Observation of Phased-Matched Third-Harmonic Generation in Photonic Crystals

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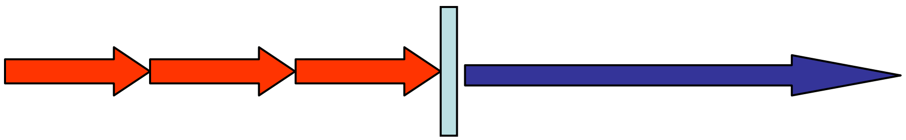
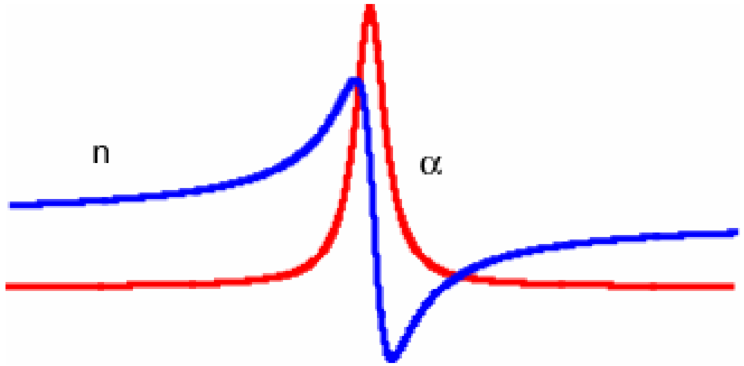
Phase matching in periodic structures

Efficient harmonic generation requires phase matching

$$\overrightarrow{k_{\omega}} + \overrightarrow{k_{\omega}} + \overrightarrow{k_{\omega}} = \overrightarrow{k_{3\omega}}$$





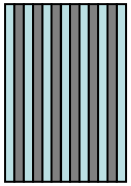
Material dispersion: $n(3\omega) > n(\omega)$

In a band-gap structure, material dispersion can be compensated by structural dispersion without inducing absorption

