

ADVANCES IN MONOLITHIC QUANTUM PHOTONICS FOR SENSING

AMR S HELMY

MIO – 2018 @ TUM

MUNICH, DECEMBER 6, 2018

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UNIVERSITY OF
TORONTO



TALK OUTLINE

GROUP STRATEGY

- TECHNOLOGY PLATFORM

SOURCES AND CIRCUITS FOR QUANTUM APPLICATIONS

- NON-CLASSICAL SOURCES

QUANTUM-ENHANCED TARGET DETECTION

- PERFORMANCE AND FIGURES OF MERIT

SUMMARY



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TEAM

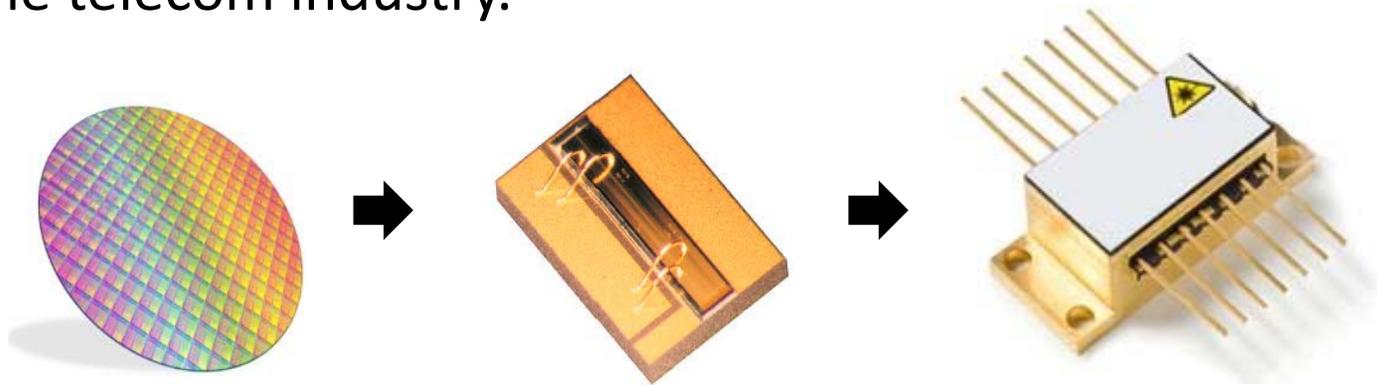
- RYAN MARCHILDON, JUNBO HAN, BHAVIN BIJLANI, TONG CUNZHU, PAYAM ABOLGHASEM, DONGPENG KANG, NIMA ZAREIAN, GREG IU, HAOYU HE, ERIC CHEN, ZACH LEGER, HAN LIU,
- NAN WU, WILSON WU, **DRS** DANIEL GIOVANNINI, AHARON BRODUTCH, ZHIZHONG YANG, BILAL JANJUA, PAUL CHARLES,
- INITIAL WORK, EARLIER THAN WHAT IS PRESENTED HERE WAS CARRIED OUT IN COLLABORATION OF WEISS, SIPE AND JENNEWAIN GROUPS
- GROUP MEMBERS CONTRIBUTING TO THE WORK OVER THE YEARS



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GROUP STRATEGY

- Pivots on **mature integrated optics technologies** developed by the telecom industry.



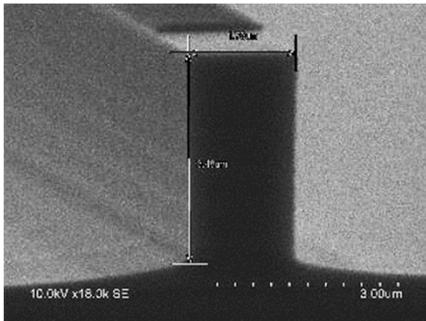
- Quantum enhancements are being explored in several other platforms but **photonics is closest to field deployment.**

