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Third harmonic generation in ultrathin epsilon-near-zero media

Ting S. (Willie) Luk
Sandia National Laboratories, Center of Integrated Nanotechnologies
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Salvatore Campione,
Sheng Liu,
Gordon A. Keeler,
Michael B. Sinclair

Sandia National Laboratories

Rohit P. Prasankumar

Los Alamos NATIONAL LABORATORY EST. 1943

Domenico de Ceglia,
Maria A. Vincenti,
Michael Scalora

Charles M. Bowden Research Laboratory

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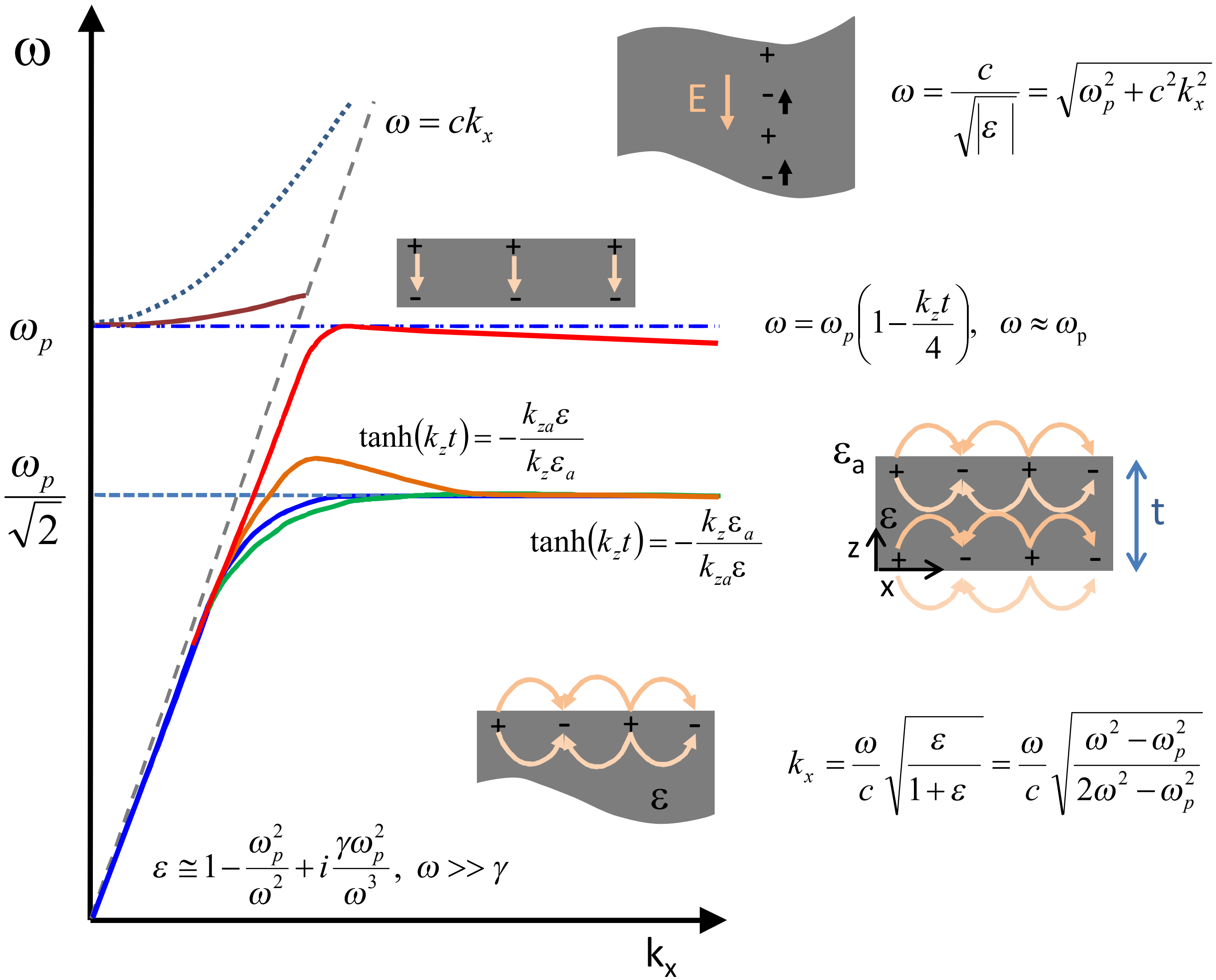
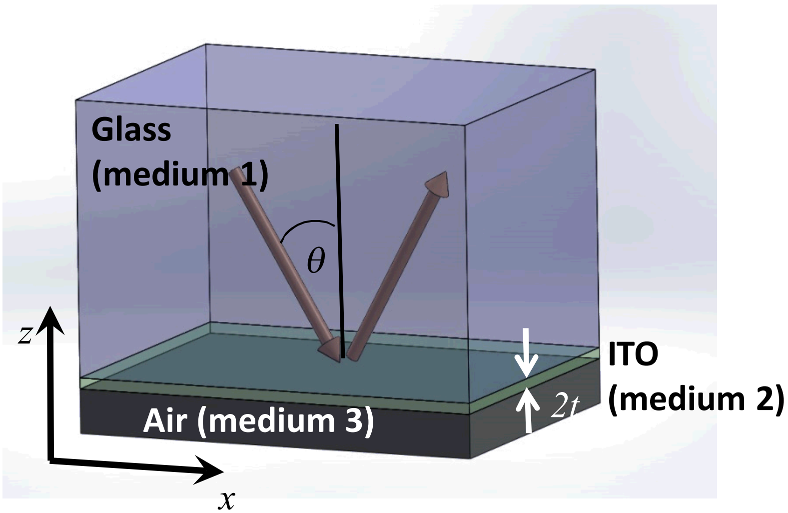
Outline

