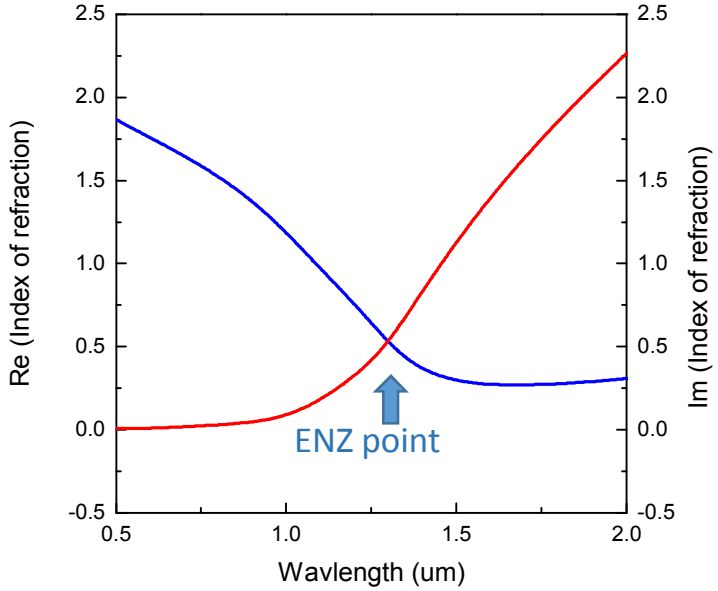
Strong Light matter interaction starts with absorption

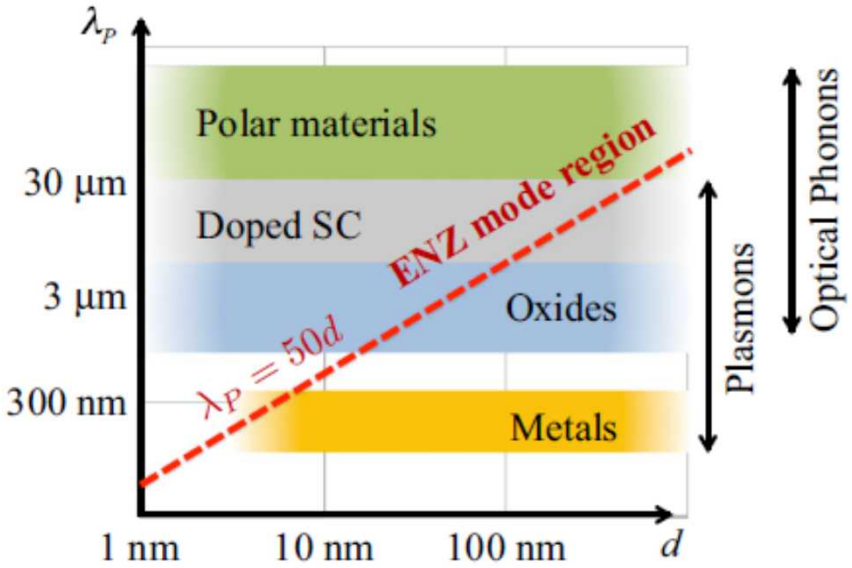


- Maximum absorption produces maximum polarization
- Free electrons are very polarizable: Re(ε)=0 at plasma frequency
- ENZ modes enable complete absorption
- Optical interaction can induce large change in permittivity
- Polarization decay slow enough for time scale of applications

Epsilon-near-zero is not so exotic







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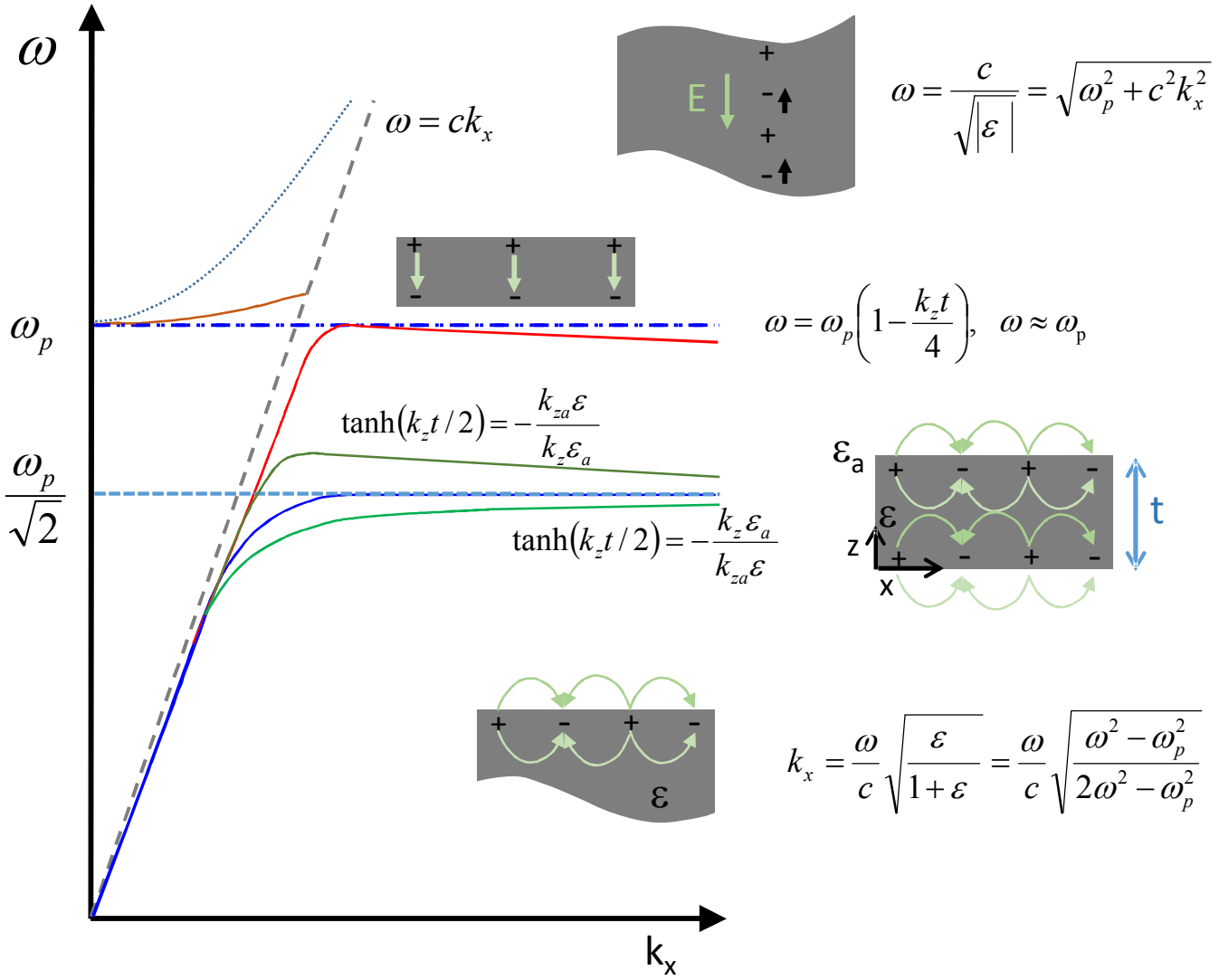
Epsilon-near-zero (ENZ) modes and dispersion

$$\varepsilon \cong 1-\frac{\omega_p^2}{\omega^2}+i\frac{\gamma\omega_p^2}{\omega^3},\ \omega >> \gamma$$



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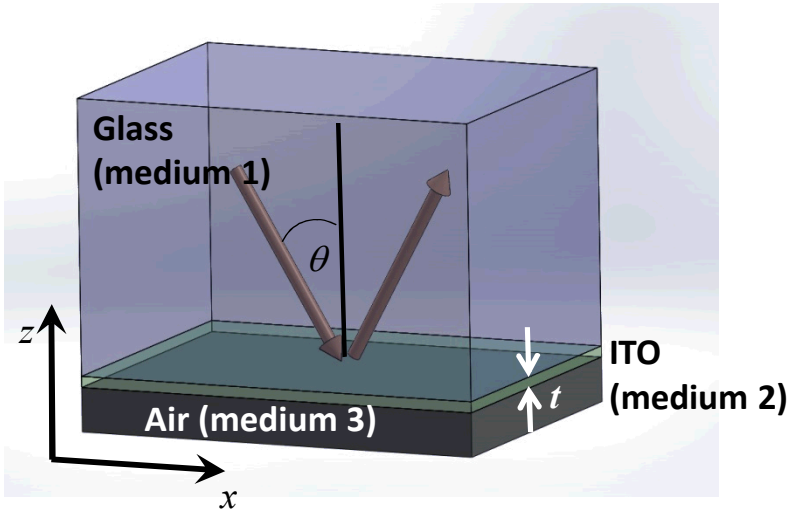
ENZ mode dispersion and critical coupling