- Cold Atoms
- Superconducting ‘Qubits’
- Trapped Ions

**Cryogenic temperatures.
Bulky, immobile systems
Not yet miniaturized.**

PLATFORM TECHNOLOGY

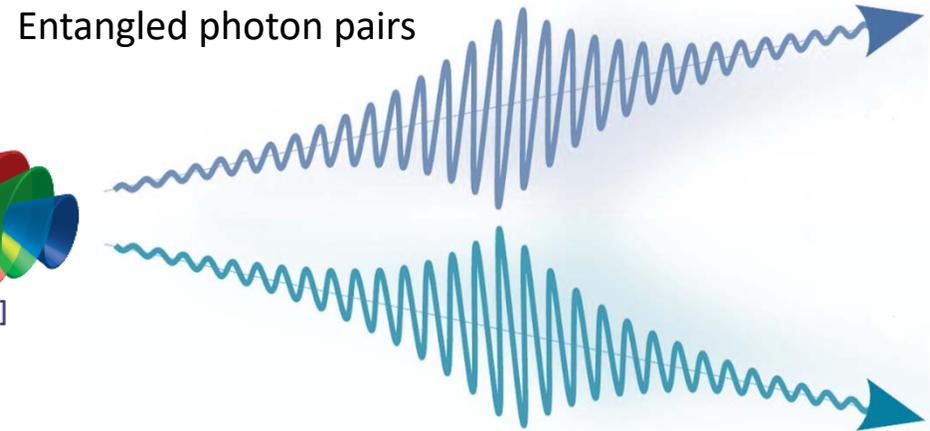
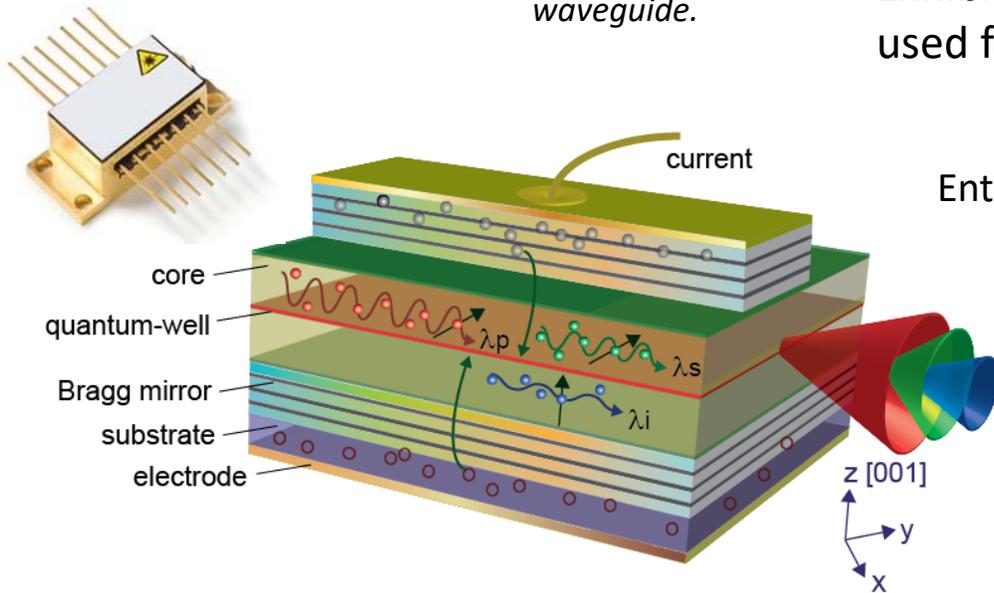
Entangled photons, generated from a room-temperature battery-powered microchip.



Micrograph image of waveguide.

Unique attributes vs. conventional laser light:

- Emitted as **time-synchronized photon pairs**
- Photon properties are **entangled** (e.g. the state of one depends on the state of the other).
- Exhibits **quadrature squeezing** which can be used for noise suppression.



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EXAMPLE OF AN ENTANGLED STATE

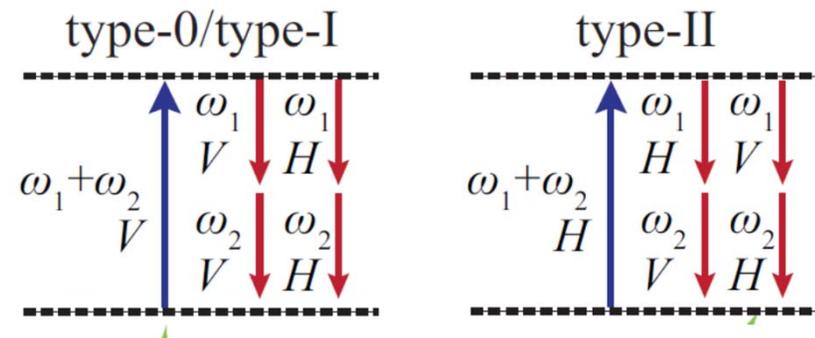
- Polarization entangled photons:

$$|\Phi^\pm\rangle = \frac{1}{\sqrt{2}}(|H\rangle|H\rangle \pm |V\rangle|V\rangle), \quad |\Psi^\pm\rangle = \frac{1}{\sqrt{2}}(|H\rangle|V\rangle \pm |V\rangle|H\rangle),$$