- ENZ mode in ultrathin film
- Critical coupling to the ENZ mode
- Results of enhanced THG using ENZ mode

ENZ mode and dispersion



ENZ mode dispersion and critical coupling

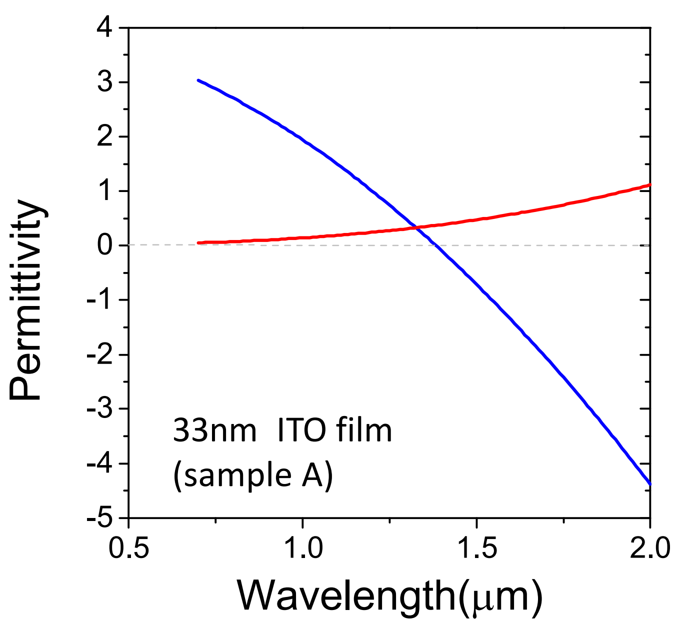


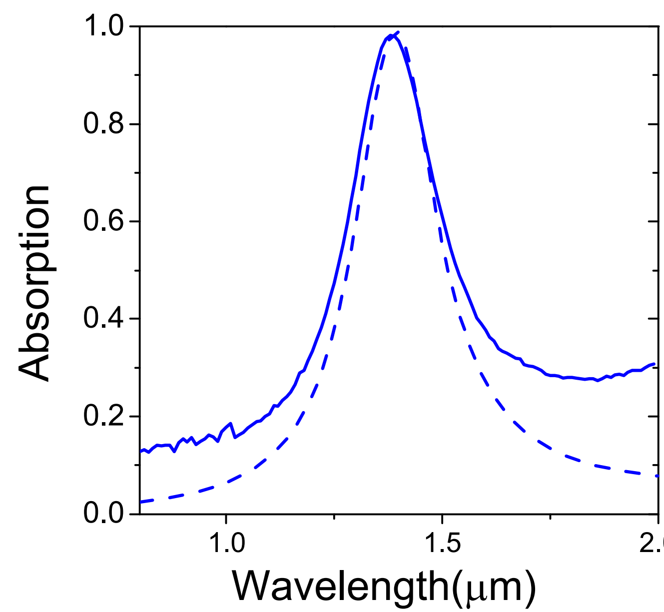
Airy Formula $$\Gamma = \frac{r_{01} + r_{12}e^{2i\phi}}{1 + r_{01}r_{12}e^{2i\phi}} \qquad \phi = k_{1\perp}t$$

Mode dispersion: $$r_{01}r_{12}e^{2i\phi} = -1$$

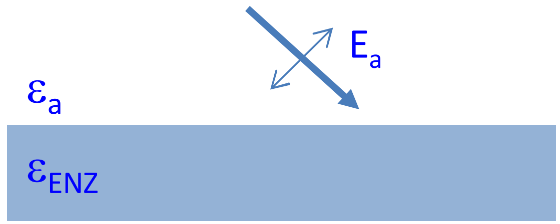
Critical coupling condition: $$r_{01} = -r_{12}e^{2i\phi}$$

