SAND2018-8723C

A Hybrid Dielectric-Semiconductor Metasurface for Efficient Second-Harmonic Generation

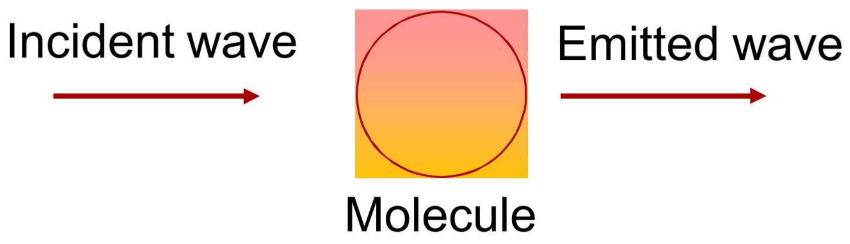
R. Sarma[1], D. de Ceglia[2], N. Nookala[3], M. A. Vincenti[4], S. Campione[1], O. Wolf[1], M. Scalora[5], M. Belkin[3], I. Brener[1]

[1]Sandia National Labs, Albuquerque, NM, USA
[2]University of Padova, Padua, Italy
[3]University of Texas at Austin, Austin, TX, USA
[4]University of Brescia, Brescia, Italy
[5]US Army AMRDEC, Huntsville, AL, USA

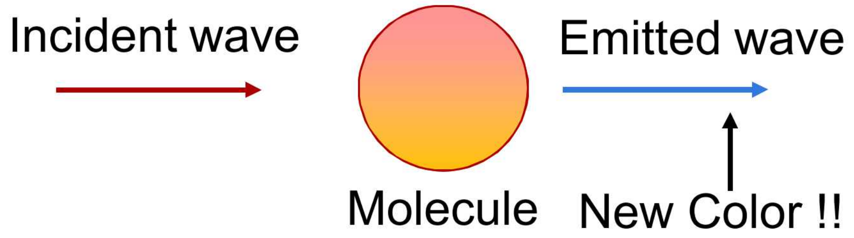
This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering and performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Nonlinear Optics : Second-Harmonic Generation (SHG)

Linear Optics



Nonlinear Optics



Strong electromagnetic field → Distorted electronic cloud → Induced dipole

Dielectric polarization density **P**(*t*)
– dipole moment per unit volume

$$\mathbf{P}(t) = \varepsilon_0(\chi^{(1)}\mathbf{E}(t) + \chi^{(2)}\mathbf{E}^2(t) + \chi^{(3)}\mathbf{E}^3(t) + \ldots),$$

where the coefficients $\chi^{(n)}$ are the *n*-th-order susceptibilities of the medium,

Prominent On-Chip Approaches for SHG

Sandia National Laboratories

IST-Plasmonic Metasurface

ADVANCED OPTICAL MATERIALS
www.advopticalmat.de
Materials Views
www.MaterialsViews.com

Ultrathin Second-Harmonic Metasurfaces with Record-High Nonlinear Optical Response

*Jongwon Lee, Nishant Nookala, J. Sebastian Gomez-Diaz, Mykhailo Tymchenko, Frederic Demmerle, Gerhard Boehm, Markus-Christian Amann, Andrea Alù, and Mikhail A. Belkin**

ARTICLE
Received 27 Mar 2015 | Accepted 31 May 2015 | Published 1 Jul 2015 DOI: 10.1038/ncomms8667 OPEN

Phased-array sources based on nonlinear metamaterial nanocavities

Omri Wolf[1,2,*], Salvatore Campione[1,2,*], Alexander Benz[1,2], Arvind P. Ravikumar[3], Sheng Liu[1,2], Ting S. Luk[1,2], Emil A. Kadlec[2], Eric A. Shaner[2], John F. Klem[2], Michael B. Sinclair[2] & Igal Brener[1,2]

All Dielectric Metasurface

NANO LETTERS
Letter
pubs.acs.org/NanoLett

Resonantly Enhanced Second-Harmonic Generation Using III–V Semiconductor All-Dielectric Metasurfaces

Sheng Liu,[*,†] Michael B. Sinclair,[†] Sina Saravi,[§] Gordon A. Keeler,[†] Yuanmu Yang,[†,‡] John Reno,[†,‡] Gregory M. Peake,[†] Frank Setzpfandt,[§] Isabelle Staude,[§] Thomas Pertsch,[§] and Igal Brener[*,†,‡]

NANO LETTERS
Letter
pubs.acs.org/NanoLett

Nonlinear Generation of Vector Beams From AlGaAs Nanoantennas

Rocio Camacho-Morales,[†] Mohsen Rahmani,[†] Sergey Kruk,[†] Lei Wang,[†] Lei Xu,[†,∥] Daria A. Smirnova,[†] Alexander S. Solntsev,[†] Andrey Miroshnichenko,[†] Hark Hoe Tan,[‡] Fouad Karouta,[‡] Shagufta Naureen,[‡] Kaushal Vora,[‡] Luca Carletti,[⊥] Costantino De Angelis,[⊥] Chennupati Jagadish,[‡] Yuri S. Kivshar,[†] and Dragomir N. Neshev[*,†]

