Enhanced Photon-Pair Generation in Nonlinear Metasurfaces through Bound States in the Continuum

106° congresso nazionale – Società Italiana di Fisica

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OUTLINE

I. Motivations

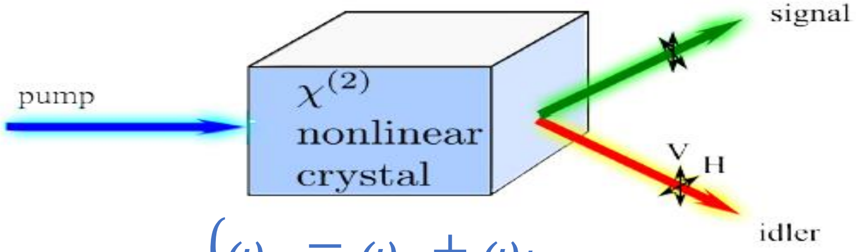
II. Metasurface Design and Nonlinear Performance

III. Characterization of Photon-Pair Generation

IV. Conclusions

Photon Pair Generation – Towards Nanoscale

SPDC in quadratically nonlinear crystal

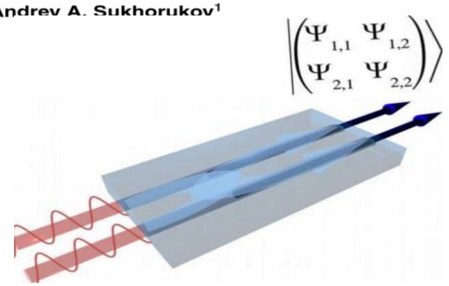


$$\begin{cases} \omega_p = \omega_s + \omega_i \\ \boldsymbol{k}_p = \boldsymbol{k}_s + \boldsymbol{k}_i \end{cases}$$

Laser Photonics Rev. **10**, No. 1, 131–136 (2016) / **DOI** 10.1002/lpor.201500216

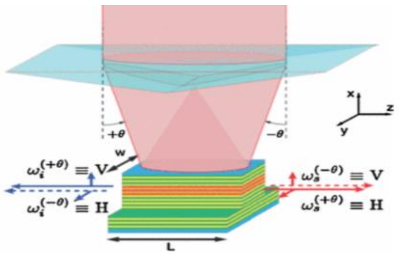
Tunable generation of entangled photons in a nonlinear directional coupler

Frank Setzpfandt[1,2,*], Alexander S. Solntsev[1,*], James Titchener[1], Che Wen Wu[1], Chunle Xiong[2], Roland Schiek[3], Thomas Pertsch[4], Dragomir N. Neshev[1], and Andrey A. Sukhorukov[1]



Direct Bell States Generation on a III-V Semiconductor Chip at Room Temperature

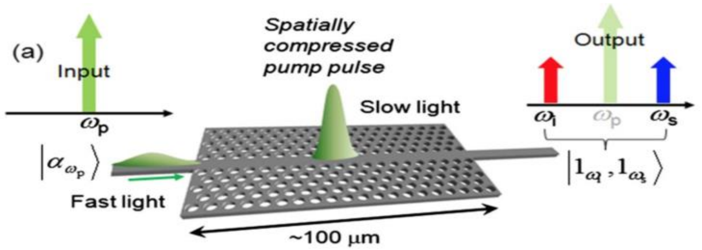
A. Orieux, A. Eckstein, A. Lemaître, P. Filloux, I. Favero, G. Leo, T. Coudreau, A. Keller, P. Milman, and S. Ducci
Phys. Rev. Lett. **110**, 160502 – Published 18 April 2013



September 1, 2011 / Vol. 36, No. 17 / OPTICS LETTERS

Slow-light enhanced correlated photon pair generation in a silicon photonic crystal waveguide

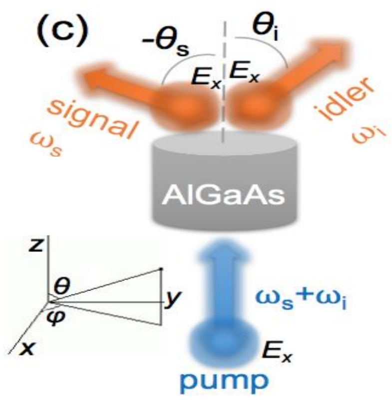
C. Xiong,[1,*] Christelle Monat,[1,2] Alex S. Clark,[1,3] Christian Grillet,[1] Graham D. Marshall,[4] M. J. Steel,[4] Juntao Li,[5] Liam O'Faolain,[5] Thomas F. Krauss,[5] John G. Rarity,[3] and Benjamin J. Eggleton[1]

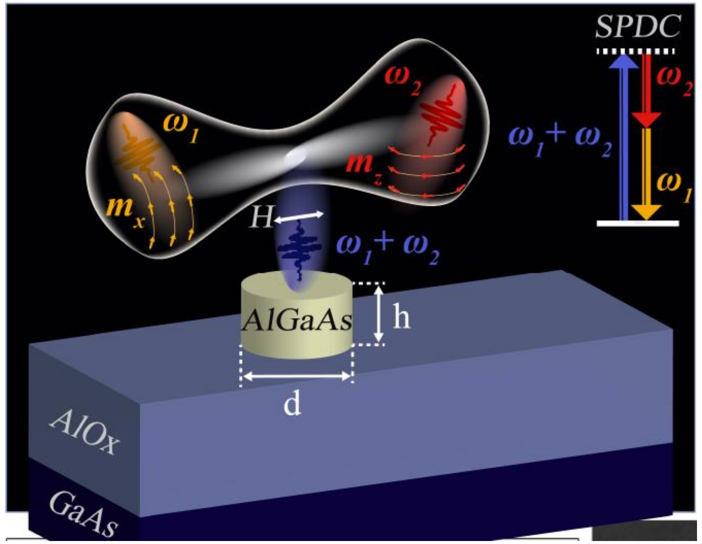


Achieving sub-μm scale?
Nonlinear nano-resonators and metamaterials!

