Enhanced nonlinear optical response of 1-D metal-dielectric photonic band-gap structures

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Outline

1. Motivation

How to access nonlinearity of metals?

Why 1-D MD-PBG?

Optical transparency

Nonlinear response?

2. How to Design 1-D MD PBG for NLO
3. Linear properties
4. Elements of nonlinear response

High EM field strength

Intrinsic susceptibility of metal

Phase response of PBG

5. Experimental observation of enhancement of NLO response in 1-D MD PBG

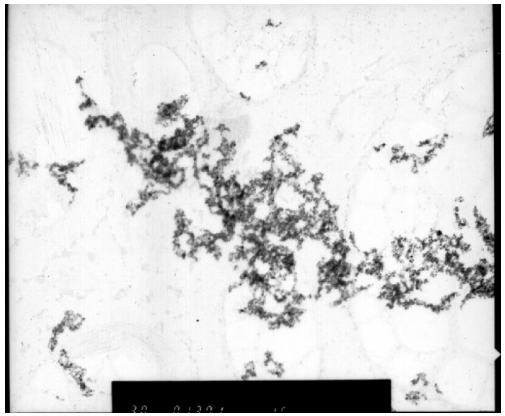
How to access nonlinearity of metals?

$$c^{(3)}_{metal} \cong 10^{-8} \div 10^{-7} \text{ esu} \;-\; \text{opaque!}$$

$$c^{(3)}_{SiO_2} \cong 10^{-14} \text{ esu} \quad -\; \text{transparent!}$$

Discontinuos composite materials:

- colloidal solutions
- metal doped glasses
- granular metal films

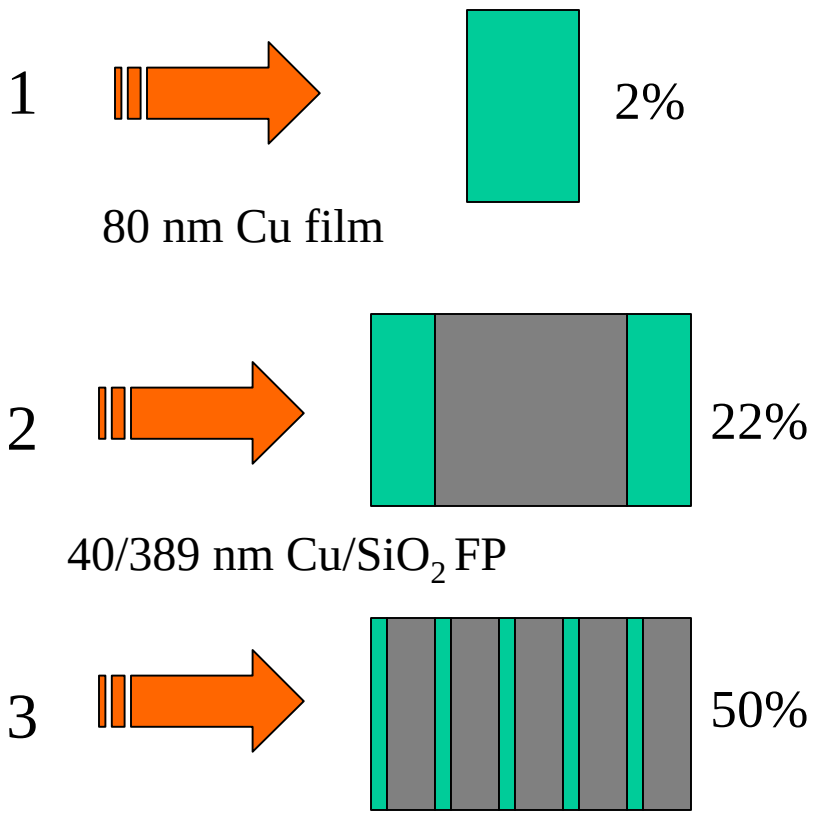


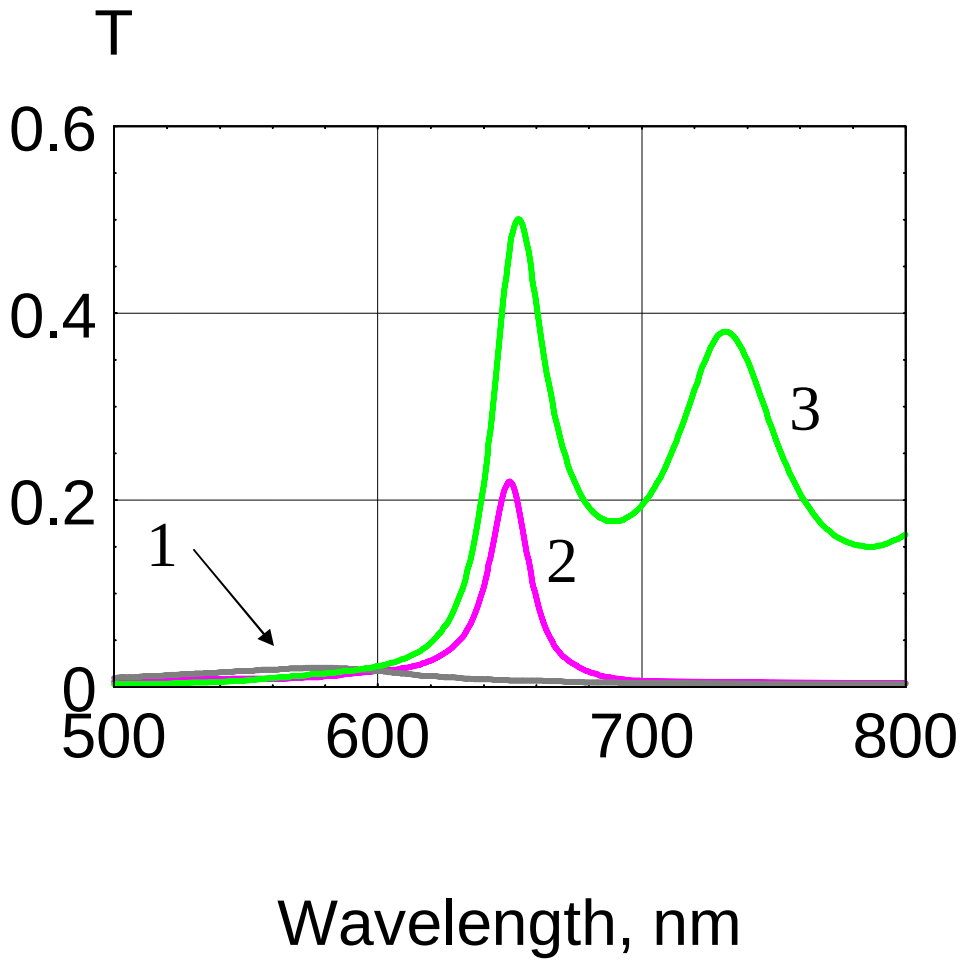
Layered periodic MD structures:

High transparency within specified spectral range (PBG effect)

Enhanced NLO response?

1-D Metal/Dielectric PBG structures





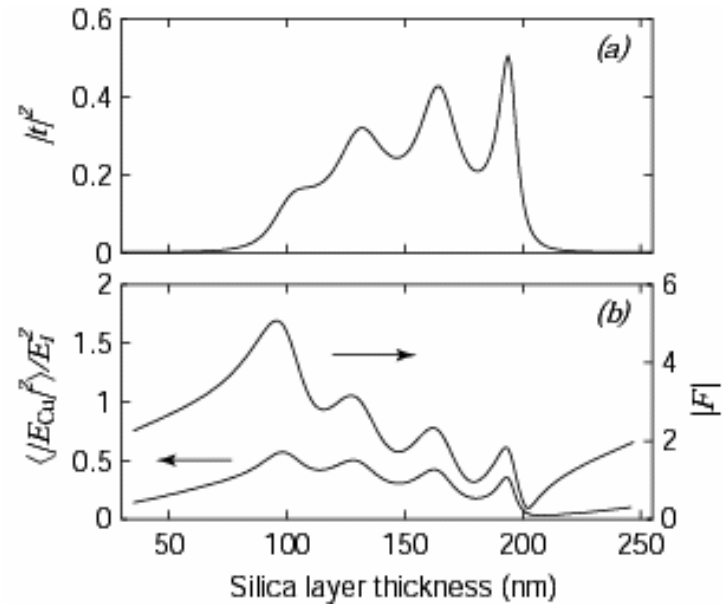
M. Scalora *et al*. J. Appl. Phys. **83**, 2377-2383 (1998)