Plasmonics

nature photonics
FOCUS | REVIEW ARTICLES
PUBLISHED ONLINE: 31 OCTOBER 2012 | DOI: 10.1038/NPHOTON.2012.244

Nonlinear plasmonics

Martti Kauranen[1] and Anatoly V. Zayats[2]

Efficient Nonlinear Metasurface Based on Nonplanar Plasmonic Nanocavities

Feng Wang[†], Alex B. F. Martinson[‡], and Hayk Harutyunyan[*†]
† Department of Physics, Emory University, Atlanta, Georgia 30322, United States
‡ Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, United States

ACS Photonics, **2017**, *4* (5), pp 1188–1194
DOI: 10.1021/acsphotonics.7b00094
Publication Date (Web): April 3, 2017

*E-mail: hayk.harutyunyan@emory.edu.
Cite this: *ACS Photonics* 4, 5, 1188-1194
RIS Citation GO

Max. Conversion factor ~ 16.8 mW/W^2
Max. Efficiency ~ 7 x 10^{-4} at 15 kW/cm^2

Max. Conversion factor ~ 2 x 10^{-5} mW/W^2
Max. Efficiency ~ 10^{-4} -10^{-5} at ~ 5 GW/cm^2

Max. Efficiency 6 x10^{-5} at ~ 0.5 GW/cm^2

Desired Properties for Nonlinear Metasurfaces

Sandia National Laboratories

1. **High second-order nonlinear susceptibility** : IST in QWs

2. **Large field enhancement** : High *Q* Resonances

3. **Large damage threshold and low loss at all wavelengths** : Dielectric structures

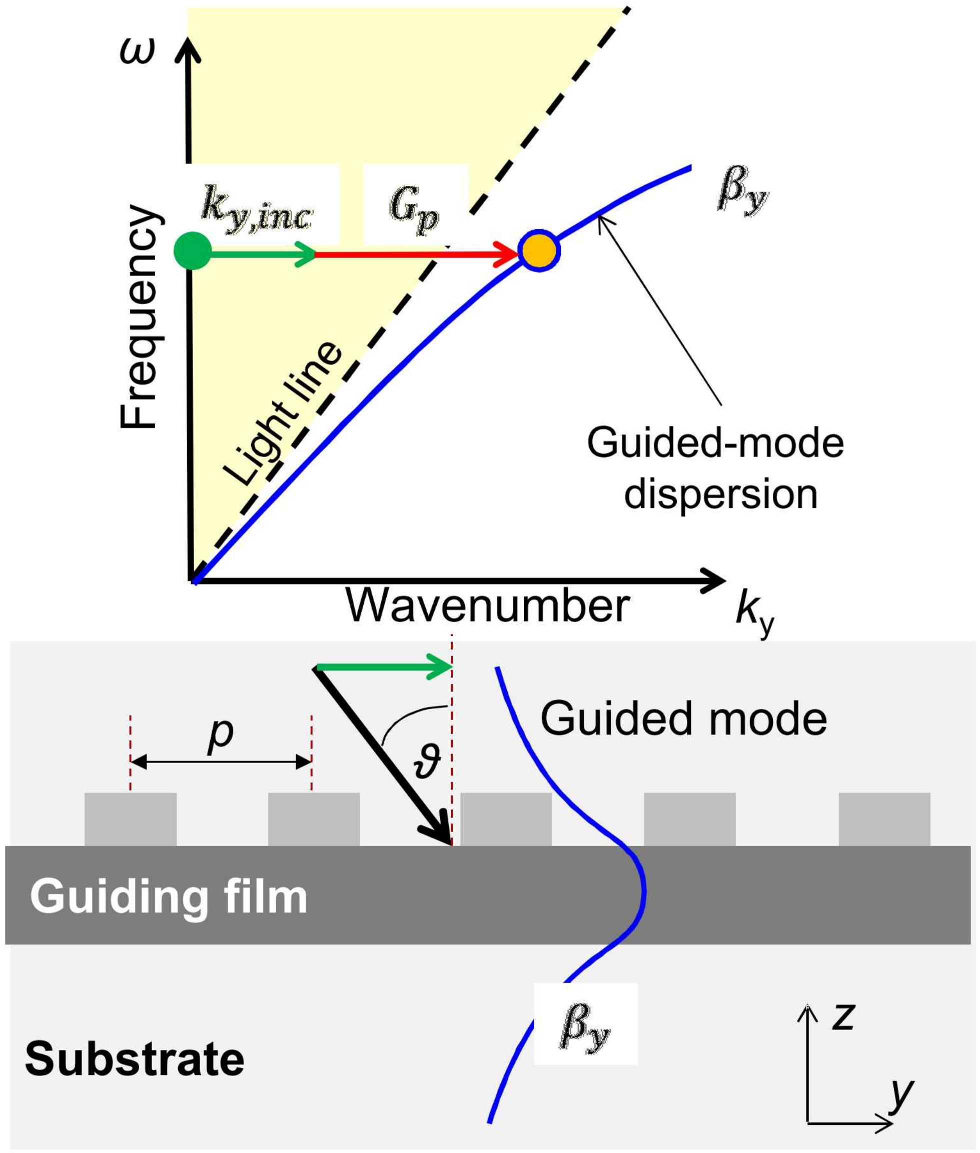
4. **Large bandwidth** : Require new type of resonances as high *Q* and bandwidth work in opposite directions

5. **Practical aspects** : Easy to fabricate, monolithically integrable, Dual mode operation (reflection/transmission)

Can we design a hybrid approach that has all these properties ?