Metasurfaces for SPDC

Mie resonances

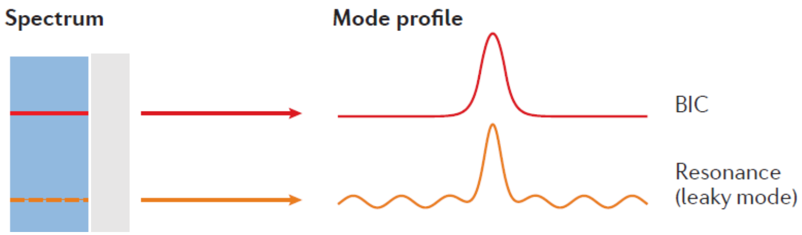




- Broad emission spectrum following from Mie resonance Q-factor
- Low rate (35 Hz) due to limited field enhancement in the resonator

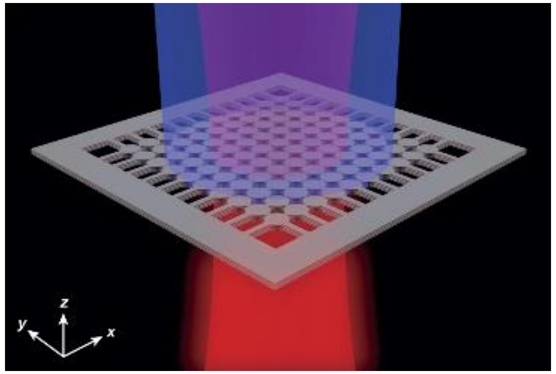
Marino *et al.*, Optica 6, 1416 (2019)

Bound States in the Continuum (BIC)



Hsu, *et al., Nat. Rev. Mat.*, **1**, UNSP 16048, (2016)

BIC features:
- Very high Q factor
- Strong field enhancement

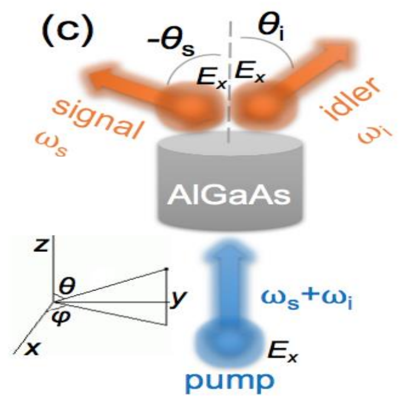


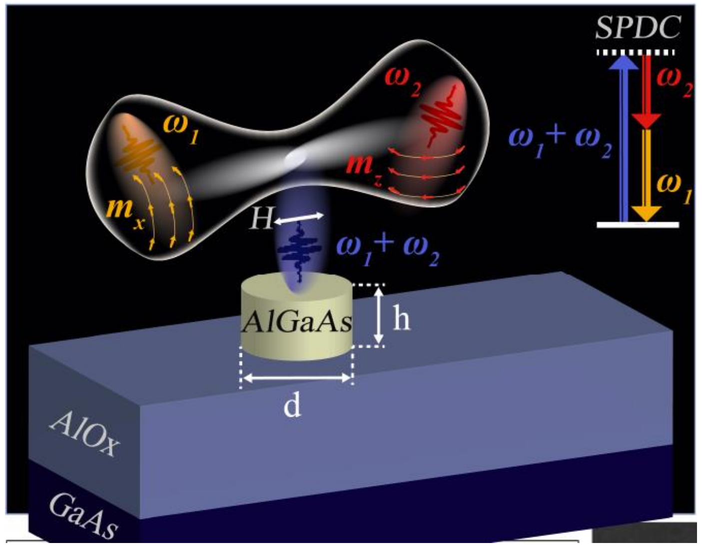
Extended Photonic crystal-type BICs:
- BICs can be implemented by the symmetry protection of collective modes that do not radiate

Kodigala, *et al.*, *Nature*, **541**, 196 (2017)
Ha, *et al.*, *Nat. Nanotech.*, **13**, 1042 (2018)

Metasurfaces for SPDC

Mie resonances





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Marino *et al.*, Optica 6, 1416 (2019)

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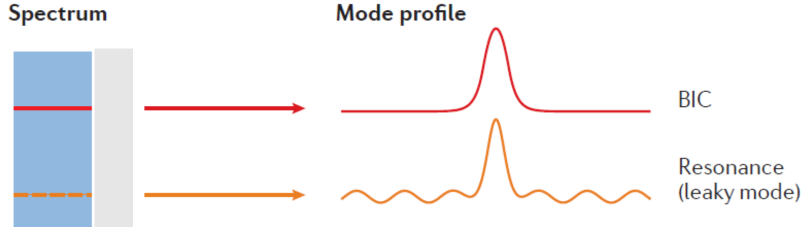

