Research Program of the Boyd Research Group

Robert W. Boyd

Department of Physics and
Max Planck Centre for Extreme and Quantum Photonics
University of Ottawa

The visuals of this talk will be posted at boydnlo.ca/presentations or elsewhere

Presented at the Annual Meeting of the Max Planck - University of Ottawa Centre for Extreme and Quantum Electronics, October 30, 2019.

Schedule of Presentation

Robert Boyd (5 min):
Intro to the group research program

Jeremy Upham (12 min):
NLO of epsilon-near-zero (ENZ) materials: Large nonlinear index change in ITO, time refraction, holography, ENZ nonlinearity of a multi-layer stack.

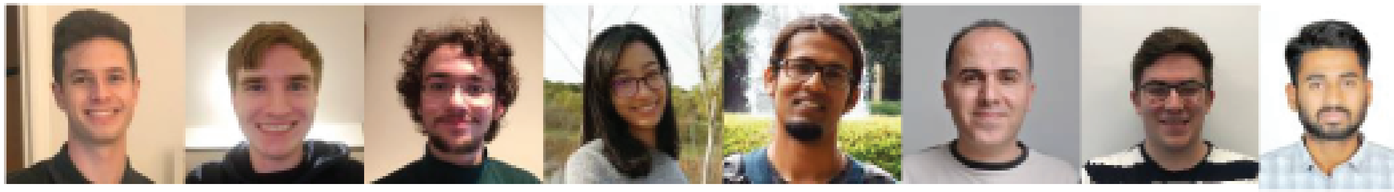
Orad Reshef (12 min):
Large nonlinearity in antenna-coupled ITO, surface lattice resonance (SLR) in metasurfaces, SLR in ITO, four-wave mixing in zero-index waveguides.

Boris Braverman (12 min):
AOMs for rapid modulation of quantum states , bright squeezed vaccum

Research Themes

- Nonlinear Optics
- Nano Optics
- Quantum Optics

Our Research Group



CURRENT PROJECTS OF THE BOYD RESEARCH GROUP

STUDIES OF ENZ MATERIALS

Adiabatic wavelength conversion (also known as "time refraction") in ITO
Nonlinear properties of layered composite metal-dielectric ENZ materials
OAM generation from circular epsilon-near-zero (ENZ) waveguide structures
Pump-probe spectroscopy of u-shaped antennas on ITO for active polarization metasurfaces
Superradiance studies

PLASMONICS

Metasurfaces for spectral filtering

LIGHT DRAG EXPERIMENTS

Transverse photon drag in ruby
Transverse photon drag in rubidium vapour using EIT

QUANTUM OPTICS

Entanglement generation with an incoherent pump
Three photon entanglement via three-photon downconversion
Induced coherence without induced emission (in both spontaneous and high-gain limits)
Looking for high-order correlations in high-gain PDC
Quantum imaging: Phase imaging with high-gain PDC

NONLINEAR OPTICS

Nonlinear interactions in a rubidium nanocell
Nonlinearity in GRIN fiber and mode self-cleaning
Nonlinear microscopy of biological samples and graphene-like carbon
Fast mode generation/analysis with AOM (two experiments)

Epsilon-near-zero and zero-index materials

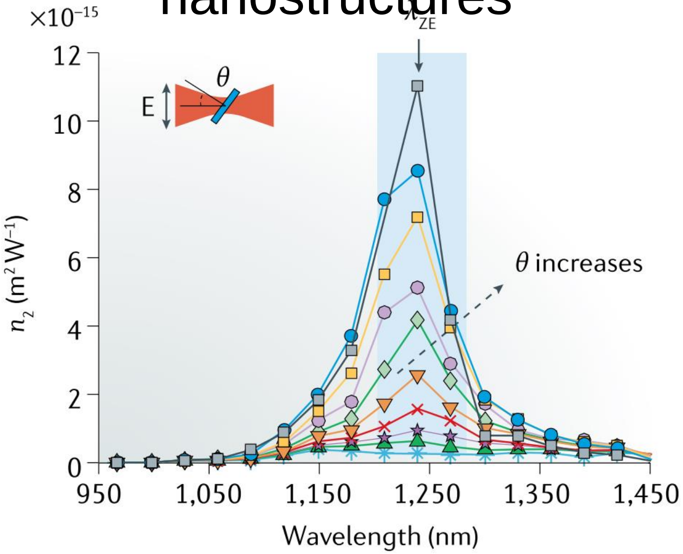
Orad Reshef, Boyd Research Group

Department of Physics
University of Ottawa, Canada

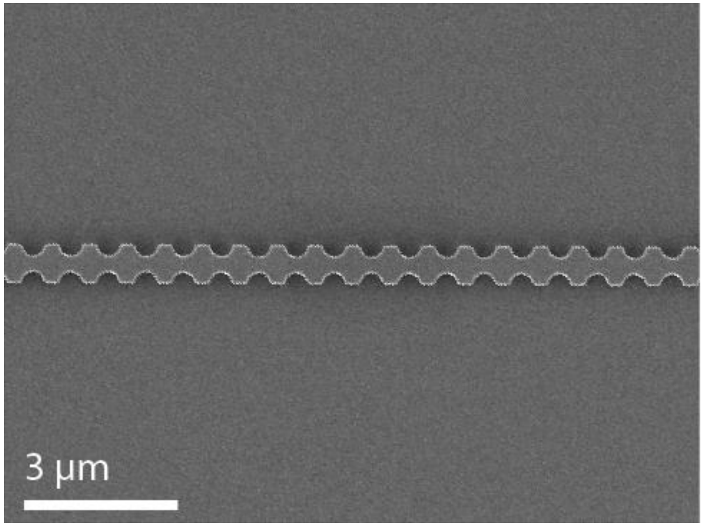
Max Planck Centre Annual Meeting
October 30, 2019

Canada Excellence Research Chairs
Chaires d'excellence en recherche du Canada
uOttawa
MAX-PLANCK-GESELLSCHAFT
Bourses postdoctorales Banting Postdoctoral Fellowships

Epsilon-near-zero materials functionalized with nanostructures



Zero-index metamaterials



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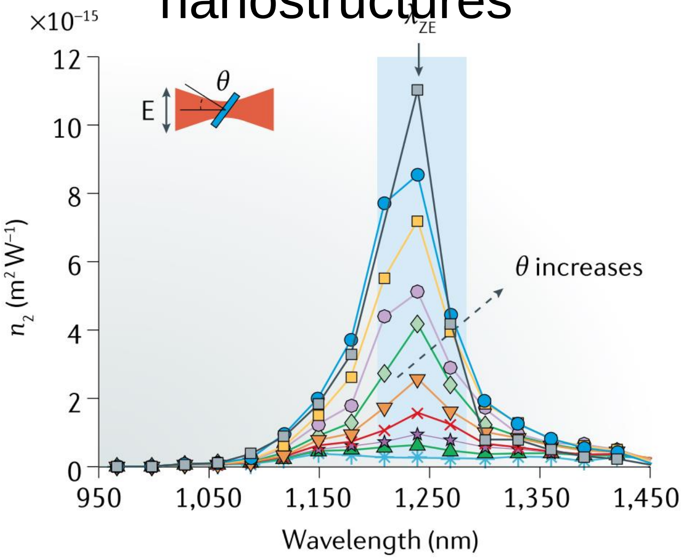
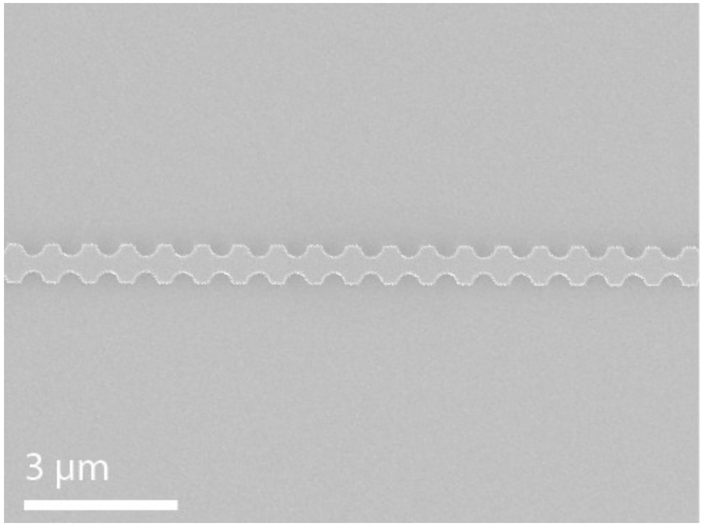
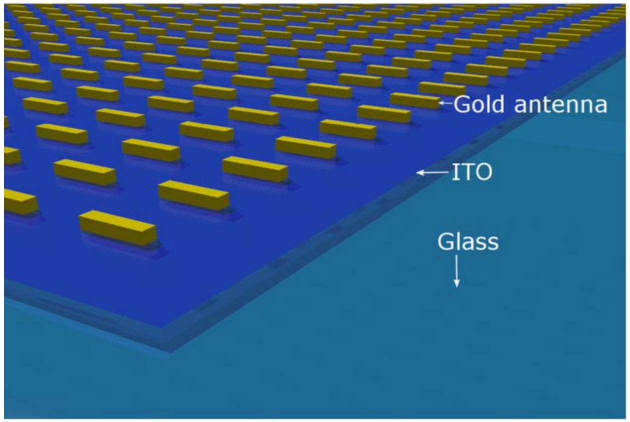


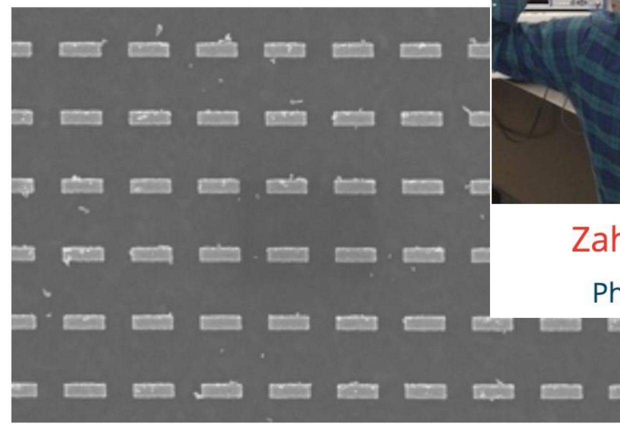
Zero-index metamaterials



1 NLO in structured ITO

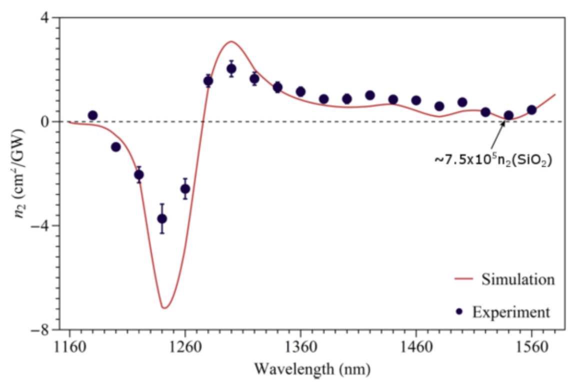
By adding nanostructured antennas to an ITO surface, we can further enhance ENZ-based nonlinearities.

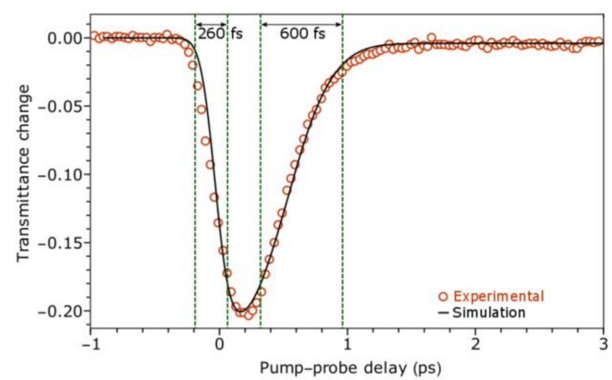




Zahirul Alam

PhD Student

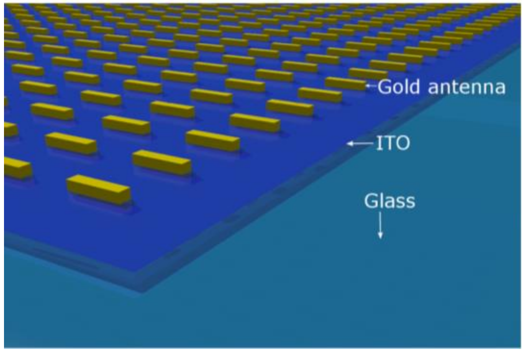




M. Z. Alam et al, Nat. Photonics 12, 79 (2018)

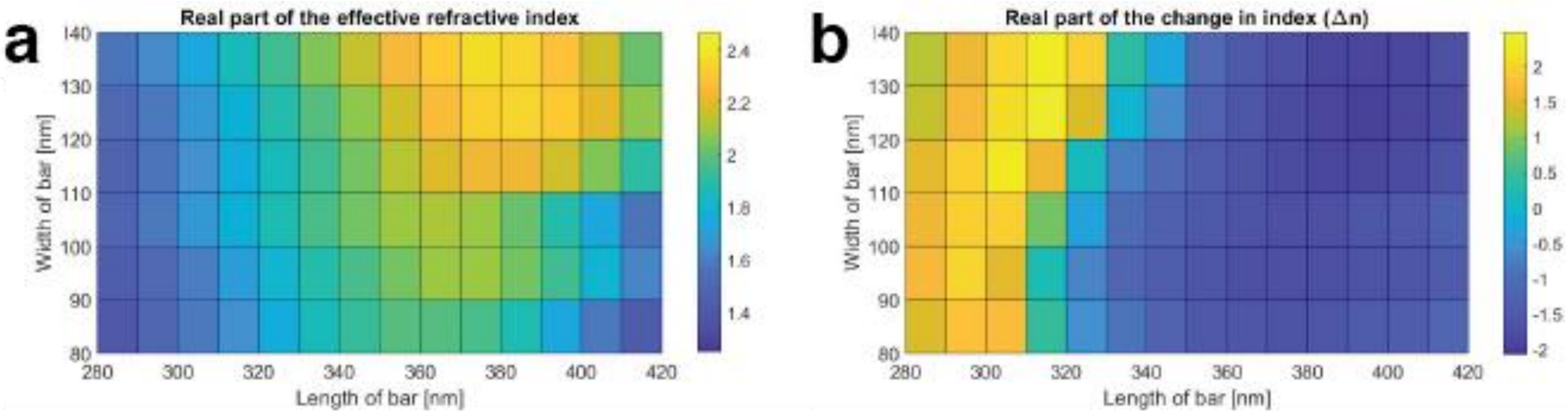
NLO in structured ITO

Nanostructures can be used to **locally tailor** the material response.



Mohammad Karimi

PhD Student



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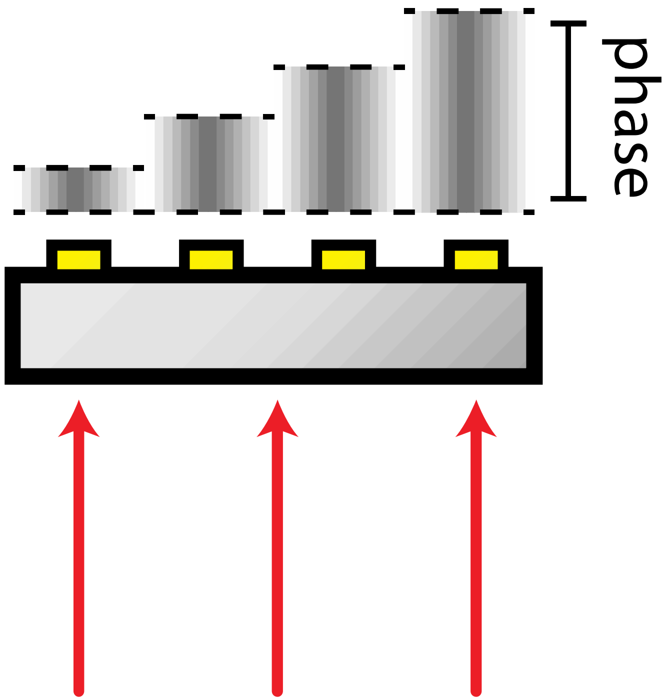

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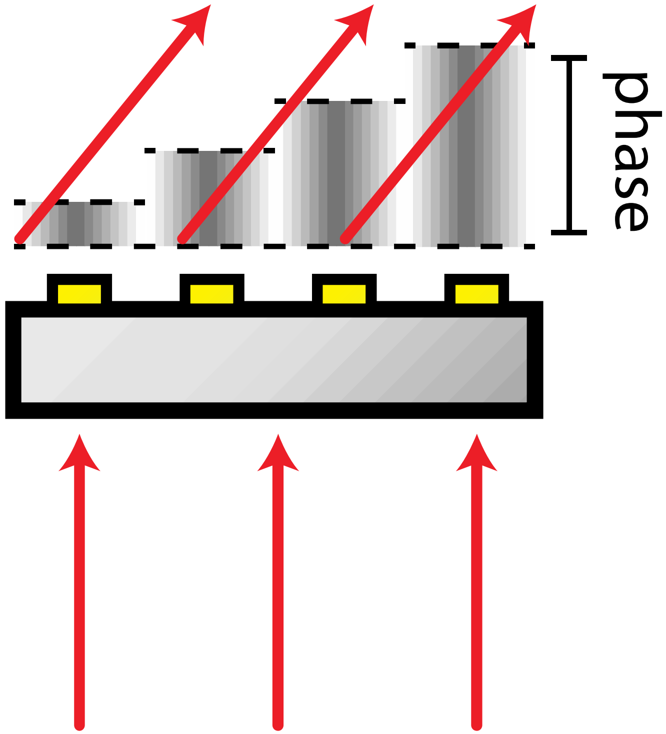

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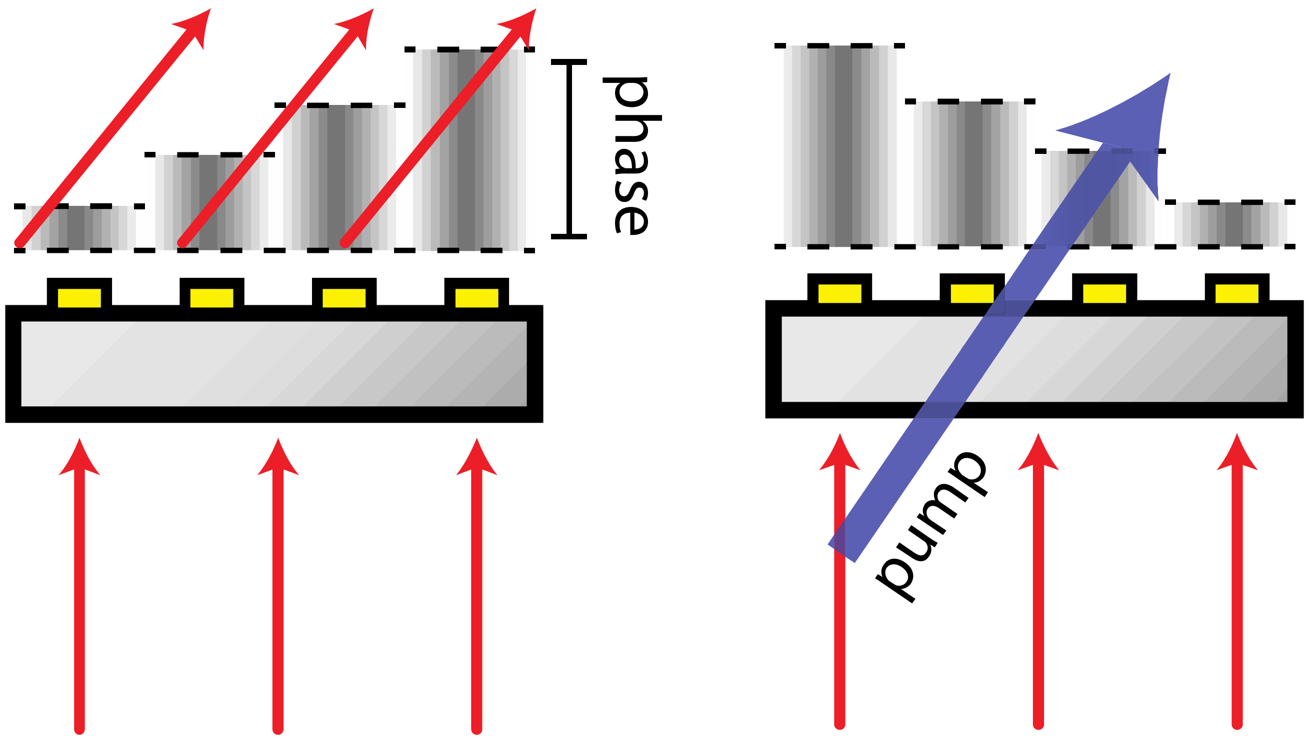