Yes, using a hybrid approach of *coupling leaky mode resonances* in dielectric structures to *ISTs* in QWs

What is a Leaky Mode Resonance ?



Incident transverse wavenumber

$$k_{y,inc} = \frac{\omega}{c} \sin\vartheta$$

Lattice transverse momentum

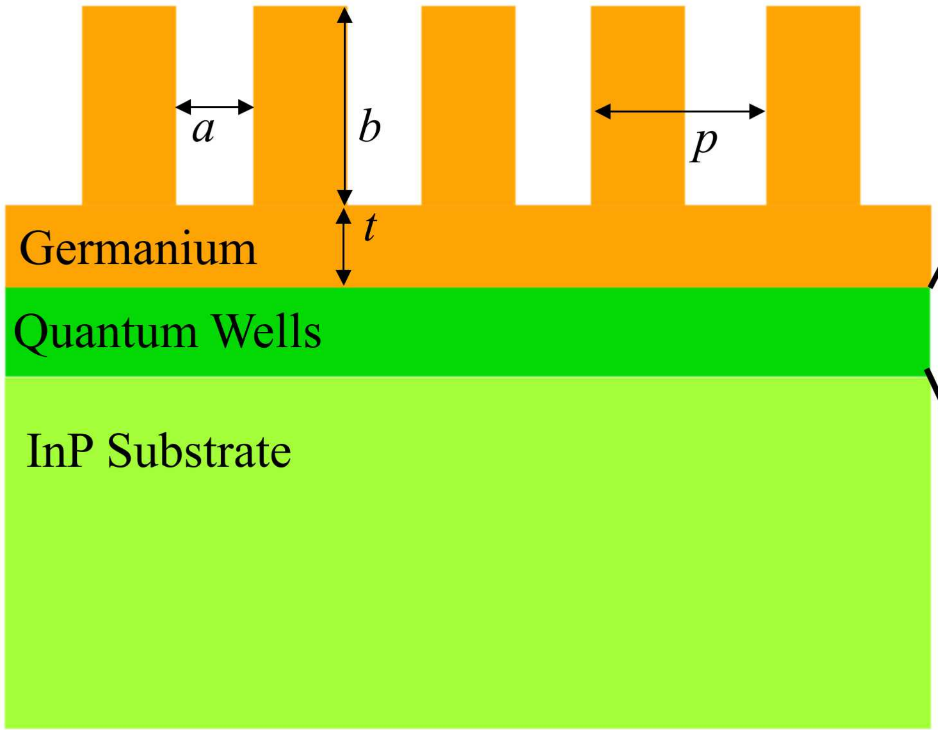
$$G_p = \frac{2\pi}{p} m, \text{where } m = \pm 1, \pm 2, \pm 3, \ldots$$

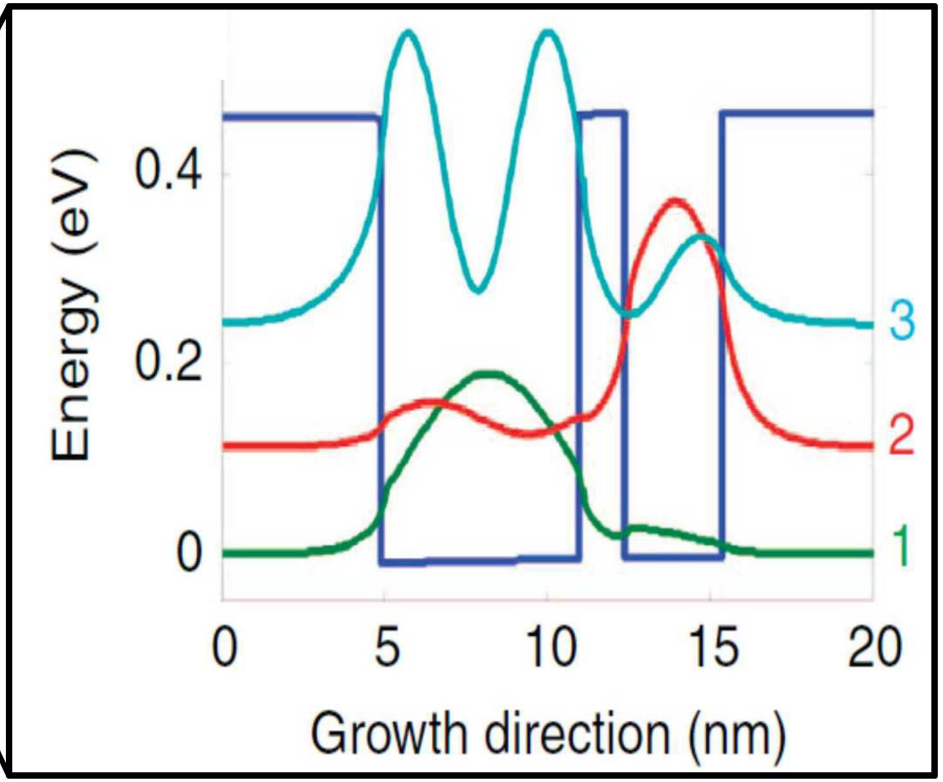
Plane wave excitation of a Leaky Mode Resonance