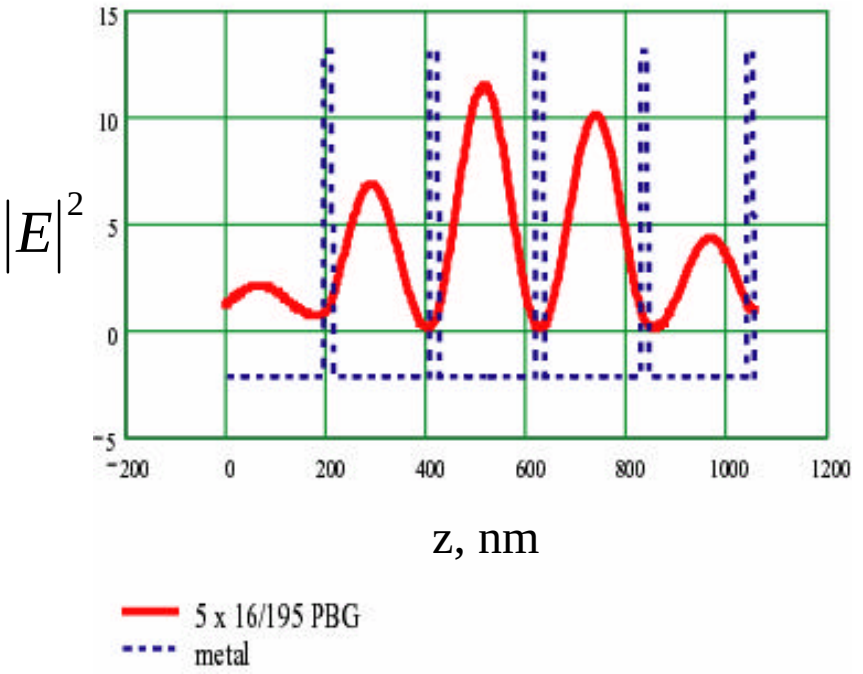
How to Design 1-D MD PBG for NLO

$$e \cong e_{lin} + c_m^{(3)} \cdot h \cdot F \cdot E^2$$

h – field factor F- phase factor

$$l = 650 \text{ nm}$$

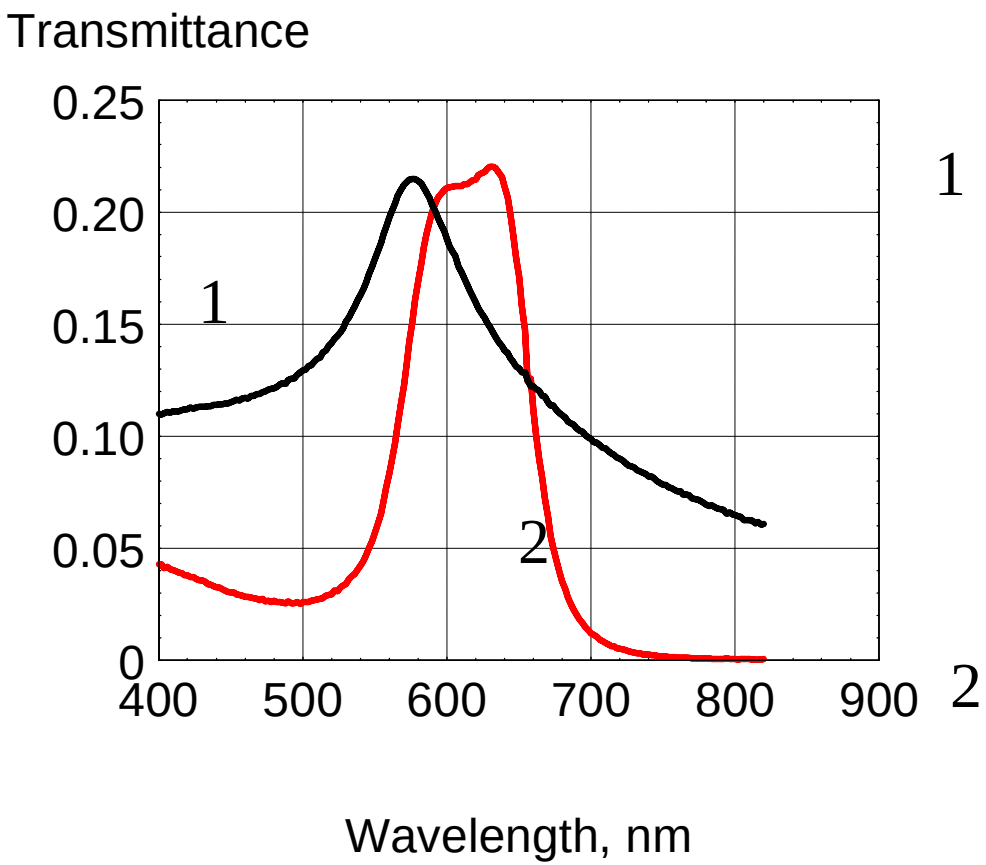




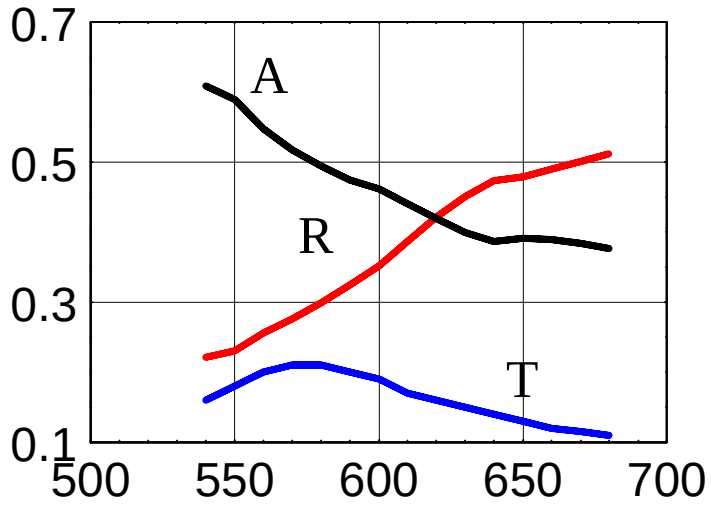
5 x 16/196 nm Cu/SiO_2 PBG

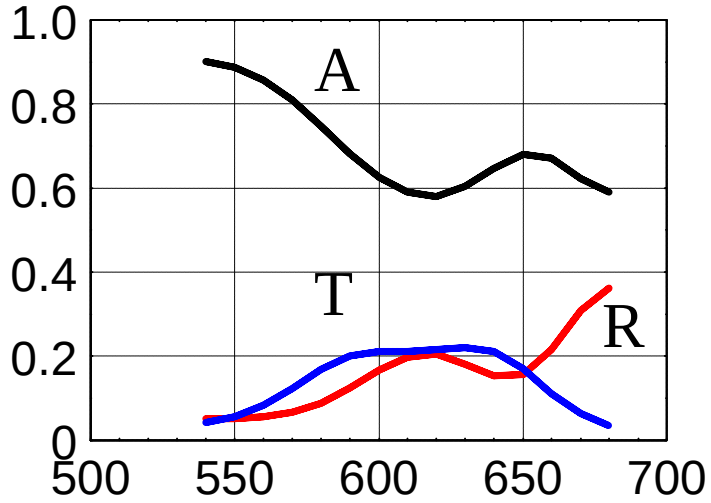
Linear optical properties