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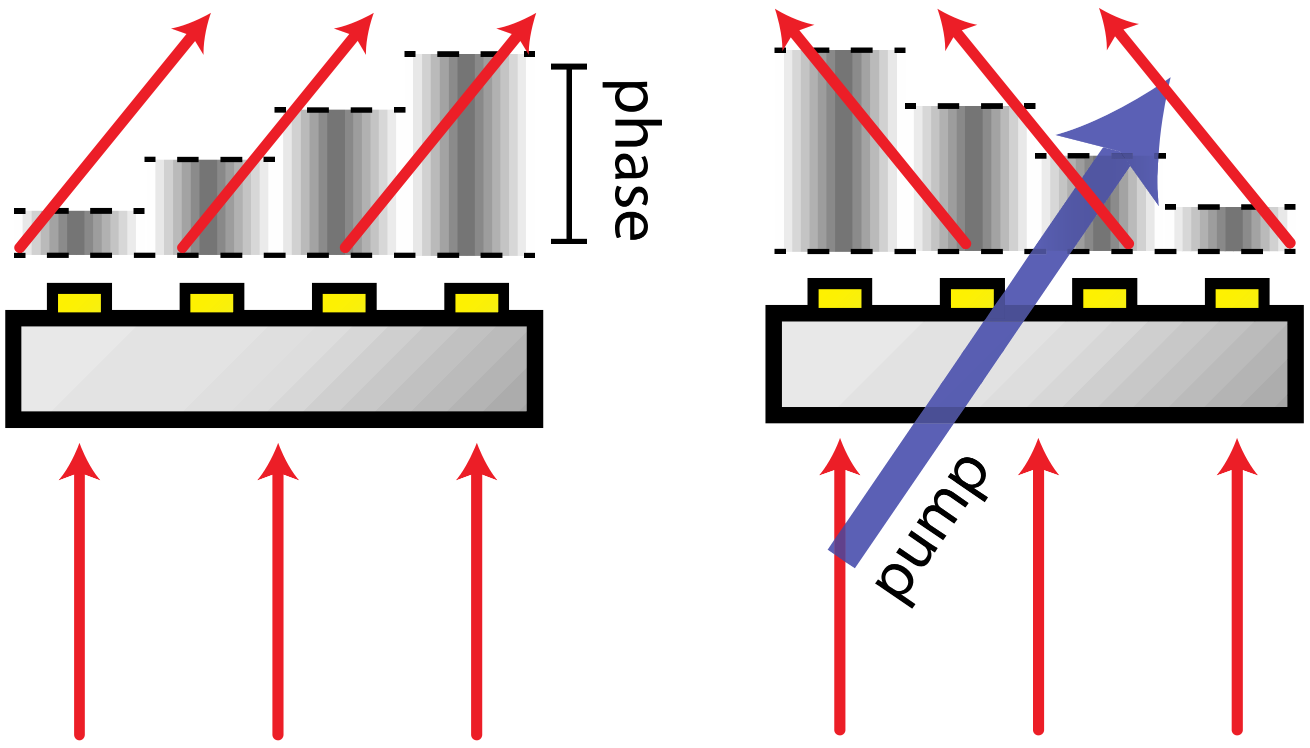
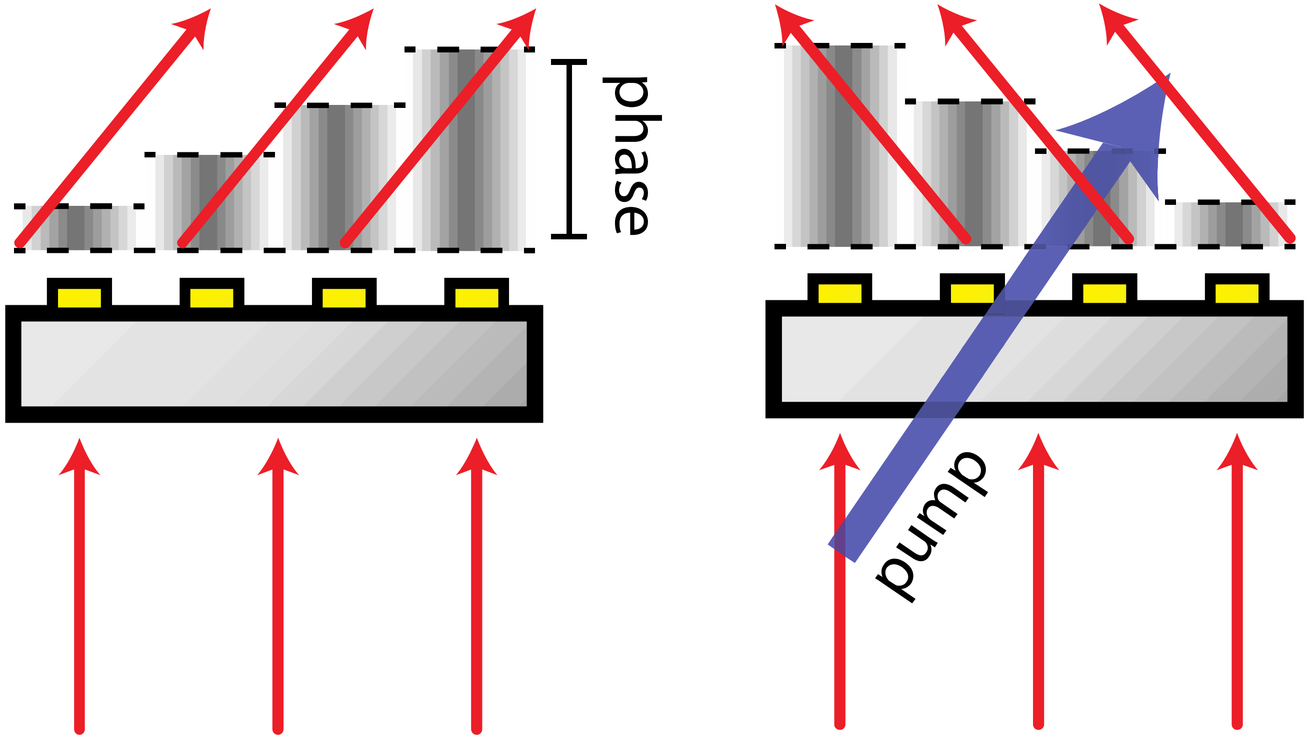


Nanostructures can be used to **locally tailor** the material response.

All-optical beam-steering

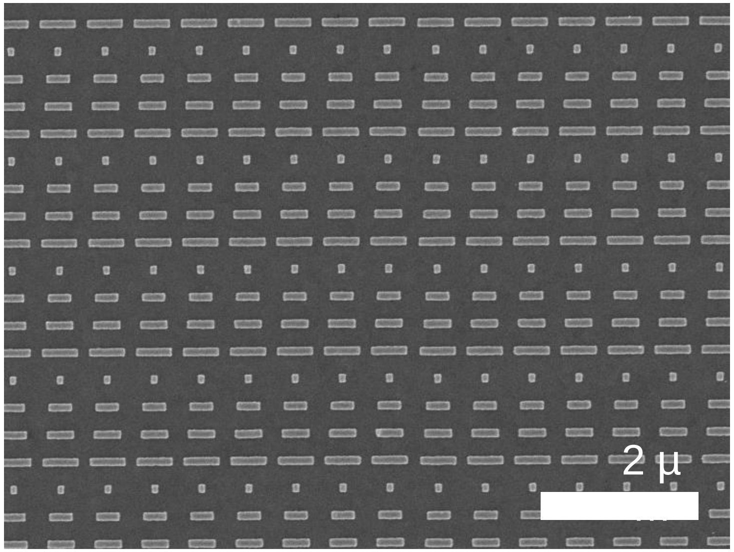


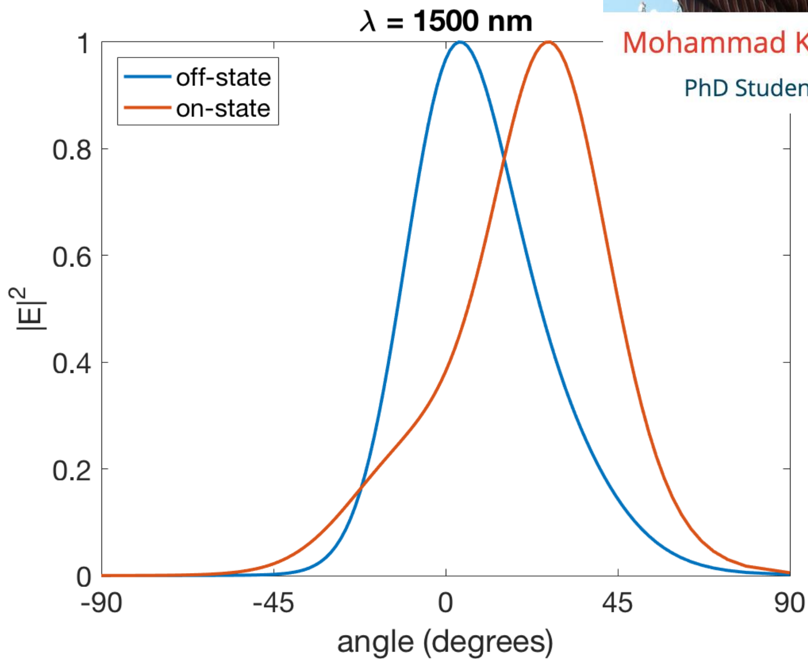
Active optical surfaces using ENZ-enhanced nonlinear optics

Experiments are underway:

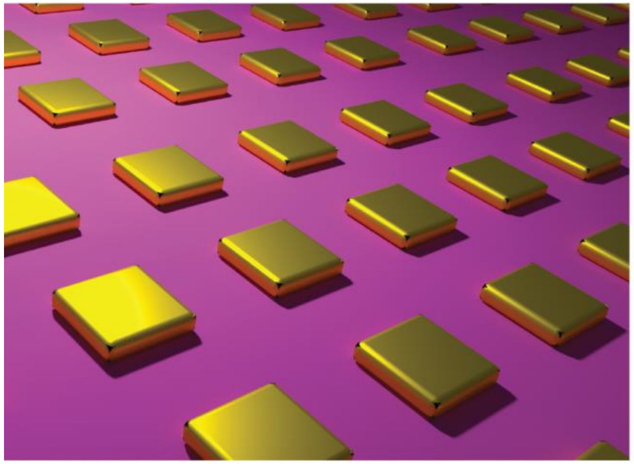
Mohammad Karimi

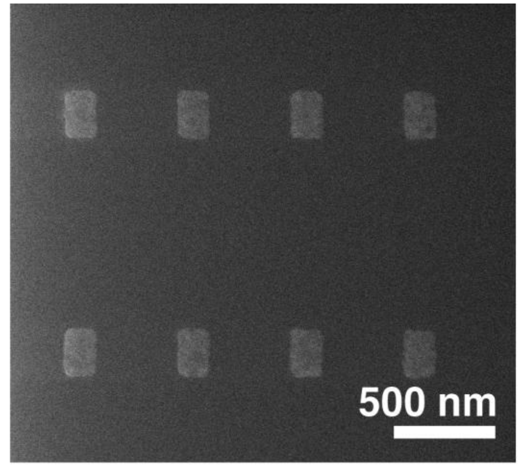
PhD Student





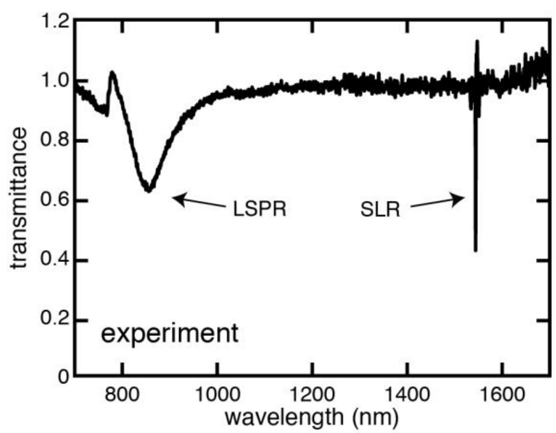
High quality-factor metasurfaces using Surface Lattice Resonances (SLRs) in plasmonic nanoparticle arrays

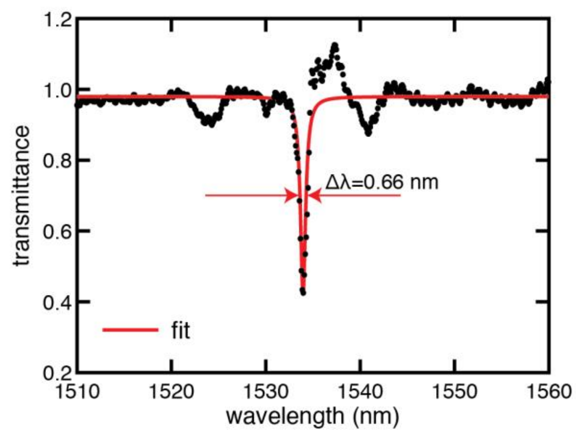




Saad Bin Alam

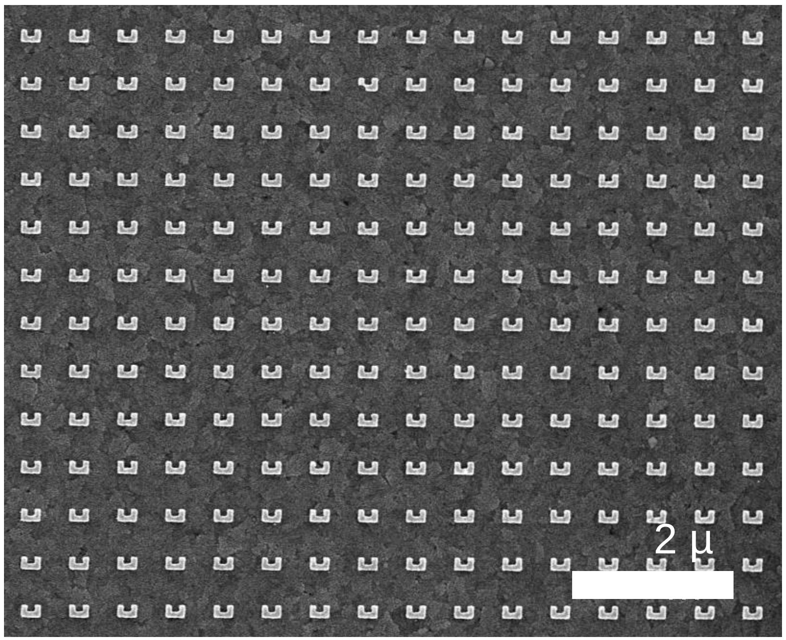
PhD Student

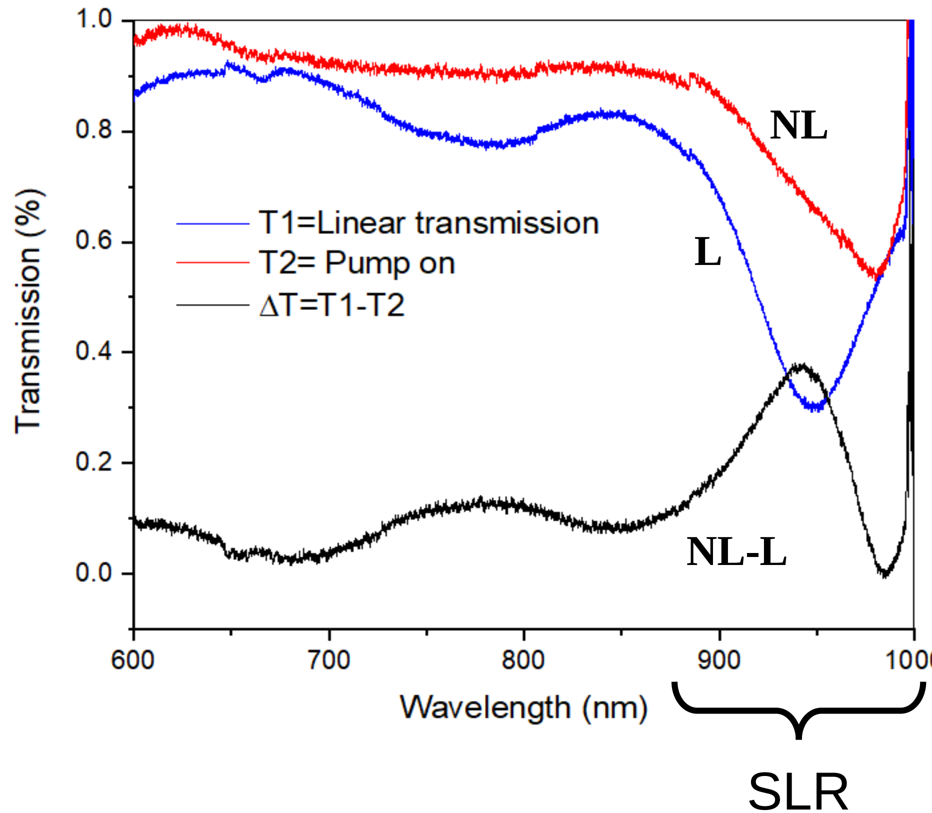




Active optical surfaces using ENZ-enhanced nonlinear optics

Ryan Hogan
PhD Student





1 NLO in structured ITO

Read our review article!

REVIEWS

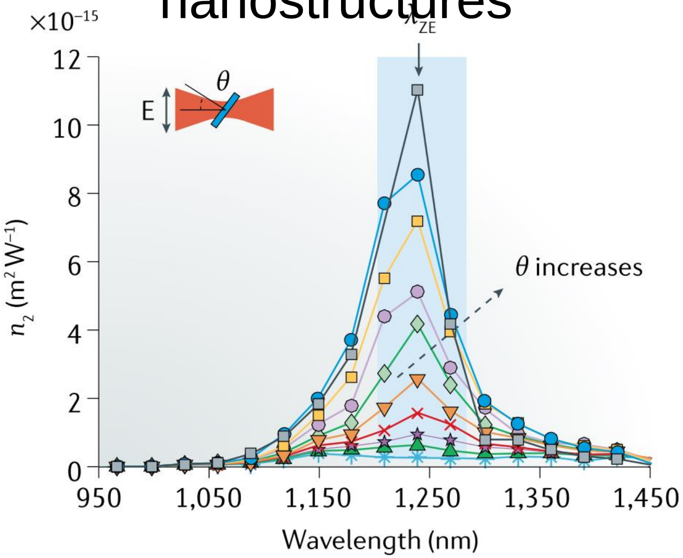
Nonlinear optical effects in epsilon-near-zero media

Orad Reshef[1], Israel De Leon[2], M. Zahirul Alam[1] and Robert W. Boyd[1,3]**

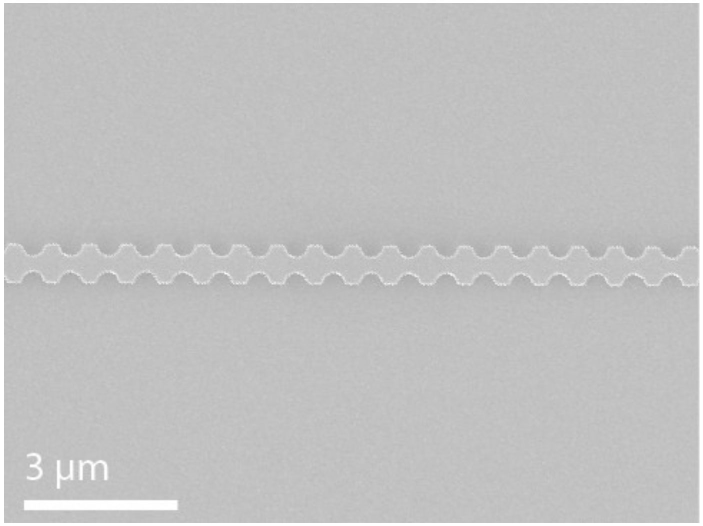
Abstract | Efficient nonlinear optical interactions are essential for many applications in modern photonics. However, they typically require intense laser sources and long interaction lengths, requirements that often render nonlinear optics incompatible with new nanophotonic architectures in integrated optics and metasurface devices. Obtaining materials with stronger nonlinear properties is a crucial step towards applications that require lower powers and smaller footprints. Recently, a new class of materials with a vanishing permittivity, known as epsilon-near-zero (ENZ) materials, has been reported to exhibit unprecedented ultrafast nonlinear efficiencies within sub-wavelength propagation lengths. In this Review, we survey the work that has been performed on ENZ materials and the related near-zero-index materials, focusing on the observation of various nonlinear phenomena (such as intensity-dependent refraction, four-wave mixing and harmonic generation), the identification of unique field-enhancement mechanisms and the study of non-equilibrium dynamics. Degenerately doped semiconductors (such as tin-doped indium oxide and aluminium-doped zinc oxide) are particularly promising candidates for ENZ-enhanced nonlinear optical applications. We conclude by pointing towards possible future research directions, such as the search for ENZ materials with low optical losses and the elucidation of the mechanisms underlying nonlinear enhancements.