N. Bloembergen and A. J. Sievers, APL, 17, 483 (1970)

THG in cholesteric liquid crystals

J. W. Shelton and Y. R. Shen, PRL 25, 23 (1970)



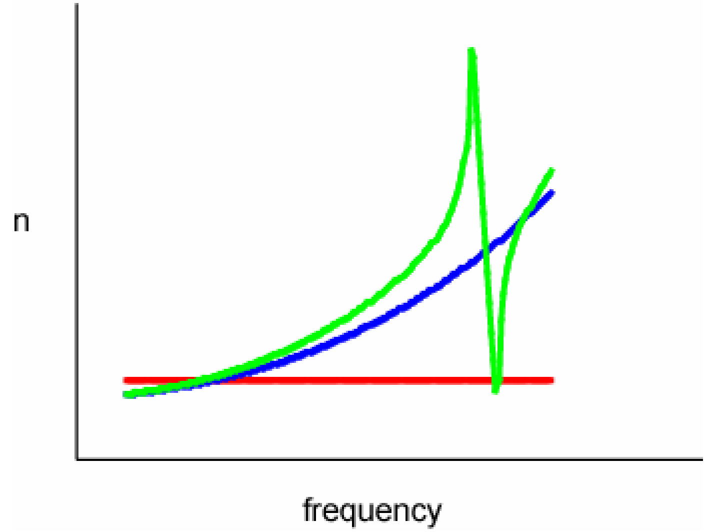
Effective Refractive Index

$$n_{eff} \equiv c\frac{k(\omega)}{\omega}$$

no dispersion

material dispersion

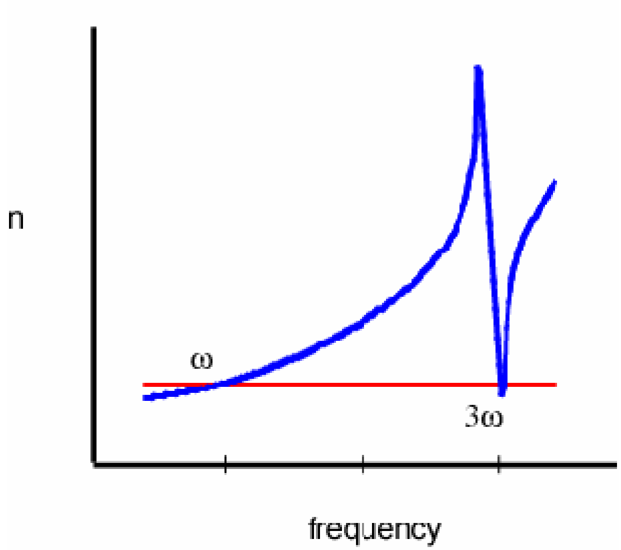
material + structural dispersion

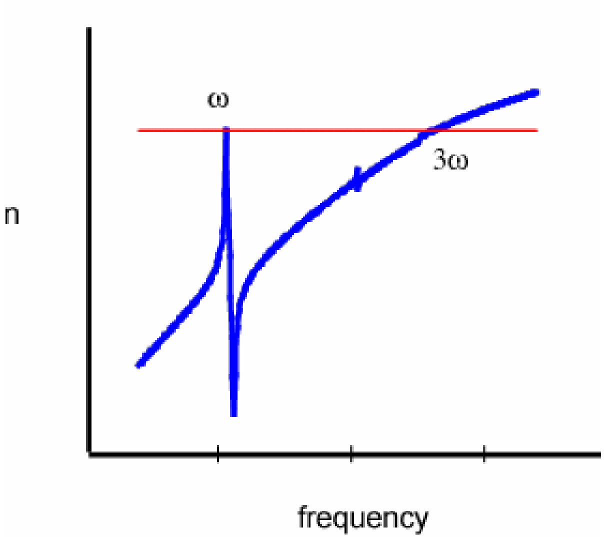


Motivation

-to revisit the idea of phase matching in periodic structures in the context of 1-D and 3-D photonic crystals

What did we expect?

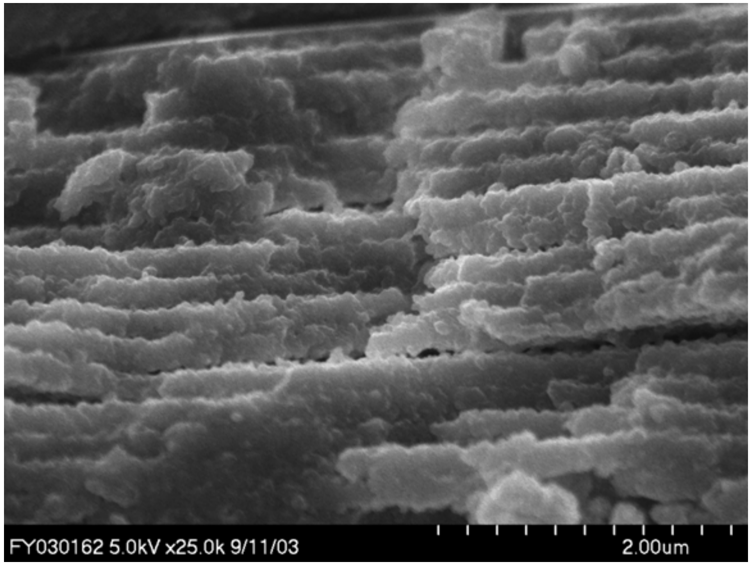




Phase-matched THG in transmission and reflection

1-D photonic crystals

Holographic polymer-dispersed
liquid crystal grating (H-PDCL)