BIC features:
- Very high Q factor
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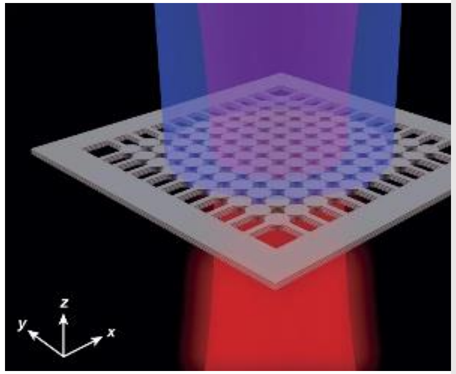
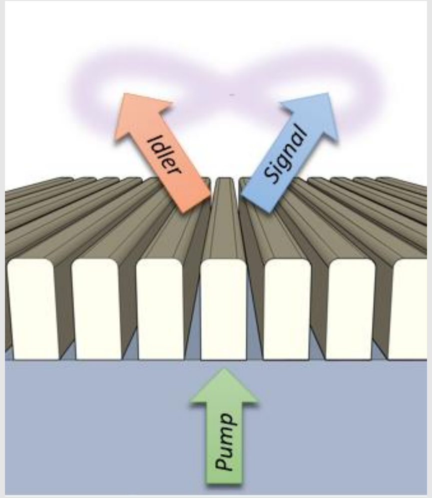
Hsu, *et al.*, *Nat. Rev. Mat.*,



Kodigala, *et al.*, *Nature*, **54**
Ha, *et al.*, *Nat. Nanotech.*,

Our work: extended BICs for quantum meta-optics

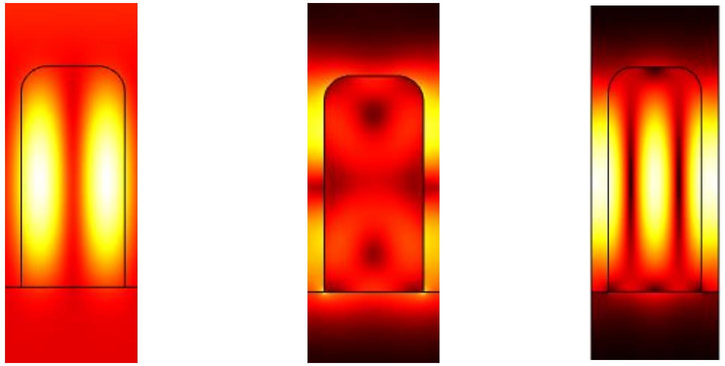


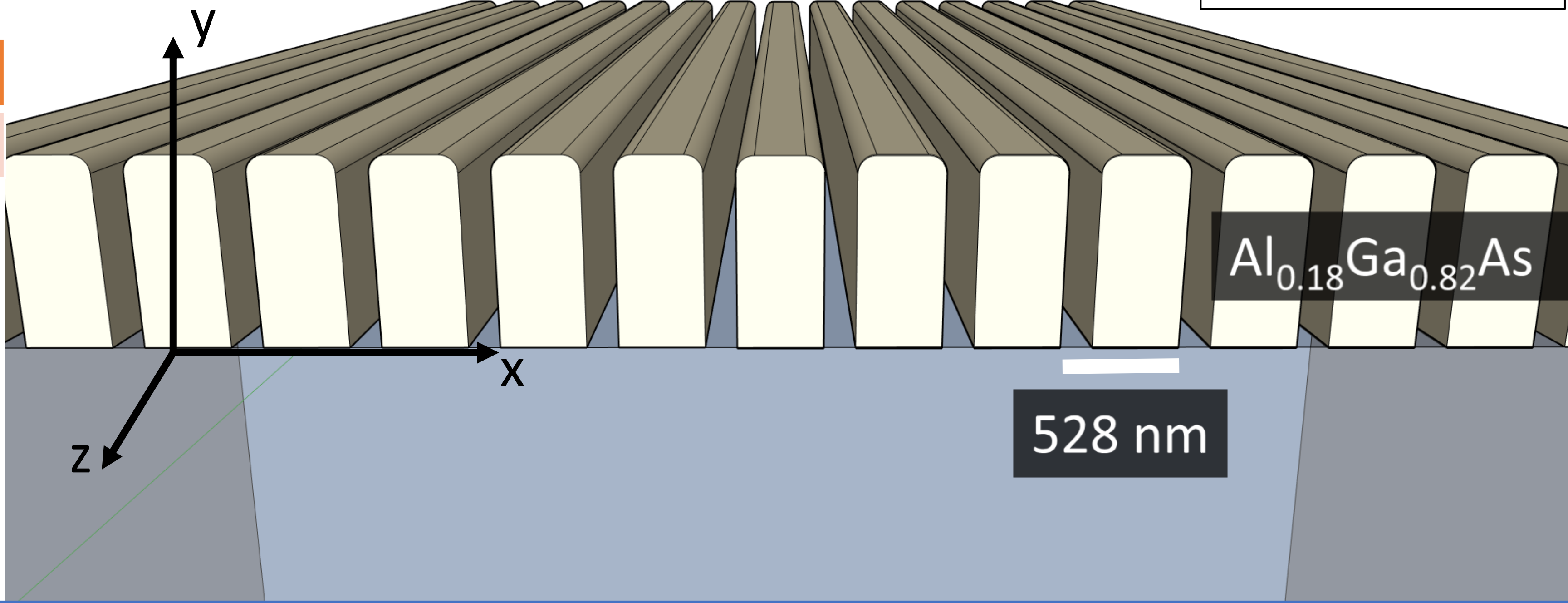
Metasurface Design

- 1D *nanofins* metasurface with subwavelength periodicity → No Diffraction orders!
- Highly directional emission at BIC resonance
- Crystal axes oriented to optimize nonlinear efficiency