NATURE REVIEWS | MATERIALS VOLUME 4 | AUGUST 2019 | 535

Epsilon-near-zero materials functionalized with nanostructures



Zero-index metamaterials



1 NLO in structured ITO

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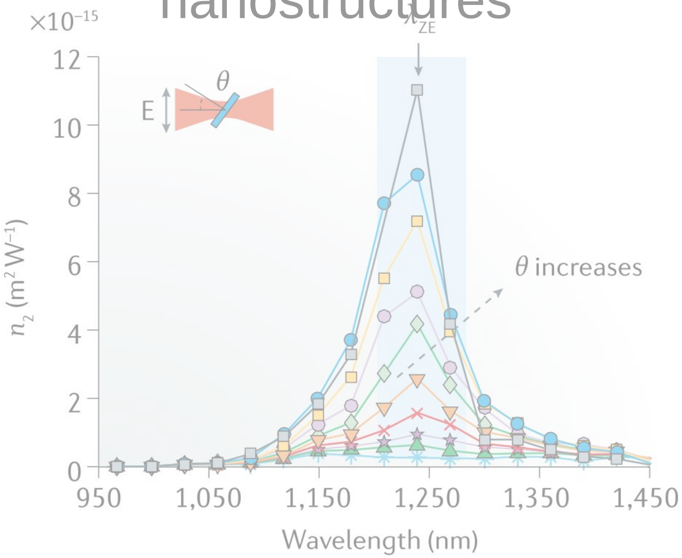
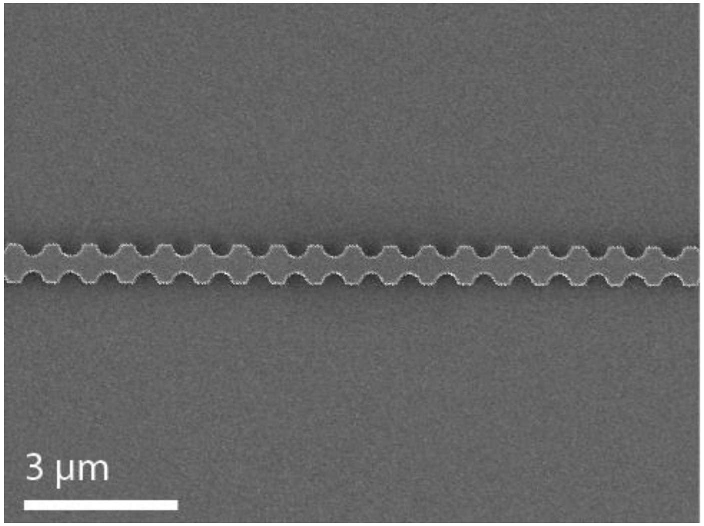


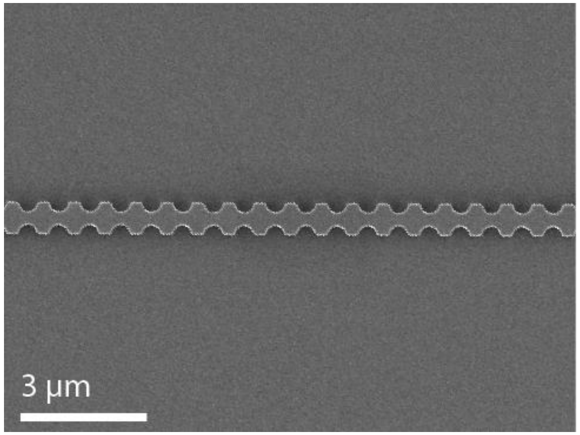
Zero-index metamaterials

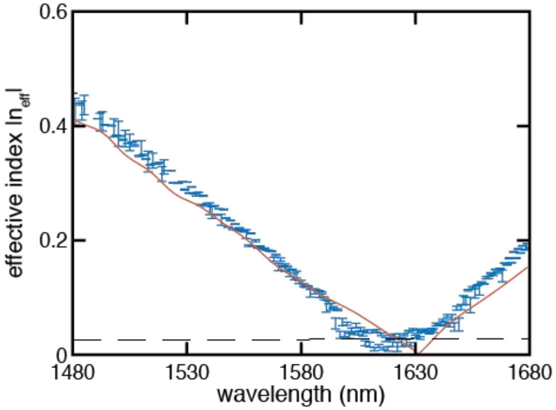


1 NLO in structured ITO

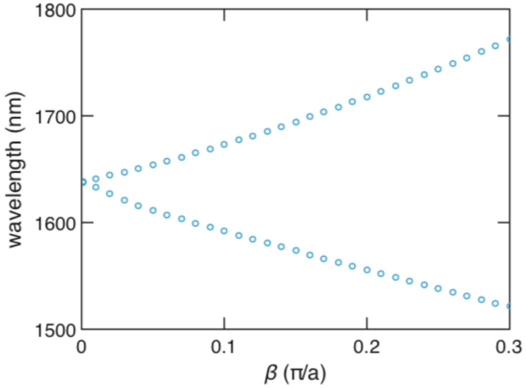
2 Zero-index waveguides

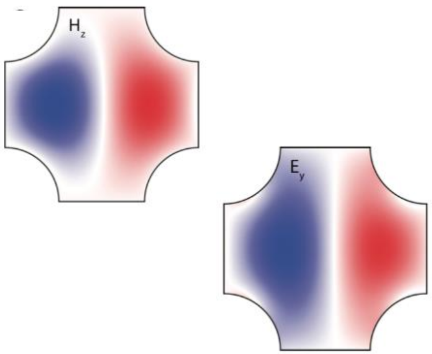
We can engineer our own ENZ materials out of silicon using Dirac Cone metamaterials:





SOI PhC waveguide that supports a mode at the $k = \dfrac{2\pi n}{\lambda} = 0$ point of the brillouin zone





Reshef, O. et al. ACS Photonics 4, 2385–2389 (2017)

We can also engineer our own ENZ materials out of silicon using Dirac Cone metamaterials:

IOP Publishing Reports on Progress in Physics

Rep. Prog. Phys. 82 (2019) 012001 (18pp) https://doi.org/10.1088/1361-6633/aad3e5

Key Issues Review

Manipulating the flow of light using Dirac-cone zero-index metamaterials

Daryl I Vulis, Orad Reshef, Philip Camayd-Muñoz and Eric Mazur[1]

Department of Physics and School of Engineering and Applied Sciences, Harvard University, 9 Oxford Street, Cambridge, MA 02138, United States of America

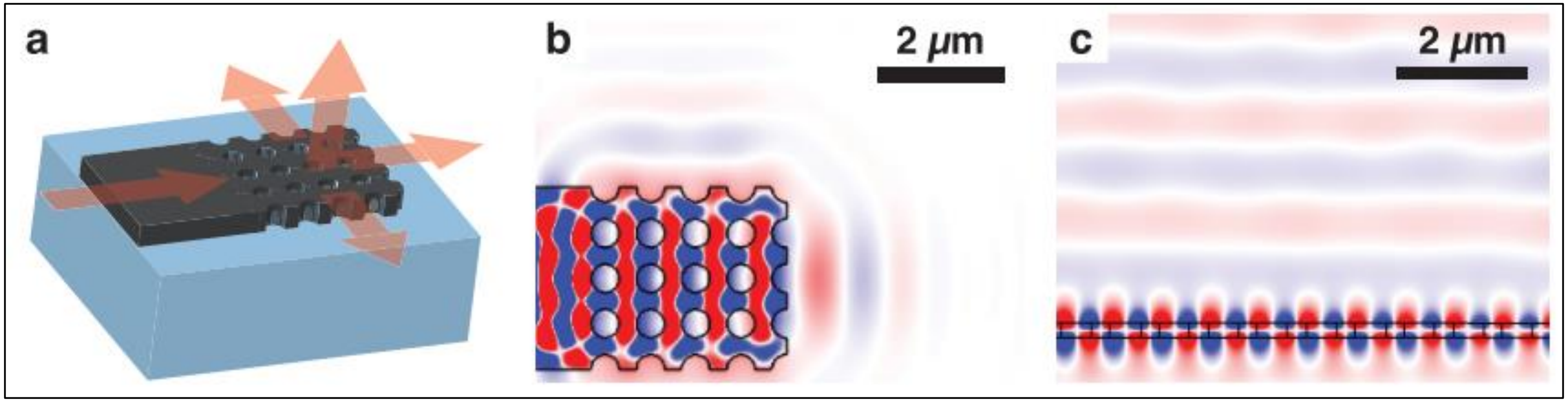
…in zone

Reshef, O. et al. ACS Photonics 4, 2385–2389 (2017)

1 NLO in structured ITO

2 Zero-index waveguides

Zero-index metamaterials radiate light normal to their surfaces



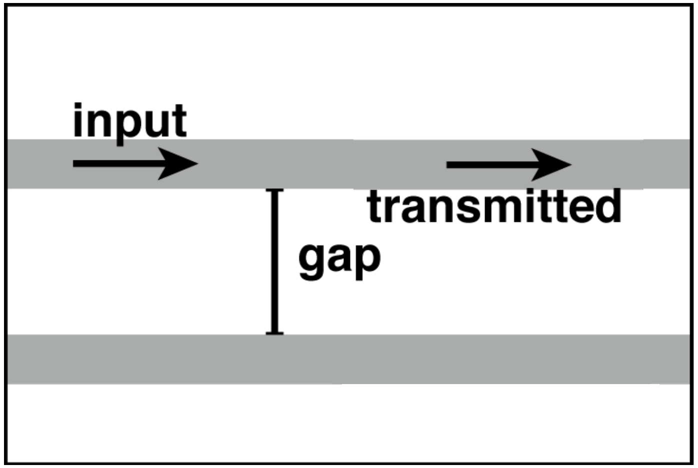
$$n \sin\theta = 0 \implies \theta = 0$$

Reshef, O. et al. ACS Photonics 4, 2385–2389 (2017)

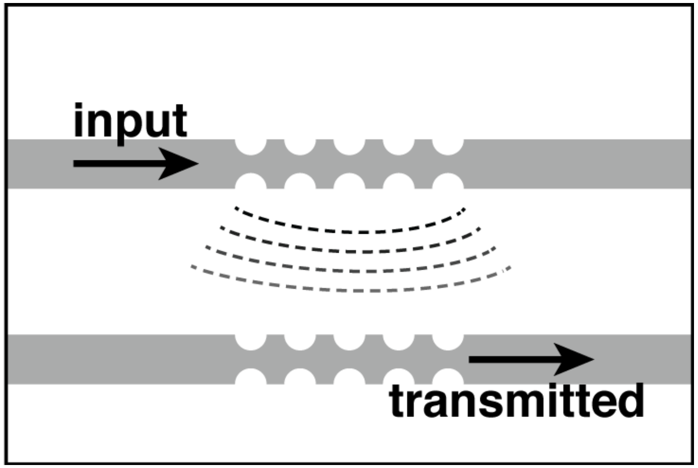
For a gap that is too large for traditional evanescent coupling, a zero-index waveguide can **radiate** light from one waveguide to another.

Codey Nacke

conventional silicon waveguides

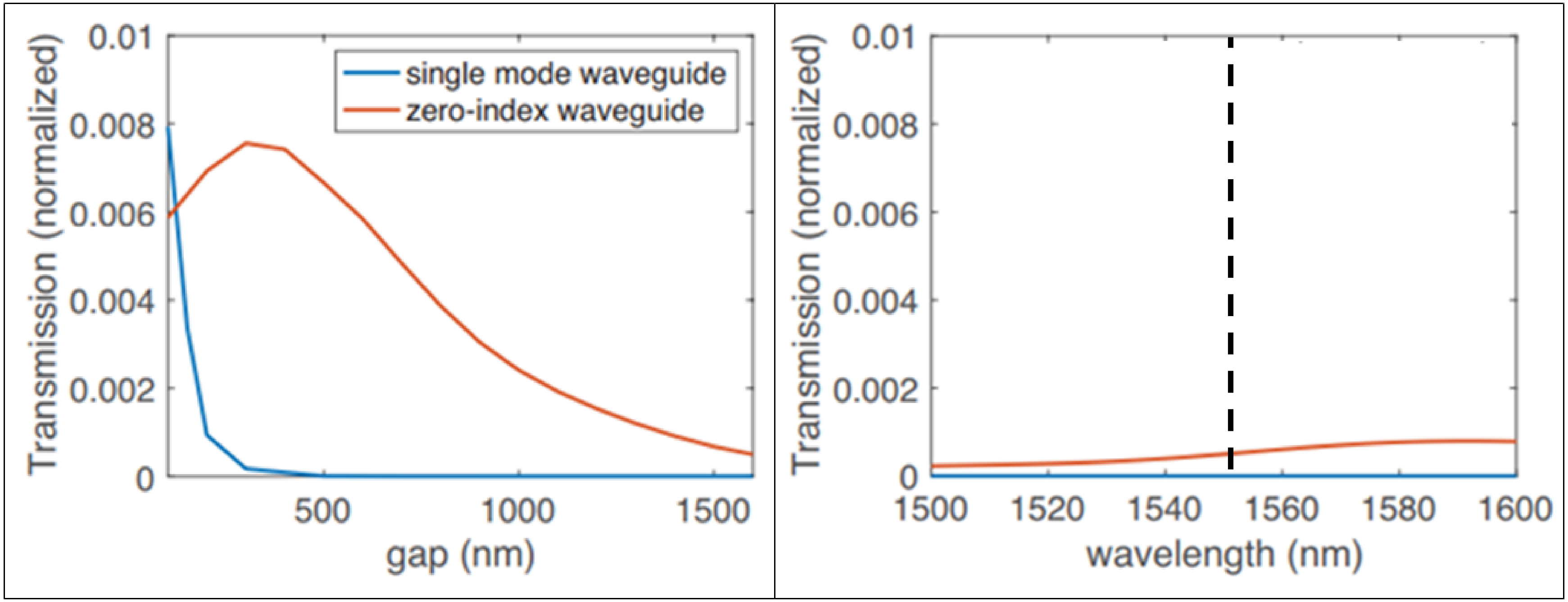


zero-index silicon waveguides

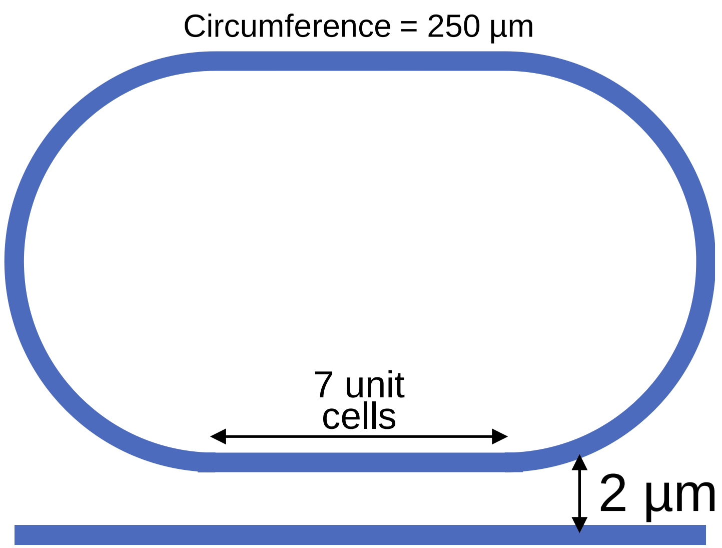


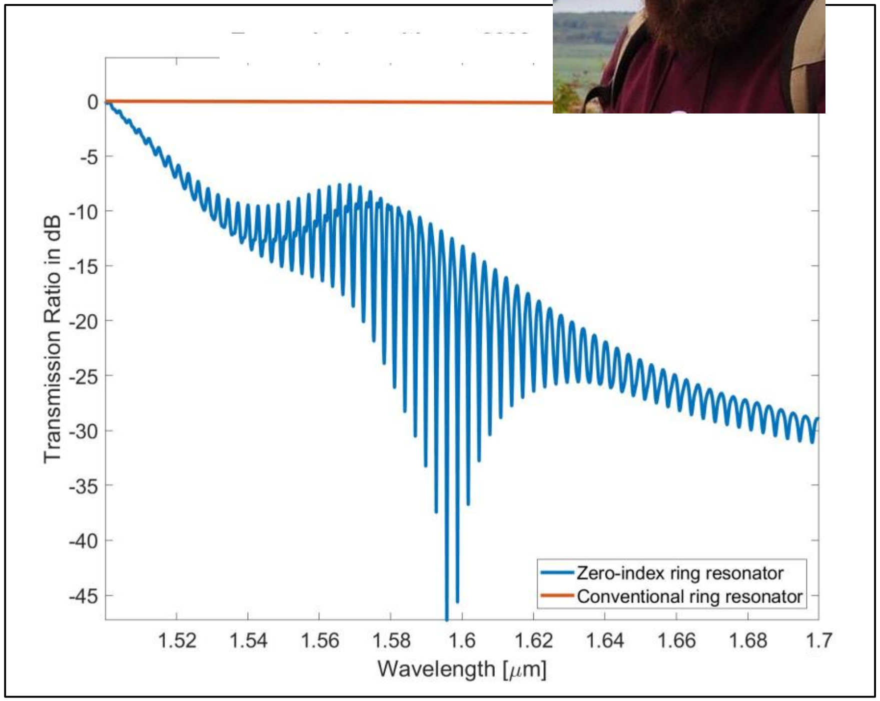
Zero-index-based couplers may couple light even for separations that exceed the free space wavelength (λ = 1550 nm).

The effect is broadband, working for *low* index as well.



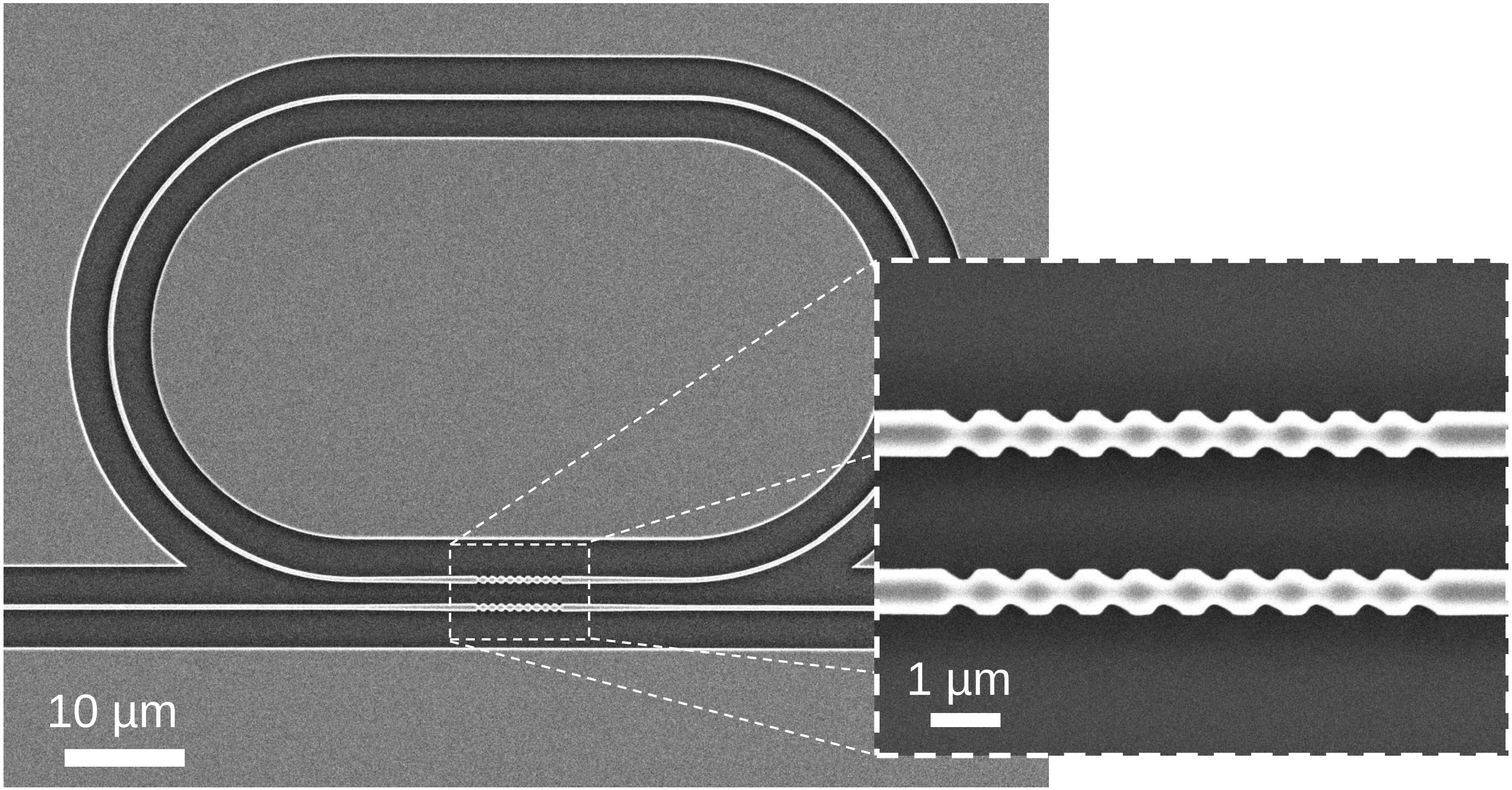
We can achieve critical coupling (>10 dB extinction ratio) over 50 nm bandwidth with an edge-to-edge gap of 2 µm.