$$|k_{y,inc} + G_p| = \tilde{\beta}_y$$

For small perturbation, $\tilde{\beta}_y \sim \beta_y$

Dielectric-Semiconductor Hybrid Structure for SHG





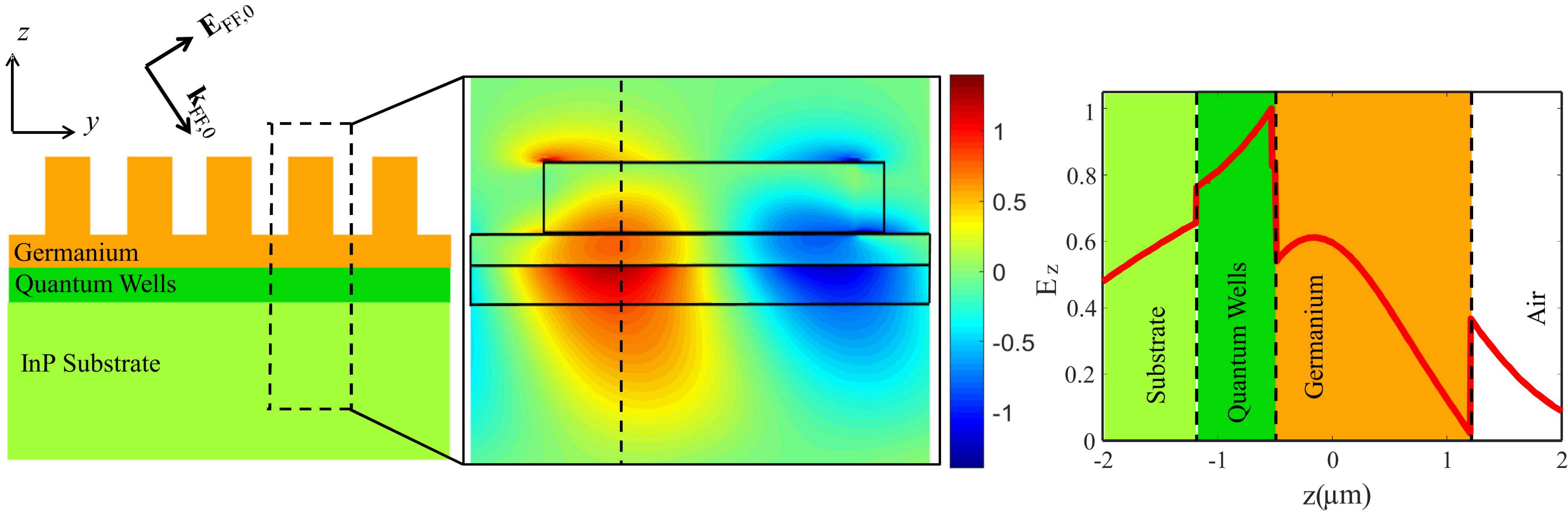
a=1070nm , *b*=1200nm , *t*=500nm
*p=31*50, 3250, 3350 nm

InGaAs QWs with AlInAs barriers

Ref. : O. Wolf et. al., Nature Comm. 6 (2015)

The thickness of the InGaAs QWs is optimized to have transitions at 10 microns and 5 microns. The geometrical parameters of the grating structure is designed for these wavelengths.