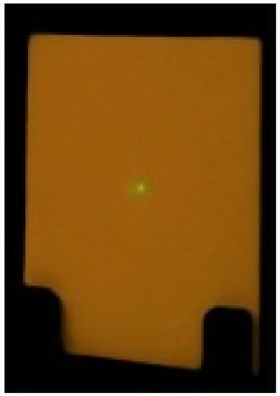
$10\ \mu\text{m film}$

$n_1 = 1.5 \quad n_2 = 1.35 \text{ at } 1550\,\text{nm}$

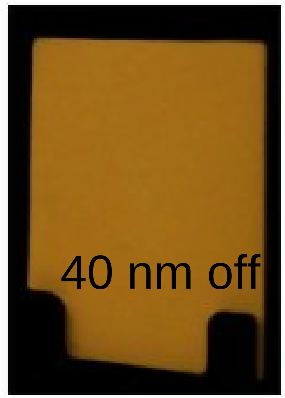
$\Delta n = 0.15$

Experimental setup

A

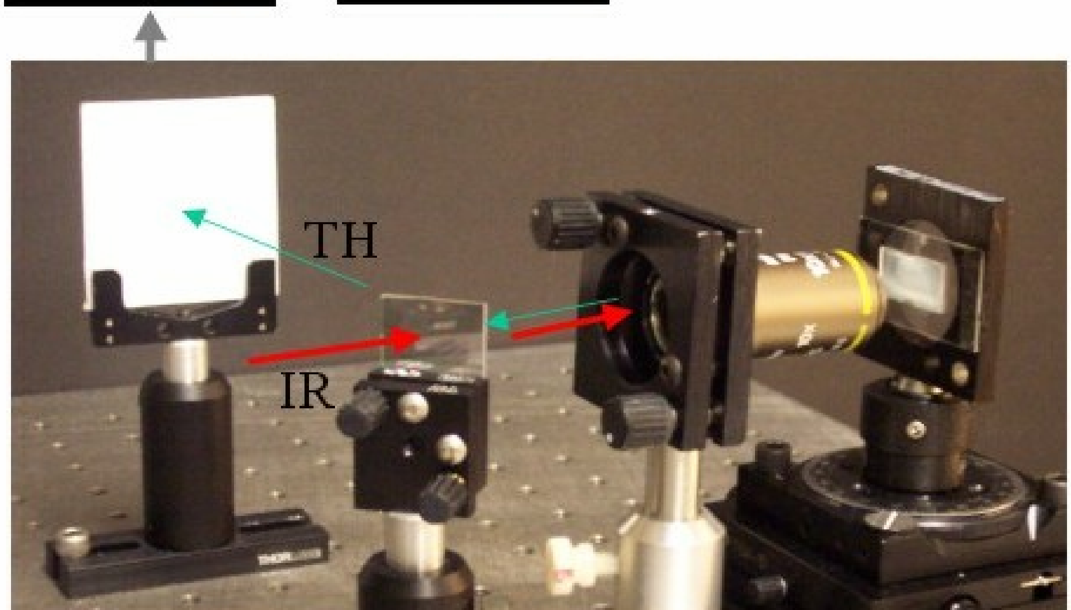


B

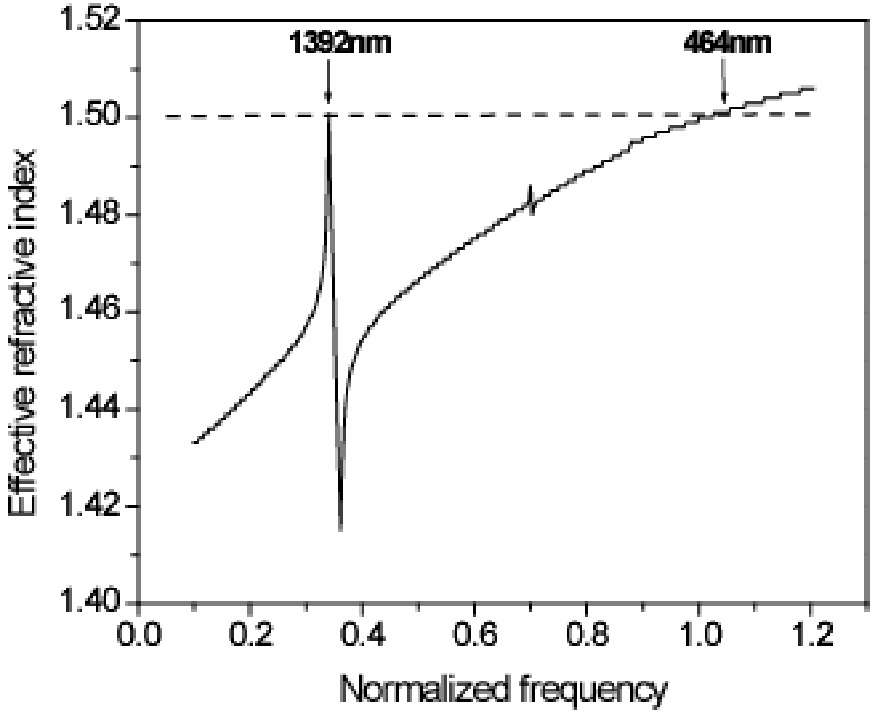


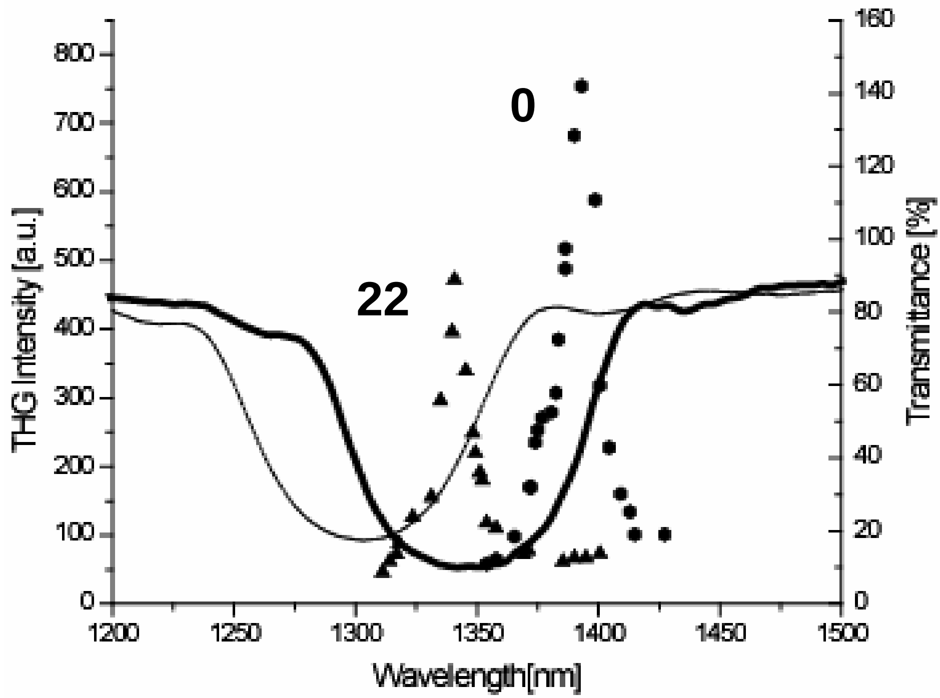
Pump (OPG):
1 kHz rep rate
160 fs pulse
Wavelength: 1.1-1.6 μm