FSR: 3 nm, as expected
Transmission loss: 20 dB, due to large propagation losses

Experiments are underway:



1 NLO in structured ITO

2 Zero-index waveguides

Nonlinear properties of Zero-index waveguides:

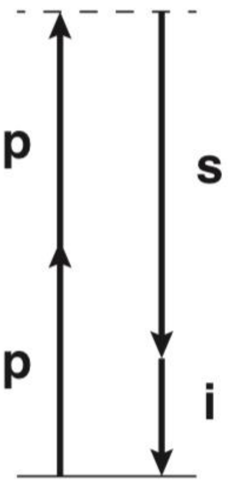
Nonlinear properties of Zero-index waveguides:

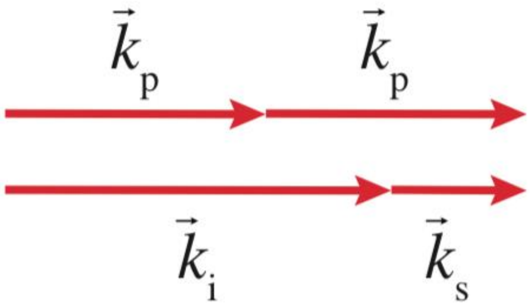
energy conservation

$$\Delta\omega = 2\omega_p - \omega_s - \omega_i = 0$$

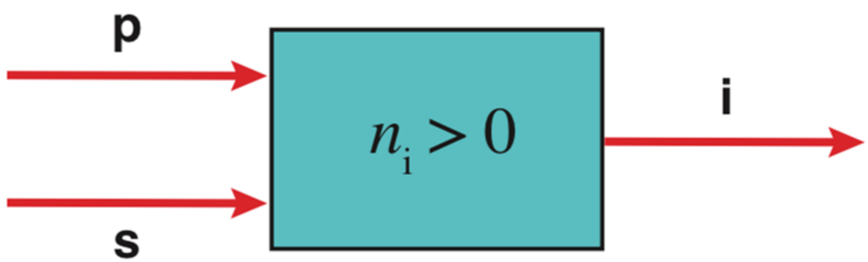
momentum conservation

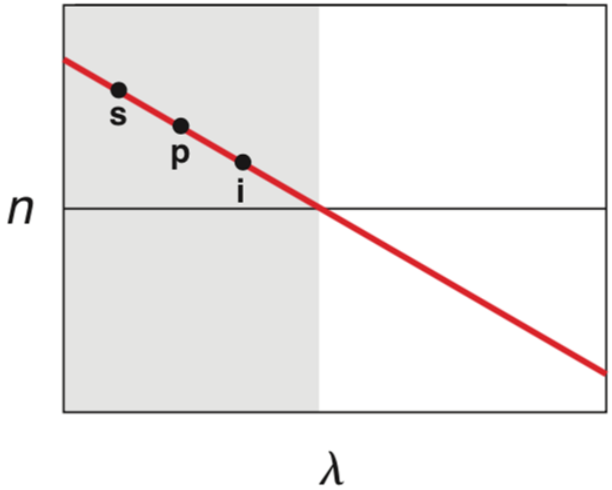
$$\Delta k = 2\vec{k}_p - \vec{k}_s - \vec{k}_i = 0$$

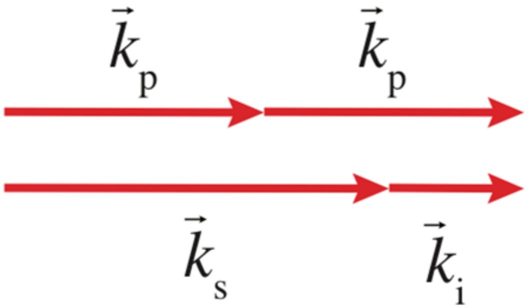




phase matching







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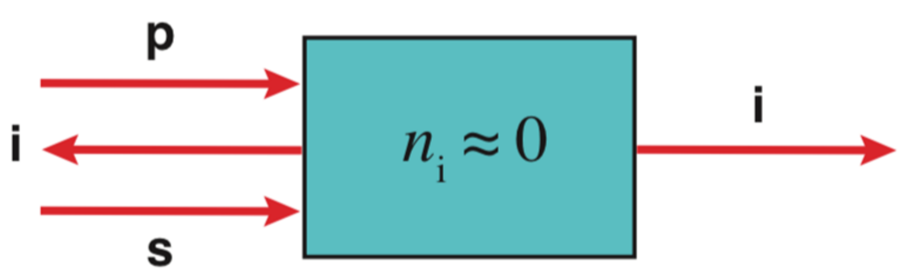
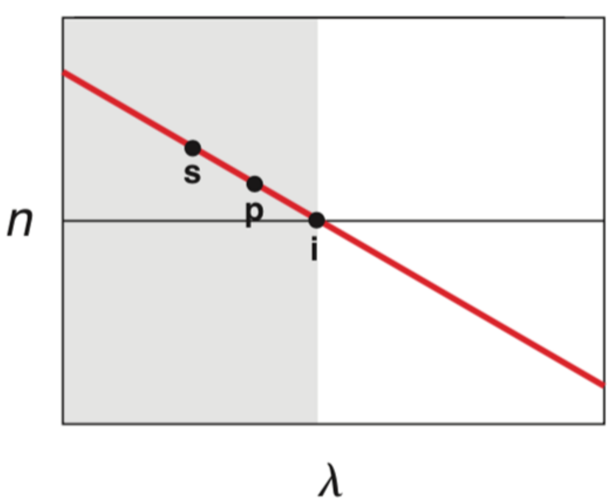
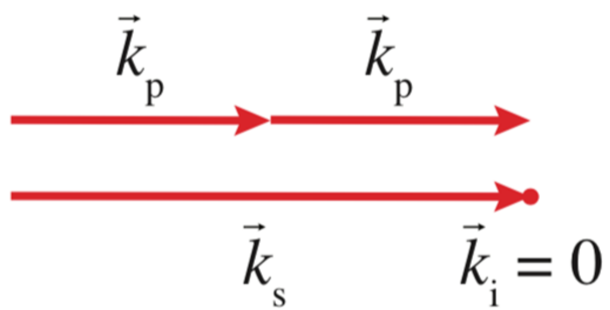
2 Zero-index waveguides



forward and backward

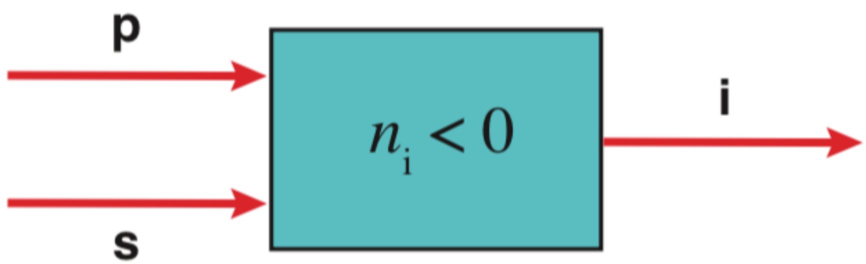


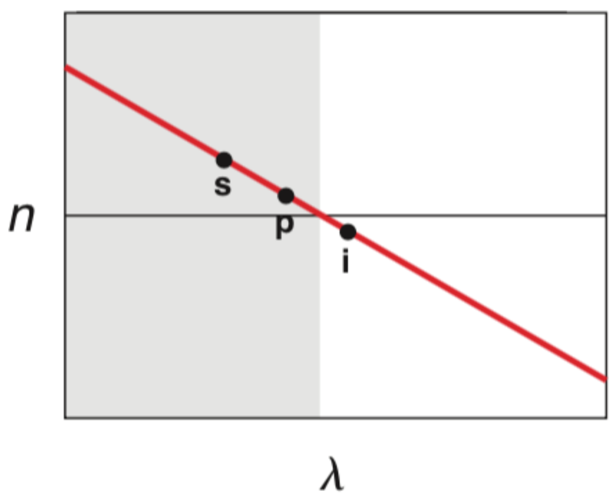


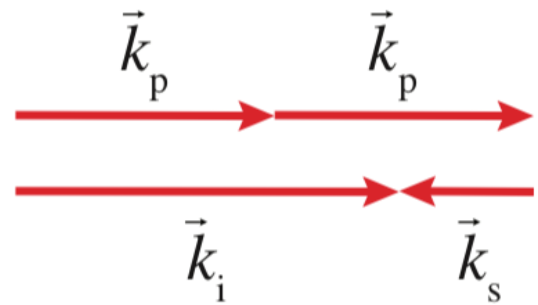
phase matching

1 NLO in structured ITO

2 Zero-index waveguides





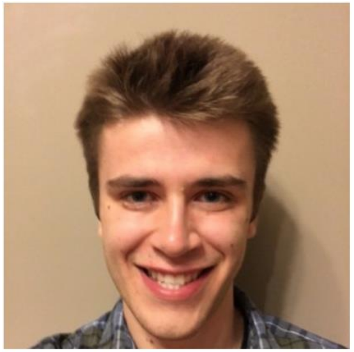


phase matching

1 NLO in structured ITO

2 Zero-index waveguides

So we measured this in the lab!



Justin Gagnon

MSc Student

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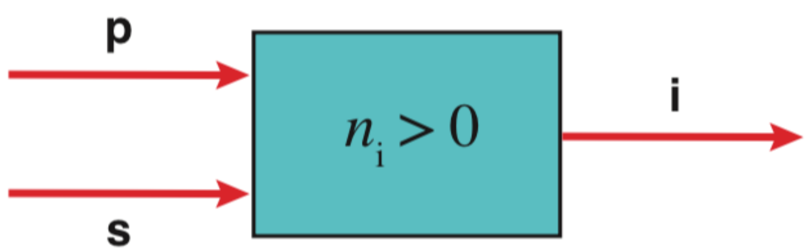

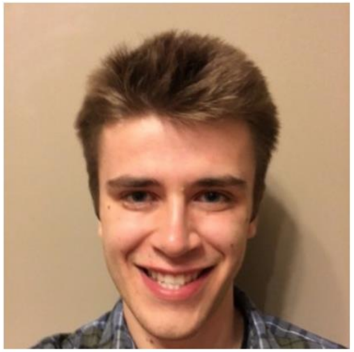

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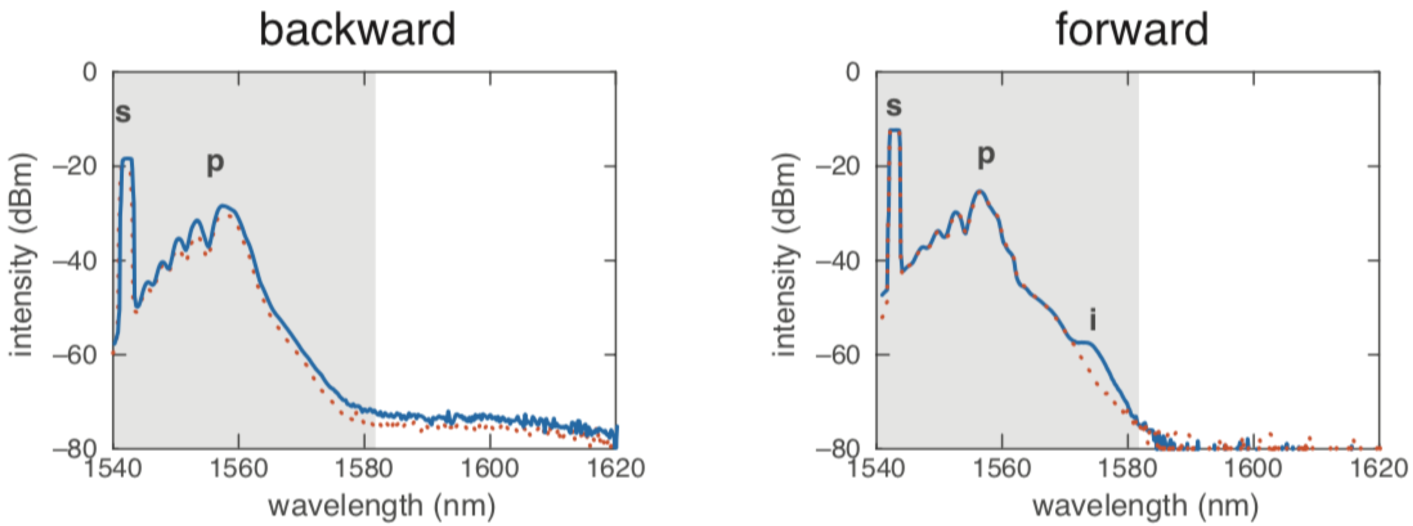

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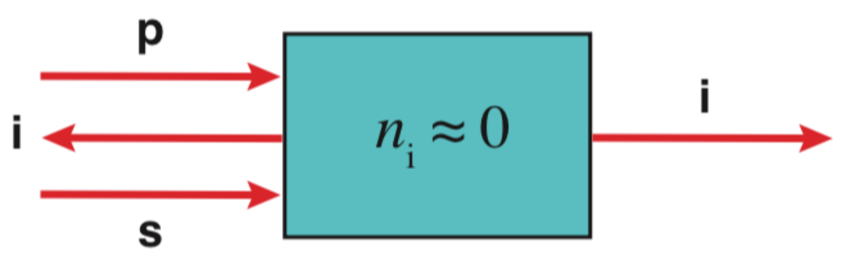
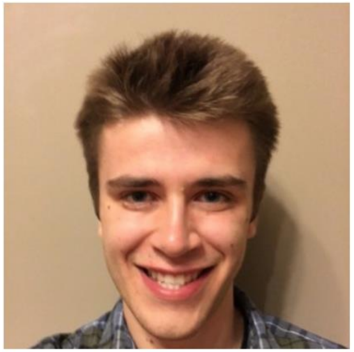
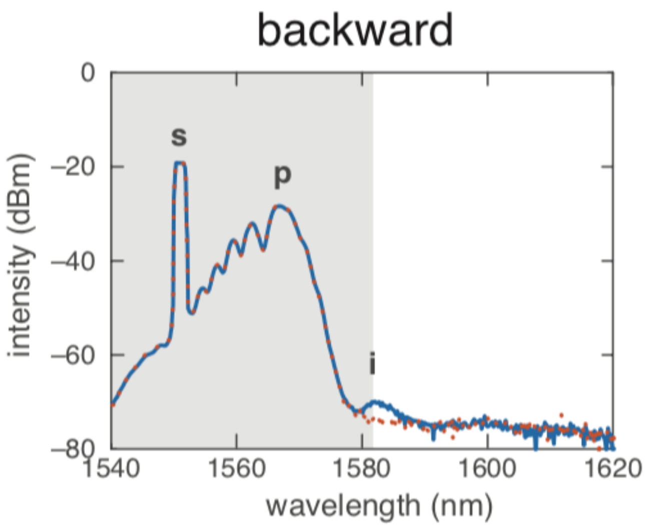
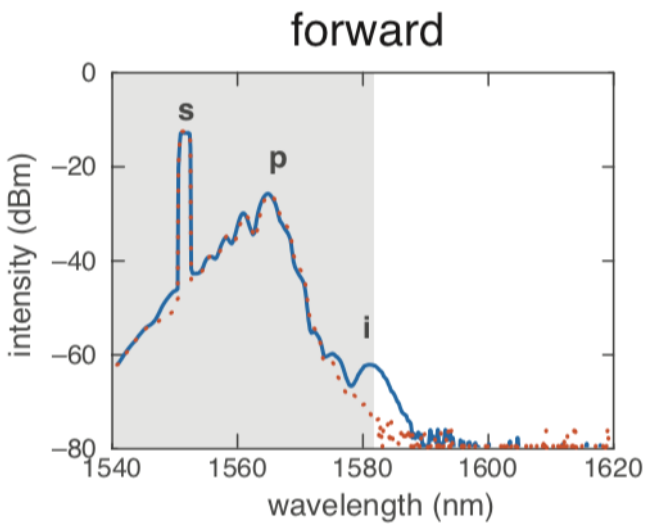




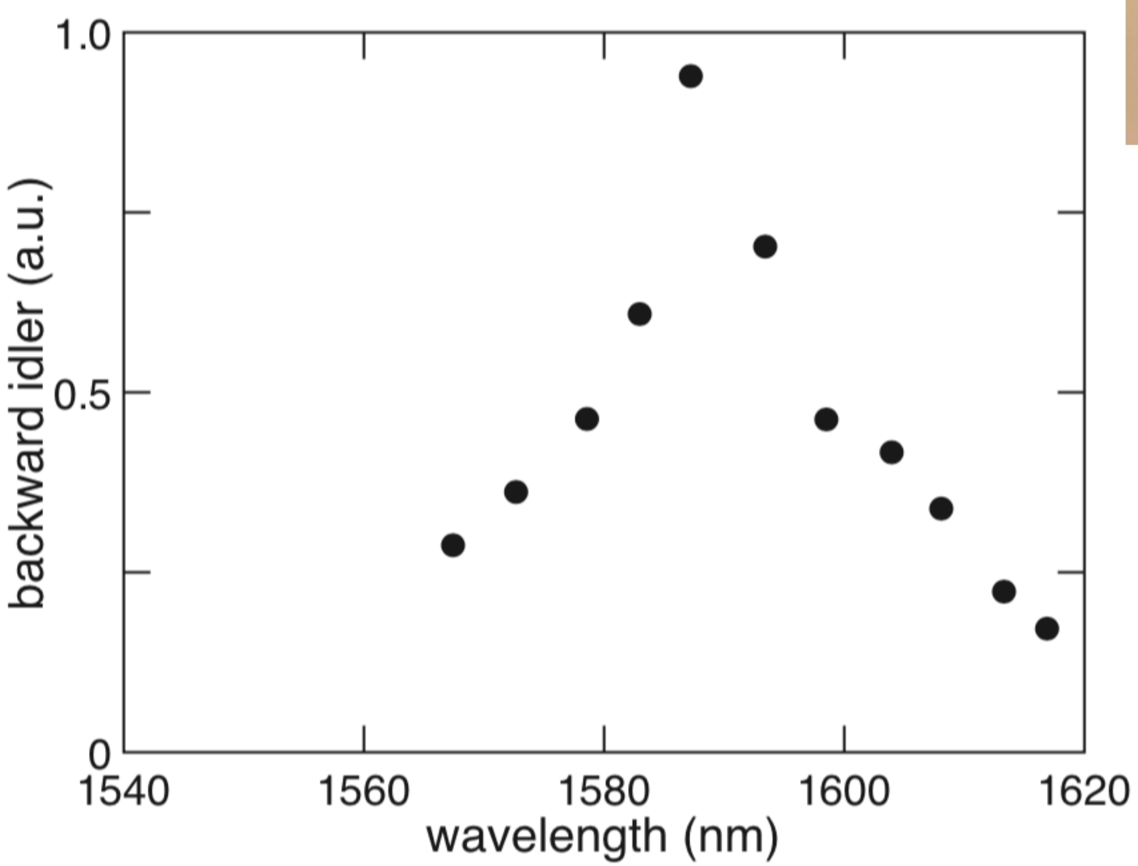
Justin Gagnon
MSc Student

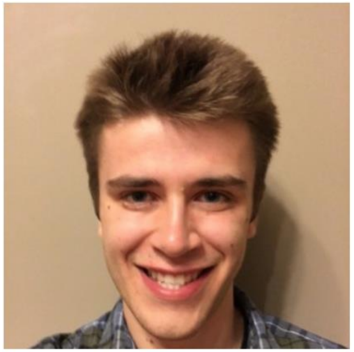
forward and backward





So we measured this in the lab!





Justin Gagnon

MSc Student

1 NLO in structured ITO

2 Zero-index waveguides

Summary

The large nonlinearity of ITO can further be enhanced using nanostructured.

We are even capable of locally defining the nonlinear properties of a surface using nanostructures.

We can also make “ENZ” metamaterials using silicon. These devices also have interesting linear + nonlinear properties:

surface-normal radiation

“directionless” phase-matching

Thank you

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Research in Quantum Photonics

- Boyd Group, University of Ottawa

Boris Braverman, October 30, 2019

Outline

Correlations in high-gain PDC


Samuel Lemieux


Jeremy Rioux


Girish Kulkarni

Rapid generation and detection of spatial modes of light using AOMs


Alexander Skerjanc


Nicholas Sullivan


Xialin Liu

Bourses postdoctorales Banting Postdoctoral Fellowships

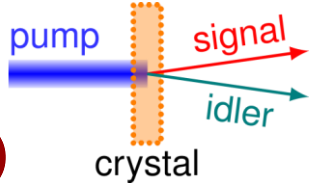
Samuel Lemieux

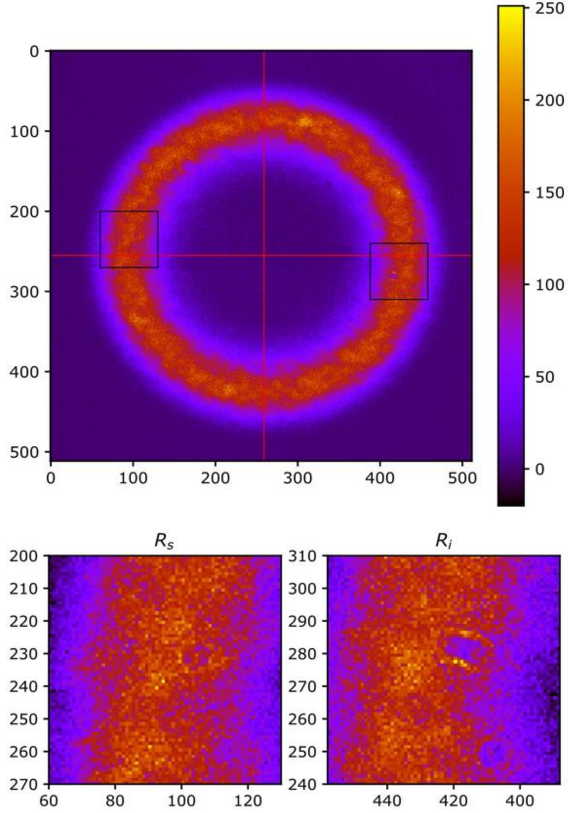
Jeremy Rioux

Girish Kulkarni

Correlations in High-Gain PDC

High-Gain Parametric Down-Conversion (PDC)





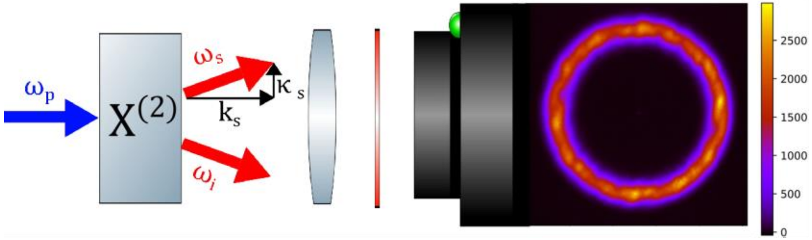
Imaging with squeezed light

Two-mode bright squeezed vacuum state:

$$|TMSV\rangle = \frac{1}{\cosh G}\sum_{n=0}^{\infty}\left(-e^{i\phi}\tanh G\right)^{n}|n_s \otimes n_i\rangle$$

Below shot-noise correlations, quantified by the noise reduction factor (NRF):

$$NRF = \frac{\langle var(N_s - N_i)\rangle}{\langle N_s + N_i\rangle}$$



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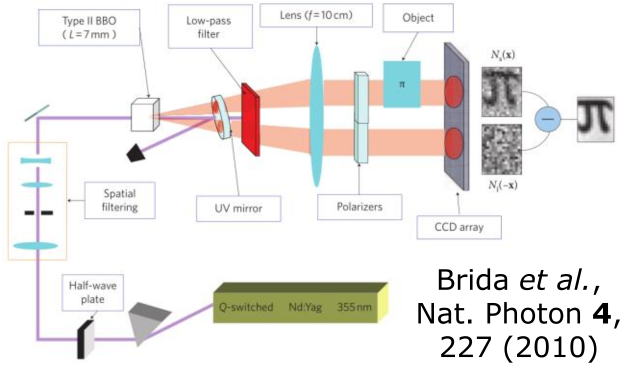
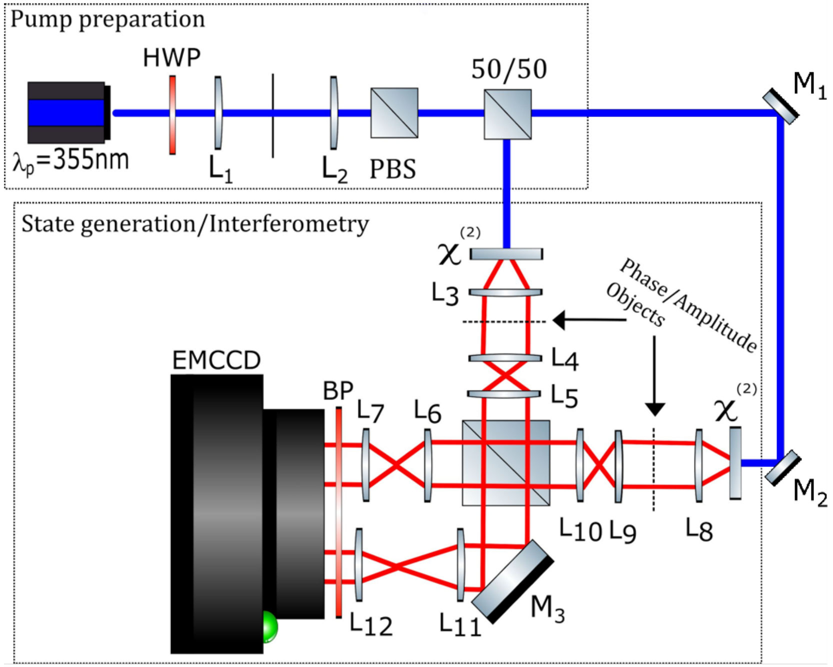
High-Gain PDC

Imaging with squeezed light



Brida *et al.*, Nat. Photon **4**, 227 (2010)



Goal: Implement phase imaging with:

- Supersensitivity (NRF<1)
- Superresolution ($\lambda_{eff} = \lambda_p$)

Correlations in High-Gain PDC

TMSV: NRF should be independent of G

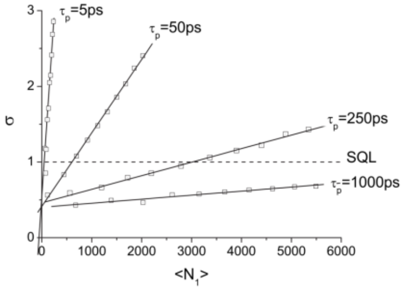
- Larger G should give more signal!