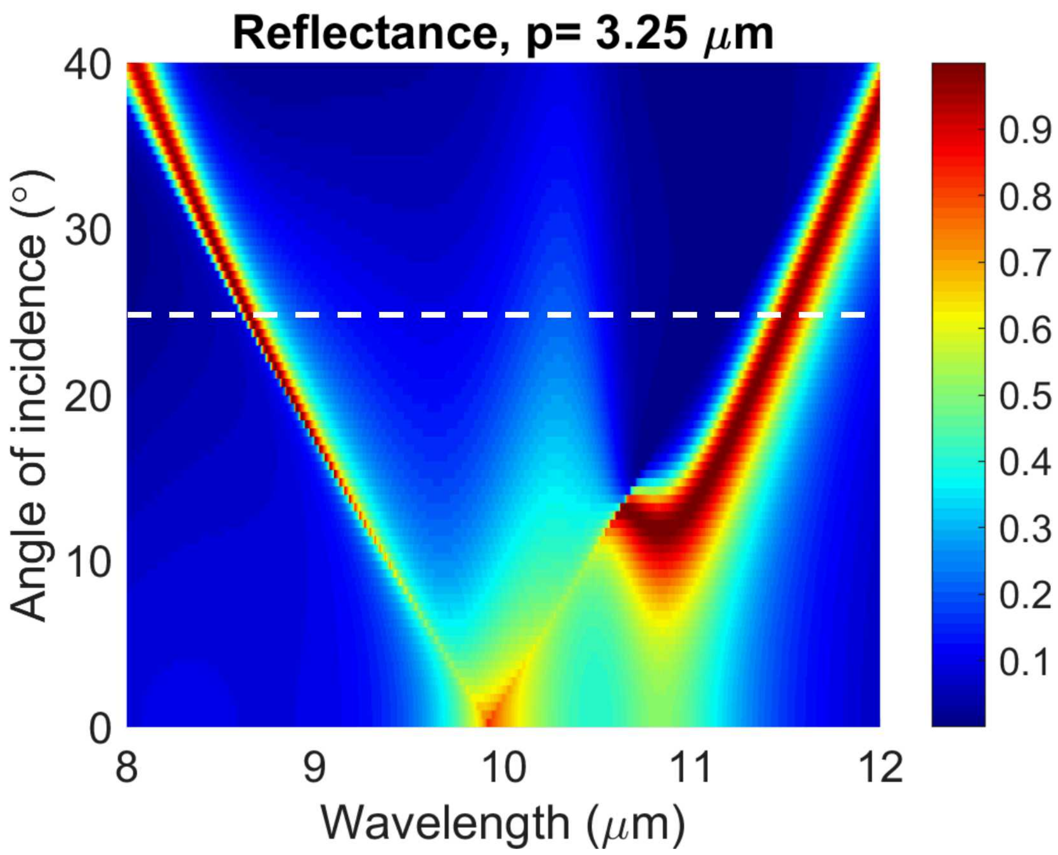
Leaky Mode Resonance Coupled to IST



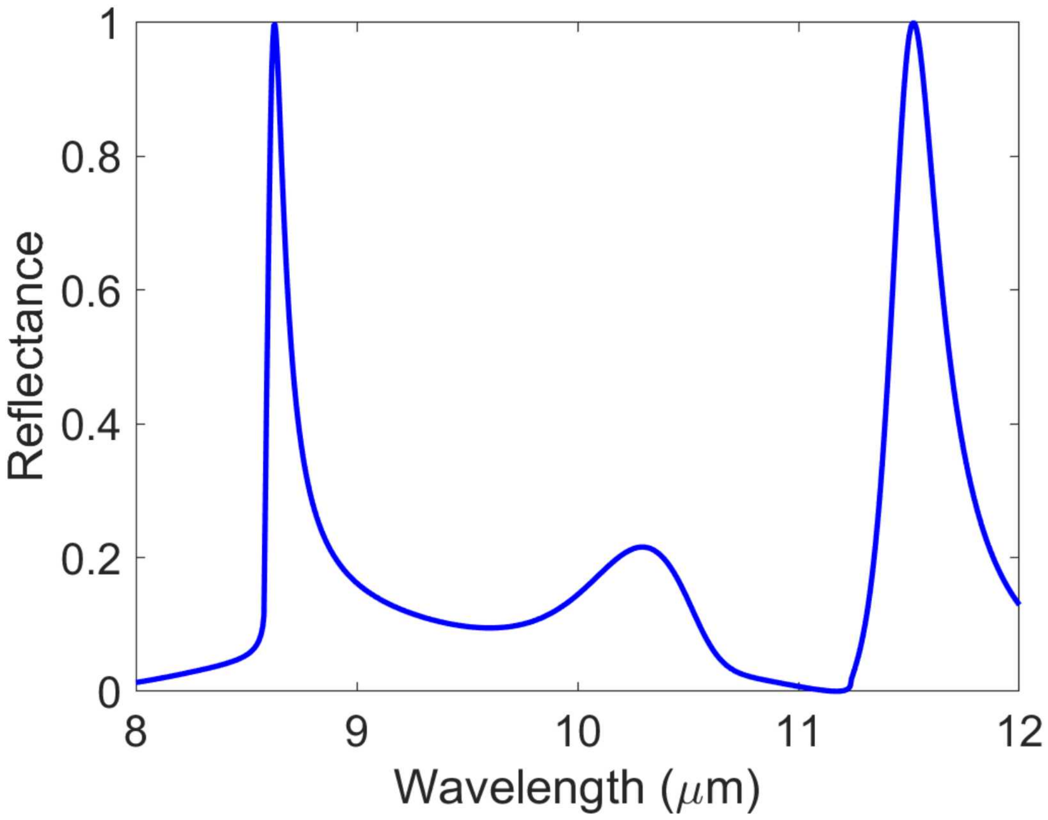
The pump wavelength (fundamental frequency, FF) is at 10 microns. The evanescent fields of the leaky mode resonance drives the ISTs in the QWs.