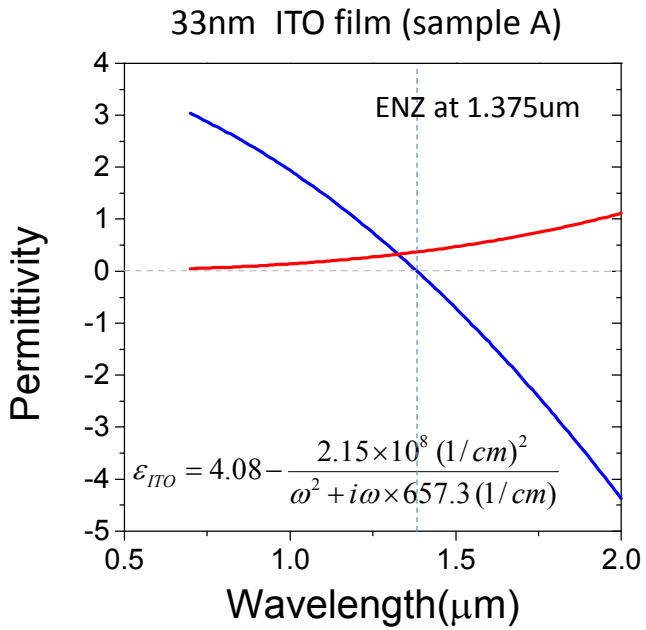


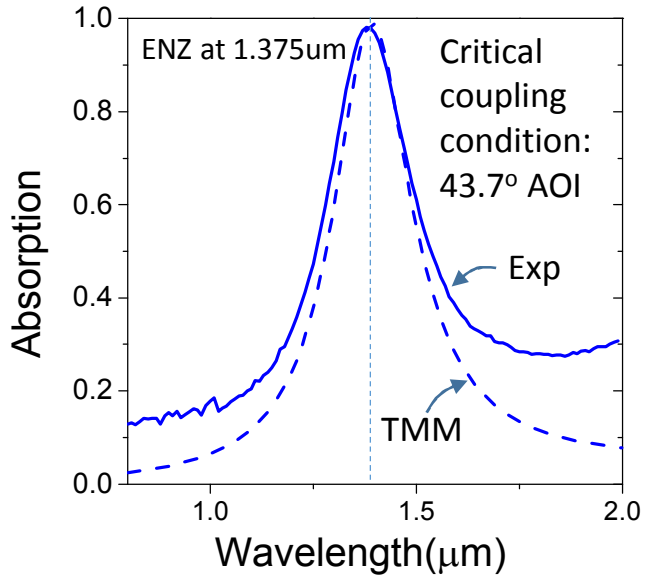
Airy Formula $\Gamma = \dfrac{r_{12} + r_{23}e^{2i\phi}}{1 + r_{12}r_{23}e^{2i\phi}} \qquad \phi = k_{2\perp}t$

Mode dispersion: $r_{12}r_{23}e^{2i\phi} = -1$

Critical coupling condition: $r_{12} = -r_{23}e^{2i\phi}$

T. S. Luk et. al, " Directional perfect absorption using deep subwavelength low-permittivity films" *PRB,* 085411(2014)

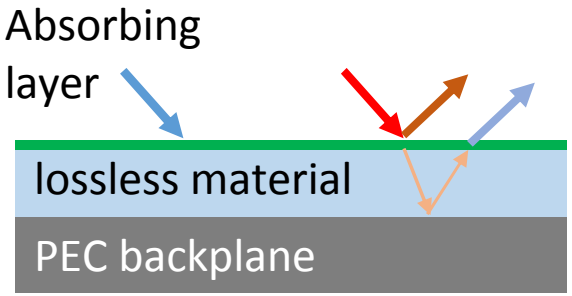




Other perfect absorption schemes

Salisbury screen: anti-reflection of planar structures

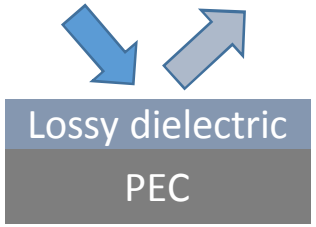
US 2599944 (A) "Absorbent body for electromagnetic waves". Salisbury W. W. June 10, 1952



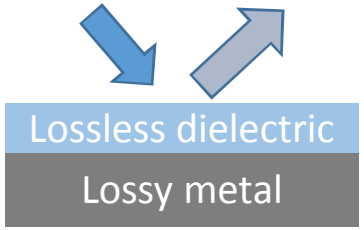
- Requires a metal backplane
- $\lambda/4$ lossless spacer material
- Thin top layer of absorbing material

Mid-IR Z. Wang et. al. APL (2015)
Vis J. Guo et. al. Optical Materials Express (2016)

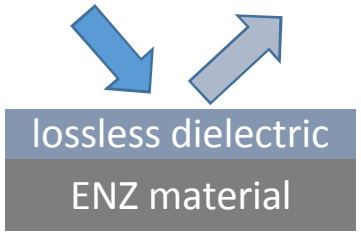
Other Impedance matching variations (2 interfaces)



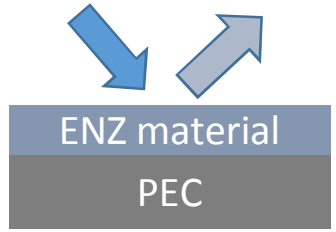
Kats, Nat. Mater. (2013)



Driessen, APL (2009)



S. Campione, T. S. Luk OE (2016)



T. S. Luk et. al., PRB (2014)

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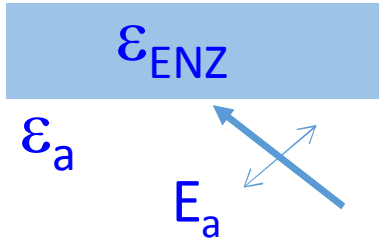
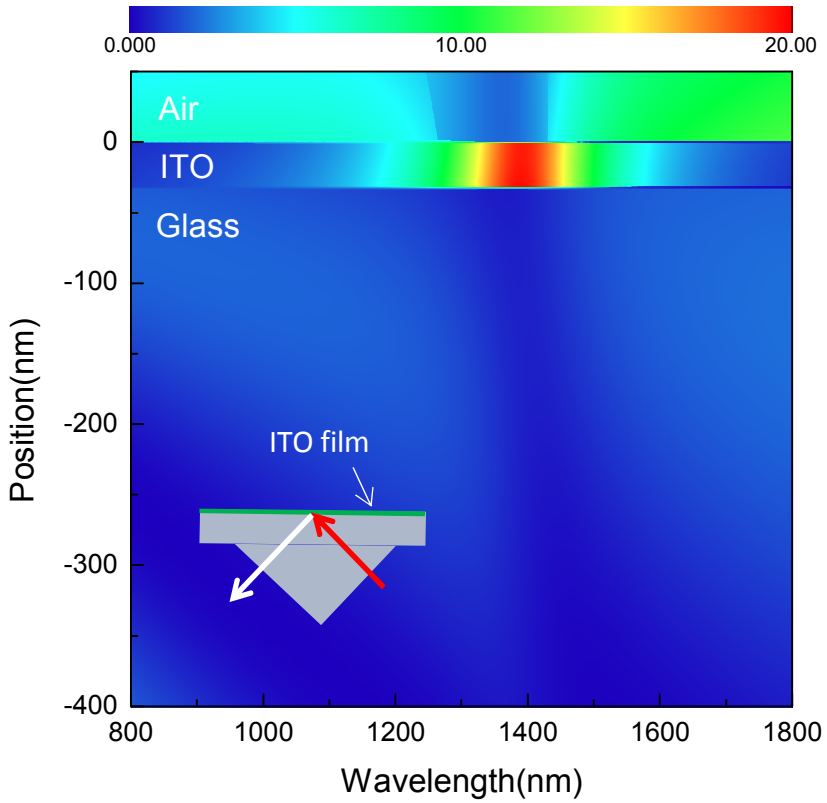
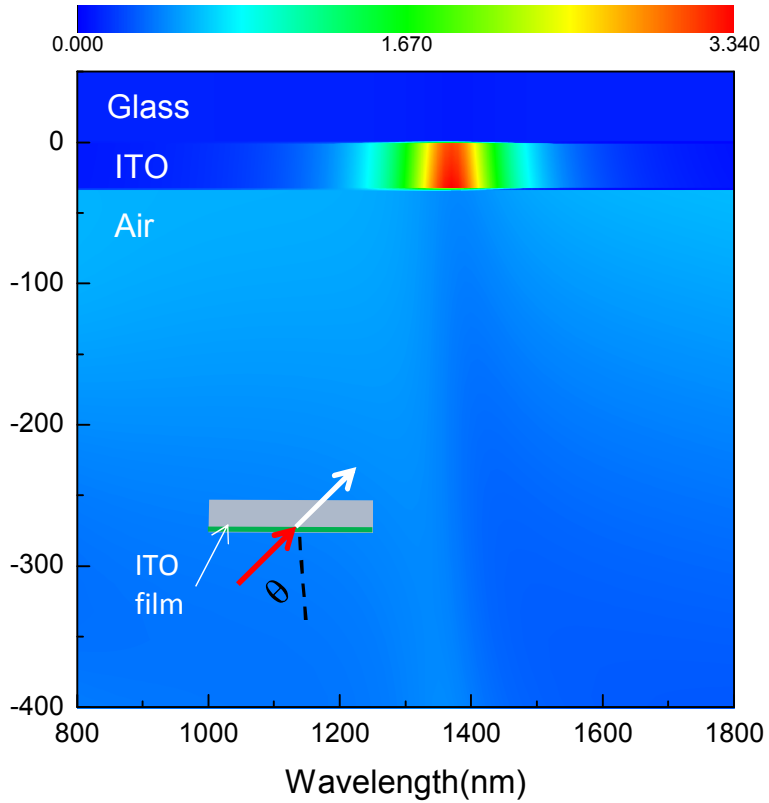
Intensity enhancement: Berreman vs ENZ mode