Experimental observation: NRF usually increases near-linearly with G

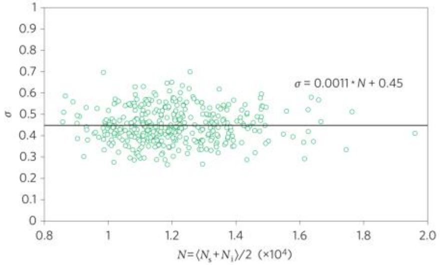
- Technical imperfections or intrinsic effect?

How can we benefit from using higher G for quantum-enhanced sensing?

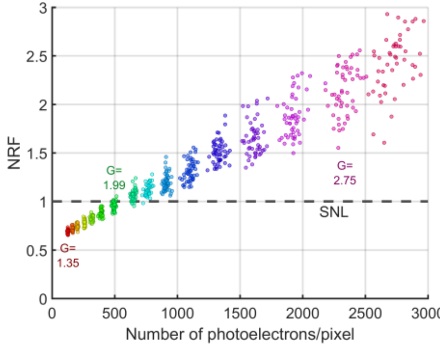
- Better alignment?
- Structuring the pump beam?
- Using higher-order correlations?



Brambilla *et al.*, PRA **77**, 053807 (2008)



Brida *et al.*, Nat. Photon **4**, 227 (2010)



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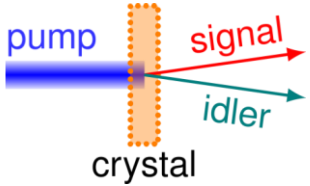
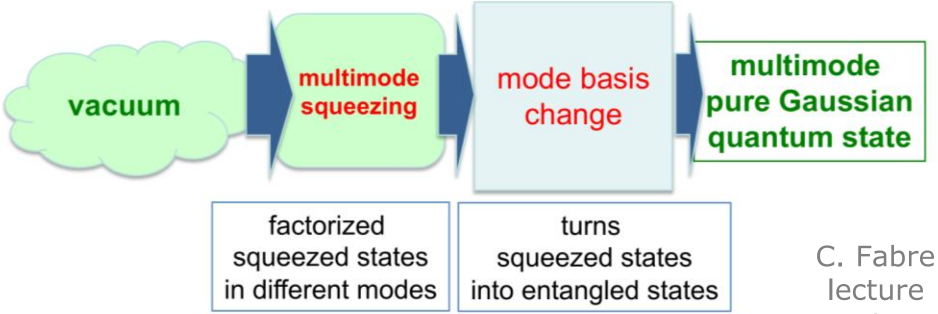
Quantum State of High-Gain PDC



What is the full state coming out of the high-gain PDC process?

- Quadratic interaction Hamiltonian:
  $H = \int dk_i dk_s c_{i,s}(\alpha_p a_s^\dagger a_i^\dagger + H.C.)$
- No loss or decoherence → output is a pure, Gaussian state
- Bloch-Messiah decomposition can be used to represent state

$$|\Psi\rangle = U_{mode\,basis\,change} U_{diag,sq}|0\rangle$$



C. Fabre lecture notes

- How many modes need to be mixed together in the mode basis change?
  - TMSV: only 2
- How strong are the higher-order correlations? How can they be controlled/used?

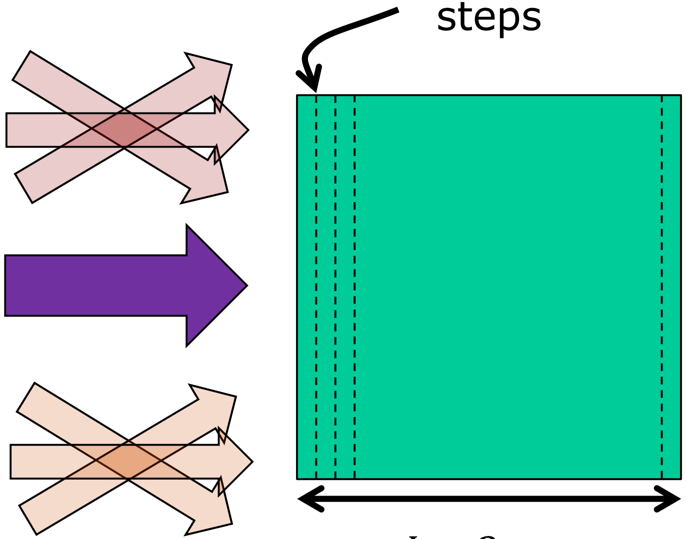
High-Gain PDC Model

Signal modes
$\lambda_s = 800\ \mathrm{nm}$

Pump
$\lambda_p = 355\ \mathrm{nm}$
30 ps pulse length
0.25 mm waist

Idler modes
$\lambda_i = 638\ \mathrm{nm}$

0.1 mm propagation steps



$L = 3\ \mathrm{mm}$
BBO crystal

Assume perfect phase matching for collinear modes ($q_s = q_i = 0$)

Derive Bogolyubov transformation for output modes in terms of input modes:

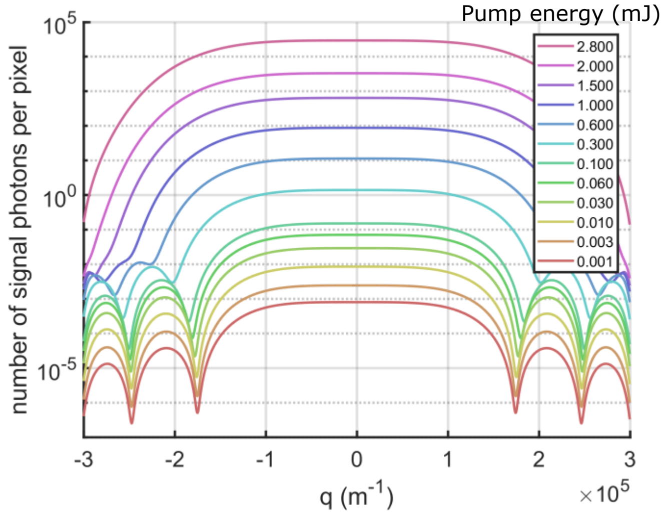
$$a_s(q_j, L) = \\ = \sum c_{i,j} a_s(q_i, 0) + d_{i,j} a_i^\dagger(q_i, 0)$$

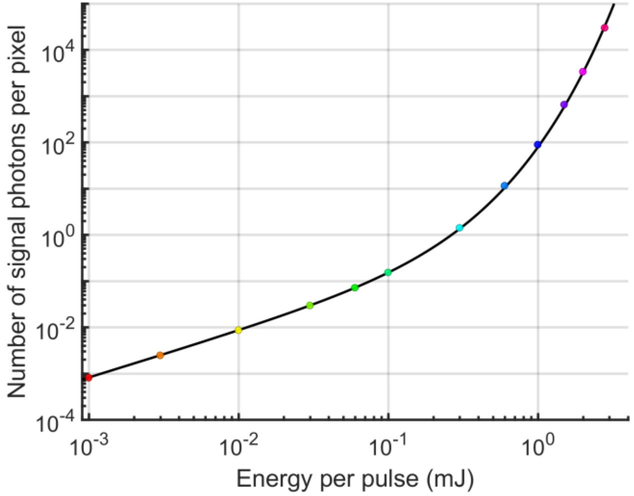
Calculate expectation values for photon numbers, correlations

High-Gain PDC Model – Single-mode properties

Photon number grows as $\langle n_s \rangle \propto \sinh^2(E_p)$

Angular spectrum of phase matching broadens with gain





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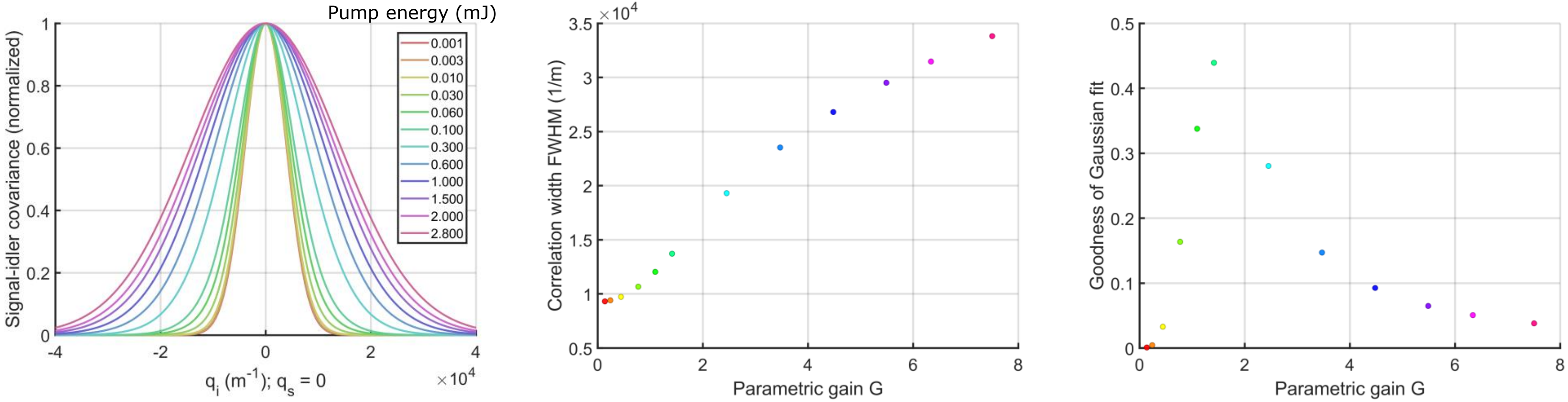
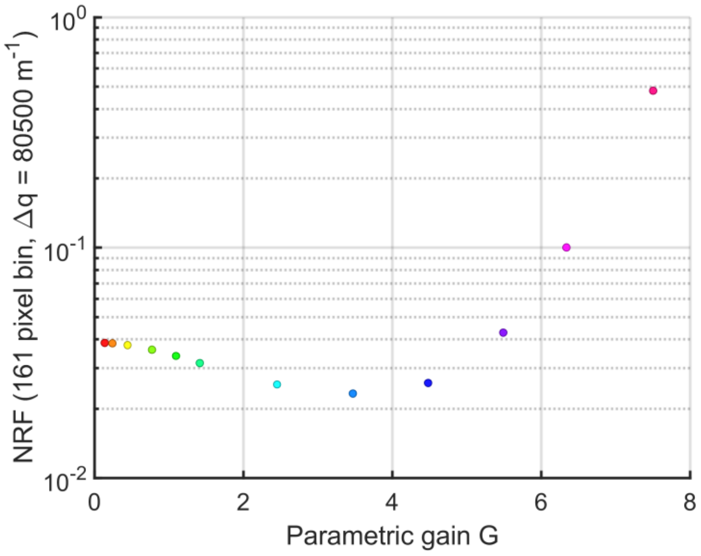
High-Gain PDC Model – Signal-Idler Correlations

Correlation width grows with gain

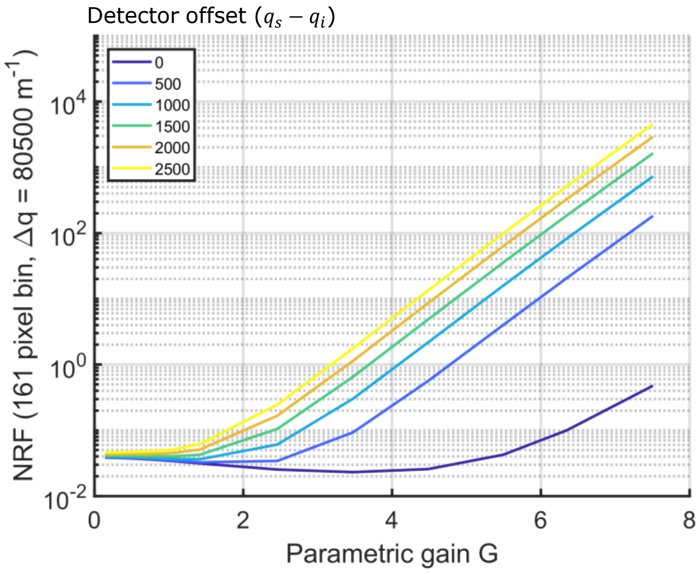
"Speckle shape" is maximally non-Gaussian at $G \approx 1.5$



High-Gain PDC Model – NRF



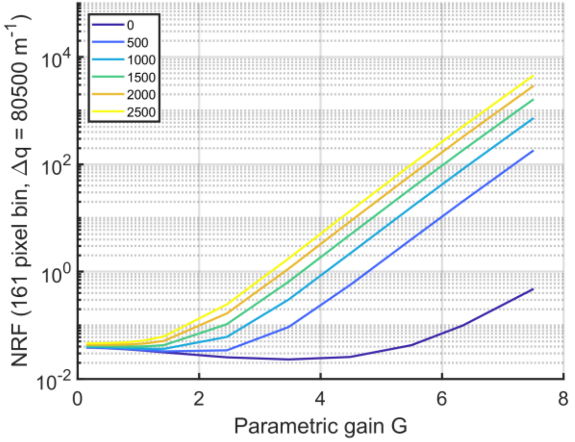
Signal, idler detectors perfectly aligned



High-Gain PDC Model – Next Steps

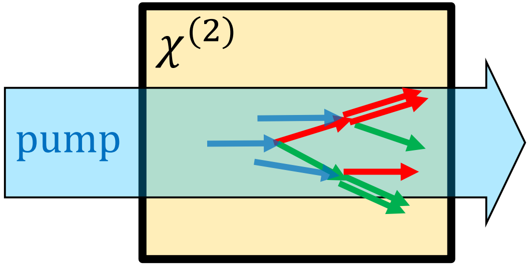
Observing below-SQL correlations at large G requires increasingly precise alignment

- What is the largest SNR attainable with a realistic experiment?



Look for higher-order correlations

- Bogolyubov → Bloch-Messiah
- Consider simplified model with fewer modes



Extend model to 2 spatial dimensions

Alexander Skerjanc

Nicholas Sullivan

Xialin Liu

Rapid Generation and Detection of Spatial Modes of Light Using AOMs

Acousto-Optic Modulators (AOMs)

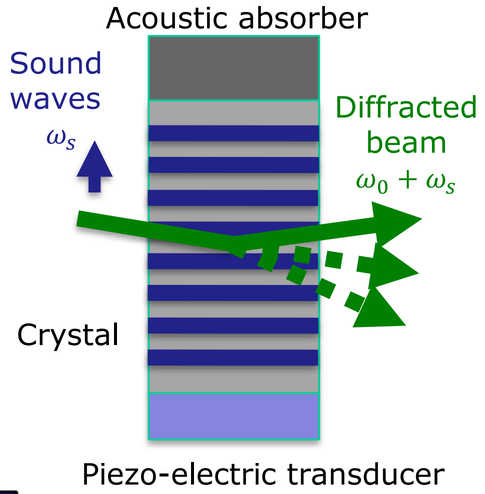
Sound waves induce density variations, which diffract the light

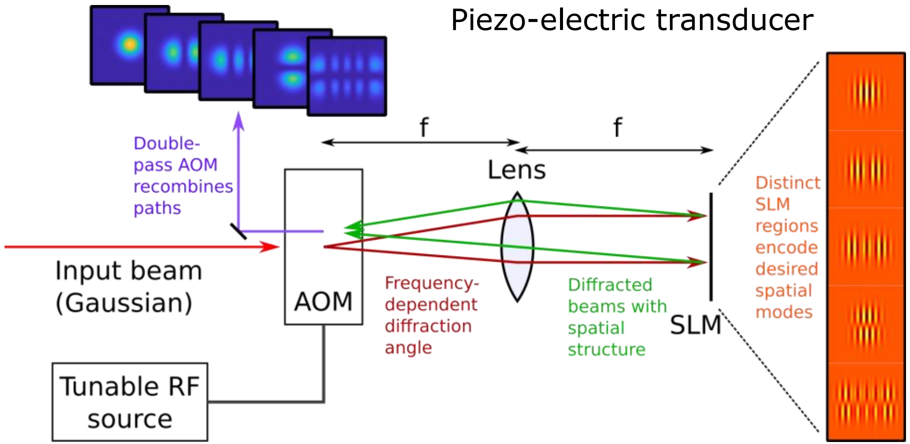
- Acts as a rapidly steerable mirror

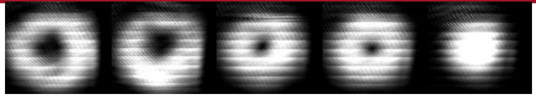
High-dimensional free-space QKD

- Require fast generation of different modes of light
- Speed limited by SLM refresh rates

Use an AOM to select one of a set of fixed holograms





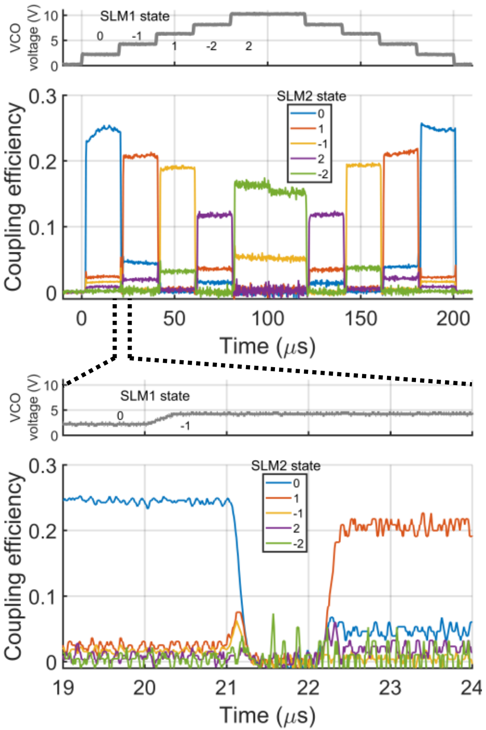


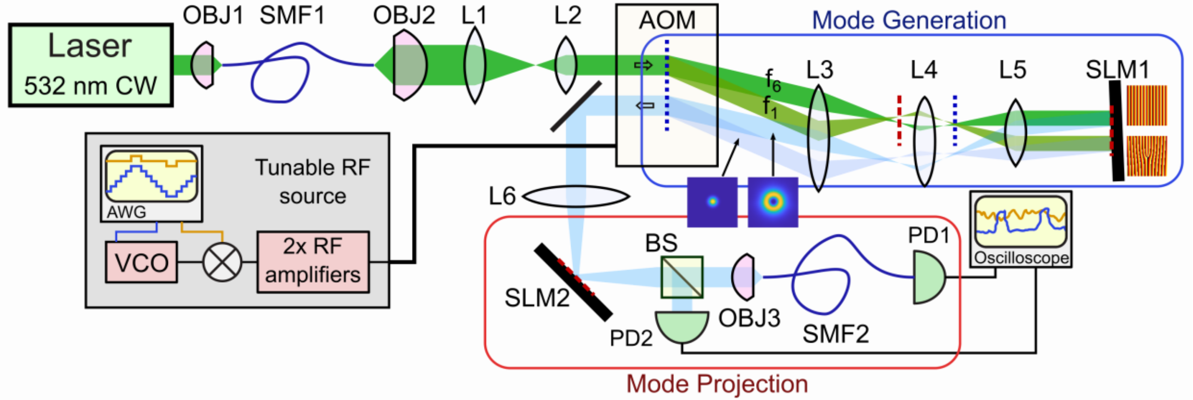
Rapid Generation of Modes

Switch between one of five sections of SLM1, each encoding a different OAM mode

Analyze state with SLM2

Refresh rates up to 500 kHz





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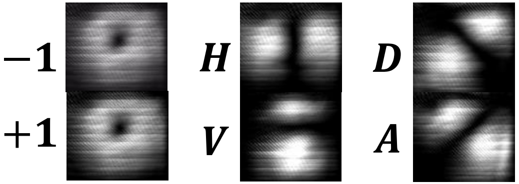
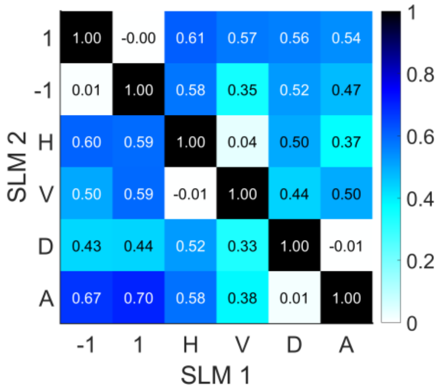
Real-Time Quantum State Tomography



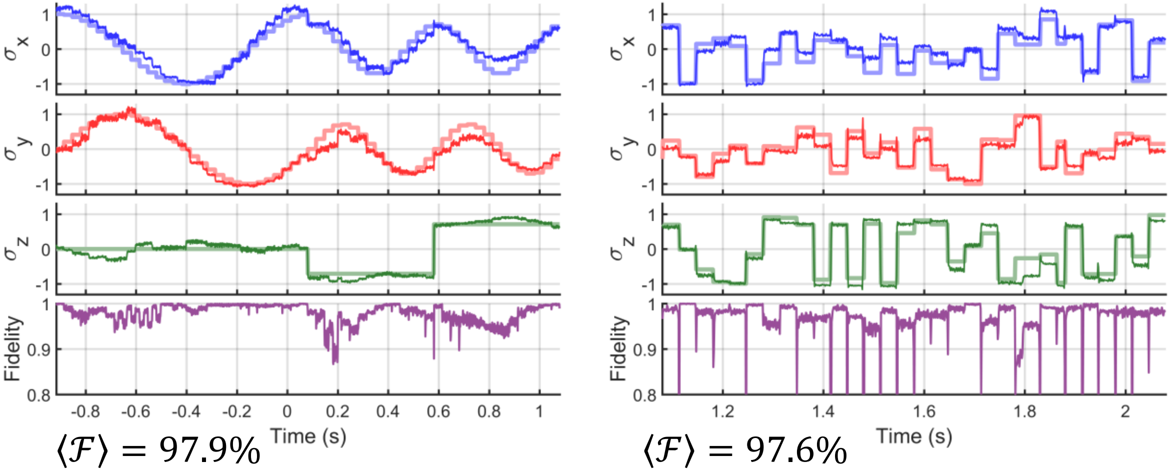


Mode generation ~ mode projection

- Hilbert space spanned by OAM $+1$, -1
- Need to perform one of 6 measurements

Each setting is measured for $100\ \mu\mathrm{s}$

- Overall measurement bandwidth is $\approx 1\ \mathrm{kHz}$



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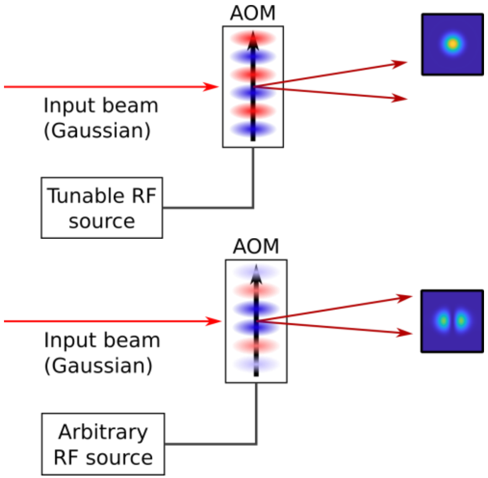
AOM as a Spatial Light Modulator

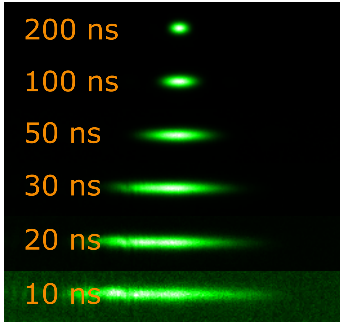


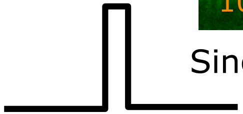
What if the sound wave is not just a single frequency?