Height = 860 nm
Width = 386 nm
Period = 528 nm
$\lambda_{BIC} \approx \mu m$

ν [THz]		
187.38	193.48	234.97



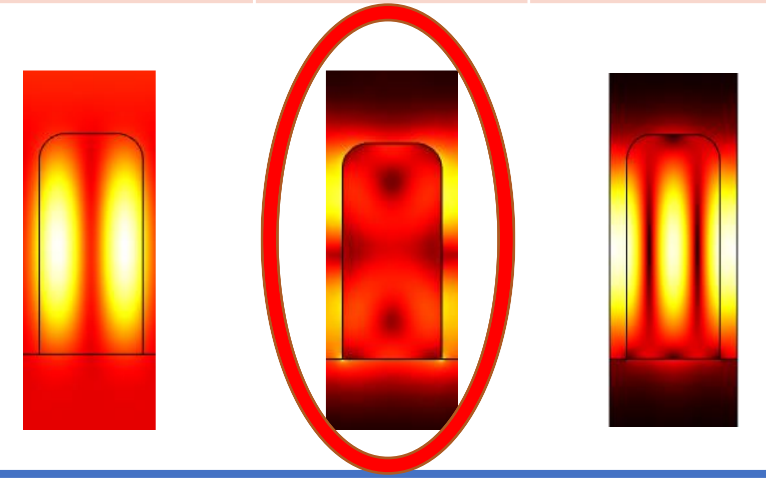


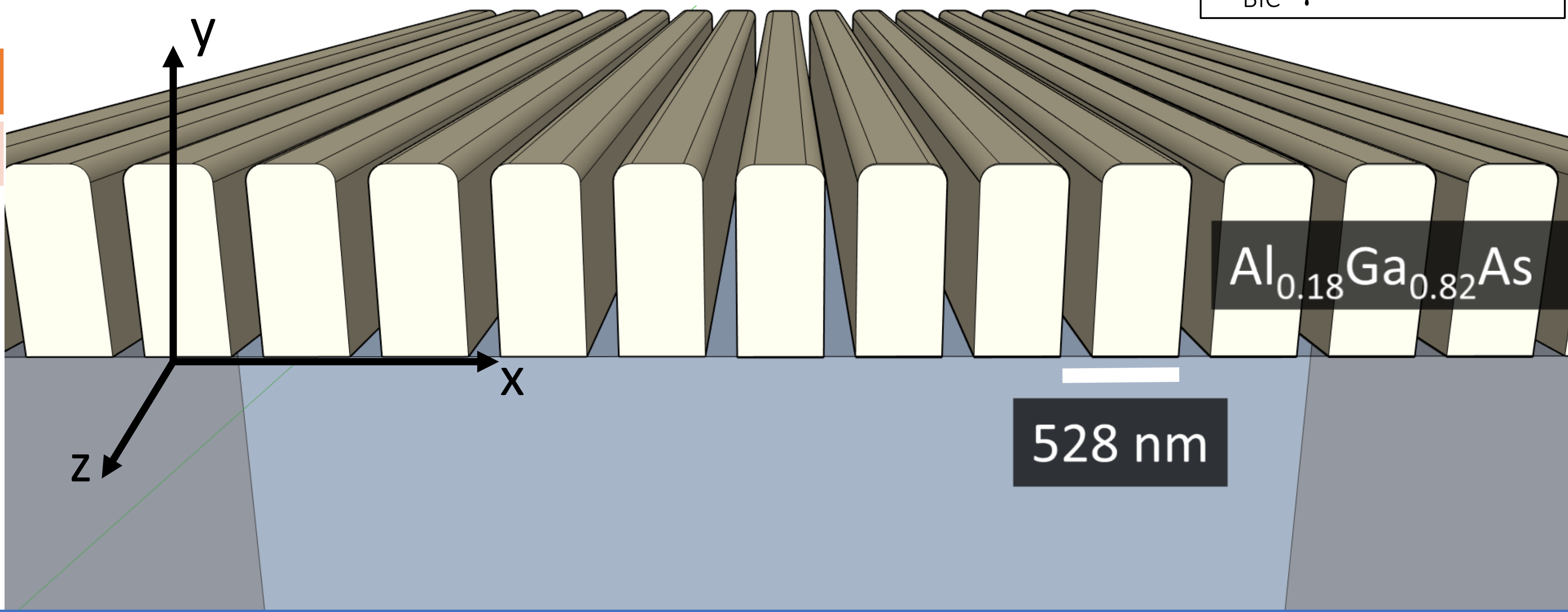
Metasurface Design

- 1D *nanofins* metasurface with subwavelength periodicity → No Diffraction orders!
- Highly directional emission at BIC resonance
- Crystal axes oriented to optimize nonlinear efficiency
- TM off-Γ BIC at telecom frequency