$$E_{ENZ} = D/\varepsilon_{ENZ} = E_a\varepsilon_a/\varepsilon_{ENZ}$$





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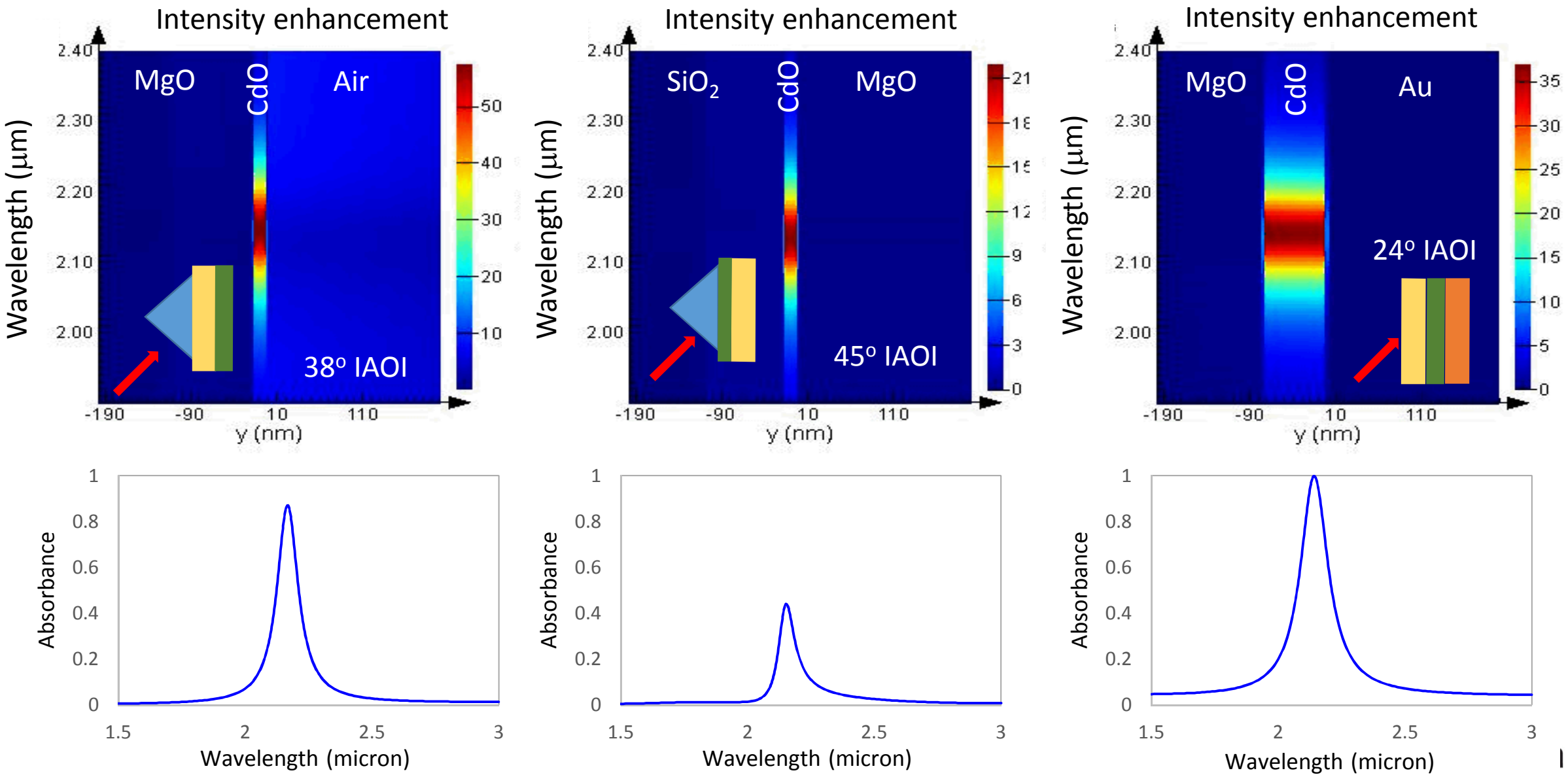
Field enhancement of CdO ENZ material



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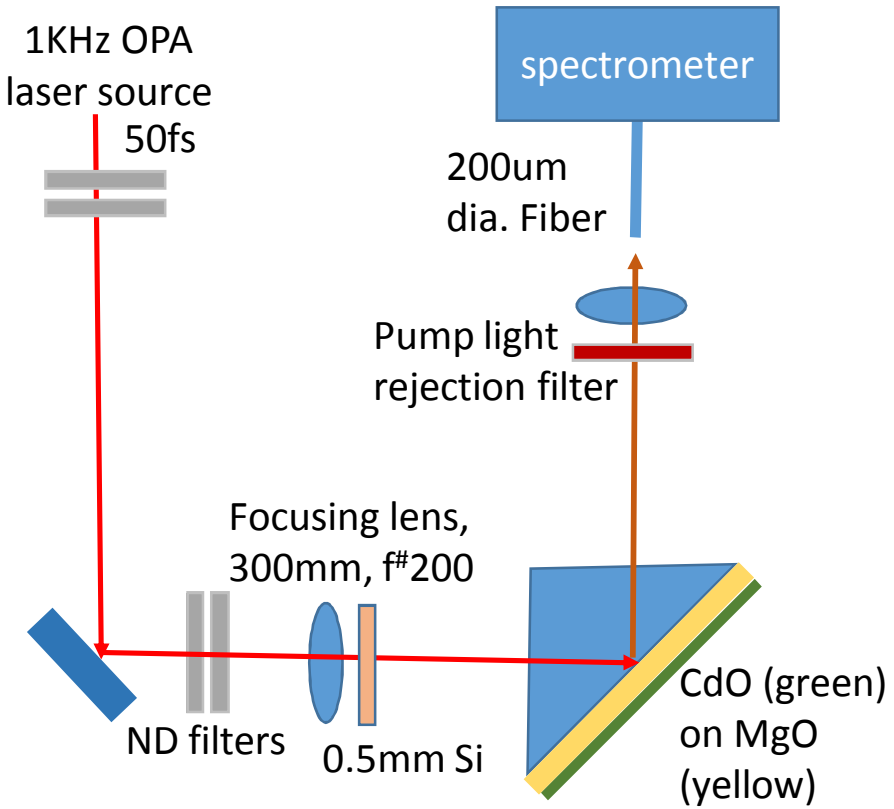
Third harmonic generation using ENZ mode

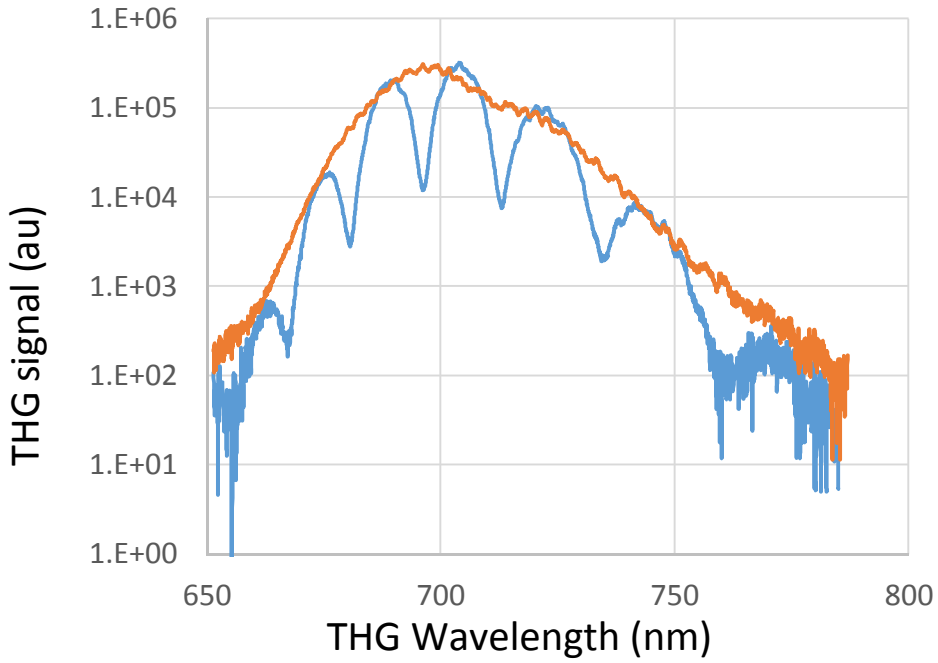


Momentum conservation: $3\vec{k}_{FF} = \vec{k}_{TH}$

Continuity condition: $3k_{FF//} = k_{TH//}$

TH emerges in specular direction: $\frac{k_{FF//}}{k_{FF\perp}} = \frac{k_{TH//}}{k_{TH\perp}}$