- Can generate multiple values of q simultaneously!
- Because pattern is dynamic (frequency shift), need to use a pulsed laser

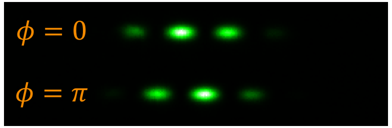
Potential applications to shaping modes of very intense lasers that would damage SLMs, i.e. for structured-beam high-gain PDC

- Spatial analogue to an acousto-optic programmable dispersive filter

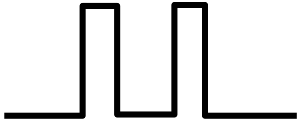




Single-slit diffraction



Double-slit interference



Quantum Photonics Research Themes

PDC in unconventional parameter regimes and systems:

- **Very strong (high gain) pumping**
- Very weak (single-photon) pumping
- Effect of incoherent pumping on entanglement

Applications to quantum metrology

- Absolute photon number measurement
- **Superresolution and supersensitivity**
- Trans-color measurement

Control of light propagation

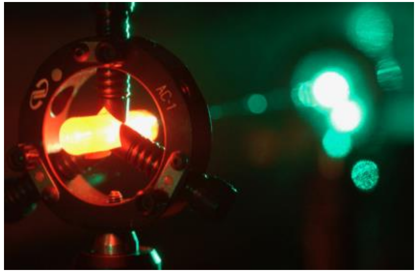
- Mode sorting in waveguides
- **AOMs for mode control**
- Slow light in moving media

Applications to adaptive optics

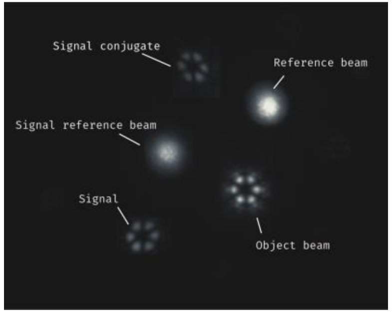
- Nonlocal aberration cancelation with entangled photons
- Mode cleaning in nonlinear fibers
- Digital phase conjugation with vector beams

Summary

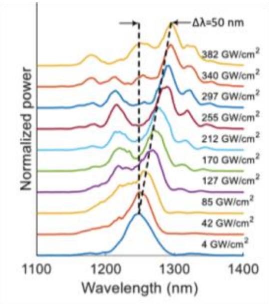
Light drag effects in slow-light media



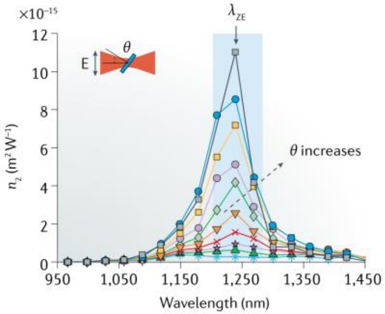
Real-time holography with ENZ nonlinearity



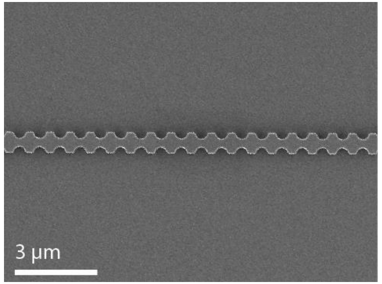
Time refraction in ENZ



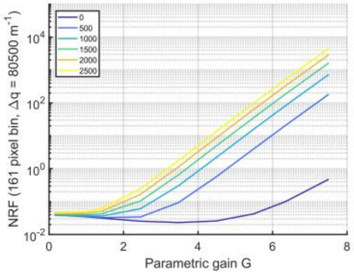
ENZ materials augmented with nanostructures



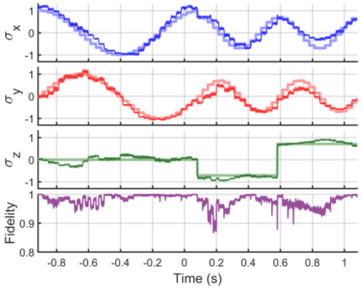
Zero-index metamaterials



Correlations in high-gain PDC



Spatial mode control with AOMs



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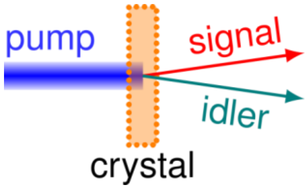
Appendix

High-Gain PDC



$$\hat{H} \sim \mathcal{E}_p \chi^{(2)} \boxed{\hat{E}_s^\dagger \hat{E}_i^\dagger} + \text{h.c.}$$

$$\hat{E}_j \sim \sqrt{\frac{\omega_j}{n_j}}$$

Vacuum amplitude

Primary Radiation Standard based on Quantum Nonlinear Optics

- Calibration of photon number, based on simple and fundamental properties of PDC

Photon number $\mathcal{N}$ depends on:

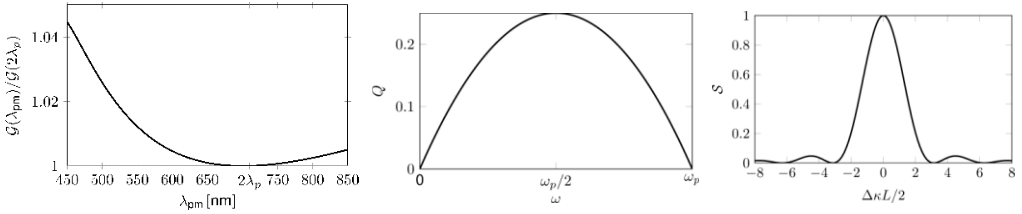
Gain function $\mathcal{G}$

- Pump amplitude $\mathcal{E}_p$
- Crystal length L

Vacuum amplitude Q

Phase matching function $\mathcal{S}$

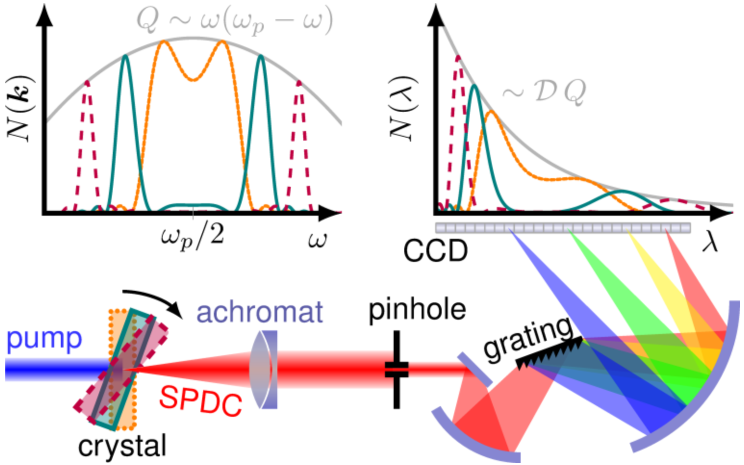
$$\mathcal{N}(\vec{k}_s) \sim \underbrace{\left(\frac{\mathcal{E}_p \chi^{(2)} L}{\sqrt{n_s n_i}}\right)^2}_{\mathcal{G}(\lambda_s)} \underbrace{\omega_s \omega_i}_{Q(\lambda_s)} \underbrace{\operatorname{sinc}^2 \frac{\Delta\kappa L}{2}}_{\mathcal{S}(\lambda_s)}$$



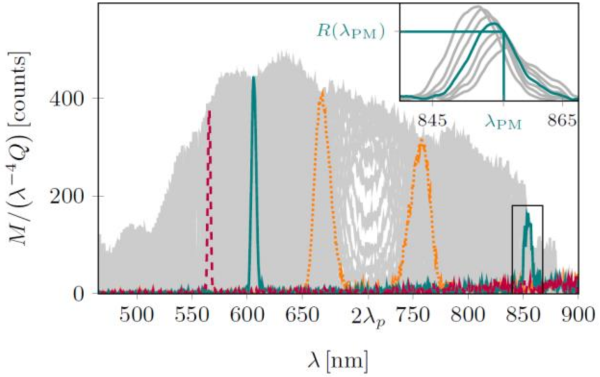
S. Lemieux, E. Giese, R. Fickler, M.V. Chekhova, R.W. Boyd, Nat. Phys., **15**, 529 (2019)

High-Gain PDC

Primary Radiation Standard based on Quantum Nonlinear Optics

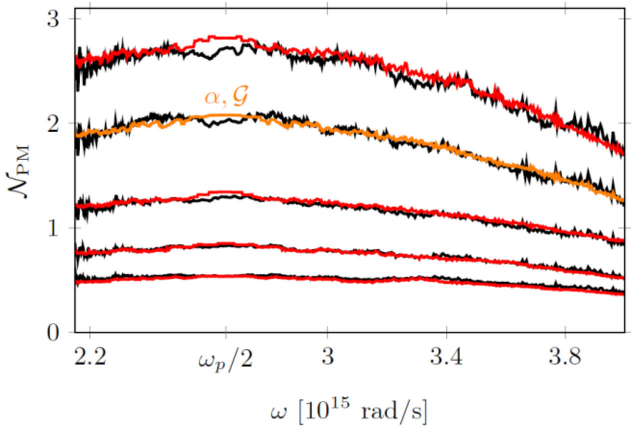


Relative calibration at **low gain**: single photon pairs with well-known spectral shape



Absolute calibration at **high gain**: exponential increase in photon number

$$\mathcal{N}(\vec{k})_{\mathrm{PM}} = \sinh^2\sqrt{\mathcal{G}Q}$$



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S. Lemieux, E. Giese, R. Fickler, M.V. Chekhova, R.W. Boyd, Nat. Phys., **15**, 529 (2019)

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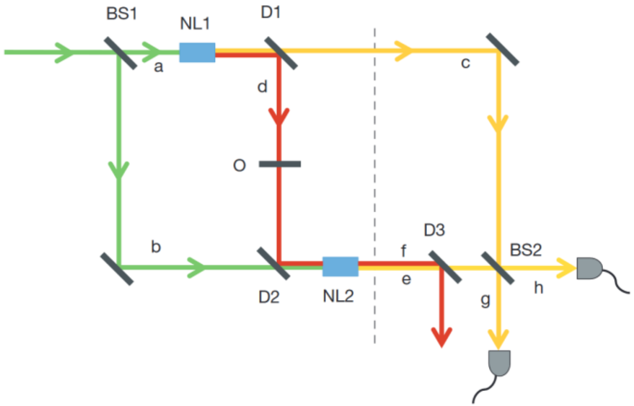
Induced Coherence Without Induced Emission

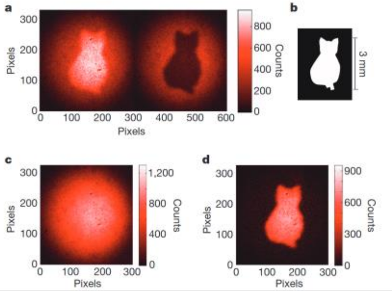
Previous experiments: CW laser pump, observe single photons

- Imaging with undetected photons
- Transcolor sensing

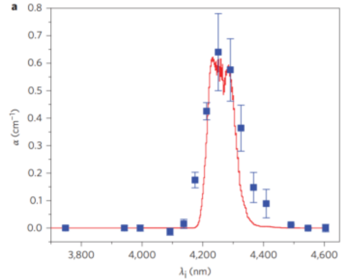
Extensions:

- Coherence *with* induced emission: strong-pumping regime
- Highly non-degenerate regime: THz spectroscopy
- Guaranteeing absence of induced emission: single-photon pump



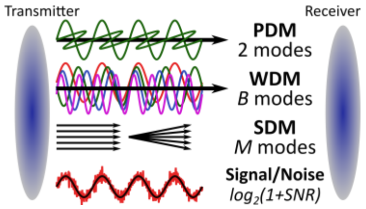


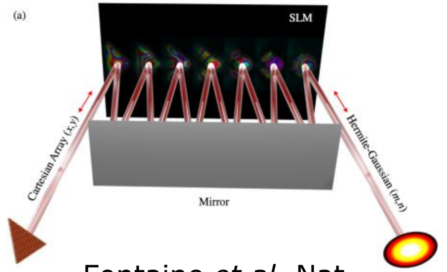
Lemos *et al.*, Nature **512**, 409 (2014)



Kalashnikov *et al.*, Nat. Photon. **10**, 98 (2016)

Free-Space Mode Sorting Using Waveguides





Fontaine *et al*. Nat. Comms., **10**, 1865 (2019)

Free-space communication with "interesting" basis states: OAM, LG, HG, …

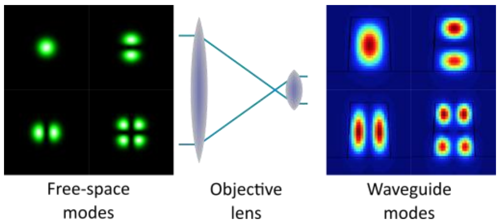
- propagation invariant, high information density

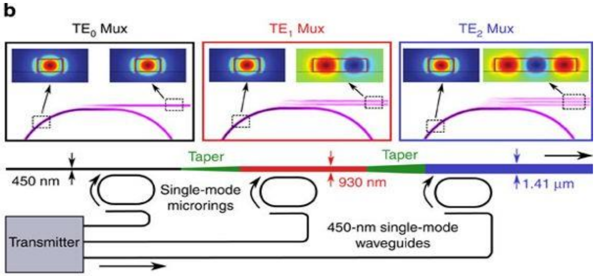
Problem: how to efficiently generate and detect?

- State of the art with free-space optics: q-plates and SLMs

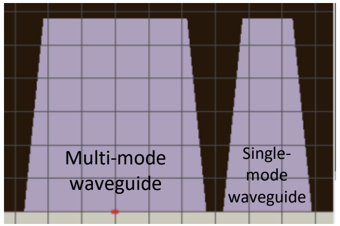
Eigenmodes of rectangular waveguides ≈ HG modes

- Use integrated optics techniques to manipulate on-chip

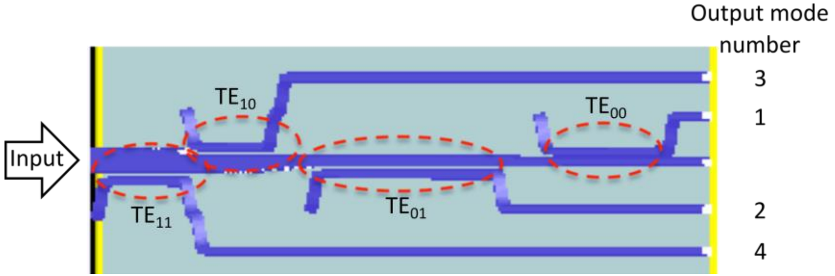




Luo *et al.* Nat. Comms., **5**, 3069 (2014)

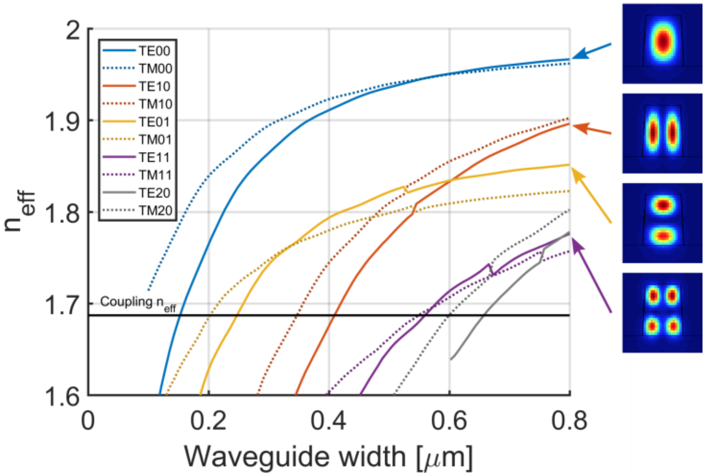


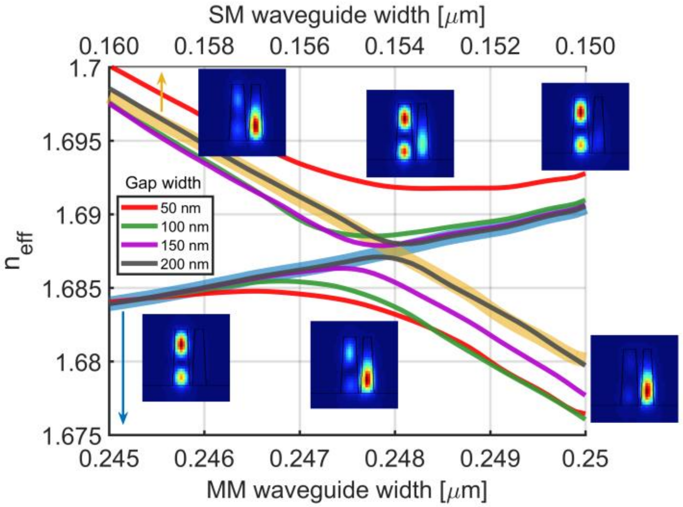
Free-Space Mode Sorting Using Waveguides



Strategy:

- Remove higher-order modes one by one
- Taper multimode waveguide to match sequential modes to a series of single-mode waveguides





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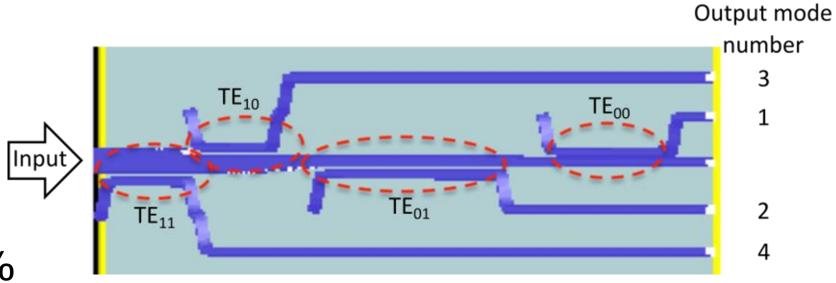
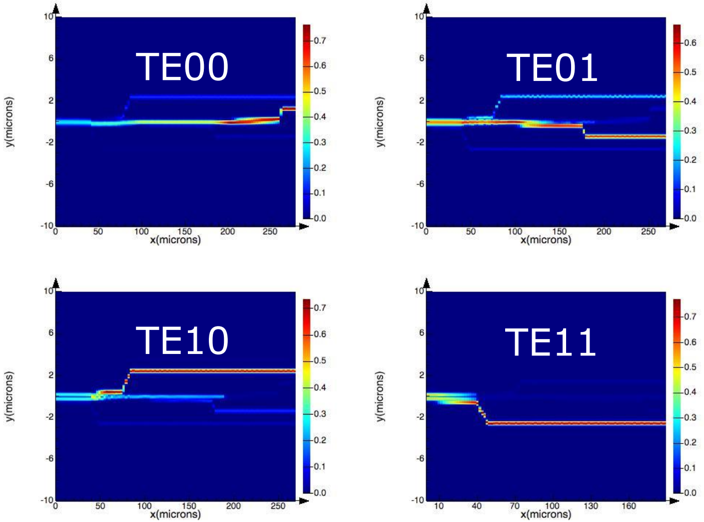
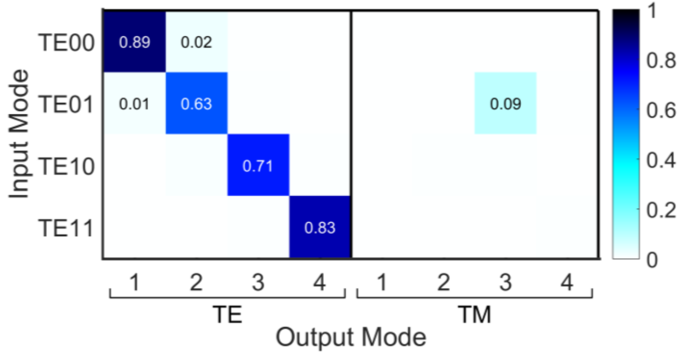
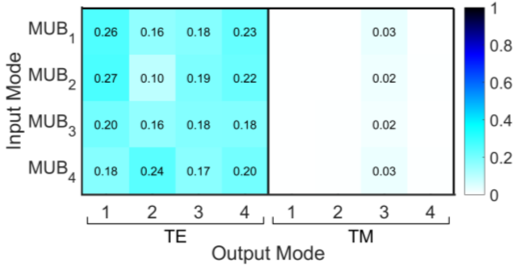
Free-Space Mode Sorting Using Waveguides