$I \leq 500\,\mathrm{GW/cm^2}$



Third-Harmonic Generation in 1-D PC

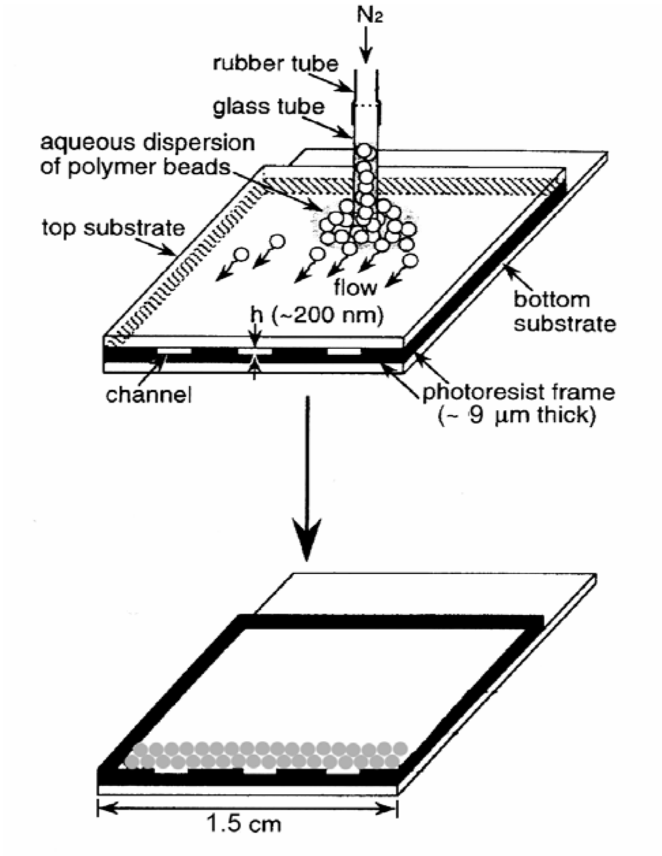




THG at the low-frequency edge of the band gap
Tuning THG by changing the incidence angle