Leaky Mode Resonances : High Q and Large Bandwidth

Linear Simulations (Ignoring IST absorption)



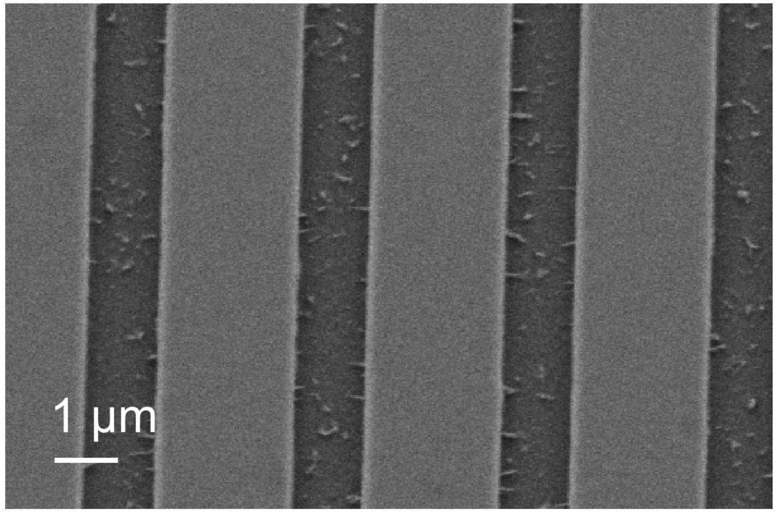
Cross Section of Reflectance (white dashed line)

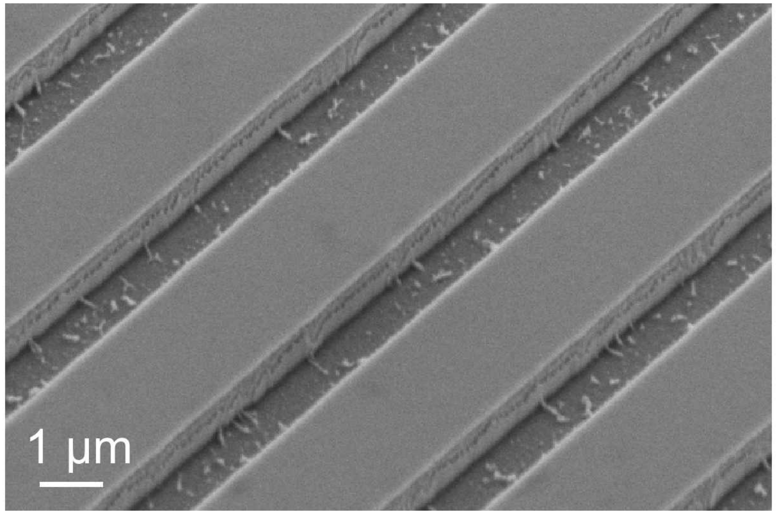


The leaky mode resonances have high *Q* with Fano features and can exist for all wavelengths between 8-12 microns

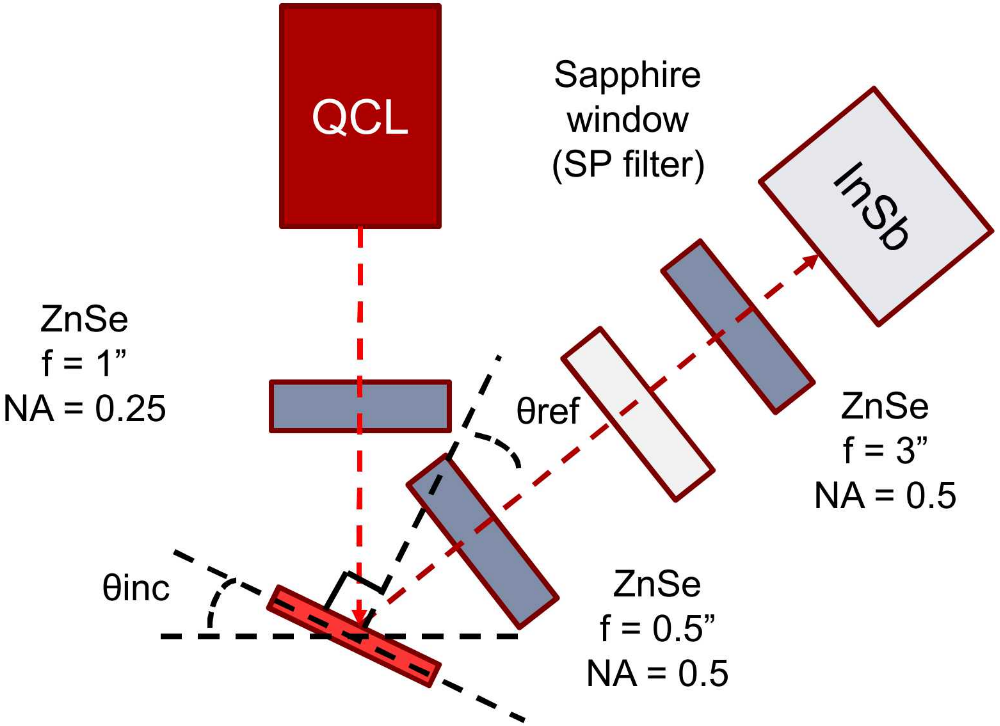
Device Fabrication and Experimental Setup