- Generation:

- Spontaneous Parametric Down-conversion (SPDC)
- Spontaneous Four-Wave Mixing
- Usually requires interferometers or birefringence compensation

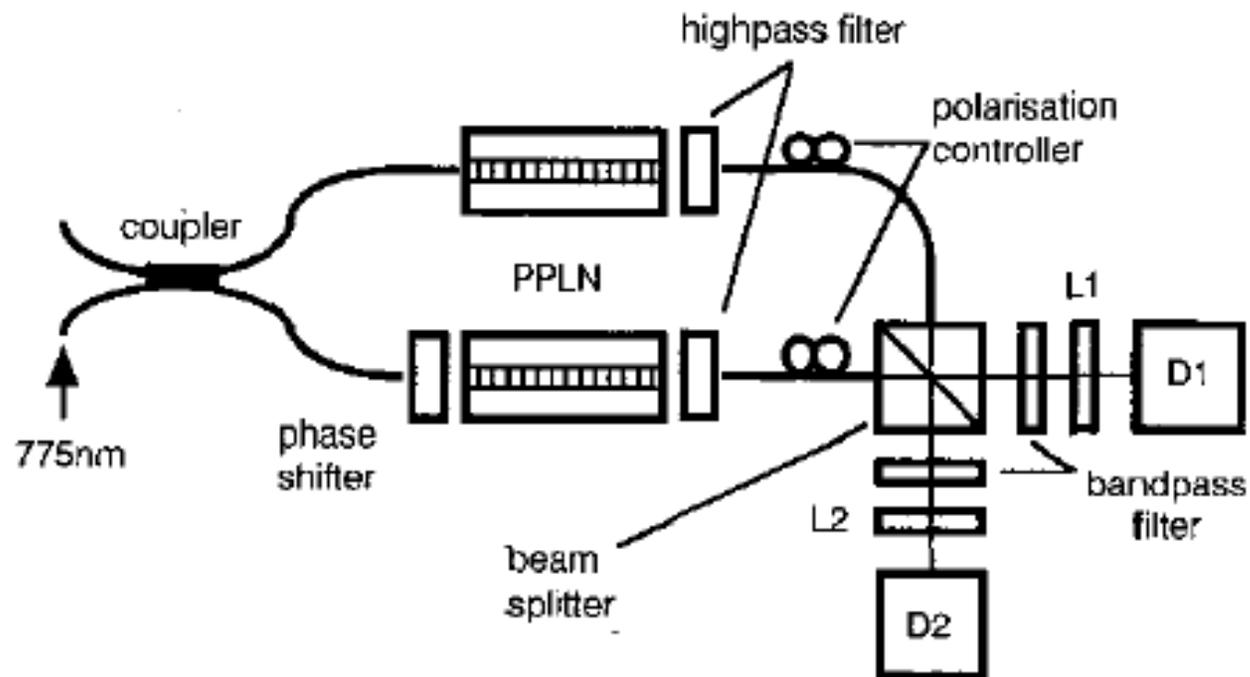
- Key goal: indistinguishability



EXAMPLE OF AN ENTANGLED STATE

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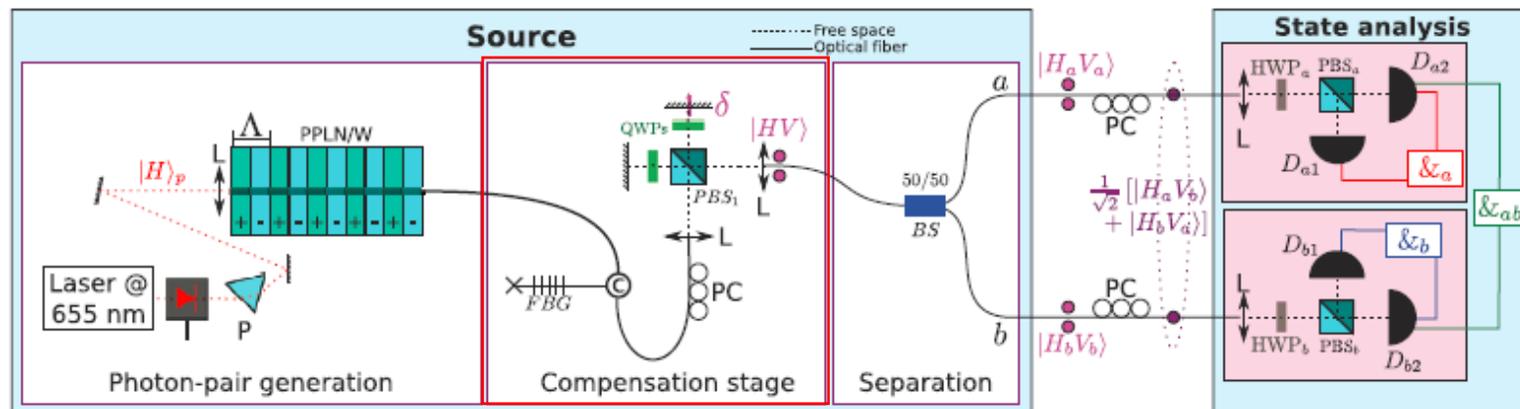


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- Generation:
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 - Spontaneous Four-Wave Mixing
 - Usually requires interferometers and birefringence compensation



Martin et al, NJP **12** 103005 (2010)

OTHER APPROACHES

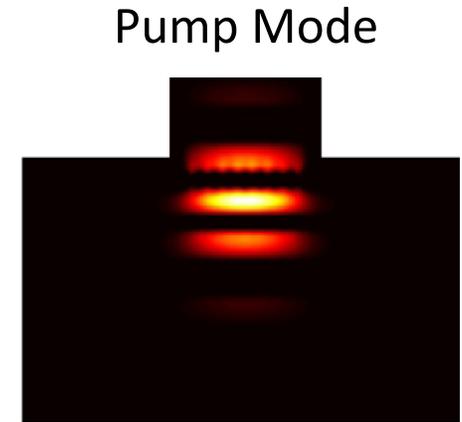
- Optical Fibers
 - Integration possibilities
 - Circular symmetry
 - Mostly uses SFWM
- Si Photonics
 - Most exciting field recently
 - Uses SFWM; challenges in filtering the pump
 - Integration possibilities
 - Power handling capabilities and nonlinear impairments
- Other materials such as AlN
 - Very promising results but passive
- Compound Semiconductors