Provided $\varepsilon_a(\omega) = \varepsilon_a(3\omega)$



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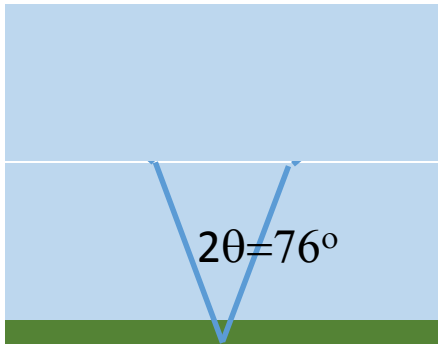
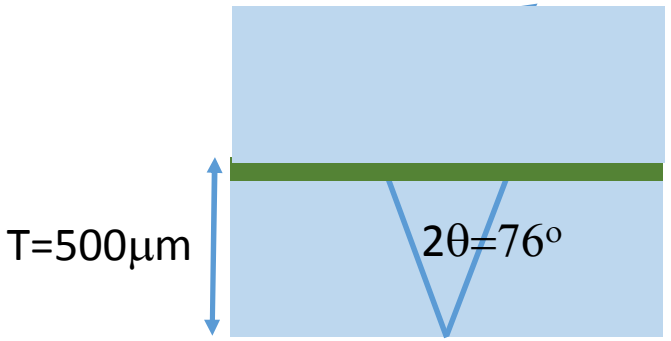
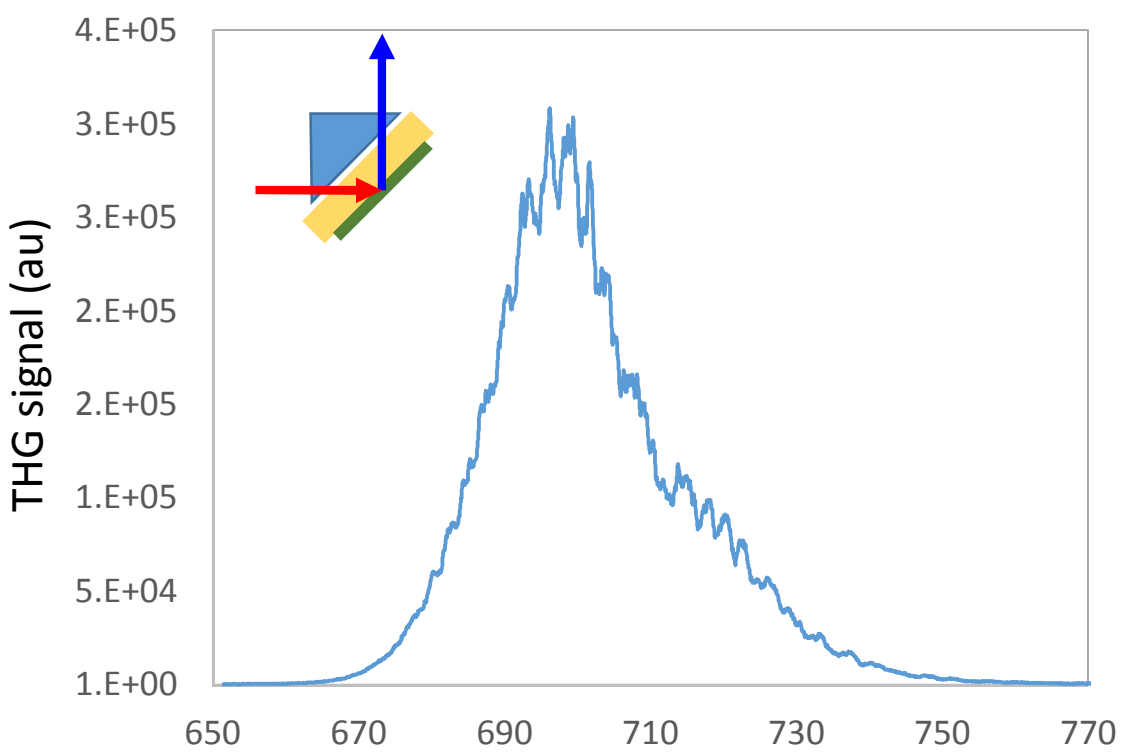
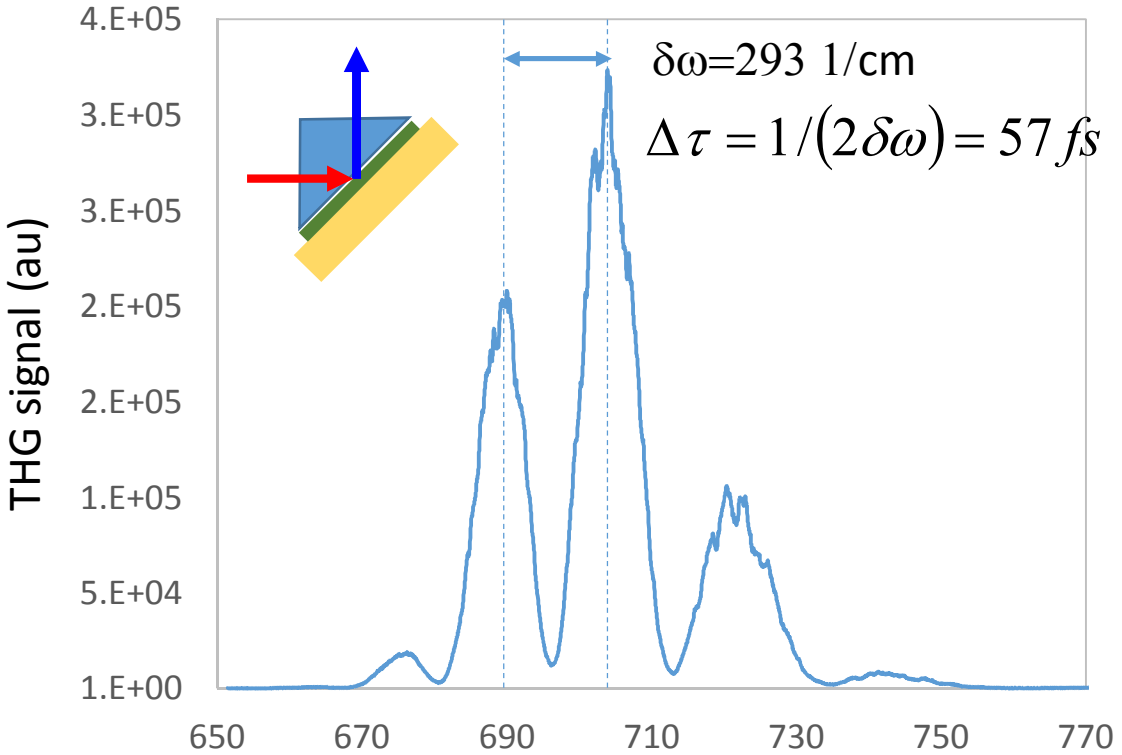
Origin of spectral modulation



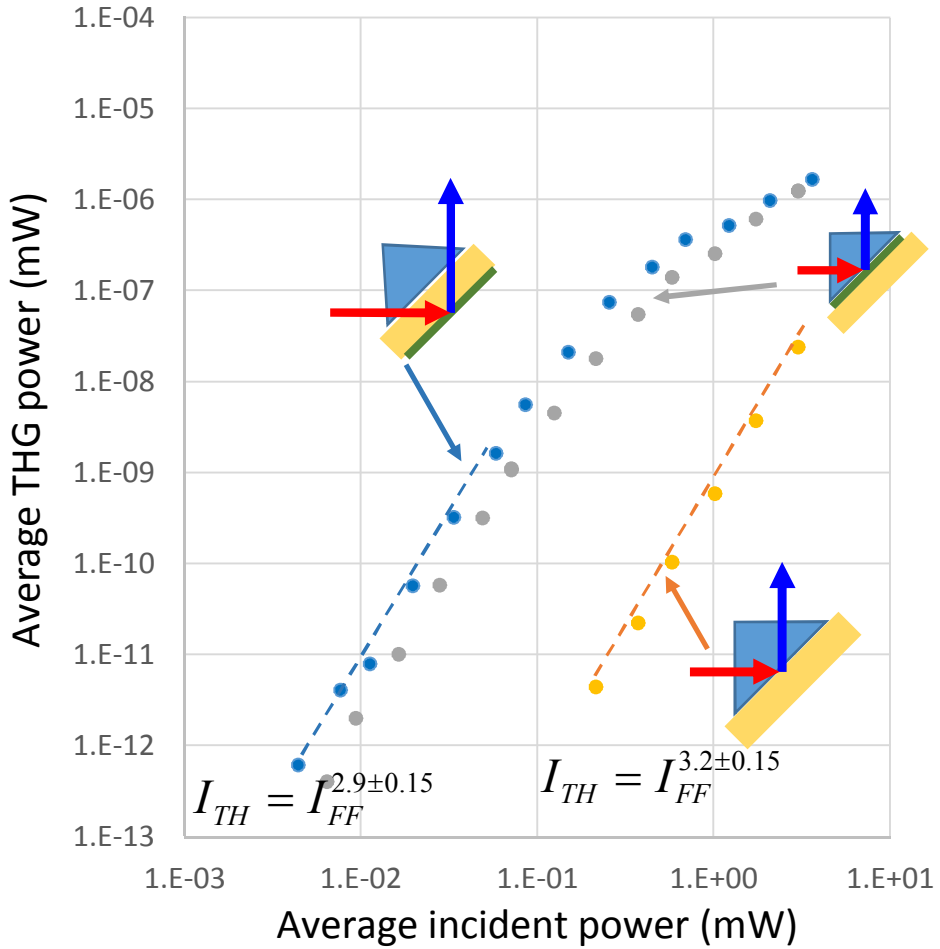


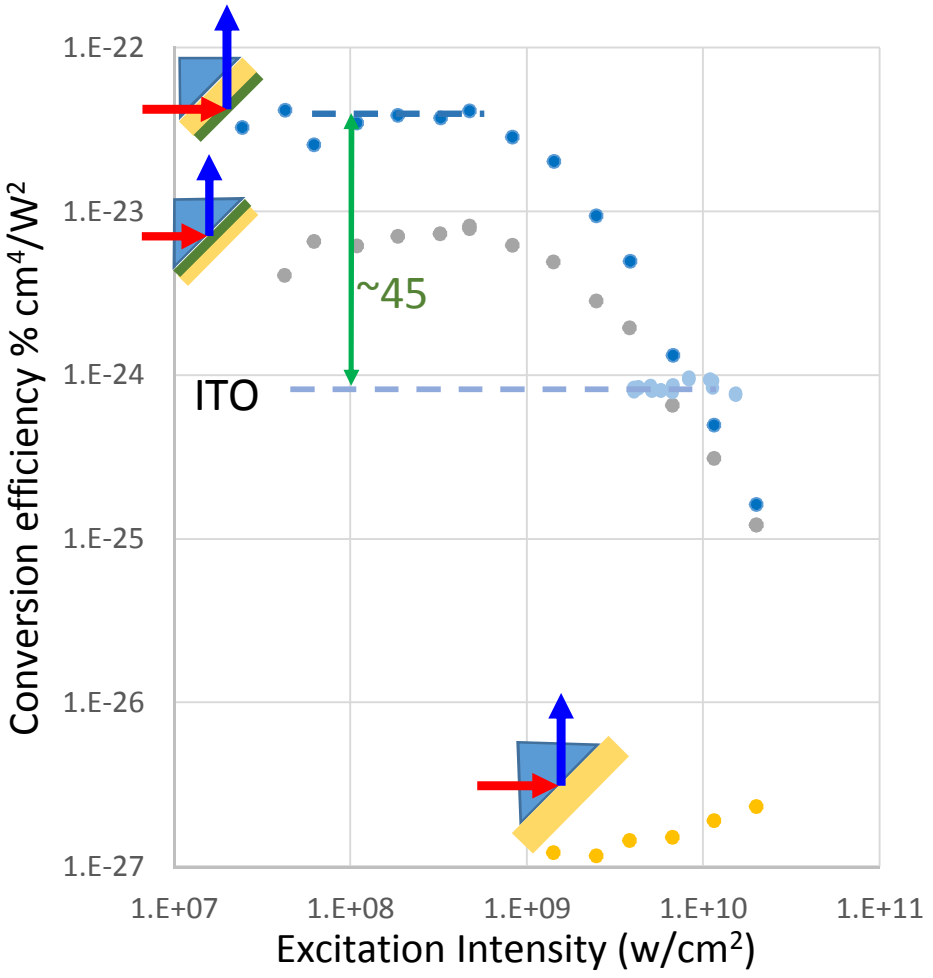
$$L = 2t/\cos(\theta)$$
$$= 1269\,\mu m$$
$$\Delta\tau = L\Delta n/c \quad = 55fs$$