Scanning Electron Micrographs





Experimental Setup

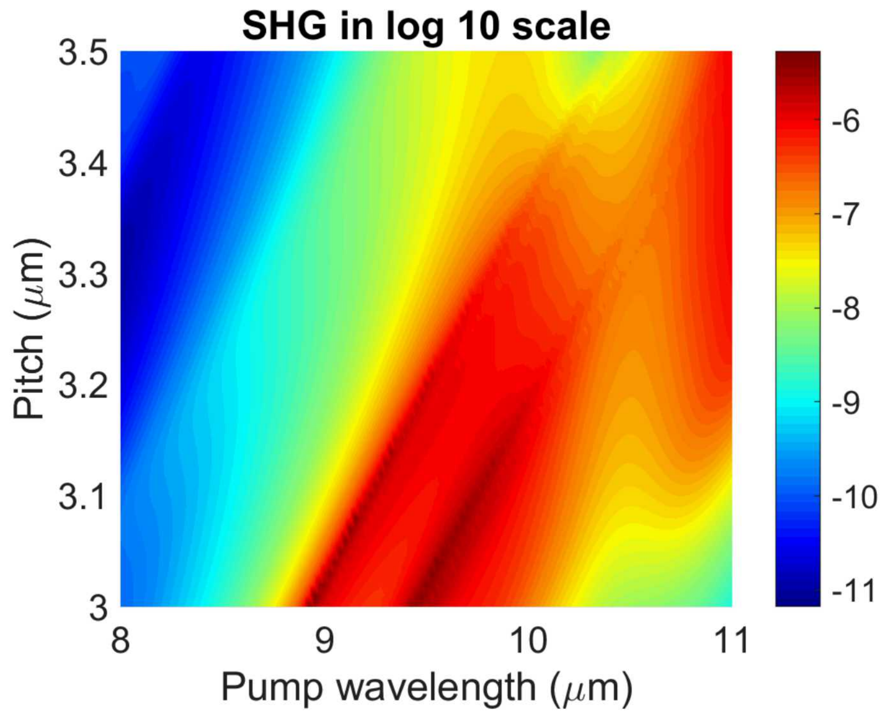


Normal incidence measurements correspond to $\Theta_{inc} = 0$

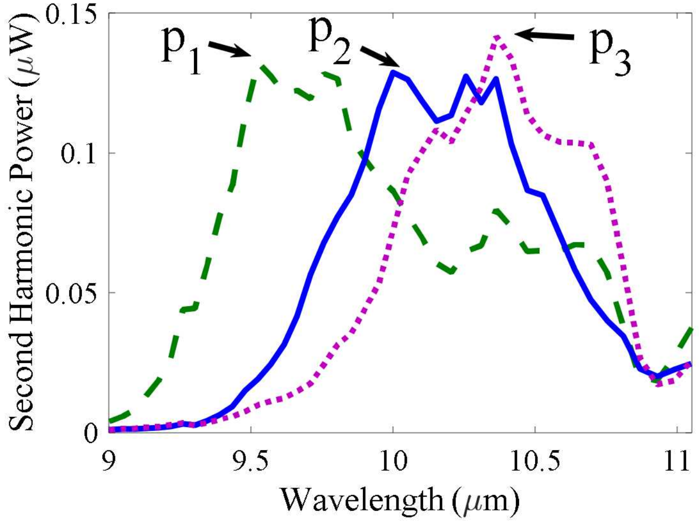
Experimental Data and Comparison to Simulations