Height = 860 nm
Width = 386 nm
Period = 528 nm
λ_{BIC}≈μm

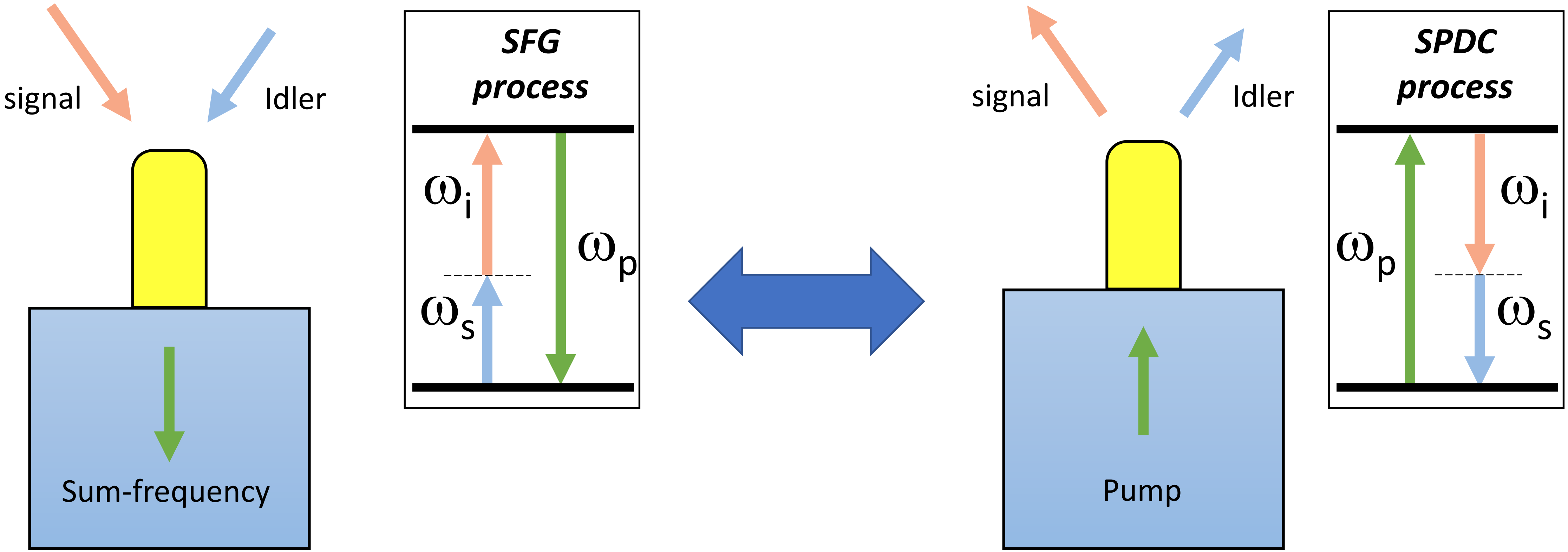
ν [THz]		
187.38	193.48	234.97





Quantum-Classical Correspondence

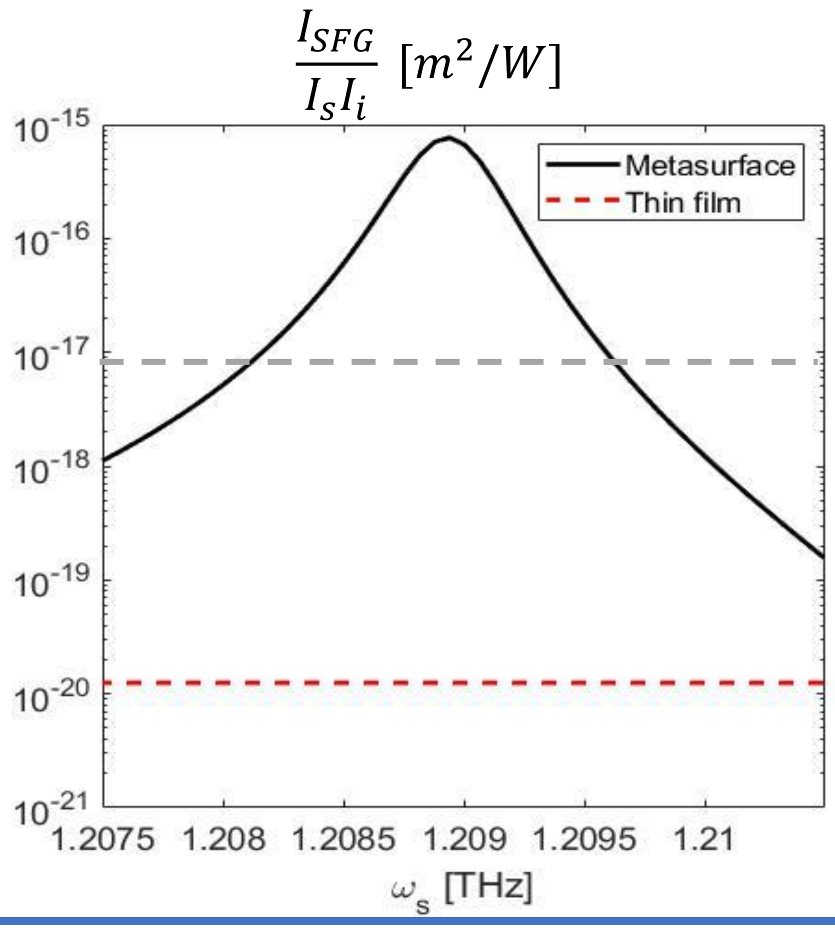
- Study nonlinear sum frequency generation in AlGaAs metasurface
- Predict quantum photon-pair rate through SPDC based on general Green function solution