Third harmonic generation from plasmonic CdO





Comparison of THG efficiency in the metric of % cm^4/W^2

CdO-19nm	3.5×10^{-23} ($\chi^{(3)}=2\times10^{-20}$ m^2/V^2 ?? from Scalora*)
Chalcogenide glass	2×10^{-19} m^2/V^2
ITO[1]	8×10^{-25} ($\chi^{(3)}=3\times10^{-21}$ m^2/V^2)
Anapole[2]	2.22×10^{-22}

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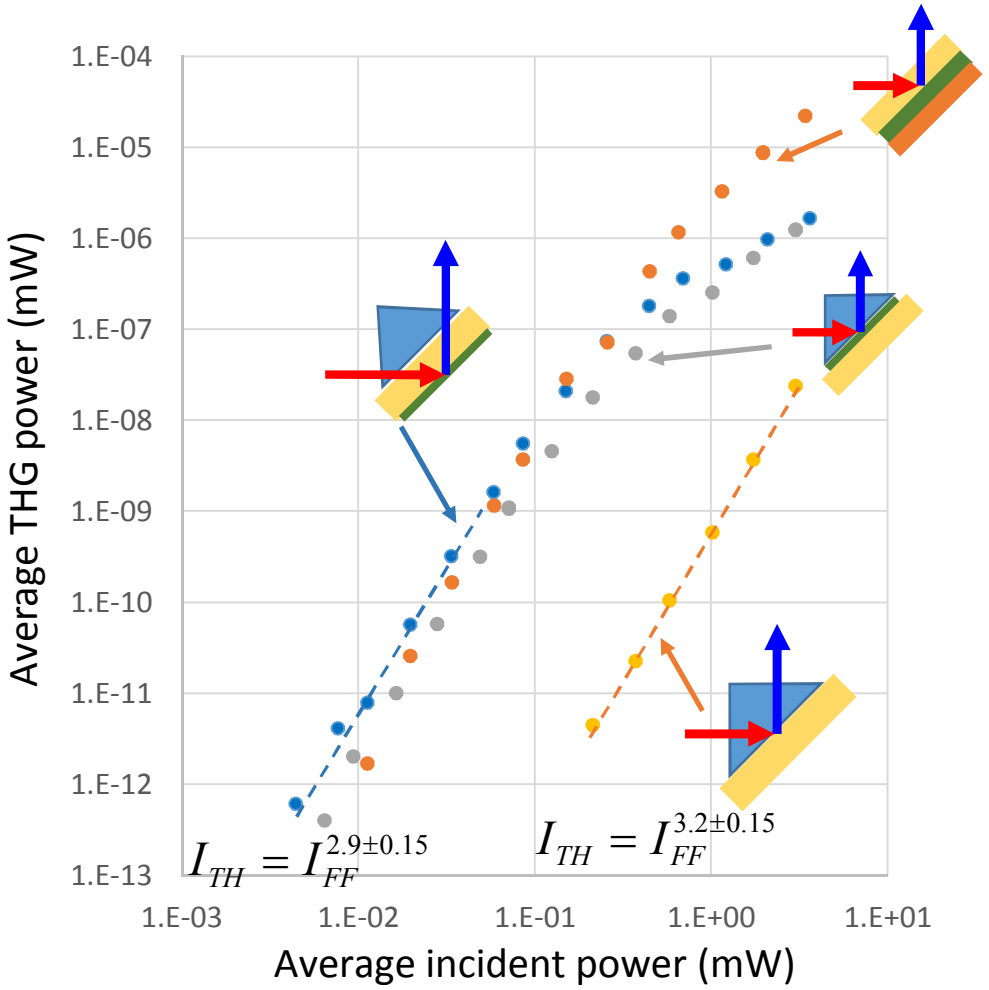
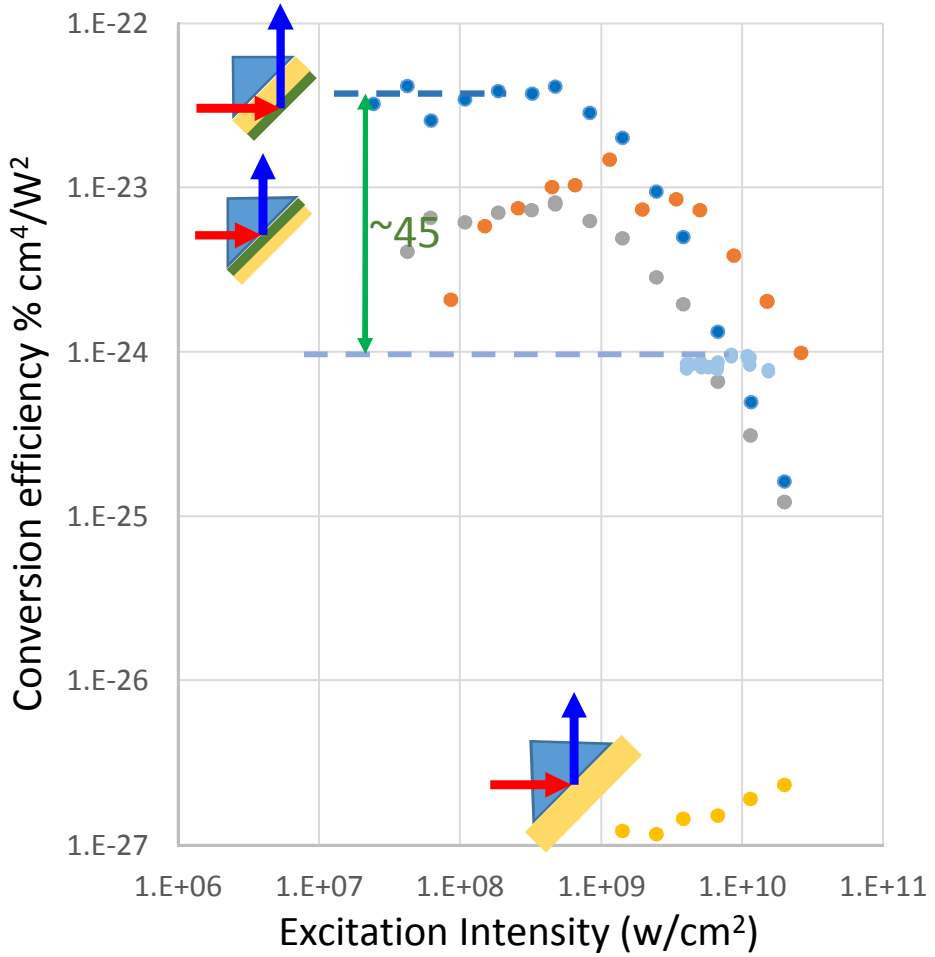
Third harmonic generation from plasmonic CdO





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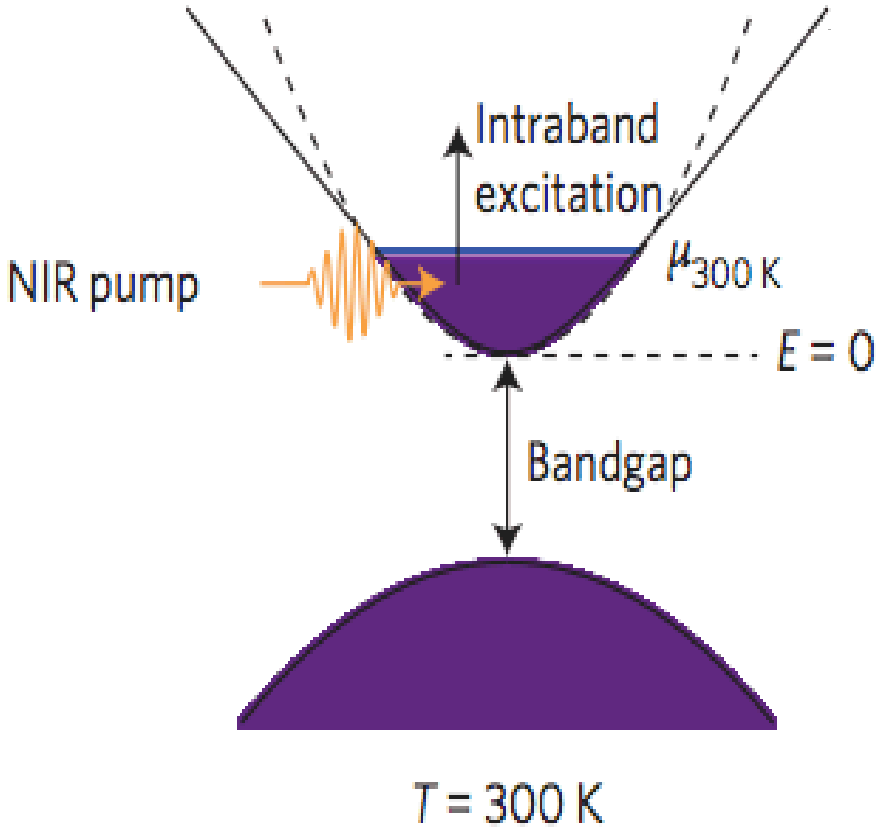
Summary of THG from plasmonic CdO

- CdO is a superior plasmonic material in the mid-IR region.
- Field enhancement from ENZ mode enables strong nonlinear effects.
- About 45 times better than ITO and comparable to nano-patterned dielectric resonators.
- Significant heating is probably the root cause of saturation behavior.