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

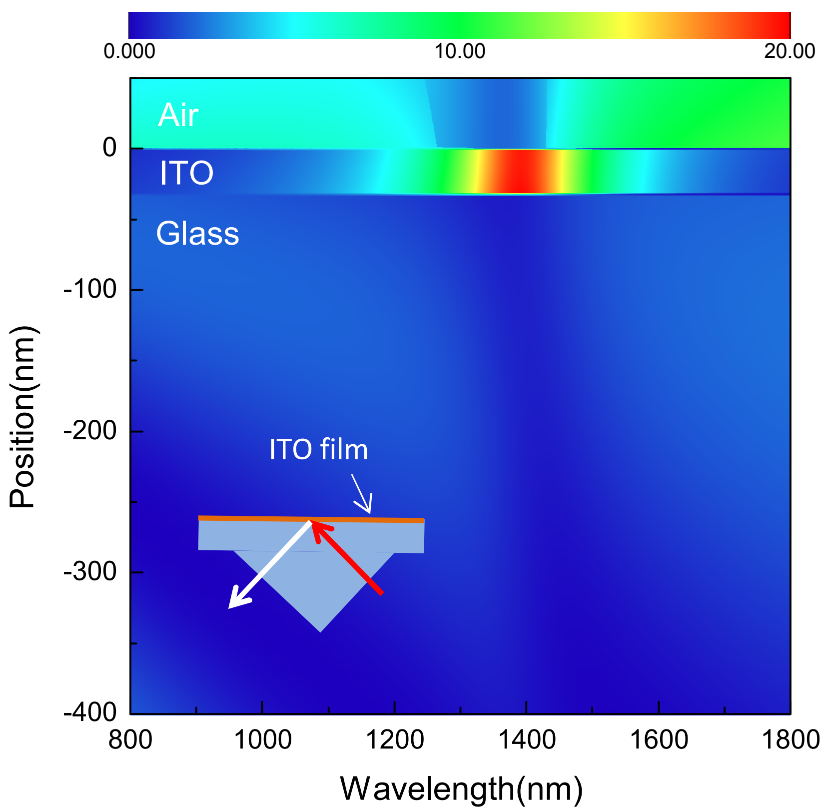


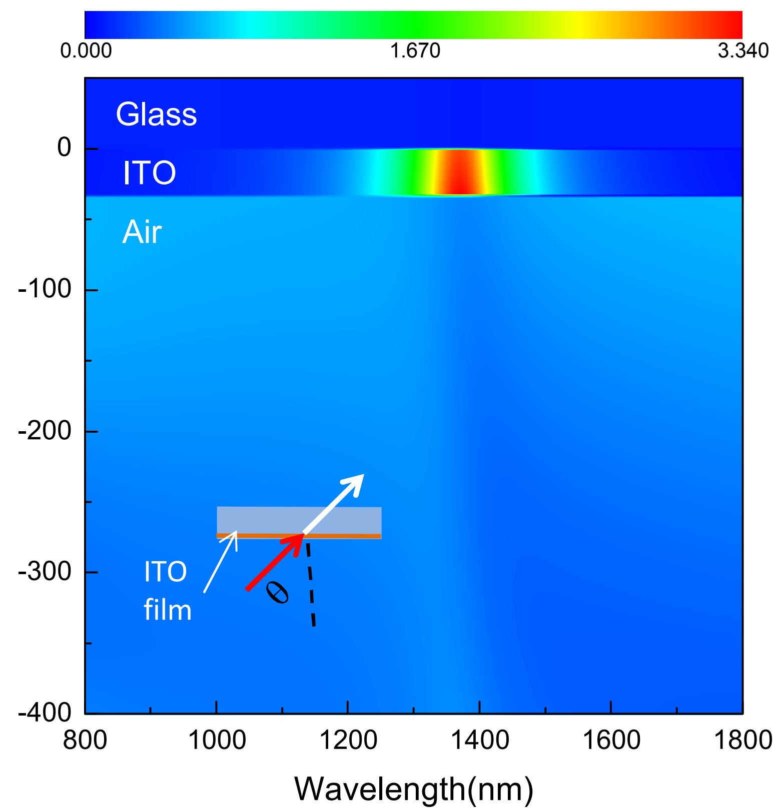


Field enhancement of ENZ mode

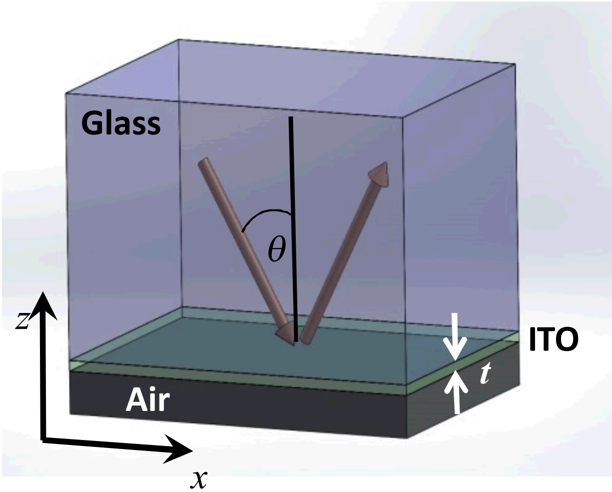


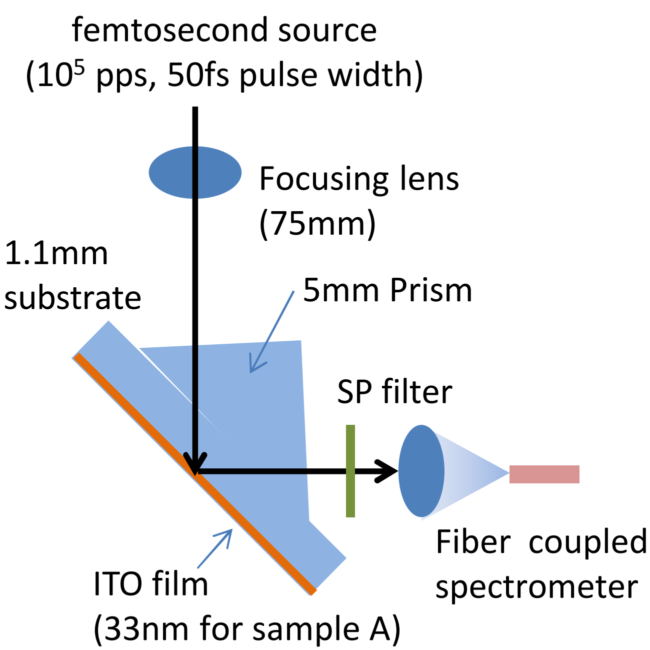
$$E_{ENZ} = D/\varepsilon_{ENZ} = E_a\varepsilon_a/\varepsilon_{ENZ}$$