COMPOUND SEMICONDUCTORS AS A QO PLATFORM

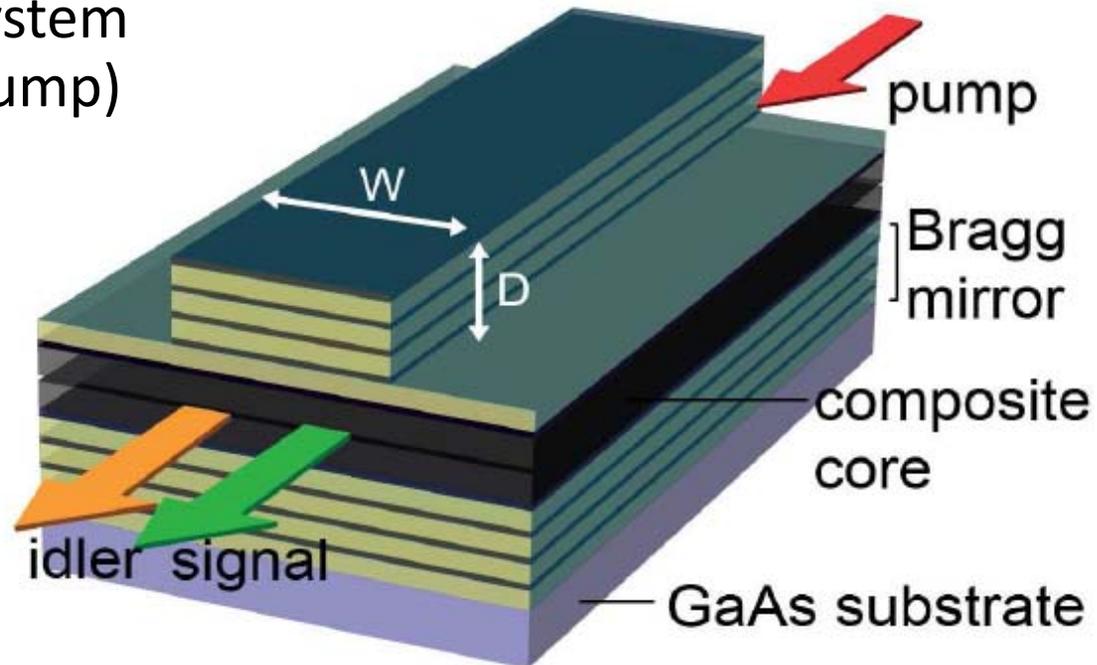
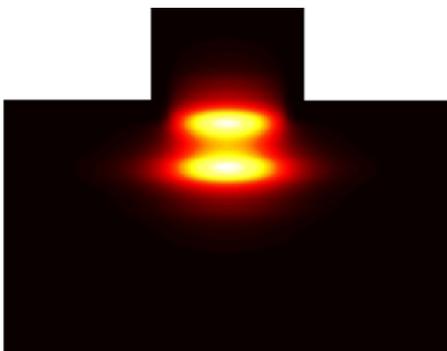
- Large nonlinear coefficients
 - Efficient interactions, compact devices
- Mature fabrication technology
 - Advanced functional components, high Q cavity, couplers, splitters etc..
- Control over dispersion
 - Tuning tool to engineer the properties of the generated pairs
- Control over birefringence
 - Opportunities to collocate TE/Tm modes for entanglement
- Integration of pump sources
 - Electrically injected room temperature circuits for quantum optical test beds
- Challenges
 - Losses, Input and output coupling, Nonlinear impairments

BRAGG REFLECTION WAVEGUIDES

- Modal phase matching of optical nonlinearity
- Dispersion controls for state tailoring
- AlGaAs material system (integration with pump)



Quantum State Mode

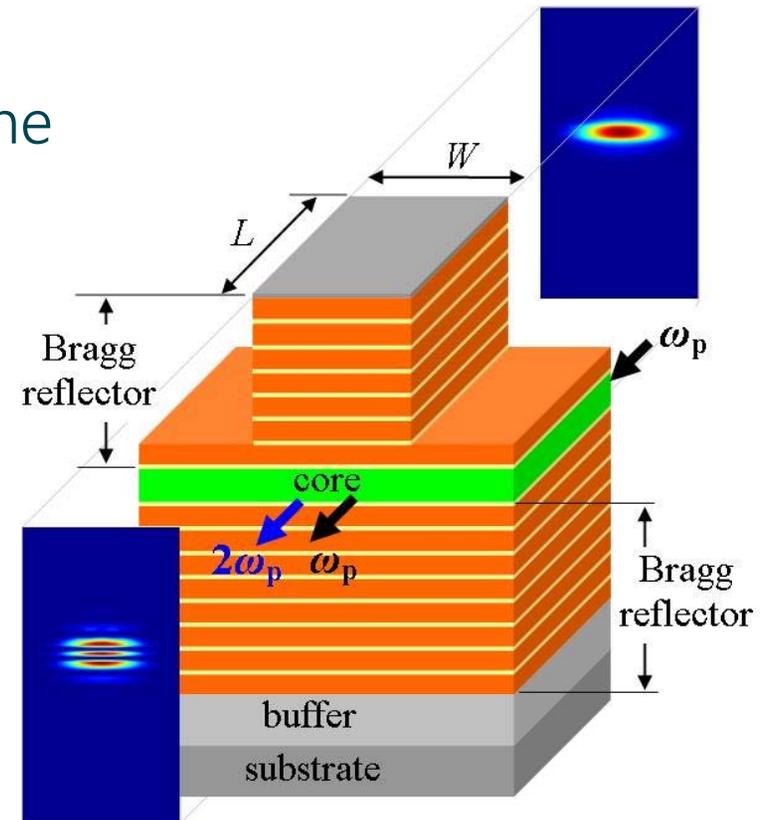


BRAGG REFLECTION WAVEGUIDES

- Closed-form dispersion 1D
- For micron-size waveguide widths the vertical design dictates waveguide dispersion, birefringence and phase matching