1- 40 nm Cu film - bulk
2- 5 x 16/98 nm Cu/SiO_2 PBG - composite



1





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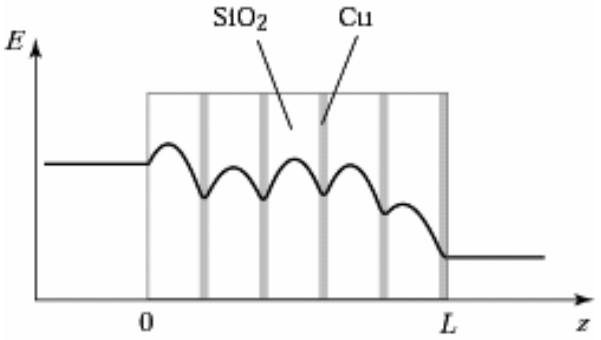
High EM field strength

1 - 5 x 16/98 nm Cu/SiO_2 PBG

2 - 40 nm Cu film

1



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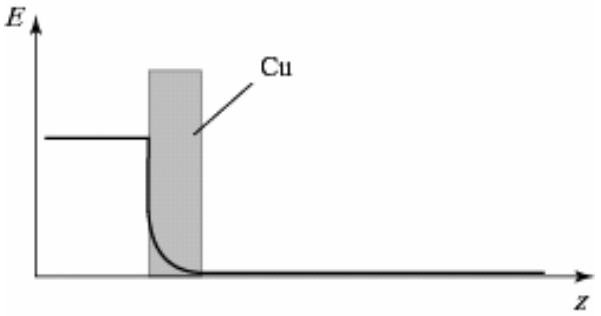
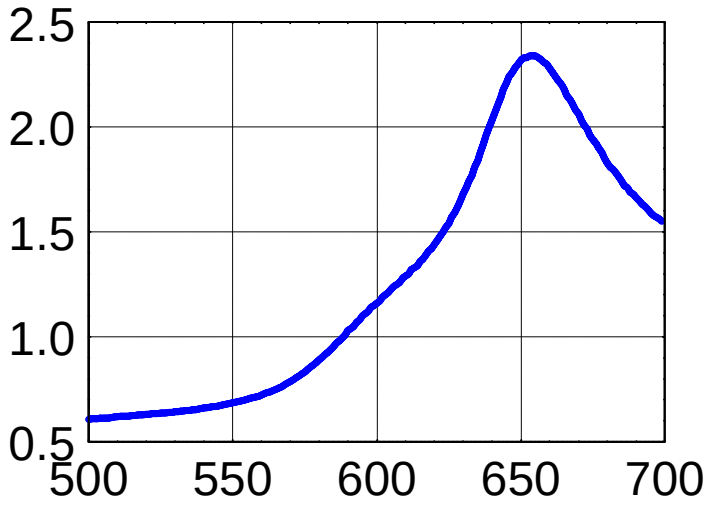