Third harmonic generation using ENZ mode

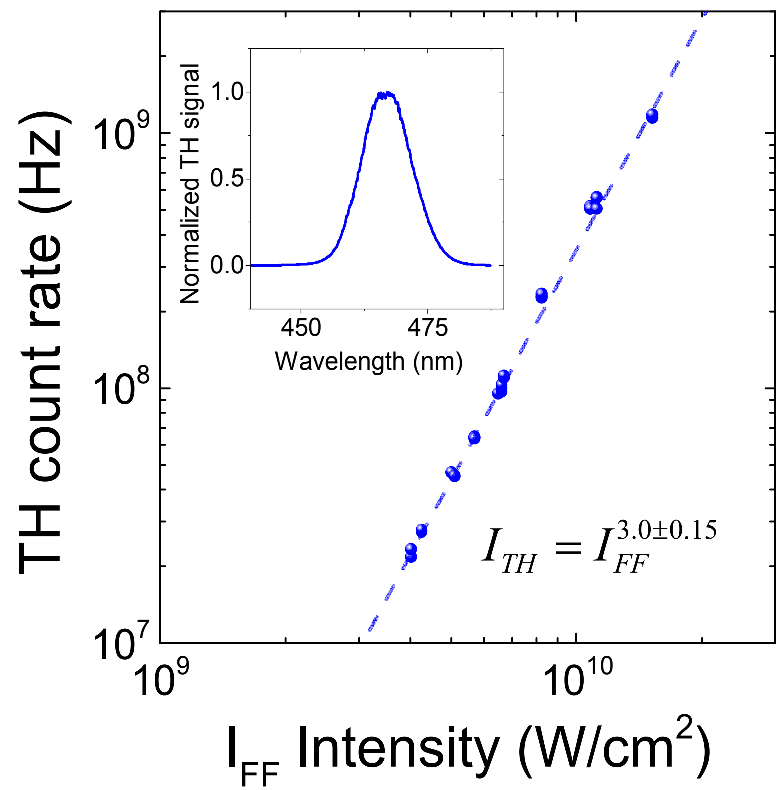




$$3\vec{k}_{FF} = \vec{k}_{TH}$$

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

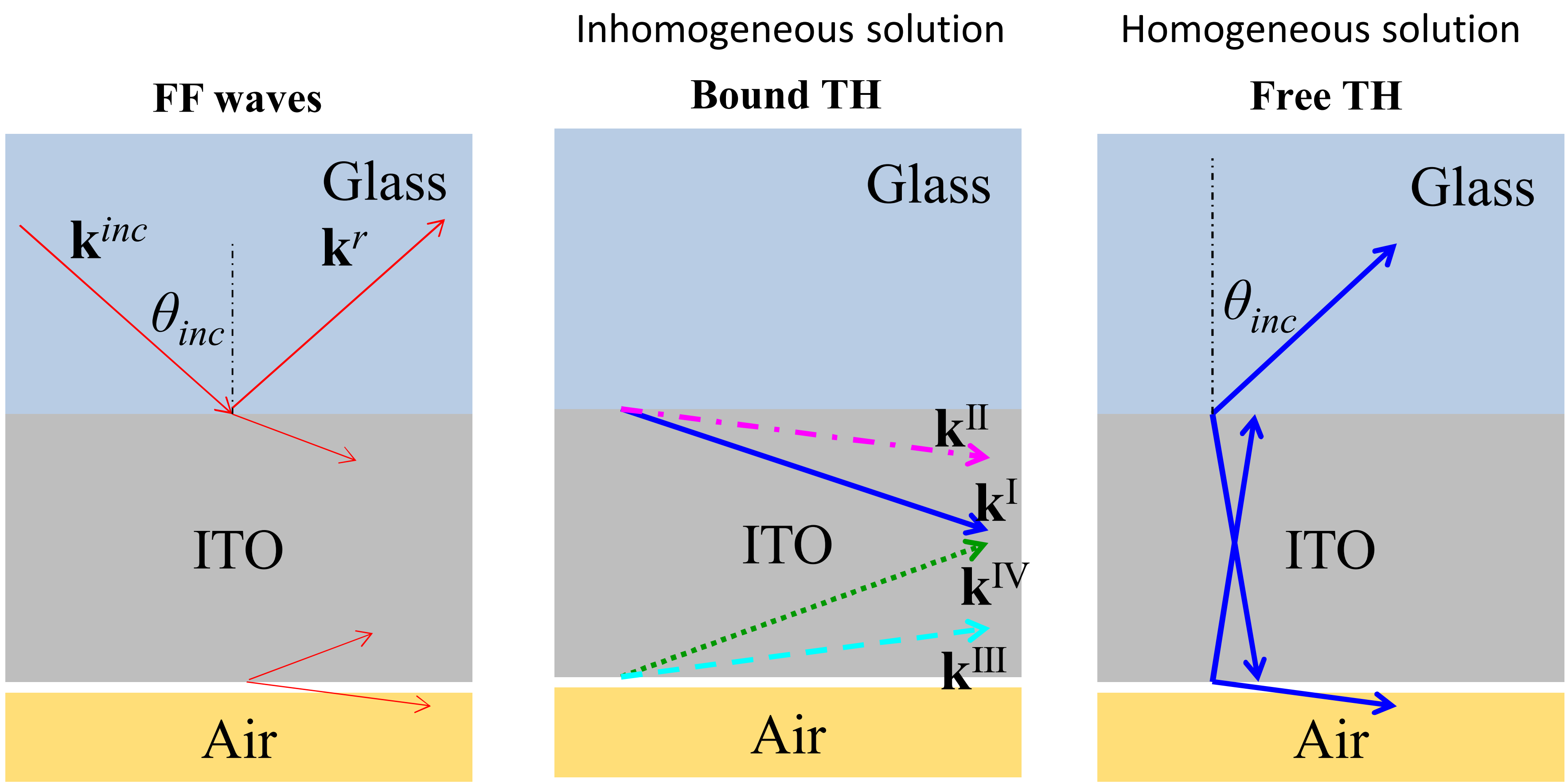
TH emerges in specular direction: $\dfrac{k_{FF//}}{k_{FF\perp}} = \dfrac{k_{TH//}}{k_{TH\perp}}$