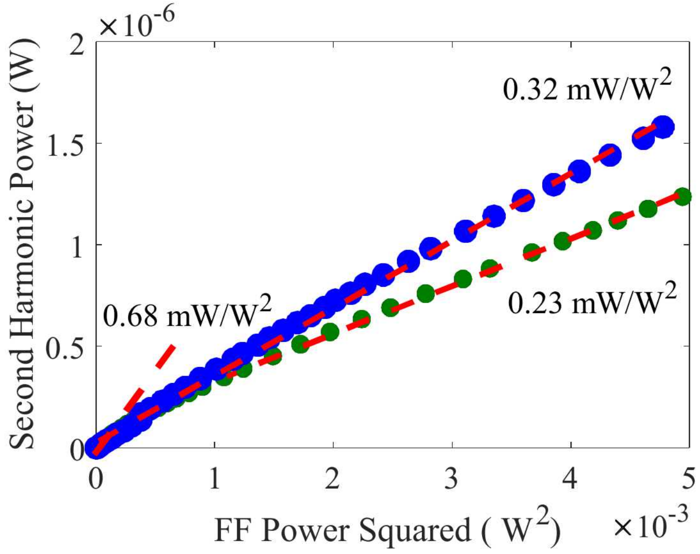
Sandia National Laboratories

Θ_{inc}=0



Θ_{inc}=0 and p = 3150, 3250 and 3350 nm





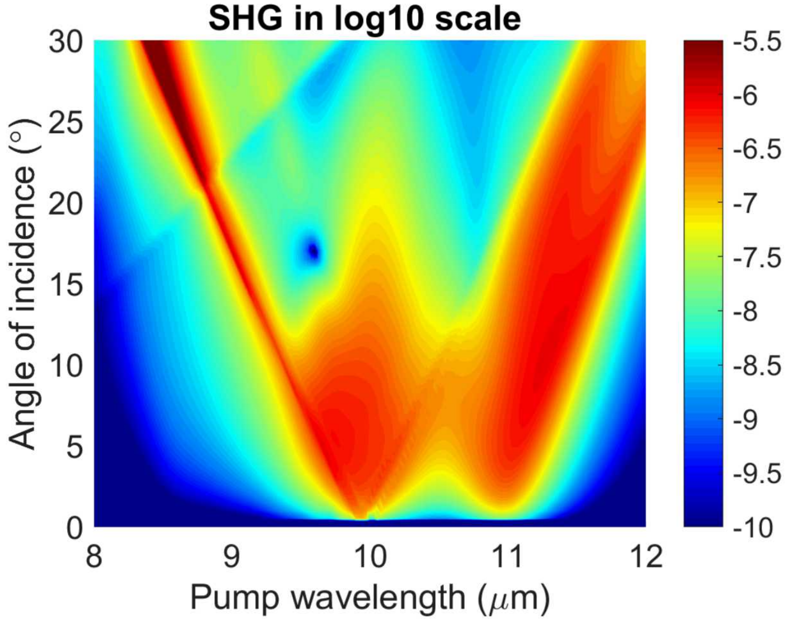
As predicted by simulations, the peak of SHG red shifts as period increases

Maximum SHG conversion factor = 0.68 mW/W^2
Max. SHG efficiency ~ 3×10^{-5} at 15 kW/cm^2

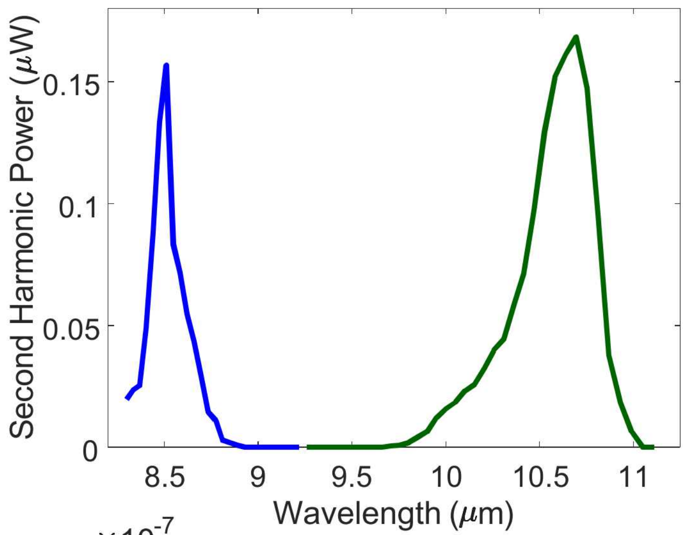
Experimental Data and Comparison to Simulations

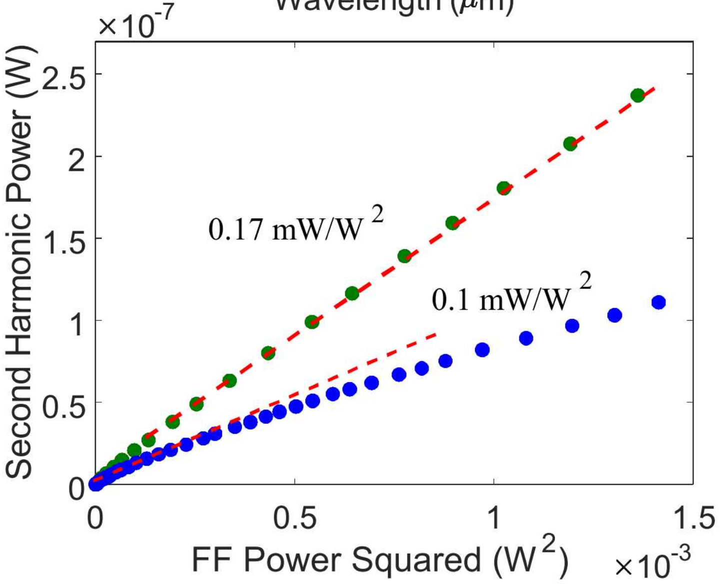
Sandia National Laboratories

p = 3250 nm



Θ_{inc}=25 degrees and p = 3250 nm





As predicted by simulations, at Θ_{inc}=25 degrees, two peaks of SHG are observed at 8.5 (narrower) and ~ 10.75 microns (broader).

Maximum SHG conversion factor = 0.17 mW/W^2
Max. SHG efficiency ~ 1.8 x 10^{-5} at ~ 10 kW/cm^2

Summary

1. We have demonstrated a hybrid approach for realizing a dielectric-semiconductor planar nanostructure for high efficiency SHG with increased bandwidth.

2. Using our devices, we demonstrate SHG at pump wavelengths ranging from ~ 8.5-11 microns. The maximum observed SHG conversion factor is 0.68 mW/W^2 and maximum conversion efficiency observed is ~3×10^{-5} at 15 kW/cm^2 pump power.

3. In addition to fundamental advantages, the approach also has practical advantages such as wavelength scalability, monolithic integrability, and ease of fabrication. The devices can also be fabricated using optical lithography.

4. The results here demonstrate a proof-of-concept and there is further scope of improvement of SHG efficiency by optimizing various parameters such as the dielectric medium of the grating, geometrical parameters, semiconductor heterostructure etc.