Enhanced Nonlinear Optical Response of 1-D Metal-Dielectric Photonic Band-Gap Structures

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How to Access Optical Nonlinearity of Metals?

\[
\chi_{metal}^{(3)} \approx 10^{-8} - 10^{-7} \text{ esu} \quad \text{opaque!}
\]
\[
\chi_{SiO_2}^{(3)} \approx 10^{-14} \text{ esu} \quad \text{transparent!}
\]

Discontinuous 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
Accessing the Optical Nonlinearity of Metals with Metal-Dielectric PBG Structures

- Metals have very large optical nonlinearities but low transmission.
- Low transmission is because metals are highly reflecting (not because they are absorbing!).
- Solution: construct metal-dielectric PBG structure.
  (linear properties studied earlier by Bloemer and Scalora)

Accessing the Optical Nonlinearity of Metals with Metal-Dielectric PBG Structures

- Metal-dielectric structures can have high transmission.
- And produce enhanced nonlinear phase shifts!

**Linear transmission of PBG sample at $\lambda = 650$ nm.**
- Copper layers 16 nm thick

**Enhancement of NL phase shift over bulk metal**
- Simple model
- Exact solution

![Graph showing linear transmission and enhancement of nonlinear phase shift over bulk metal](image)
1-D Metal/Dielectric PBG structures

1. 80 nm Cu film

2. 40/389 nm Cu/SiO$_2$ FP

3. 5 x 16/98 nm Cu/SiO$_2$ PBG

Wavelength, nm
Linear Optical Properties

Bulk: 40 nm Cu film
PBG: 5 x 16/98 nm Cu/SiO
Model of Enhanced Nonlinear Optical Response

\[ \varepsilon \approx \varepsilon_{\text{lin}} + \chi_m^{(3)} I F E^2 \]

where

\[ I = \frac{\langle E_{m,\text{pbg}}^2 \rangle}{\langle E_{m,\text{bulk}}^2 \rangle} \]

\[ F = \frac{\Delta \phi}{\lambda} \int \Delta n \, dz \]

I = intensity enhancement factor
F = phase enhancement factor

I and F calculated numerically for our five layer design
Nonlinear Susceptibility of Bulk Copper

• We find $\text{Im} \chi^{(3)} \gg \text{Re} \chi^{(3)}$ at all wavelengths where response is measurable.
• Near interband threshold, Fermi smearing is dominant nonlinear process (Hache et al., Appl. Phys. A 47, 347-357 (1988)).
• Width of resonance is approximately $4kT$. 

\text{Z-scan data} \\
\text{Fermi smearing model}
Z-Scan Comparison of M/D PBG and Bulk Sample

Open-aperture Z-scan
(measures $\text{Im} \chi^{(3)}$)

$I = 500 \text{ MW/cm}^2$
$\lambda = 640 \text{ nm}$

$\frac{\delta \phi_{\text{PBG}}^{''}}{\delta \phi_{\text{Cu}}^{''}} \approx 35$
Spectral Dependence of the Nonlinear Response

**Graph:**

- **Y-axis:** \(\text{Im } \phi_{NL}\)
- **X-axis:** Wavelength, nm

**Legend:**
- **PBG**
- **Bulk**

**Graph Information:**
- **OPG:**
  - \(t = 25\) ps
  - \(Q = 2\) to \(5\) mJ
  - \(I \approx 100\) MW/cm\(^2\)
Conclusions

We produced a stable, artificial, solid-state NLO material with a tunable transmission band and high damage threshold.

We experimentally demonstrated enhanced nonlinear response of 1-D MD PBG structure. The enhancement factor was measured to be as high as 35.