Nonlinear polarization

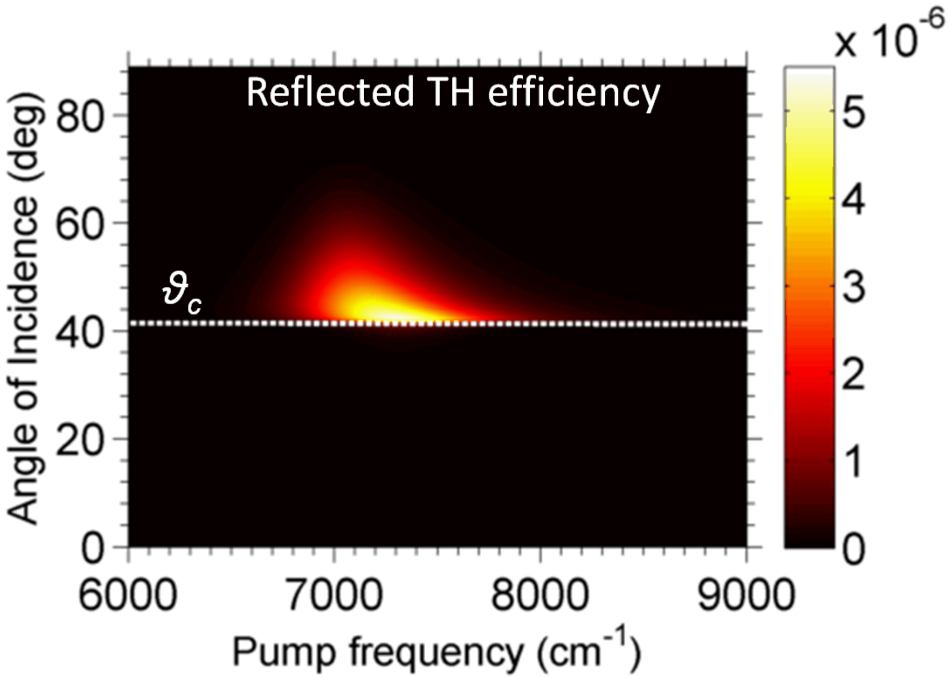
$$\nabla\times\nabla\times\vec{E}_{TH}-\frac{\omega_{TH}^2}{c^2}\overset{\leftrightarrow}{\varepsilon}\cdot\vec{E}_{TH}=\mu_0\omega_{TH}^2\vec{P}_{TH}$$

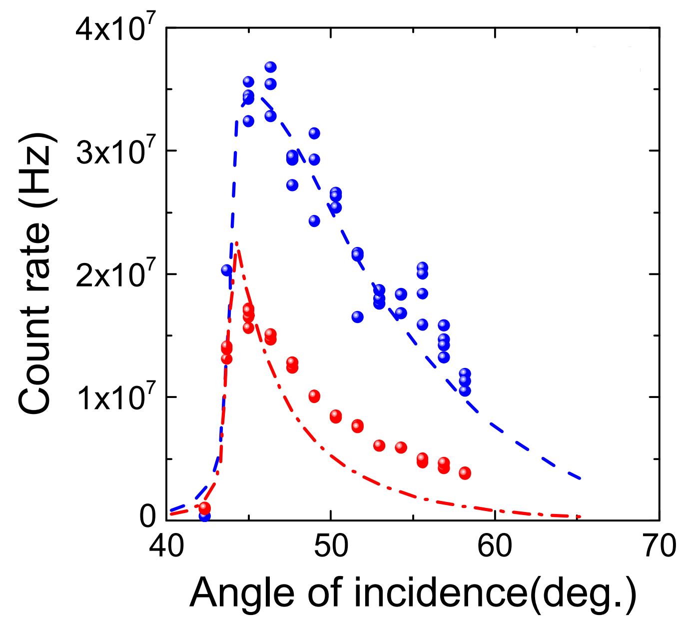
$$\vec{P}_{TH}=e^{i3k_xx}\varepsilon_0\chi^{(3)}(\omega_{TH},\omega_{FF},\omega_{FF},\omega_{FF})\cdot\left[\vec{E}_+\vec{E}_+\vec{E}_+e^{i3k_zz}+3\vec{E}_+\vec{E}_+\vec{E}_-e^{ik_zz}+3\vec{E}_+\vec{E}_-\vec{E}_-e^{-ik_zz}+\vec{E}_-\vec{E}_-\vec{E}_-e^{-i3k_zz}\right]$$