3-D Photonic crystal fabrication methods

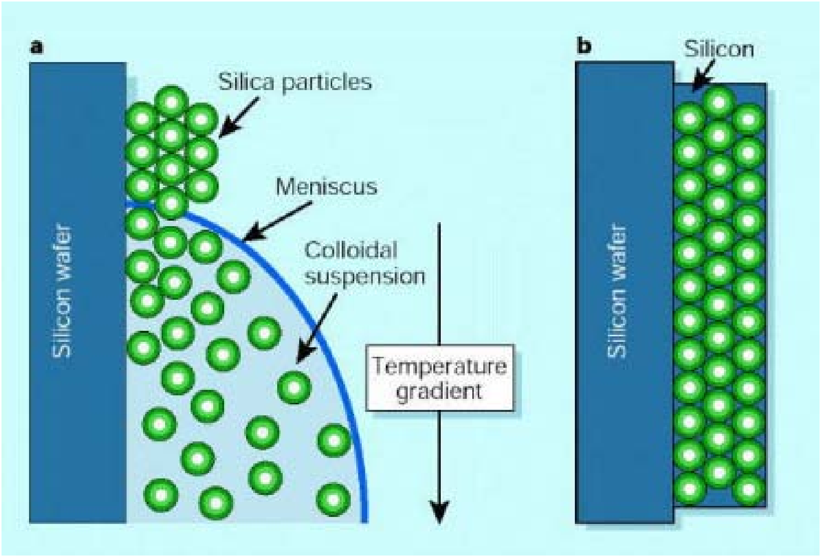
Cell method



B. Gates, D. Qin and Y. Xia;

Advanced Materials 1999, 11, 466

Vertical deposition technique

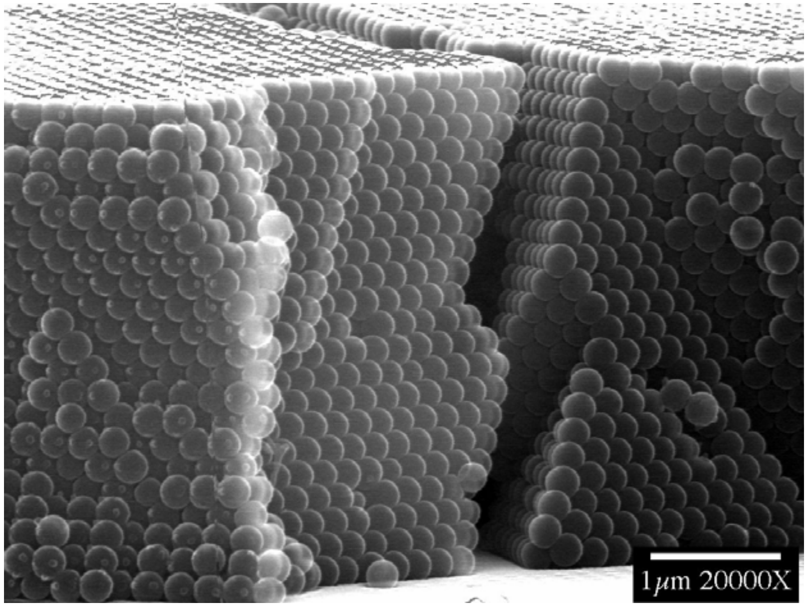


Y. Vlasov et al. Nature 414, 289-293 (2001)

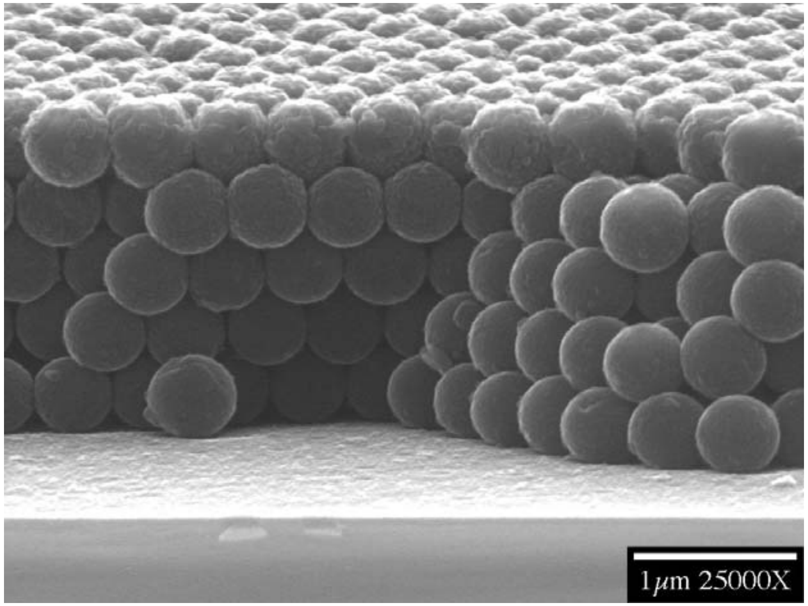
3-D photonic crystals

Close-packed FCC crystal structures of polystyrene micro-spheres
Thickness: ~10 microns (~50 layers)