$$\frac{\langle E^2_{PBG} \rangle}{\langle E^2_{Cu} \rangle}$$



Wavelength, nm

Nonlinear susceptibility of bulk metal

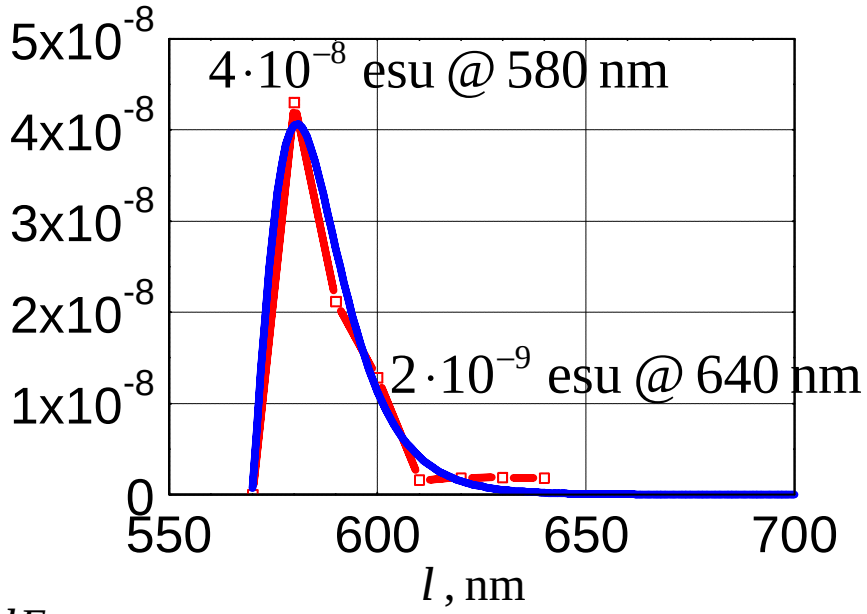
NLO properties of copper

@ interband threshold -

Fermi smearing

$$\mathrm{Im}(c^{(3)})$$

$$dE = E_g - hn$$



$$\mathrm{Re}(c^{(3)})_{FS} << \mathrm{Im}(c^{(3)})_{FS}$$

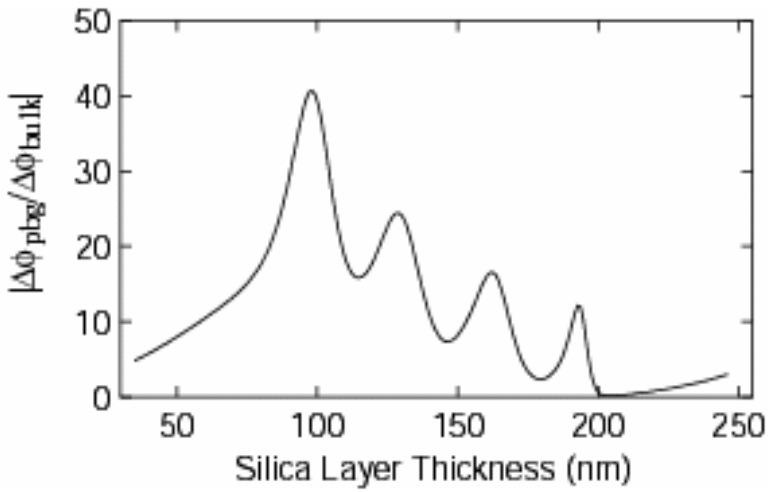
$$\mathrm{Im}(c^{(3)})_{FS} = C\,\frac{dE}{k_B T}\,\frac{e^{-\frac{dE}{k_B T}}}{\left(1+e^{-\frac{dE}{k_B T}}\right)^2} \qquad \Delta l_{FS} \cong \frac{hc}{E_g^2}\,k_B T$$