Result: 76.3% average sorting efficiency, 1.4% average cross-talk









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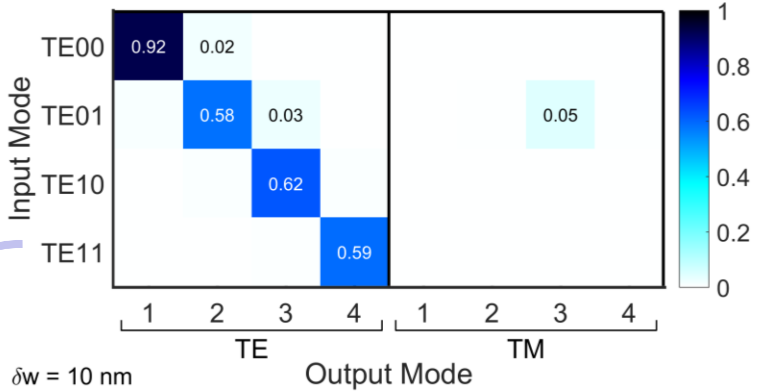
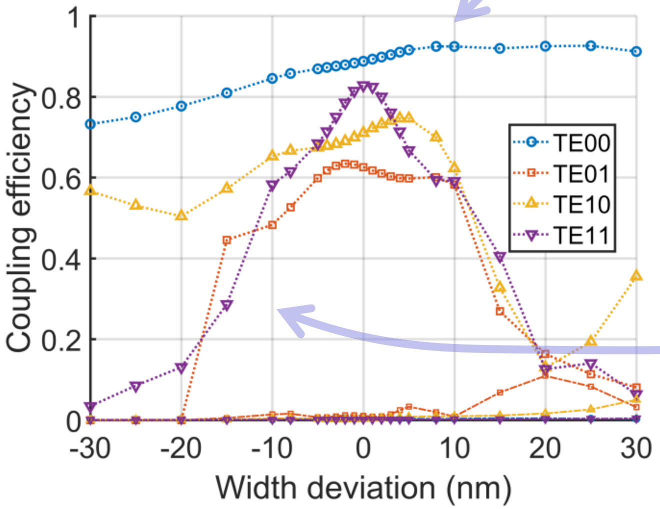
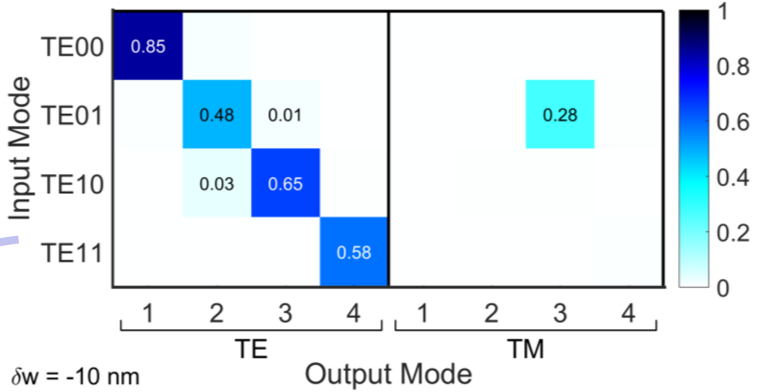
Fabrication Tolerance

How robust is the design to manufacturing imperfections?



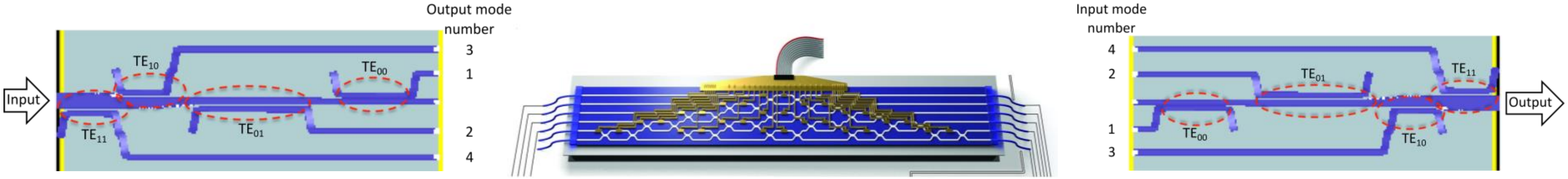




± 10 nm variation is acceptable

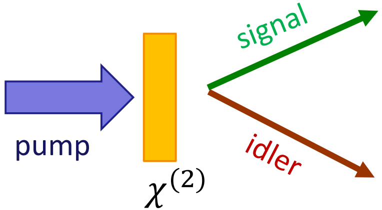
Arbitrary Mode Transformations

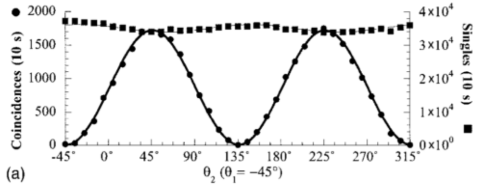
- Modes are de-multiplexed into single-mode waveguides with our device
- On-chip interferometer arrays enable arbitrary operations with fast update rates
  - Thermal tuning: 100's of MHz
  - Electro-optic tuning: 10's of GHz
- Modes are multiplexed with a second mode sorter



Carolan *et al.*, Science, **349**, 711 (2015)

Entangled Photons





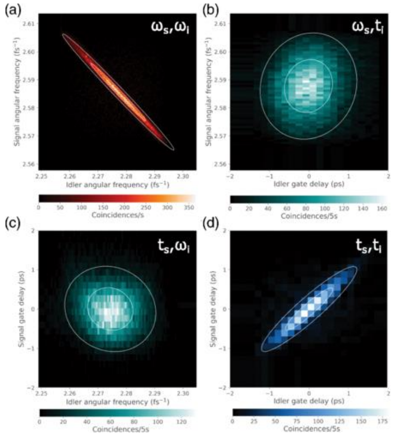
Kwiat *et al.* PRA **60** R773 (1999)

Correlations can exist (often simultaneously) in any degree of freedom:

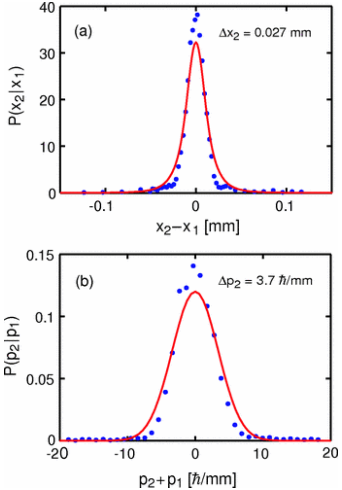
- Polarization (spin)
- Time & energy (spectral)
- Position & momentum (spatial)

If generated by SPDC with laser pump, produce a pure state

- Perfect correlations!



MacLean *et al.* PRL **120** 053601 (2018)



Howell *et al.* PRL **92** 210403 (2004)

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Dispersion Cancellation

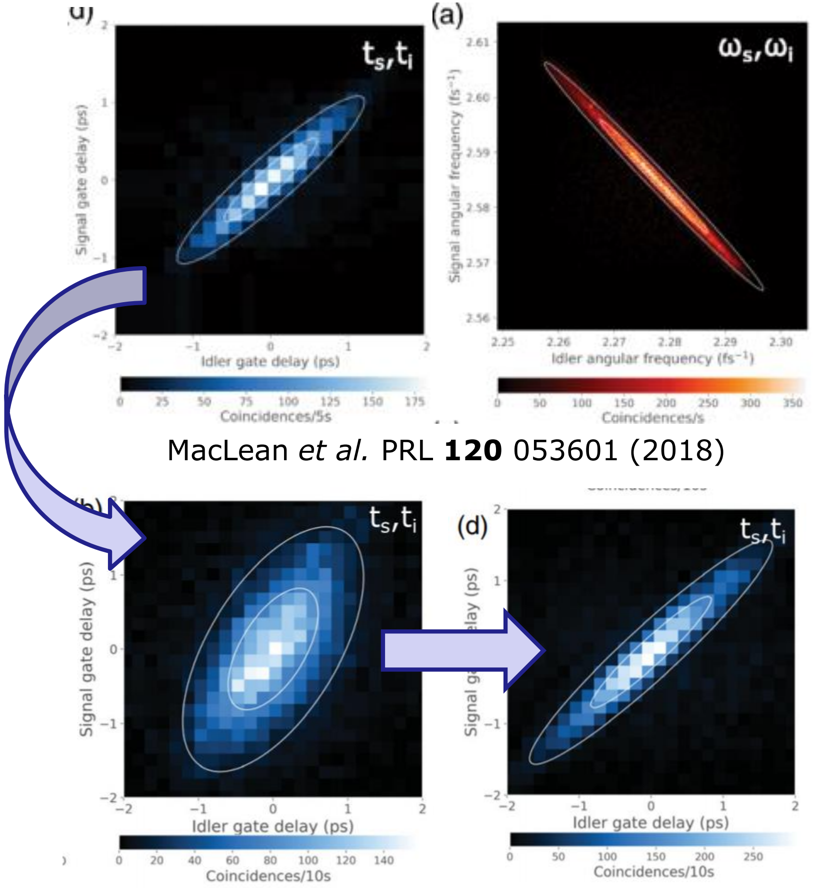
Start out with perfectly correlated photons (EPR state):

$$t_s = t_i, \qquad \omega_s = \omega_p - \omega_i$$

- Frequency dispersion in signal photon lengthens its pulse and weakens time correlations

Perfect correlations can be recovered!

- Proposal for nonlocal scheme: Franson, PRA **45** 3126 (1992)
- Experimental realization: MacLean *et al.* PRL **120** 053601 (2018)



MacLean *et al.* PRL **120** 053601 (2018)

Birefringence Cancellation

Polarization entanglement (spin singlet):

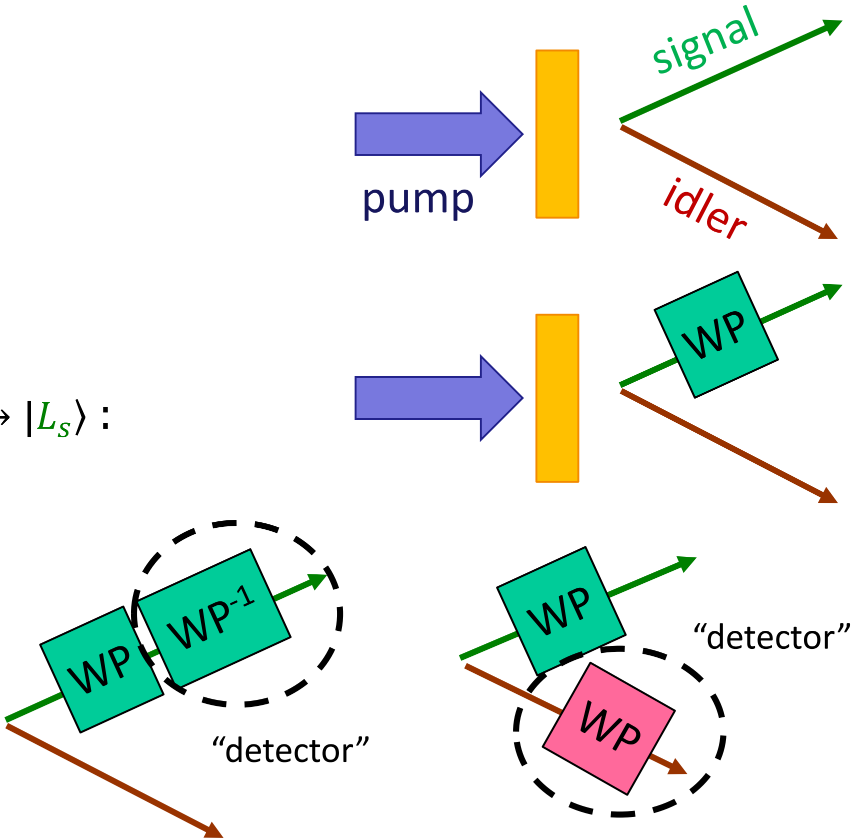
$$|\psi\rangle = \frac{|H_s V_i\rangle - |V_s H_i\rangle}{\sqrt{2}}$$

Perturb signal photon, i.e. $|H_s\rangle \to |R_s\rangle$, $|V_s\rangle \to |L_s\rangle$:

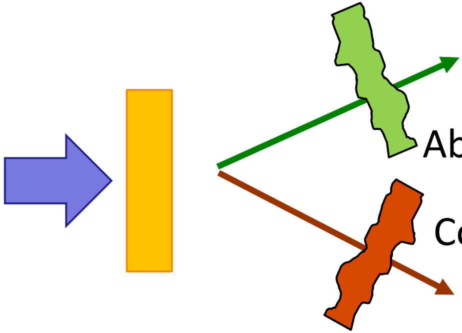
$$|\psi'\rangle = \frac{|R_s V_i\rangle - |L_s H_i\rangle}{\sqrt{2}}$$

Original state can be recovered:

- Locally: $|R_s\rangle \to |H_s\rangle$
- Non-locally: $|H_i\rangle \to |R_i\rangle$
- Both are a change of measurement basis



Aberration Cancellation



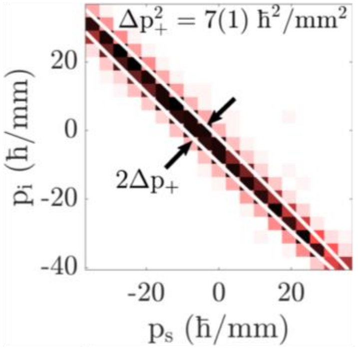
Conceptually, the same as dispersion cancellation:

$$t \to X, \qquad \omega \to P$$

In practice, more challenging to align, but…

- Can select functional form & variable for aberration
  - Frequency dispersion fixed by material parameters
  - 2^{nd} order frequency dispersion (GVD) typically dominates
  - Hard to implement temporal dispersion (a fast chirp!)
- Can be applied to imaging
  - Rather than spectroscopy/photon timing experiments

Aberration Cancellation



Initial entangled state:

$$\psi(p_s, p_i) = A(p_s - p_i) \times v(p_s + p_i) \times e^{i(\phi_s(p_s)+\phi_i(p_i))}$$

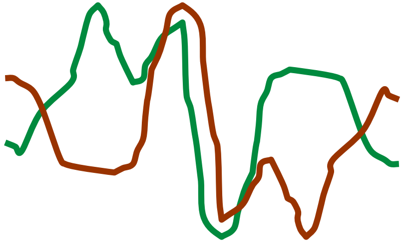
- Phase matching: $A(p_s - p_i) = A_0 \mathrm{sinc}\left(\frac{l_c|p_-|^2}{4k_0}\right) \times \exp\left(-i\frac{l_c|p_-|^2}{4k_0}\right)$
- Pump angular spectrum: $v(p_s + p_i) = \exp\left(-\frac{|p_+|^2 w^2}{4}\right)$
- Aberration (and compensation): $e^{i(\phi_s(p_s)+\phi_i(p_i))}$

Plane wave pump:

$$v(p_s + p_i) = \delta(p_s + p_i) \ \rightarrow p_s = -p_i$$

To recover the initial state, simply require

$$\phi_s(p) = -\phi_i(-p)$$



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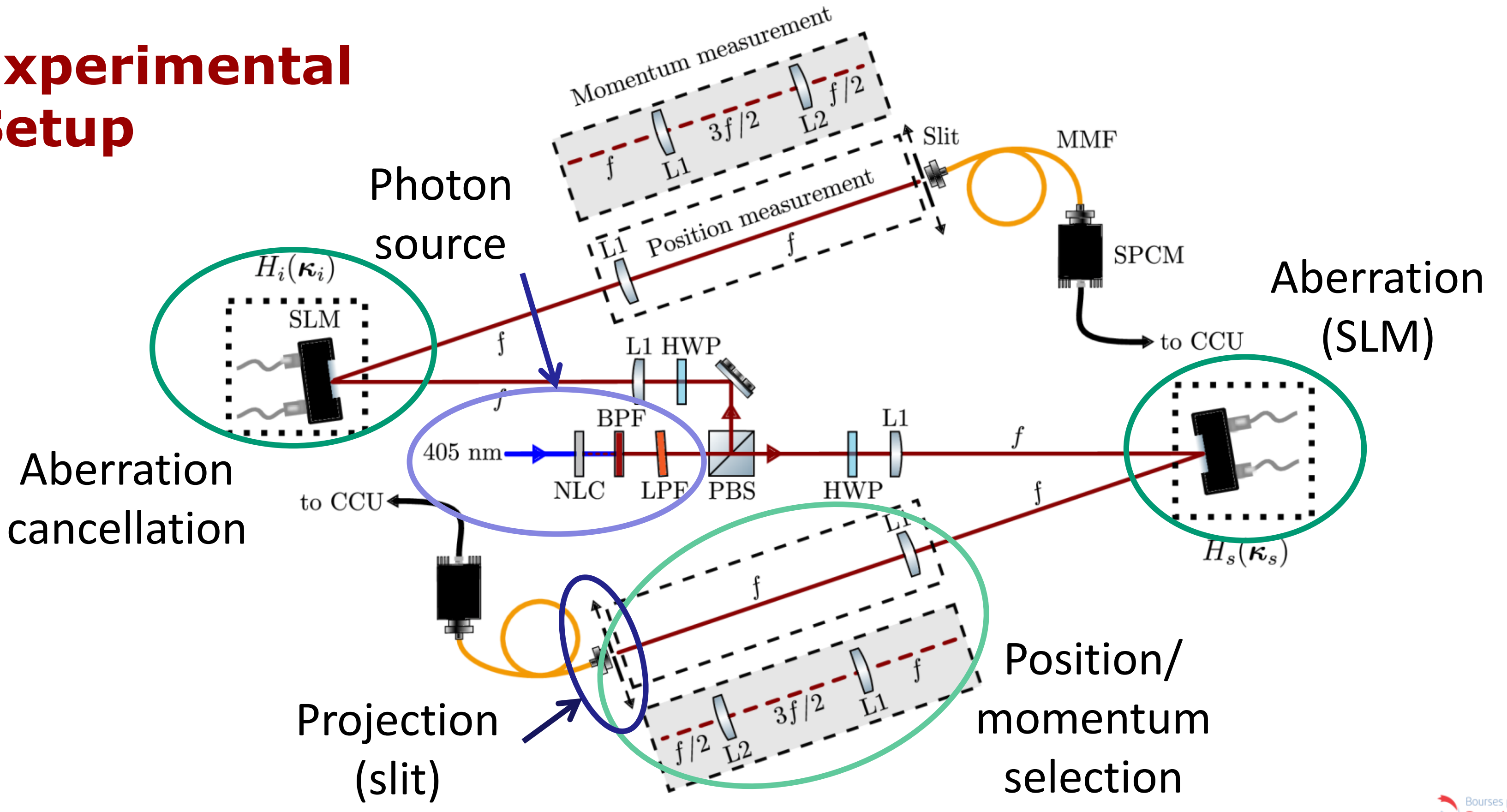
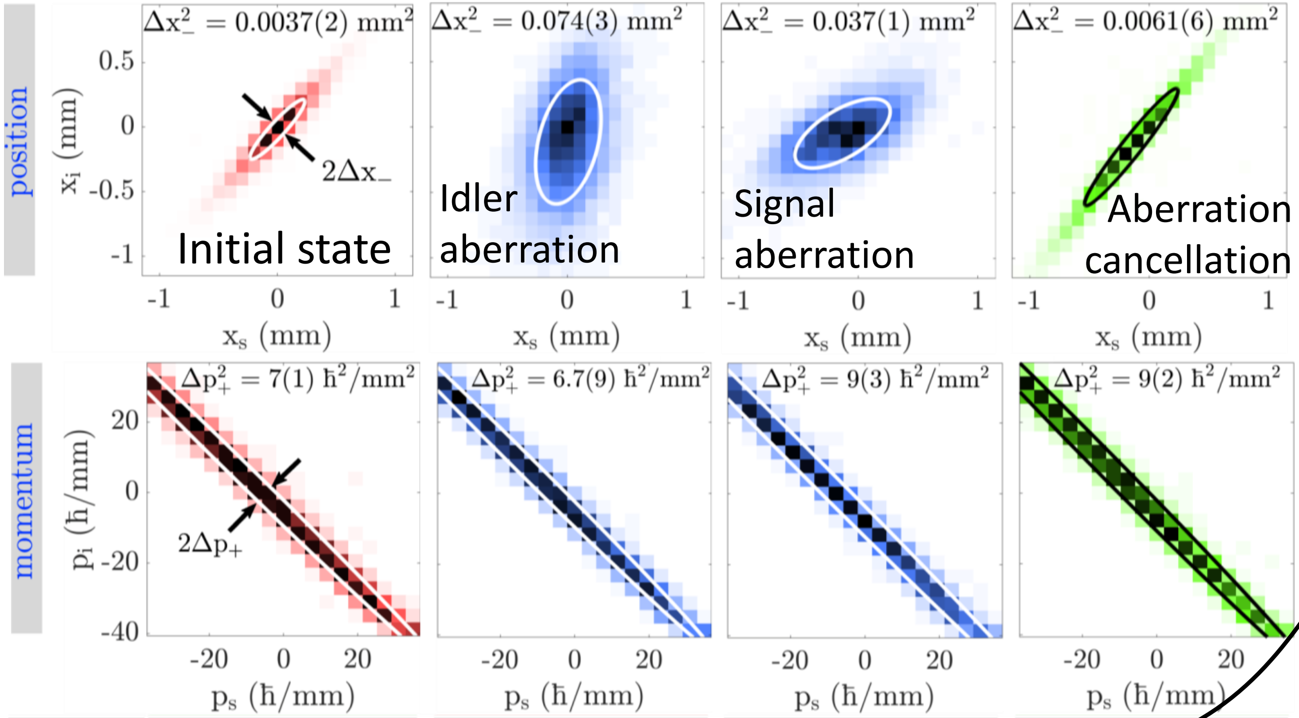
Experimental Setup