Heating modifies optical dielectric function and for switching applications

Photon-"perturb" electrons:



$$m^* = \frac{\hbar^2 \int f(E,T)\,dk}{\int f(E,T)\left(d^2E/dk^2\right)dk}$$

Plasma frequency:

$$\omega_p = \sqrt{ne^2/\varepsilon_0 m^*}$$

Speed limitations:

- Hot carrier lifetime

Guo et. al., Nat. Photon, (2016)

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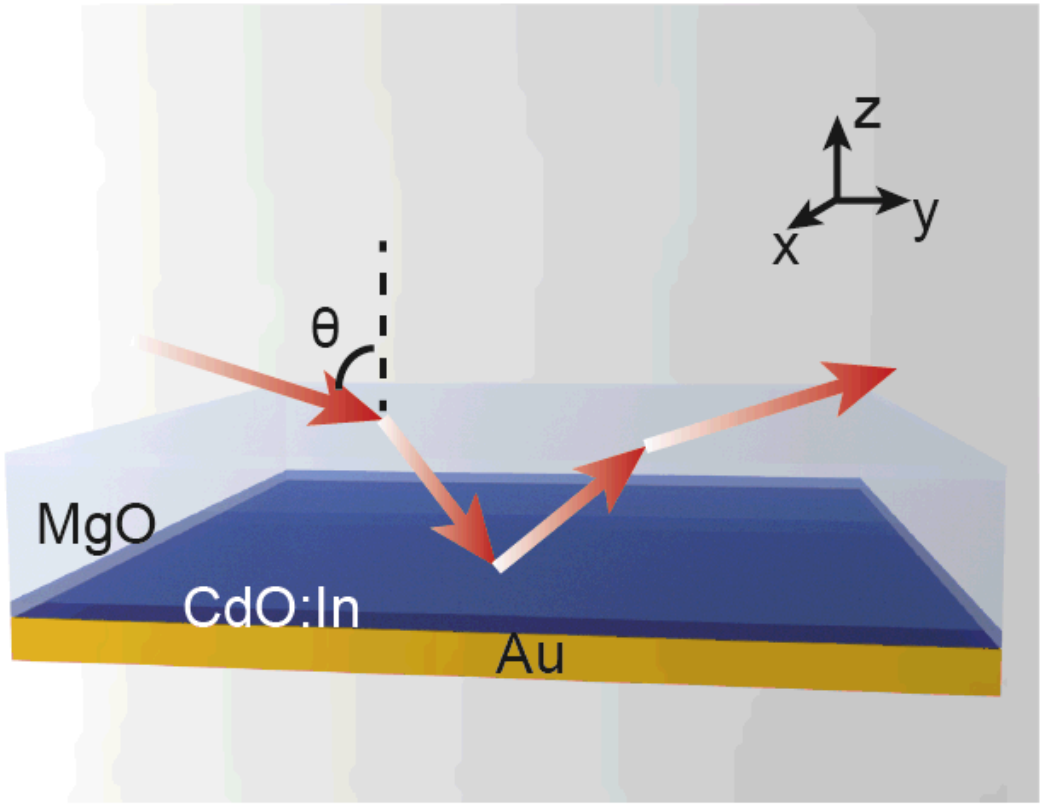
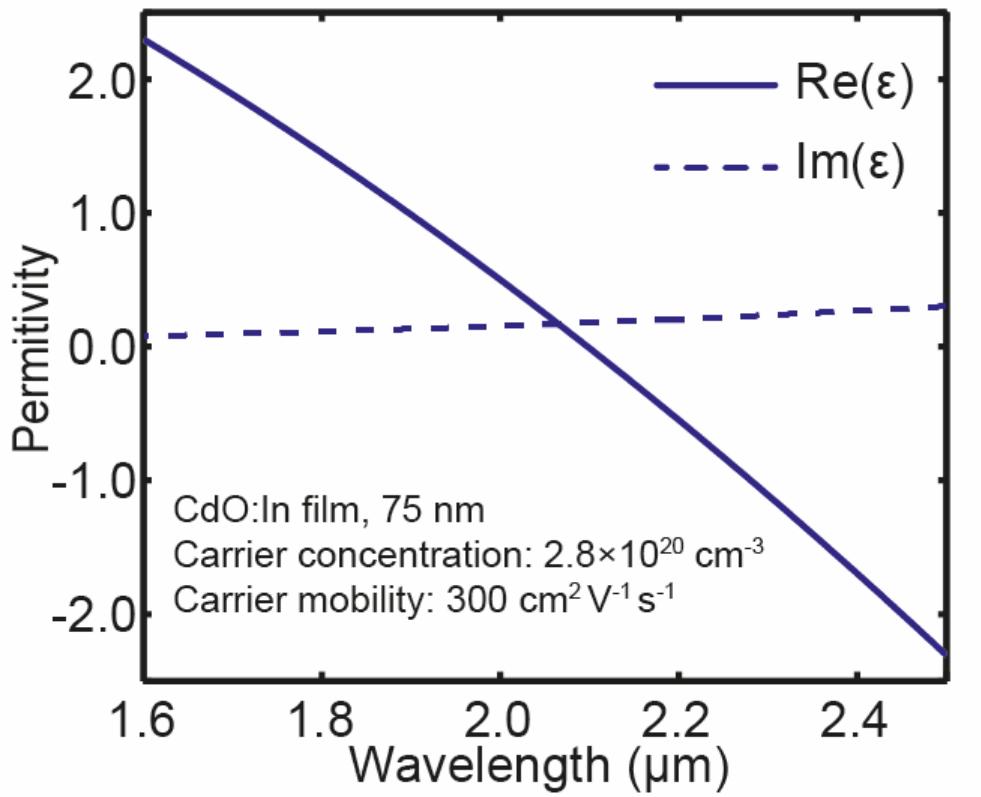
CdO-based Berreman-mode Perfect Absorber





Yang et. al., Nature Photonics, Advanced Online Publication

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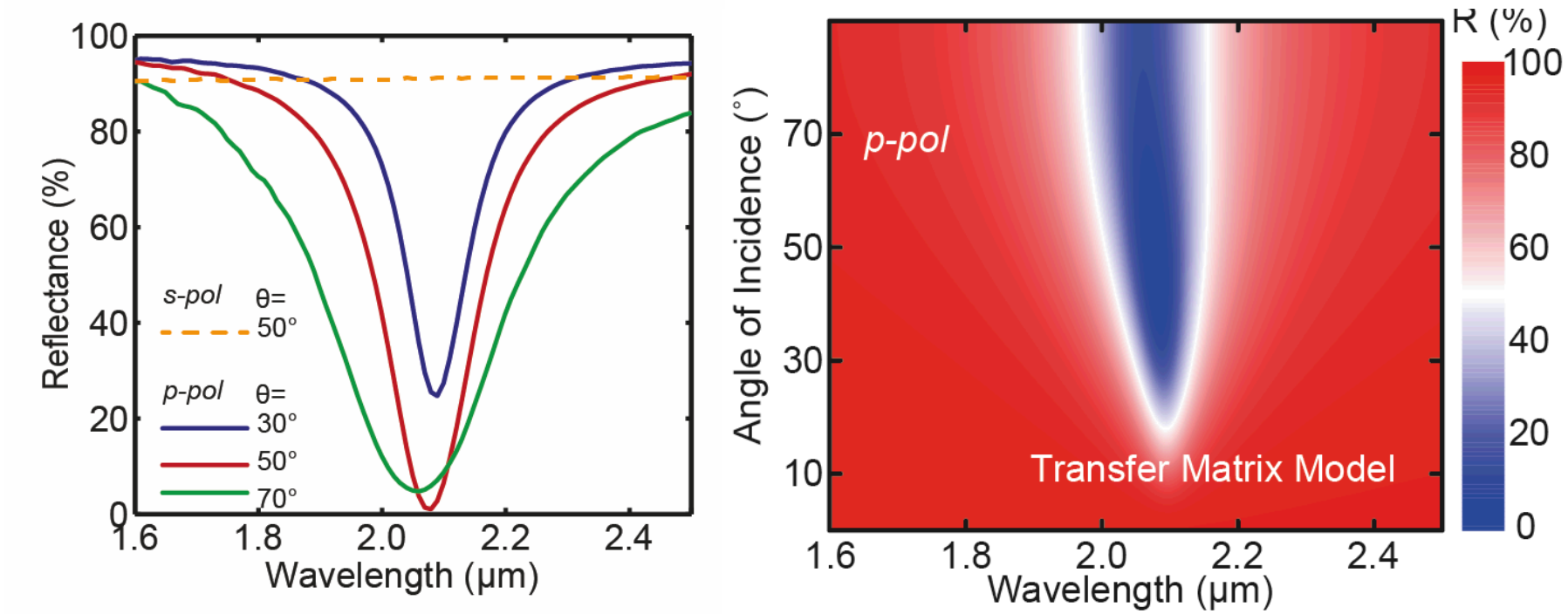
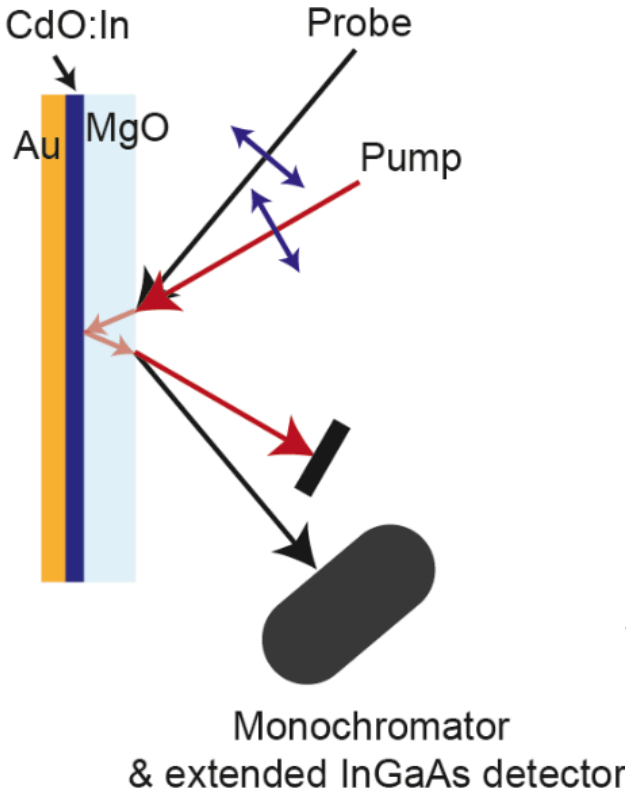
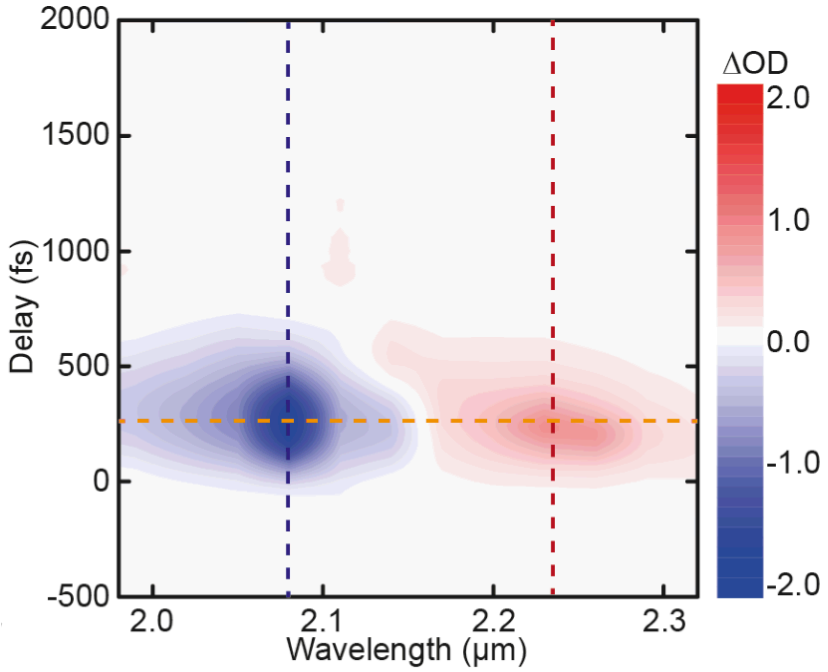