Cell method



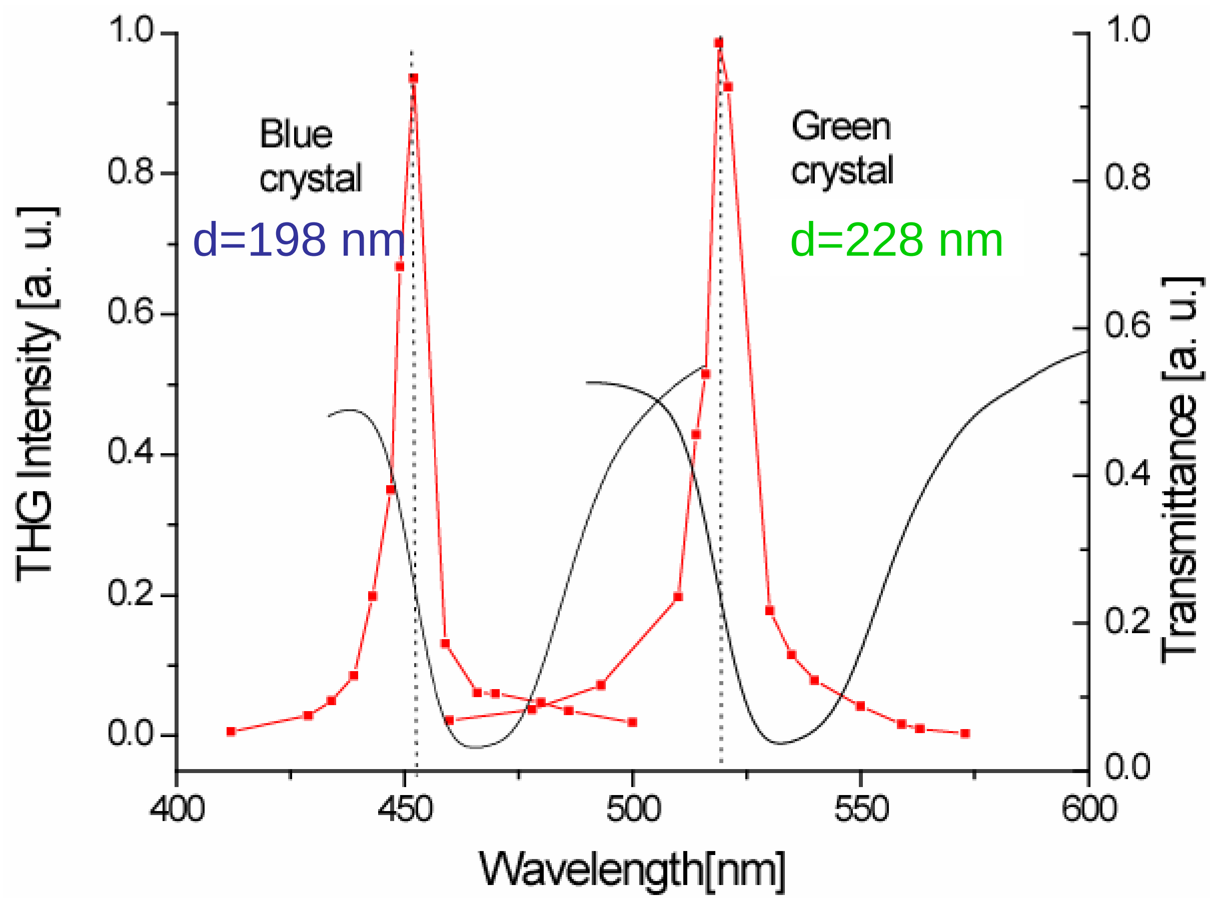
Vertical deposition technique



Low concentration of defects and long-range order

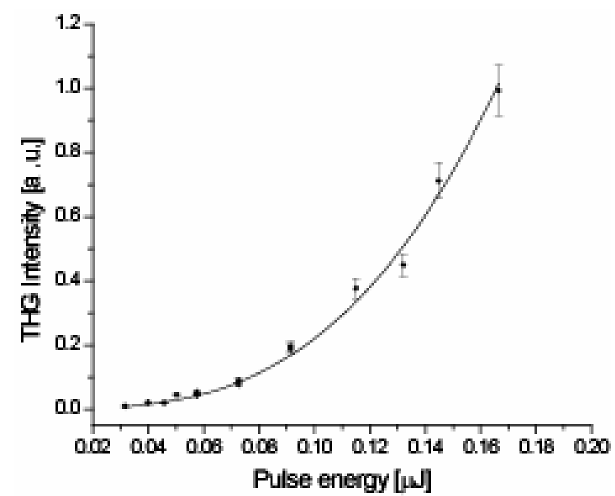
Third-Harmonic Generation in 3-D

Phase-matched THG at the high-frequency edge of the band gap in the [111] crystallographic direction