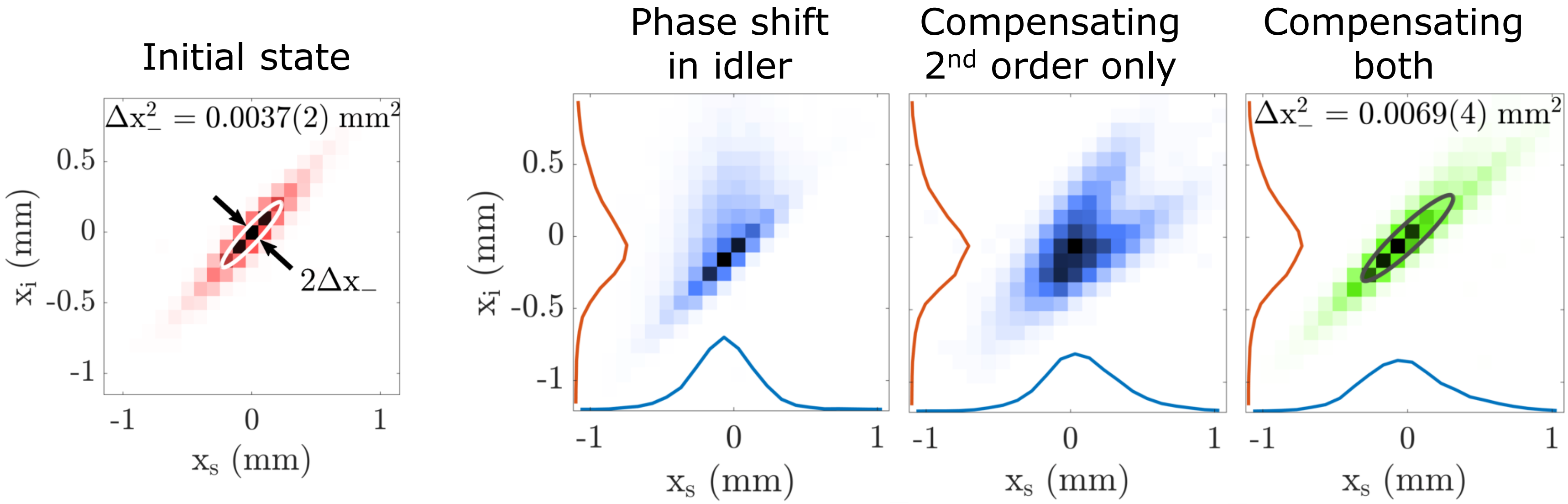
Experimental Results: 2nd Order



$\Delta x_-^2 \Delta p_+^2$	0.026(4) ħ^2	0.50(7) ħ^2	0.3(1) ħ^2	0.05(1) ħ^2

Entanglement not witnessed (need $\Delta x_-^2 \Delta p_+^2 < 0.25$)

Experimental Results: 2nd+3rd Orders



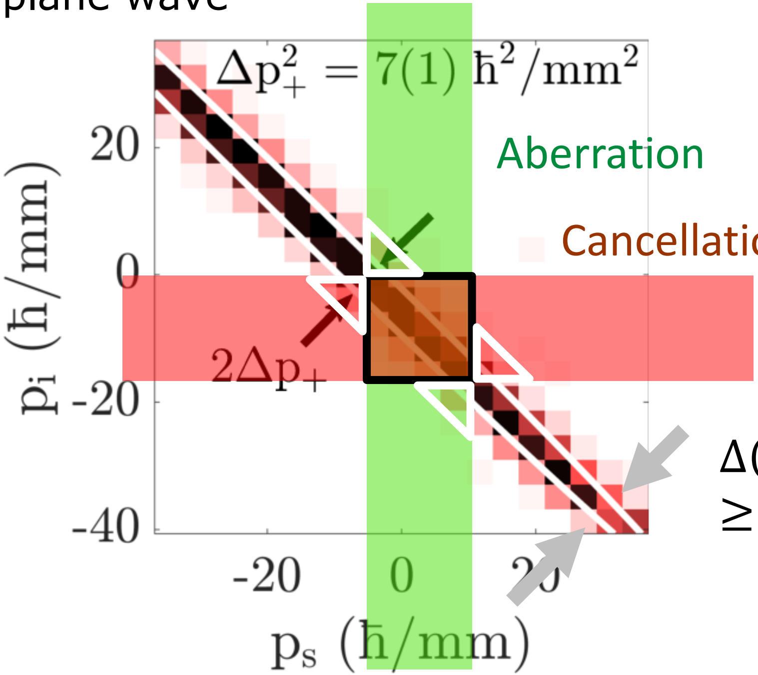
Momentum correlations (not shown) are unaffected, as expected

Higher-order aberrations produce interesting, non-Gaussian two-photon wavefunctions

Impact of Pump Beam Profile

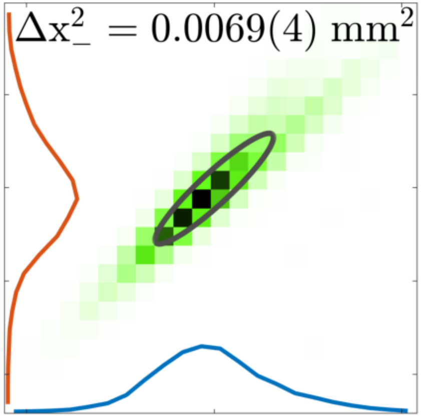
Perfect aberration cancelation can only be observed when the pump is a plane wave

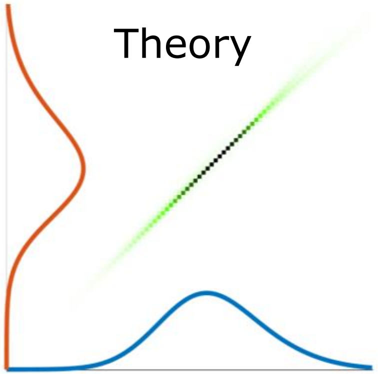
Two-photon momentum wavefunction:



$\Delta(p_s + p_i) \geq \Delta(p_p)$

Position correlations:





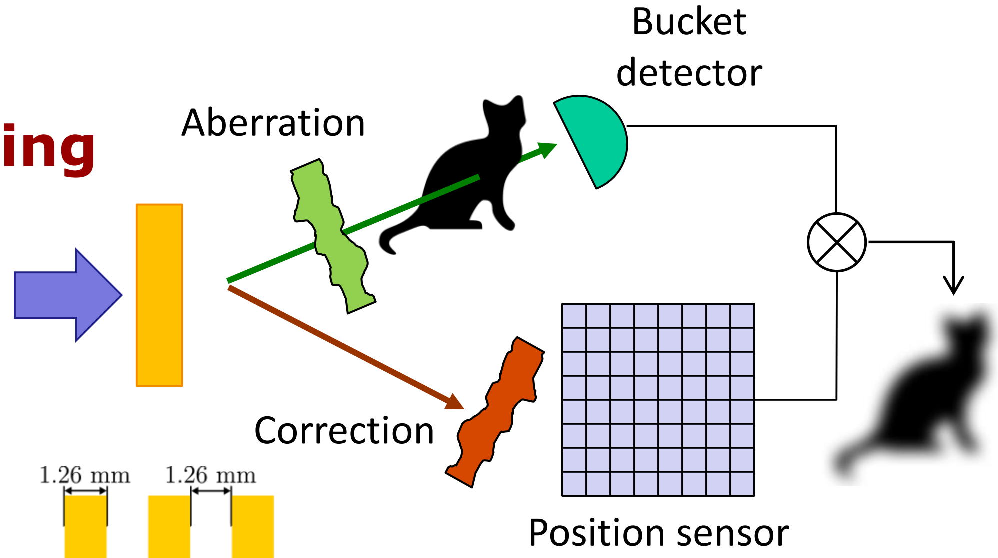
Application: Ghost Imaging

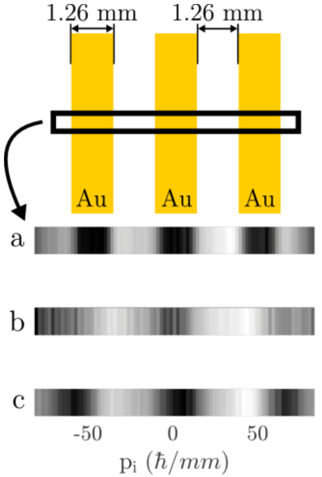
Can correct for signal noise by acting on idler photon

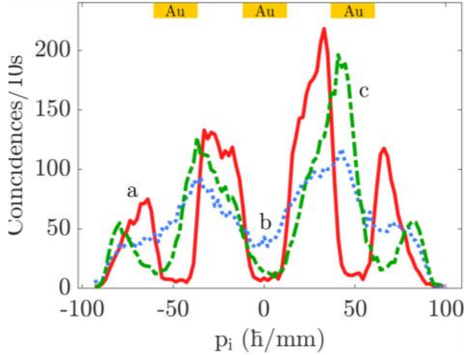
No need for adaptive optics at signal wavelength or near bucket detector

Where does entanglement come in?

- Can compensate for aberrations in any plane (even a 3D distribution)
- "image" vs "hologram"

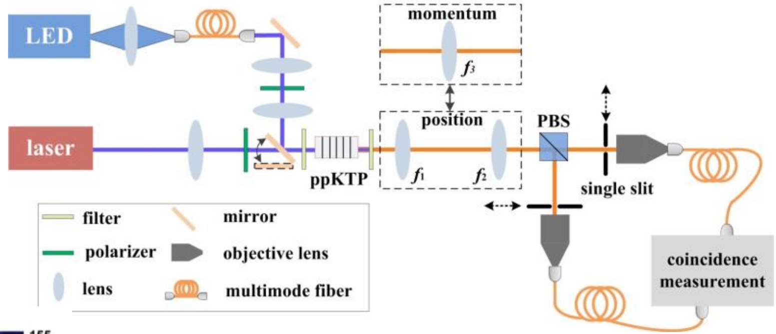




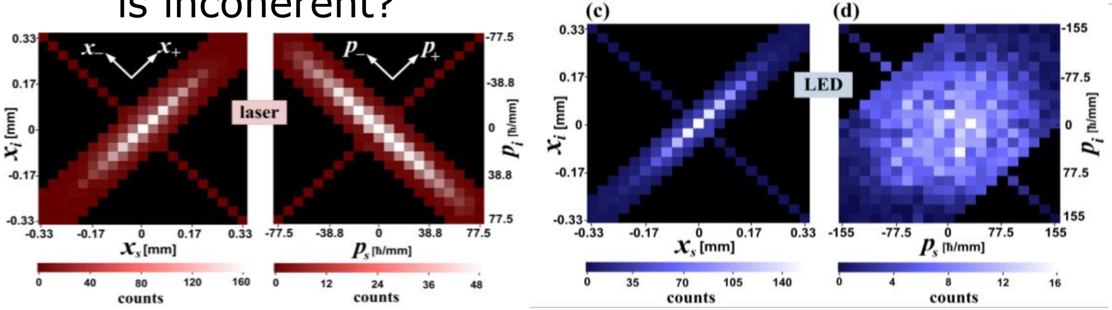


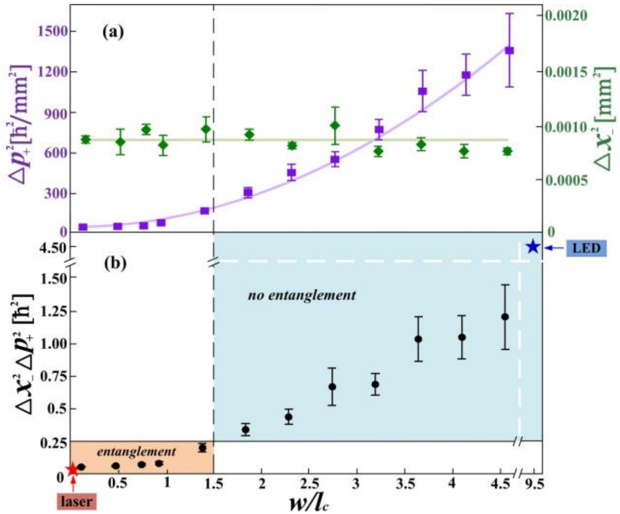
boydnlo.ca A. N. Black, E. Giese, B. Braverman, N. Zollo, S. M. Barnett, R. W. Boyd, PRL **123**, 143603 (2019)

Quantum Optics with LEDs



- Can entanglement be observed if the pump is incoherent?



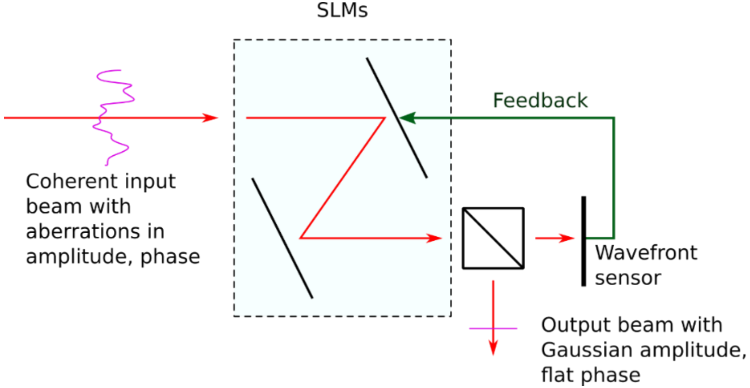


  - EPR correlations degrade linearly with mode number
  - No entanglement above a certain point!
- Next step: Polarization entanglement

Theory: E. Giese, R. Fickler, W. Zhang, L. Chen, R.W. Boyd, Phys. Scr. **93** 084001 (2018)
Experiment: W. Zhang, R. Fickler, E. Giese, L. Chen, R.W. Boyd, Opt. Express, **27**, 20745 (2019)

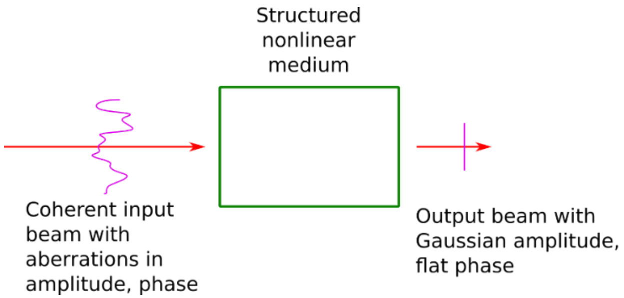
Mode Cleaning in Nonlinear Fibers

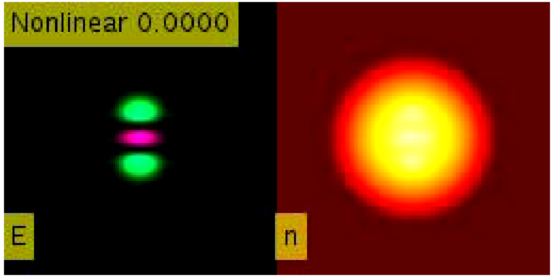
Can adaptive optics be implemented passively, using nonlinear optics?

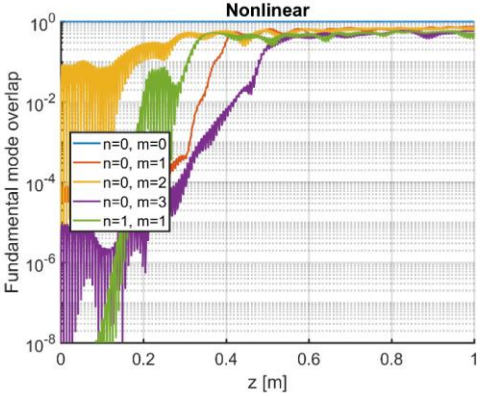


Analogous to polariton condensation

- Modes thermalize via nonlinearity

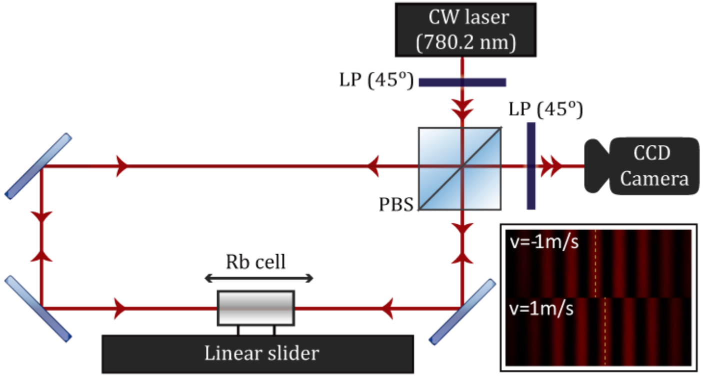






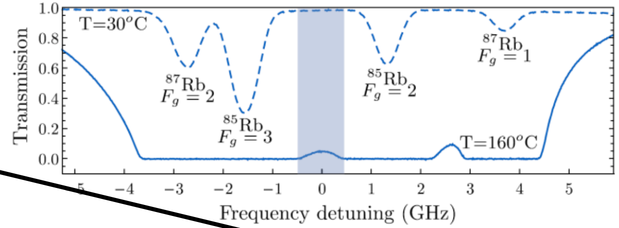
Kasprzak *et al.*, Nature **443** 409 (2006)
Wu *et al.*, Nat. Photon. 1749-4893 (2019)

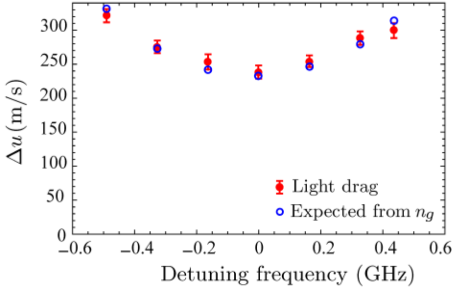
Longitudinal Photon Drag

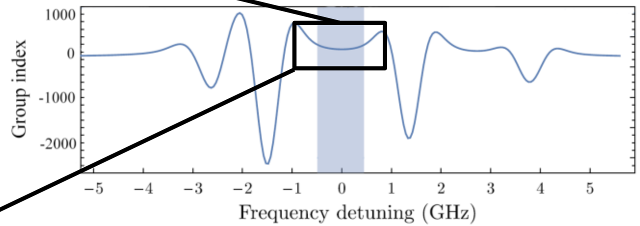


Light propagating through a traveling medium is dragged along (Fizeau, 1851)

- For slow light ($n_g \gg n$), drag proportional to the group velocity: $\Delta Z = \frac{2vLn^2}{\lambda c}\left(\frac{1}{n} - \frac{1}{n^2} + \frac{n_g - n}{n^2}\right)$
- A manifestation of the Doppler effect in a highly dispersive medium







boydnlo.ca

A. Safari, I. De Leon, M. Mirhosseini, O. Magaña-Loaiza, R. W. Boyd, PRL **116**, 013601 (2016)

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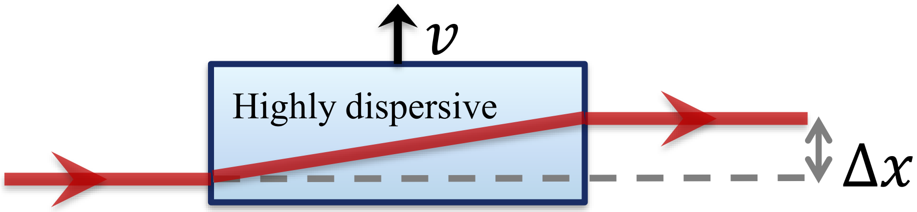
Transverse Photon Drag

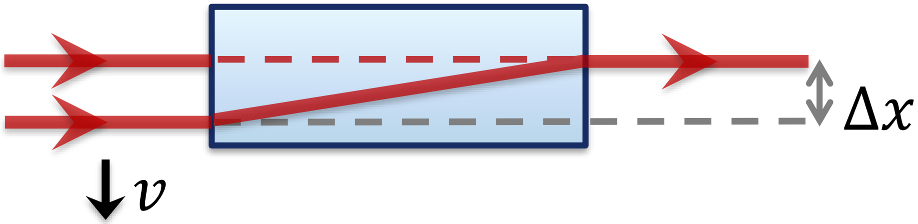
For transverse motion, no Doppler effect present

- $\Delta x = \frac{vL}{c}\left(n_g - \frac{1}{n}\right)$



Drag is a consequence of medium-induced delay in pulse propagation

- Most easily understood in frame co-moving with medium
- Small non-dispersive contribution from stellar aberration



R.V. Jones, Proc. R. Soc. Lond. A. **345**, 351-364 (1975)

Photon Drag with Negative Group Velocity

Expect upstream photon drag

- Photons move opposite to the medium!

Analogous to superluminal group pulse propagation

- Peak of output pulse exits medium before input peaks
- Possible in conditions of reverse saturable absorption

Potential experimental platforms:

- Highly-doped ruby crystal
- EIT in rubidium vapour