Angular dependence and conversion efficiency

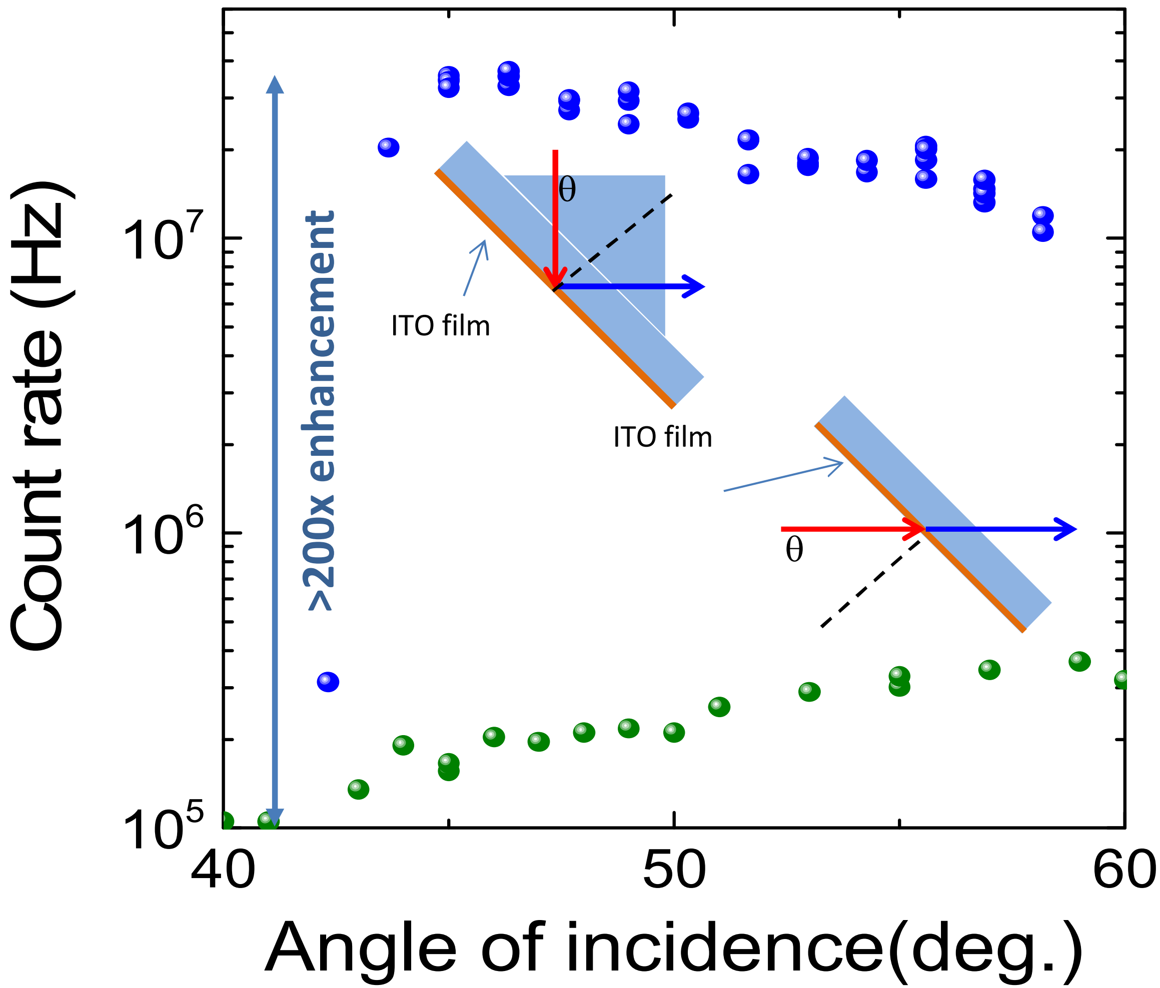
Conversion efficiency at $2x10^{10}$ W/cm^2 pump is $3.3x10^{-6}$





T. S. Luk et. al, *APL, (*2015)

ENZ mode effect



Summary

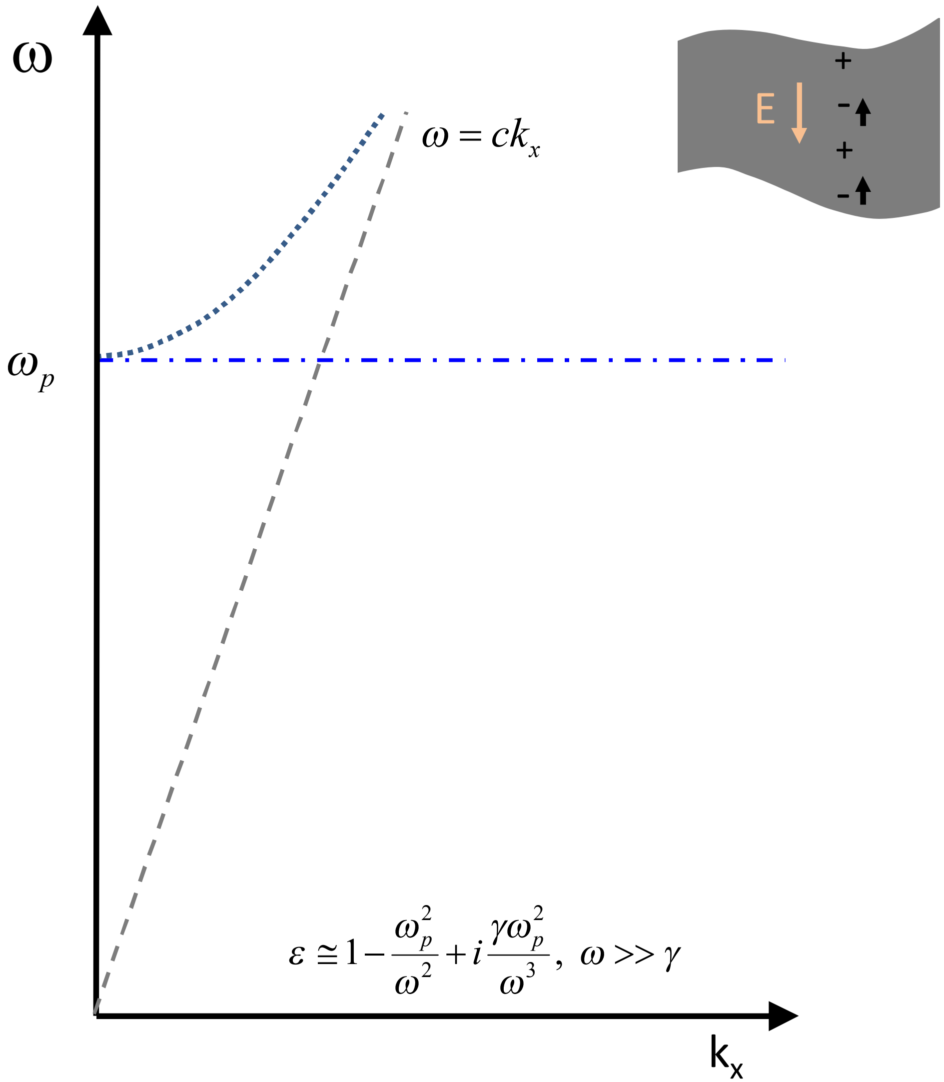
- Ultrathin film
- ENZ mode
- Efficient mode coupling