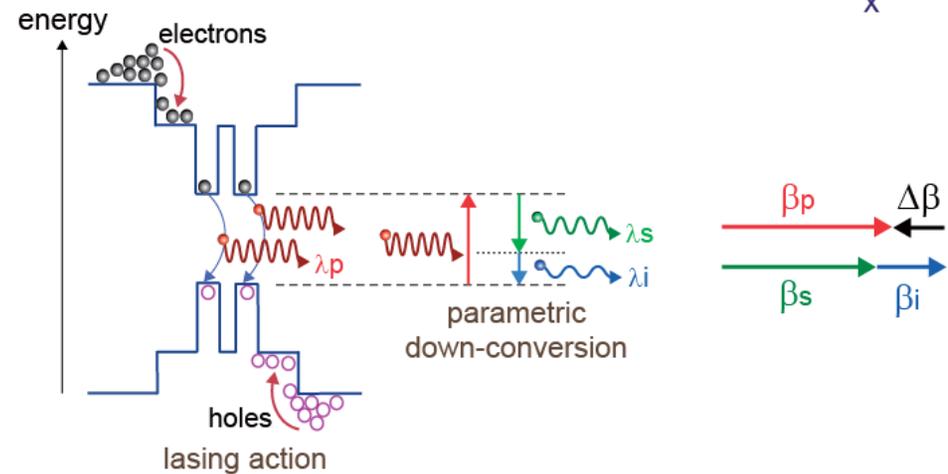
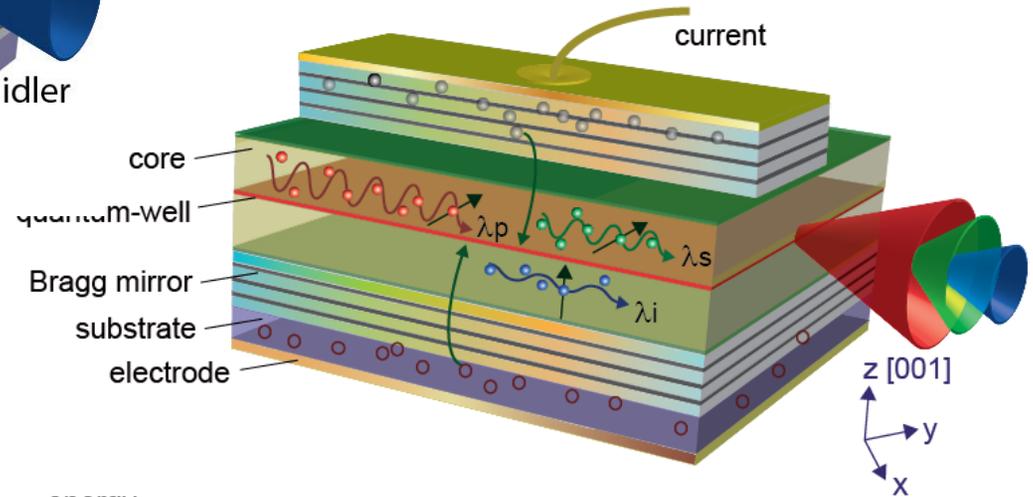
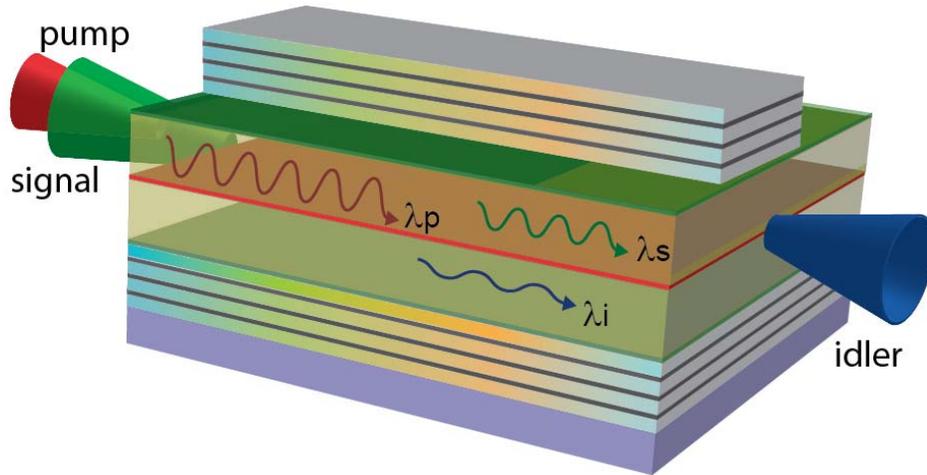
To first order in the perturbation,