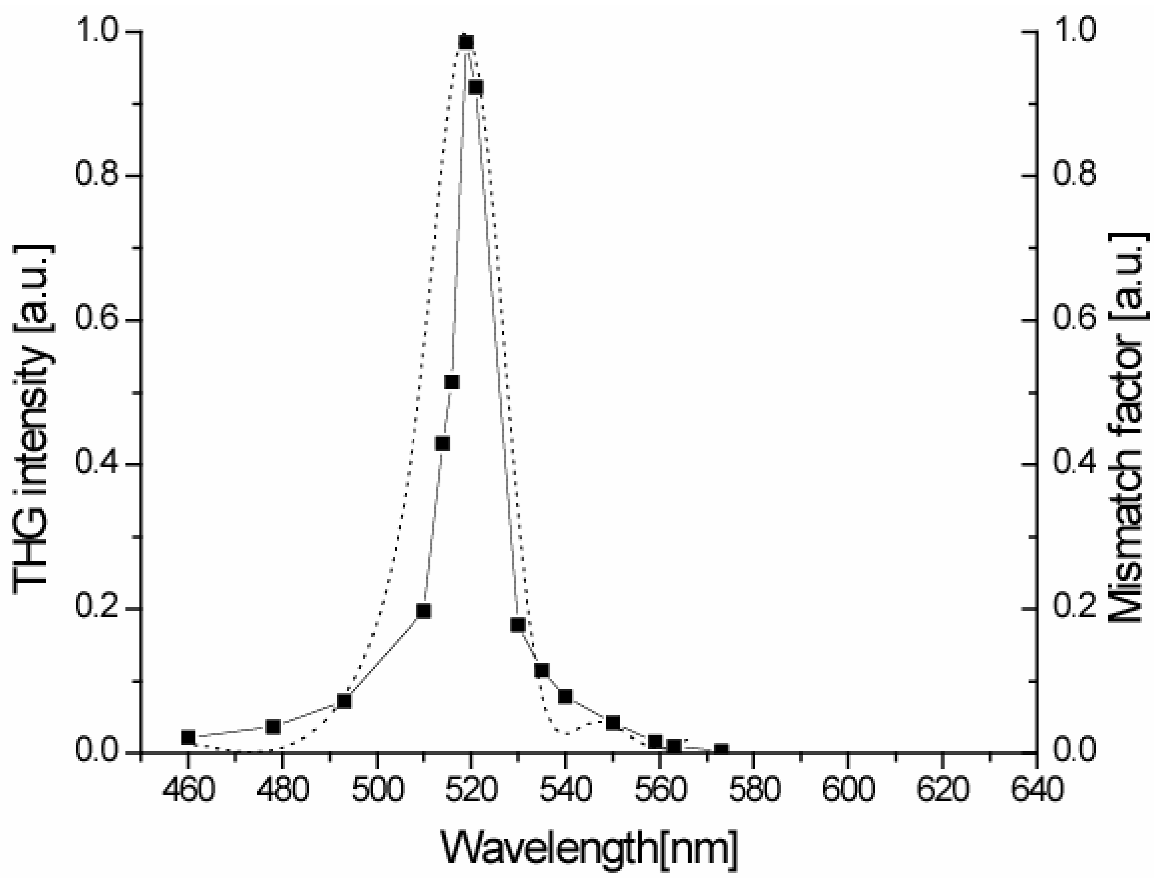
1350 nm → 450 nm

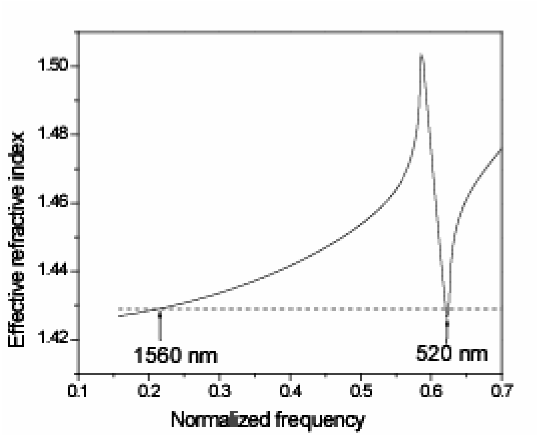
1560 nm → 520 nm



PRL 92, 083903 (2004)

Model of Phase Matching





$$I_{THG}(\lambda) \propto \mathrm{sinc}^2(\Delta k(\lambda)L/2)$$

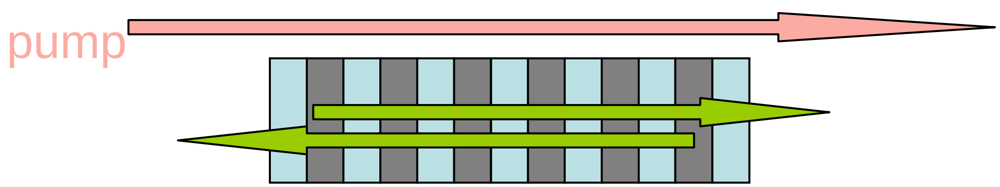
Conversion efficiency

$$\eta = (3\omega)^2 \frac{(2\pi)^4}{(nc)^4} I^2 L^2 \chi^{(3)^2}$$

THG observed both in transmission and reflection

$$\eta_{measured} \approx 10^{-4}$$

Scaling law $\eta(L)$, L^2 ?



$$A_{pump} \xrightarrow{\chi^{(3)}} A_{THG}^{forward}$$

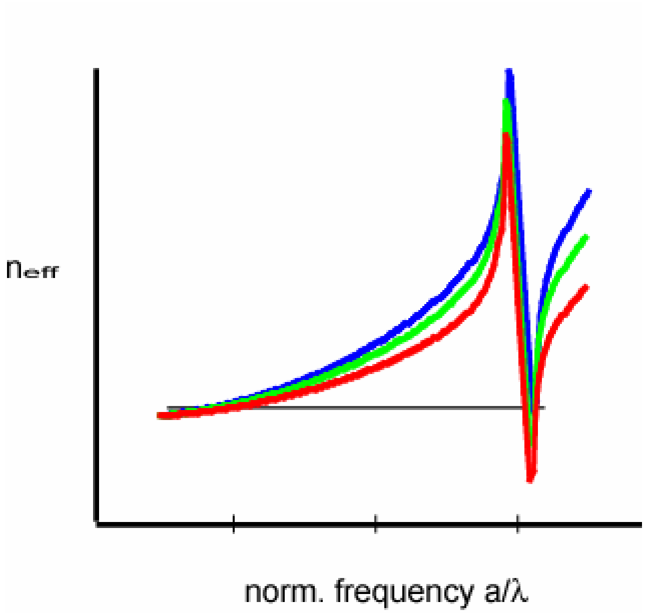
$$A_{THG}^{forward} \xleftrightarrow{PBG} A_{THG}^{backward}$$