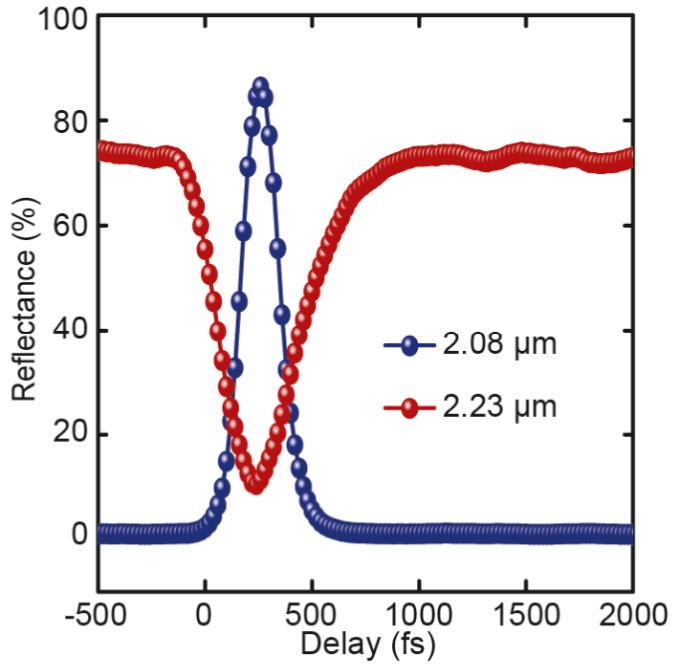
Yang et. al., Nature Photonics, Advanced Online Publication

Ultrafast AMPLITUDE SWITCHING of the Perfect Absorber

- ***Absolute reflectance* modulation *from 1% to 86%!***
- ***Pump energy density: 339 μJ/cm²***







- ***Absolute reflectance* modulation *from 1% to 86%!***
- ***Pump energy density: 339 μJ/cm²***

Yang et. al., Nature Photonics, Advanced Online Publication

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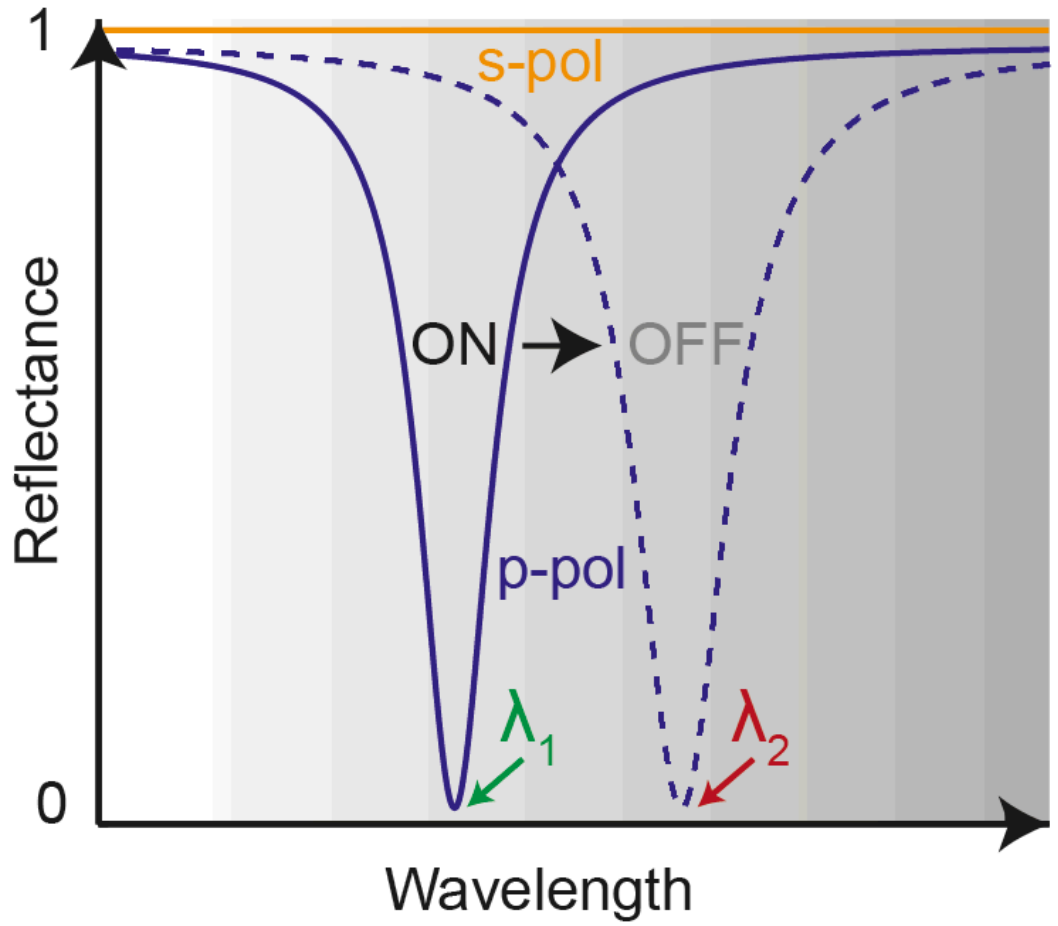
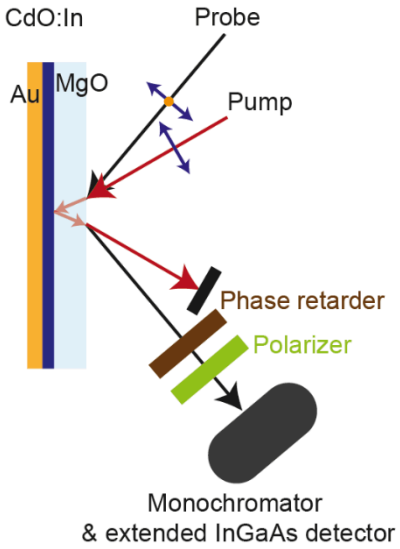
Ultrafast POLARIZATION SWITCHING