→ Efficient TH generation

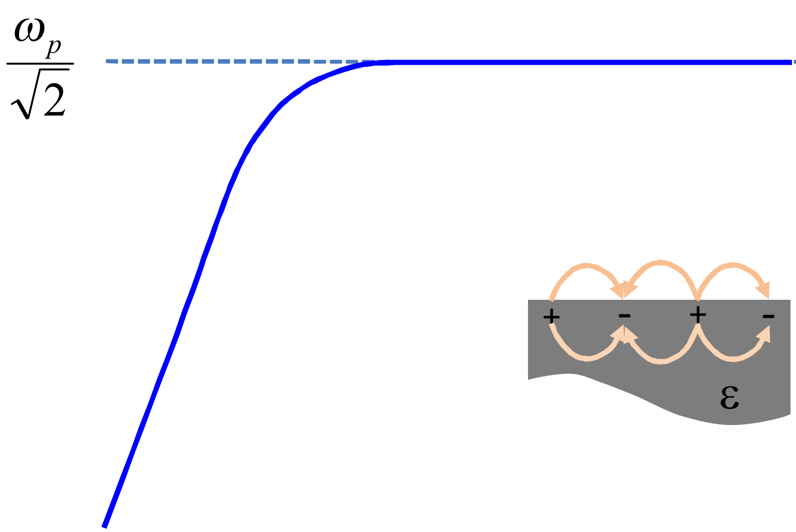
Thank you for your attention

Storyline –

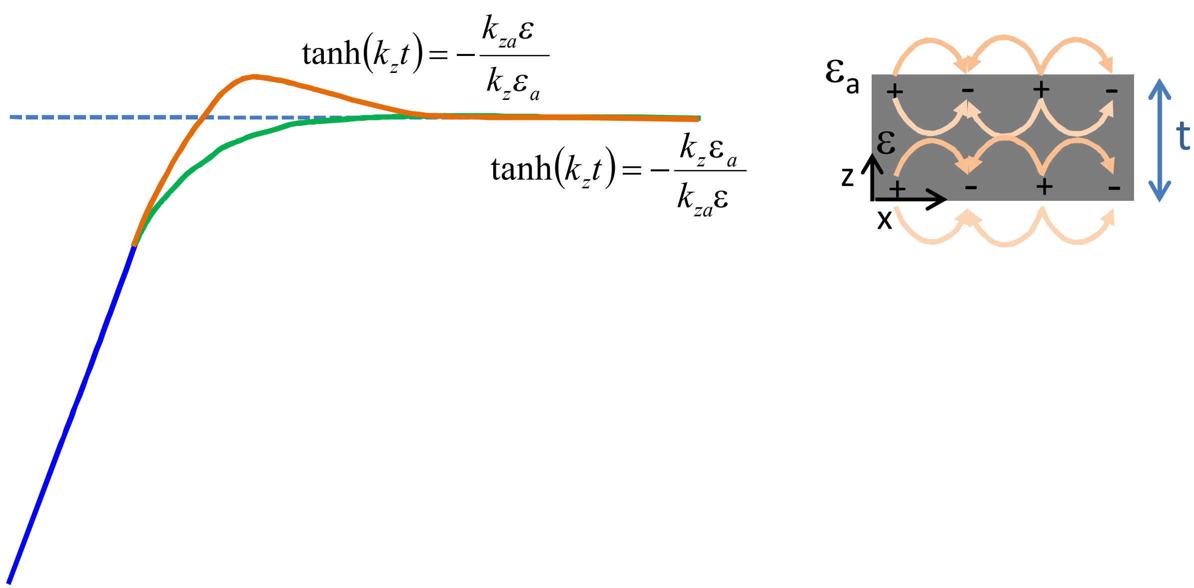
- This paper is a story about of ultrathin film optics, ENZ optics and nonlinear optics.
- This work specifically illustrates a unique aspect of ultrathin film optics that goes hand-in-hand with ENZ material.
- Examples of ultrathin film optics: metasurfaces for phase front texturing, Salisbury screen for enhanced absorption, surface plasmon waves, ENZ for enhanced field and density of states.
- Brief history of ENZ:
    - Bulk plasmon
    - Coupling to EM planewave (Ferrell recognized that under thin film condition, bulk plasmon osciallation is radiative).
    - Field enhancement
    - Optical modes in ENZ material
    - Critical coupling and perfect absorption
- We illustrate how to exploit this optical structure in the form of nonlinear third harmonic generation.
- Ultrathin epsilon-near-zero material exhibits strong field enhancement.
- The mode properties enables critical coupling of external planewave to the mode leading to perfect absorption.
- I will provide evidences that this maximum utilization of the incident field produces enhanced third harmonic generation.