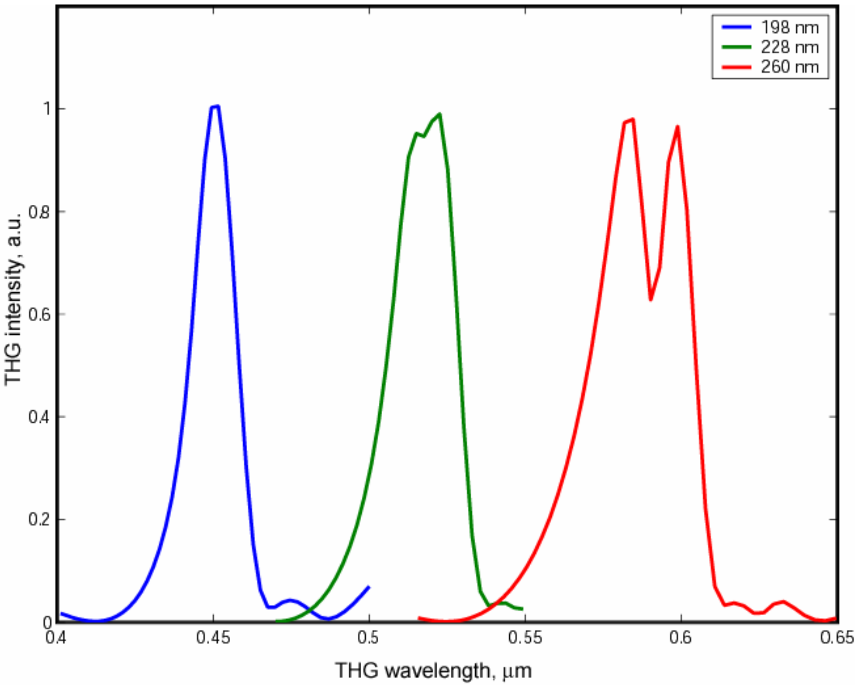
Double-peak scenario

d=198 nm

d=228 nm

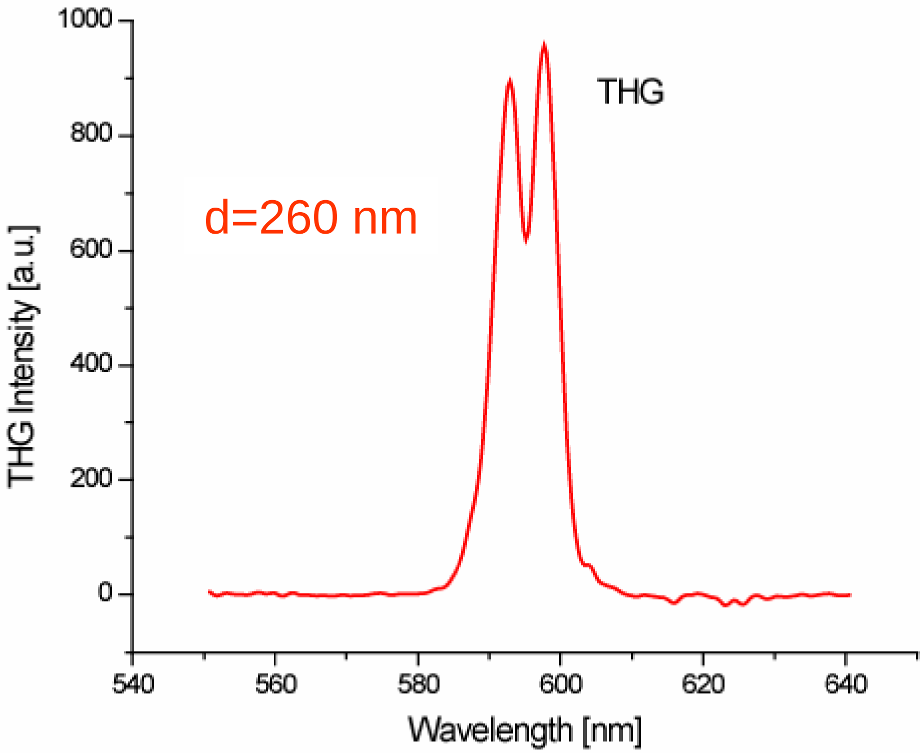
d=260 nm

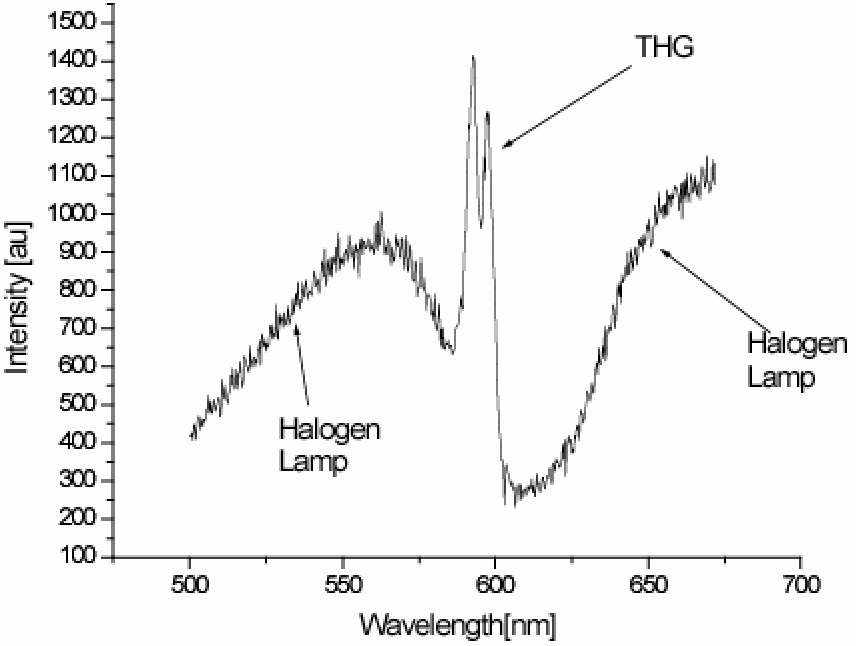




Double-peak scenario

Broadband input pulse → split THG peak





Conclusions

Enhancement of phase-matched THG in photonic crystals is demonstrated.

Nonlinear coupling of “gap” frequencies is possible.

Future Goals

Improve the tuning range by exciting different crystallographic axis of a 3-D crystal

Obtain better conversion efficiency by employing other nonlinear materials and growing bigger crystals