Lenzini *et al.*, Light-Sci & Appl 7, 17143 (2018)

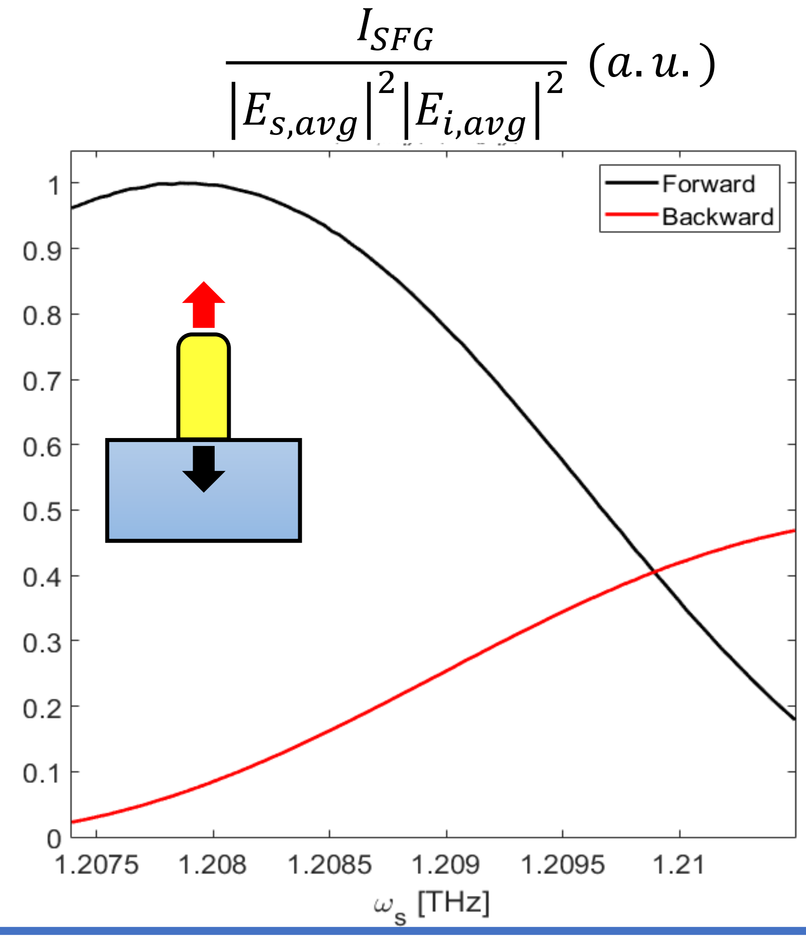
SFG Performance

- Peak SFG efficiency is orders of magnitudes higher than thin films or Mie nano-resonators
- SFG intensity is approximately proportional to the product of the fields inside the nanofin



Measured peak efficiency in:

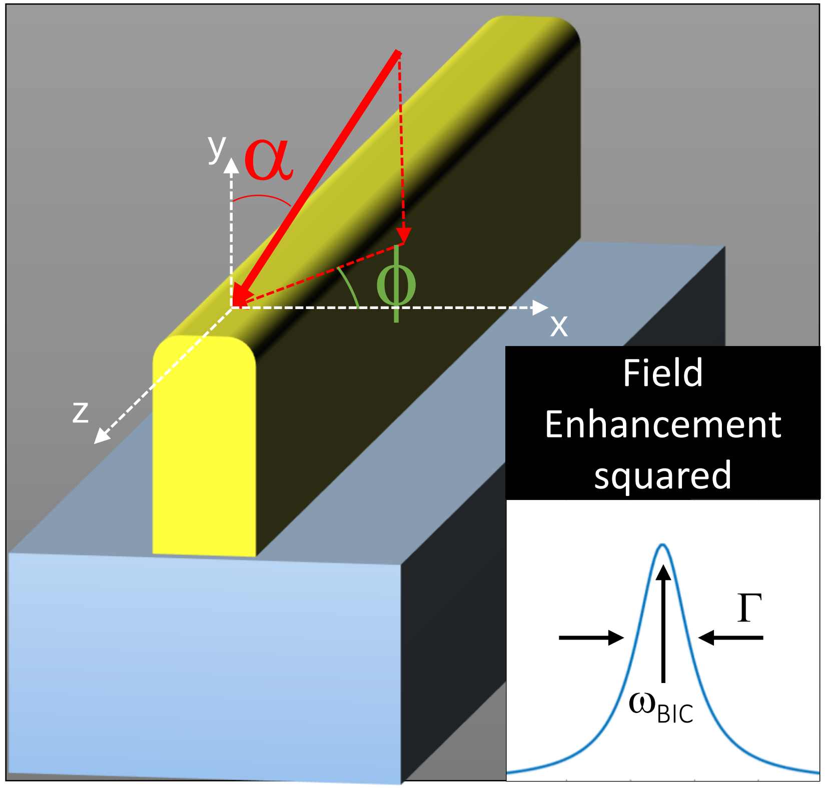
Marino *et al.*, Optica 6, 1416 (2019)