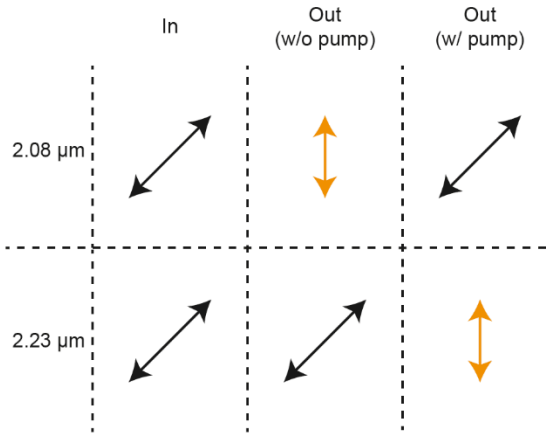


Yang et. al., Nature Photonics, Advanced Online Publication

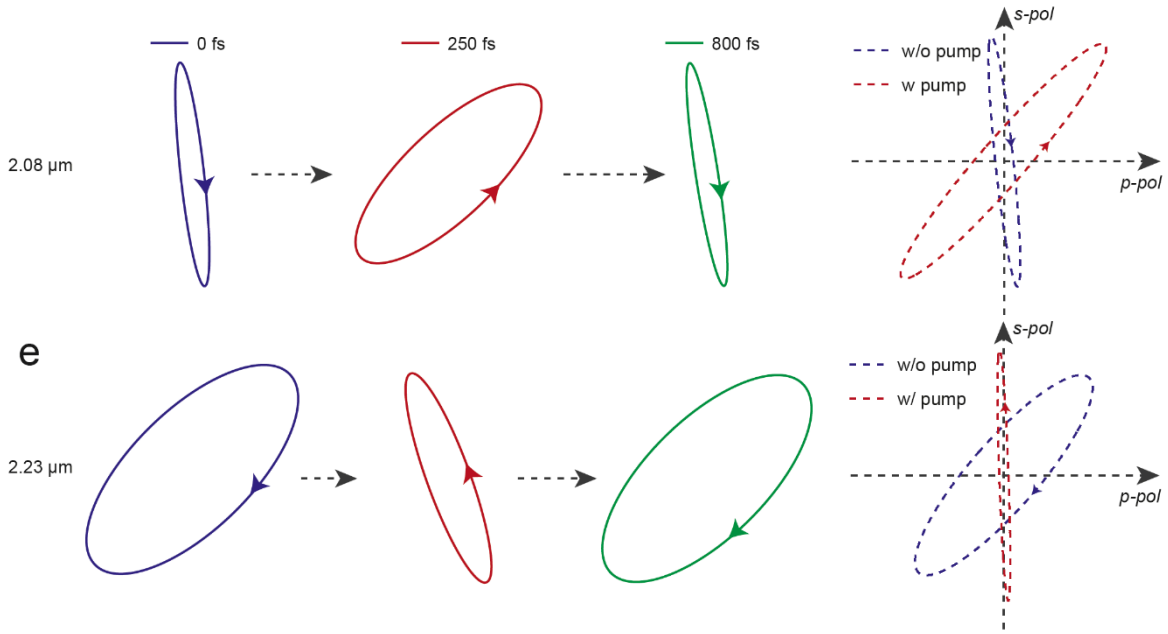
Ultrafast POLARIZATION SWITCHING



Predicted polarization input/output:



Experiments ***Simulations***



Yang et. al., Nature Photonics, Advanced Online Publication

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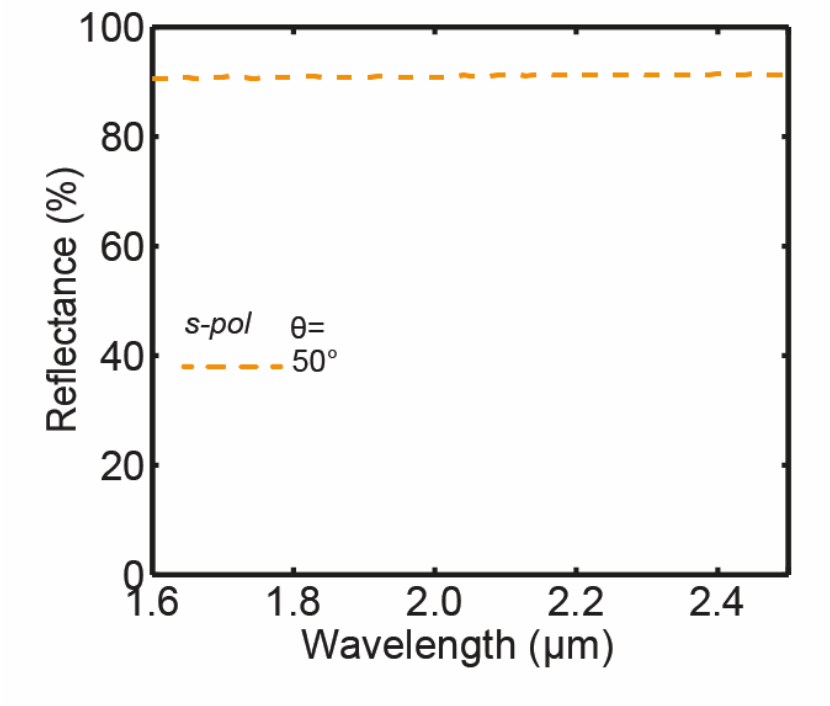
Summary

- A great deal can be accomplished with a simple thin film structure
- Field enhancement from ENZ enables efficient TH generation
- Thicker film can reduce saturation effect
- Heating effect enables ultrafast reflectivity or polarization switching

Thank you for your attention

CdO-based Berreman-mode Perfect Absorber



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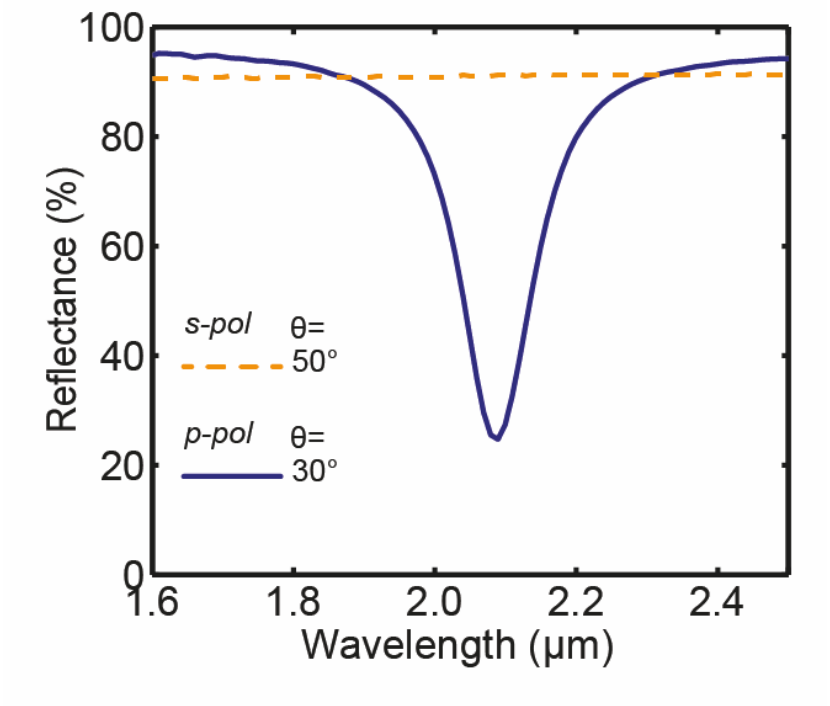
CdO-based Berreman-mode Perfect Absorber



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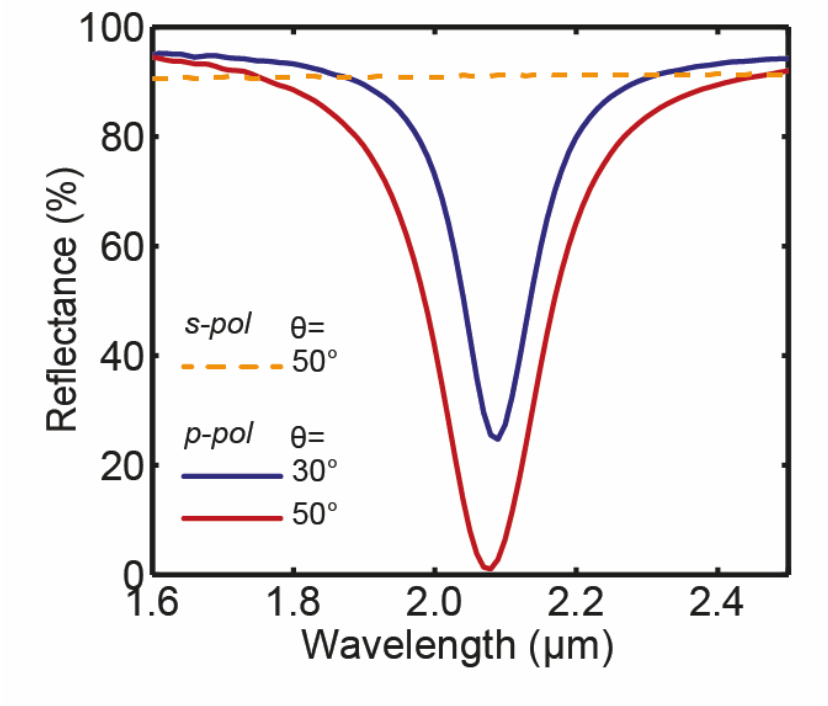
CdO-based Berreman-mode Perfect Absorber



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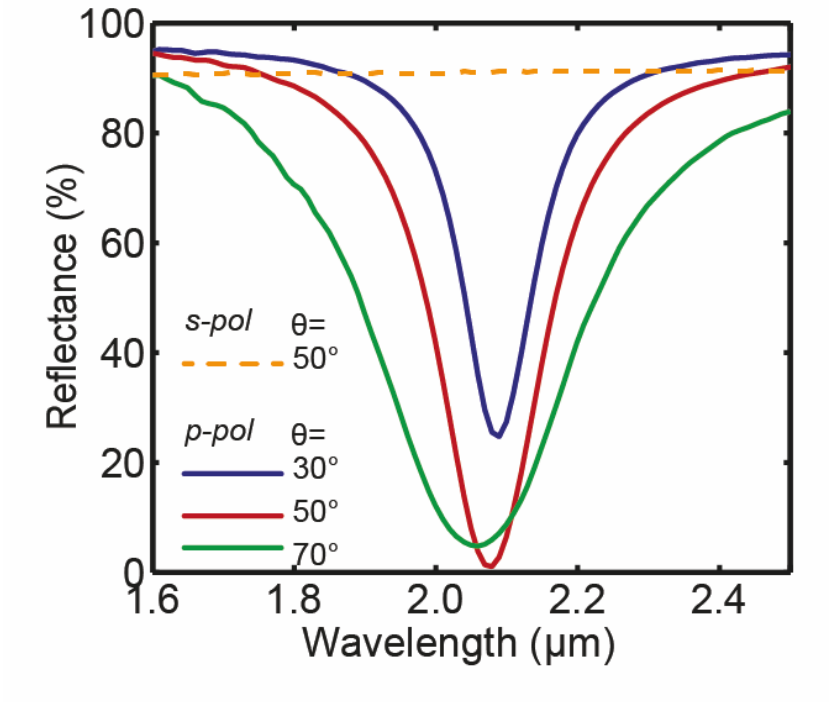

Yang et. al., Nature Photonics, Advanced Online Publication