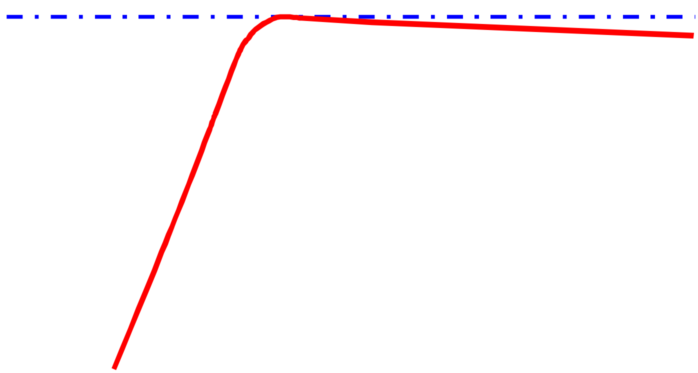
$$\omega = \frac{c}{\sqrt{|\varepsilon|}} = \sqrt{\omega_p^2 + c^2k_x^2}$$



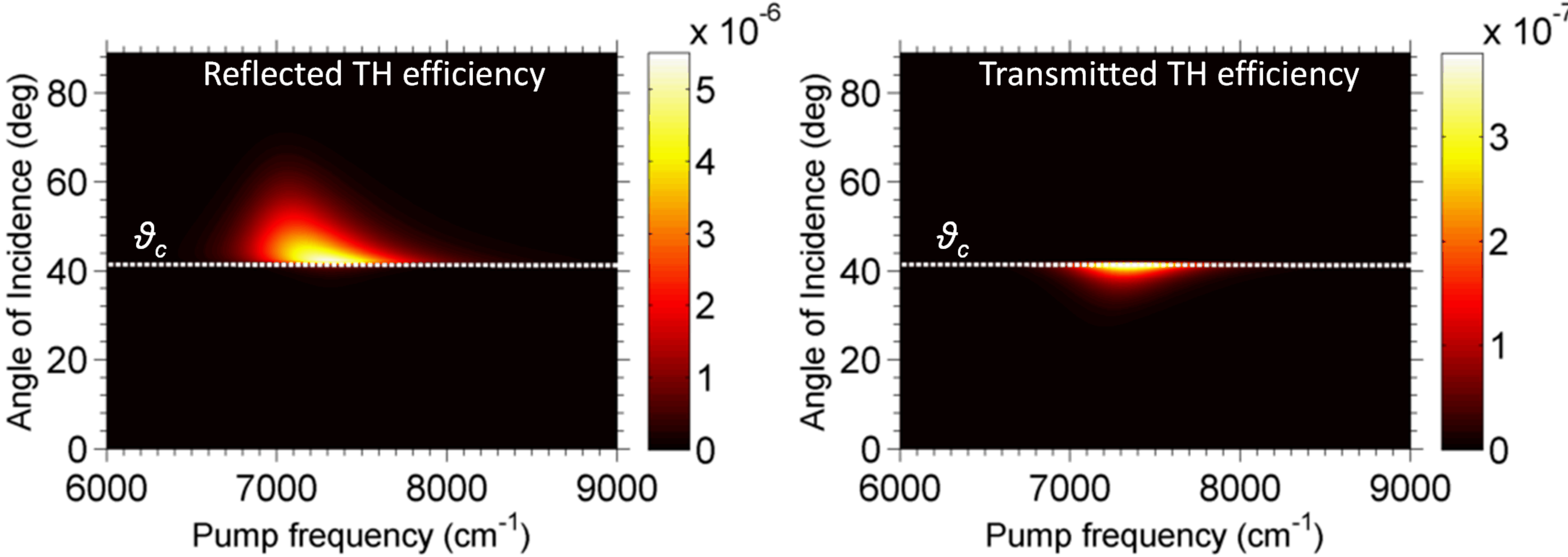
$$k_x = \frac{\omega}{c}\sqrt{\frac{\varepsilon}{1+\varepsilon}} = \frac{\omega}{c}\sqrt{\frac{\omega^2-\omega_p^2}{2\omega^2-\omega_p^2}}$$



$\tanh(k_z t) = -\frac{k_{za}\varepsilon}{k_z\varepsilon_a}$
$\tanh(k_z t) = -\frac{k_z\varepsilon_a}{k_{za}\varepsilon}$
ε_a
ε
z
x
t



$\omega = \omega_p\left(1 - \frac{k_z t}{4}\right), \quad \omega \approx \omega_p$



Reflected TH efficiency
Transmitted TH efficiency
Angle of Incidence (deg)
Pump frequency (cm^{-1})
x 10^{-6}
x 10^{-7}
ϑ_c
0
20
40
60
80
6000
7000
8000
9000