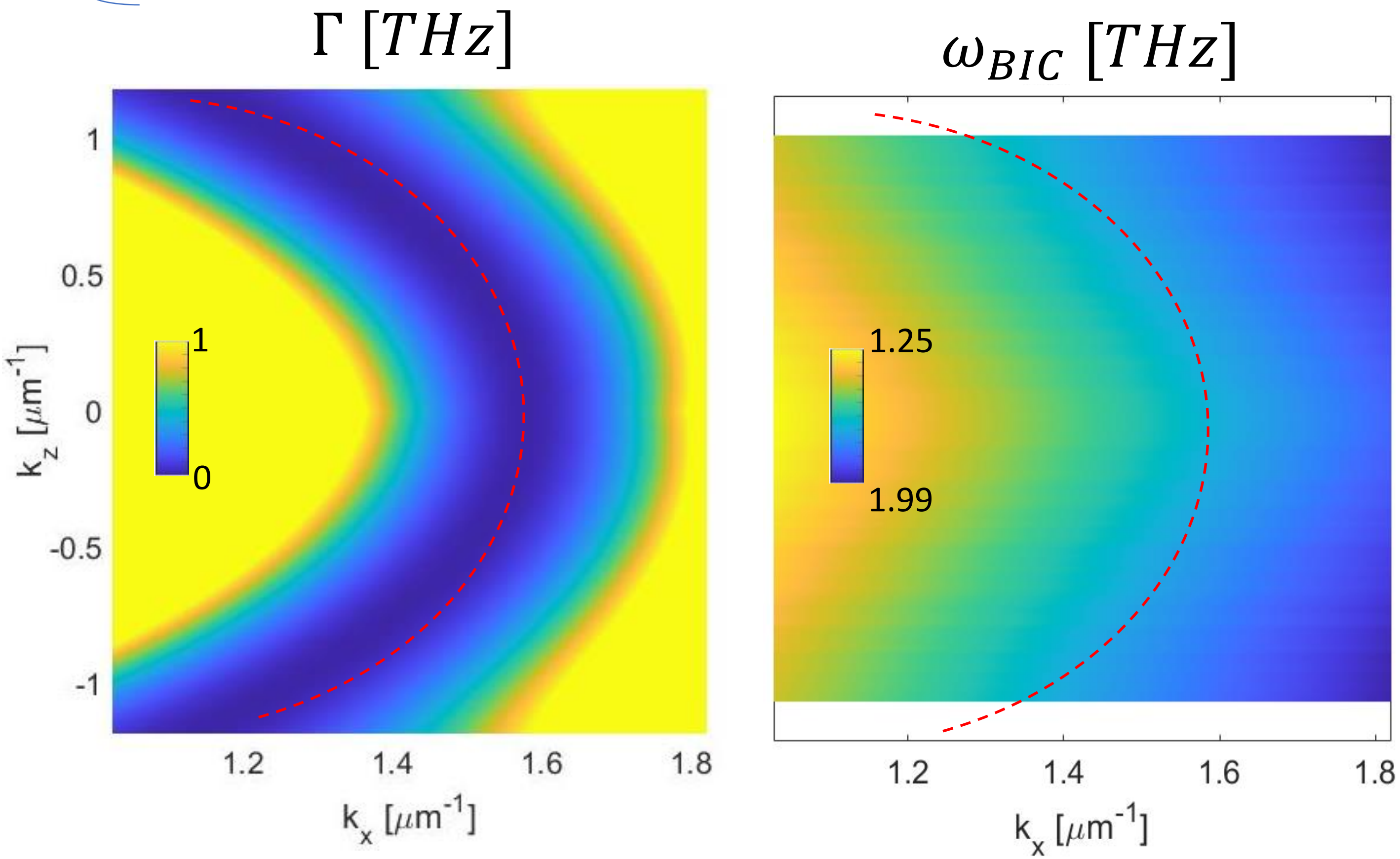


BIC Dispersion

- For SPDC every radiation channel has to be considered
- The BIC has a parabolic dispersion

$$\begin{cases} \Gamma(k_x,k_z) = a(k_z)\left(k_x - k_x^{BIC}(k_z)\right)^2 \\ \omega_{BIC}(k_x,k_z) = b(k_z)\left(k_x - k_x^{BIC}(k_z)\right) + \overline{\omega_0} \end{cases}$$