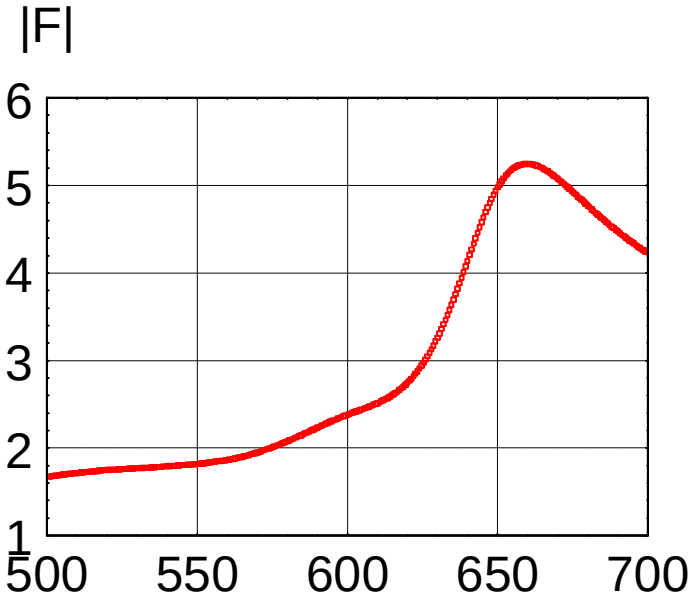
E_g=2.15 eV

F. Hache *et al*. Appl. Phys. A **47**, 347-357 (1988)

Phase response

$$F = \frac{\Delta f}{\frac{2p}{l}\int_0^L \Delta n \, dz}$$ -phase sensitivity





Wavelength, nm

NLO response of MD PBG

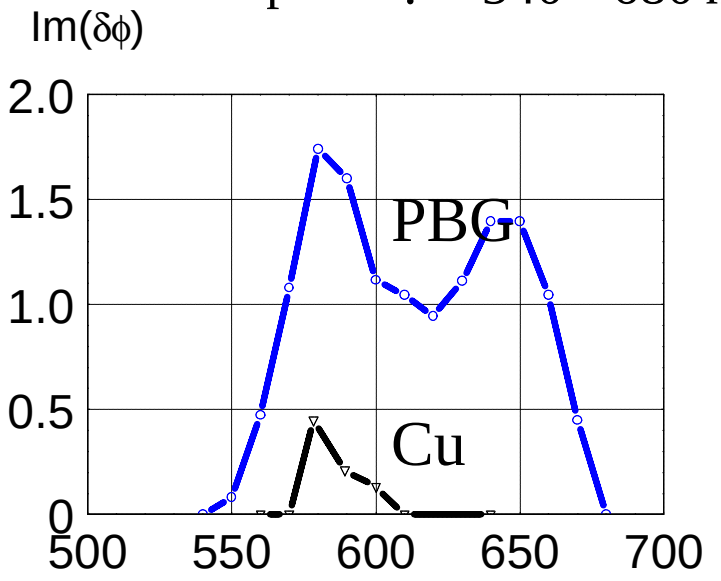
$df = df' + i \cdot (\ln(\sqrt{T_{lin}}) - \ln(\sqrt{T(I)}))$ - complex nonlinear phase shift

$df' << df''$ $\quad df \leftarrow$ Z-scan

EKSPLA OPG

E=2-5 uJ I=100 MW/cm^2

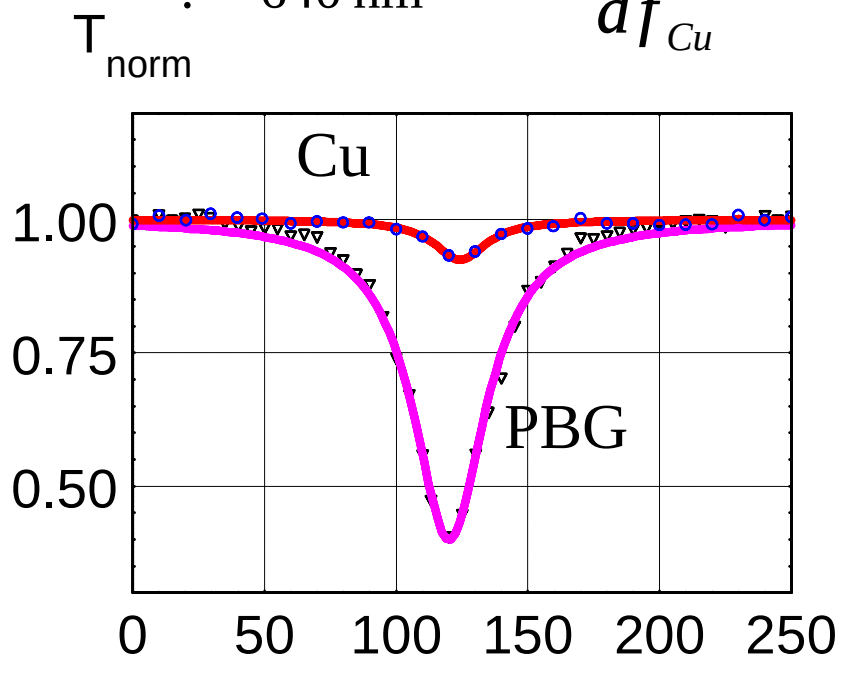
t=25 ps $\quad ? = 540 - 680$ nm



$I = 500$ MW/cm^2

$? = 640$ nm

$\frac{df''_{PBG}}{df''_{Cu}} \cong 35$



Conclusions

We introduced artificial, stable, solid state NLO material with tunable (by design) transmission band and high damage threshold.

We experimentally demonstrated enhanced nonlinear response of 1-D MD PBG structure within the passband compared to that of bulk metal. The enhancement factor was measured to be as high as 35.