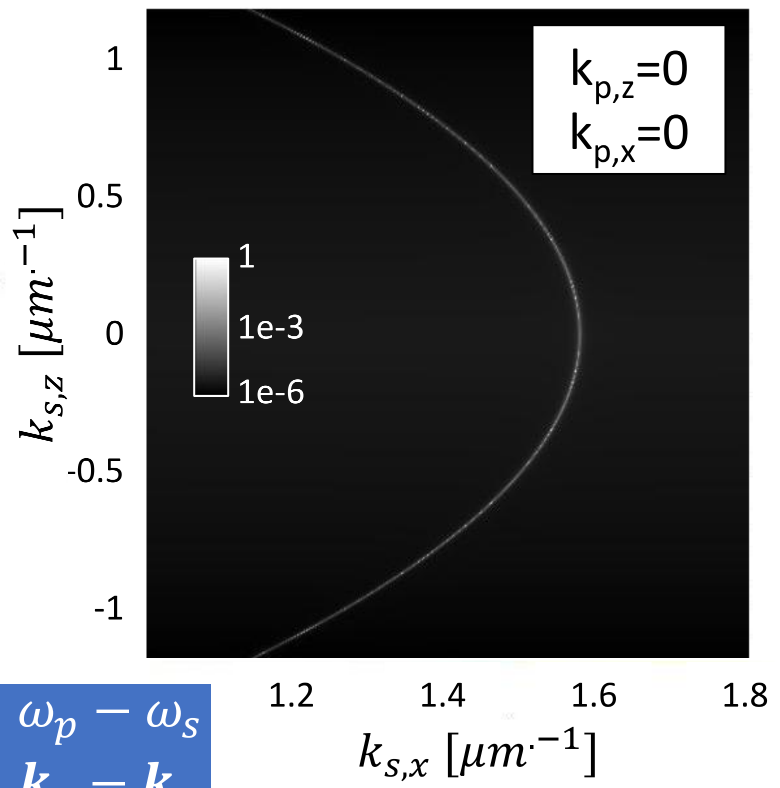




Photon-Pair Generation Rate

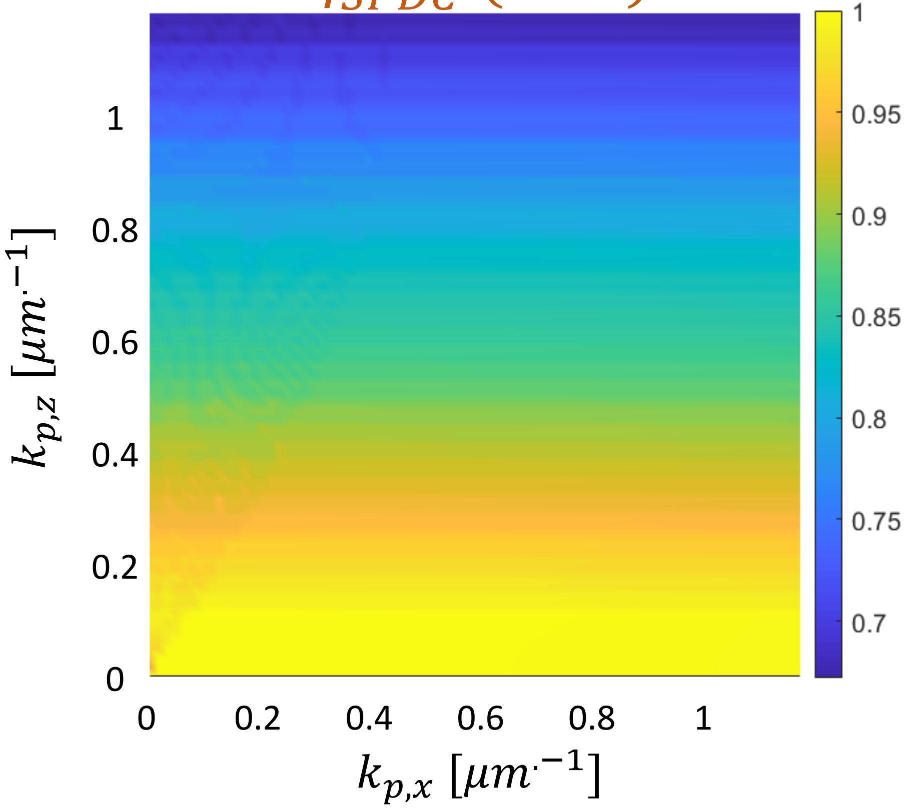
$$\frac{dN_{pair}}{dt} = A_{tot}\,\Phi_p\,\frac{\lambda_p^2}{(2\pi)^3\lambda_s\lambda_i}\Theta_0 \iiint_{-\infty}^{\infty} L(\omega_s,\boldsymbol{k_s})L(\omega_i,\boldsymbol{k_i})\,d\omega_s\,dk_{s,x}\,dk_{s,z}$$

$\eta_{SPDC}\ (a.u.)$



$$\begin{cases}\omega_i = \omega_p - \omega_s \\ \boldsymbol{k_i} = \boldsymbol{k_p} - \boldsymbol{k_s}\end{cases}$$

$\eta_{SPDC}^{TOT}\ (a.u.)$



- Extremely sharp emission spectrum
- Weak dependence on pump angular spectrum
- Finite value of the integral!
- photon pair generation rate of 5.4 KHz for pump power of 2 mW

Conclusions

- We designed a nonlinear metasurfaces optimized for nonlinear three wave mixing in terms of, spatial coherence, narrow spectrum, sharp emission directionality and generation efficiency
- Our approach in the design is applicable to different quadratically nonlinear material platforms
- We estimate a photon pair generation rate of 5.4 KHz for pump power of 2 mW

Thank you for your attention