$$\frac{-\Delta k_{co} t_{co}}{2k_{co}} \approx \frac{-i}{k_1} \left(\frac{\Delta(e^{iK\Lambda}) - \Delta A + \Delta B}{e^{iK\Lambda} - A - B} \right)$$



$$\frac{1}{k_{co} + \Delta k_{co}} \cot\left(\frac{(k_{co} + \Delta k_{co}) t_{co}}{2}\right) = \frac{-i}{k_1 + \Delta k_1} \left(\frac{[e^{iK\Lambda} + \Delta(e^{iK\Lambda})] - [A + \Delta A] + [B + \Delta B]}{[e^{iK\Lambda} + \Delta(e^{iK\Lambda})] - [A + \Delta A] - [B + \Delta B]} \right)$$

BRAGG REFLECTION WAVEGUIDES - ACTIVE/PASSIVE



TYPES OF NONLINEAR INTERACTIONS – TYPE 0

- Type-0 $TM_\omega \rightarrow TM_{2\omega}$ second-harmonic generation:
 - For TM propagating mode:
 - field components in laboratory frame $(x'y'z')$ are $(H_{x'}, E_{y'}, E_{z'})$
 - $E_{y'}$ is a small field component
 - nonzero $E_{y'}$ initiates $TM_\omega \rightarrow TM_{2\omega}$ interaction

$$\chi_{x'x'z'}^{(2)} = \chi_{x'z'x'}^{(2)} = \chi_{z'x'x'}^{(2)} = +\chi_{xyz}^{(2)}$$

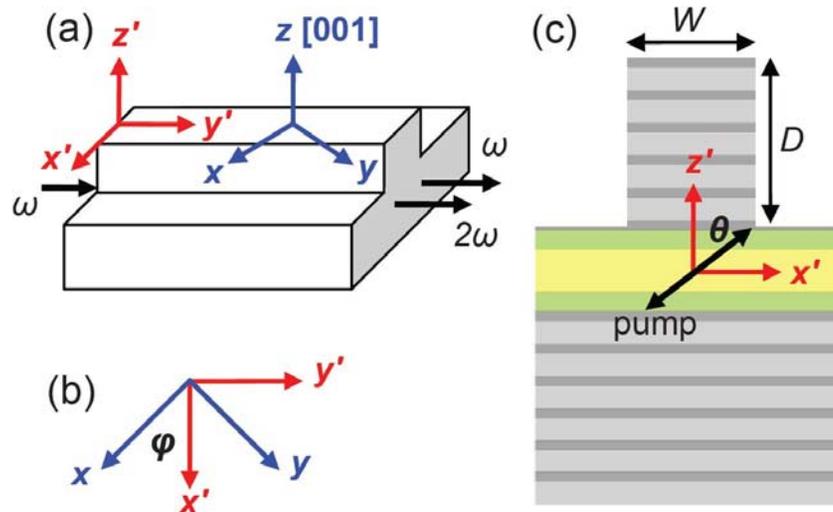
$$\chi_{y'y'z'}^{(2)} = \chi_{y'z'y'}^{(2)} = \chi_{z'y'y'}^{(2)} = -\chi_{xyz}^{(2)}$$

$$[P_{2\omega}^{(2)}]_{x'} = 0$$

$$[P_{2\omega}^{(2)}]_{y'} = -\epsilon_0 \chi_{xyz}^{(2)} E_{y'} E_{z'}$$

$$[P_{2\omega}^{(2)}]_{z'} = -\epsilon_0 \chi_{xyz}^{(2)} E_{y'} E_{y'} / 2$$

small $E_{y'}$; $TM_{2\omega}$ should be weak

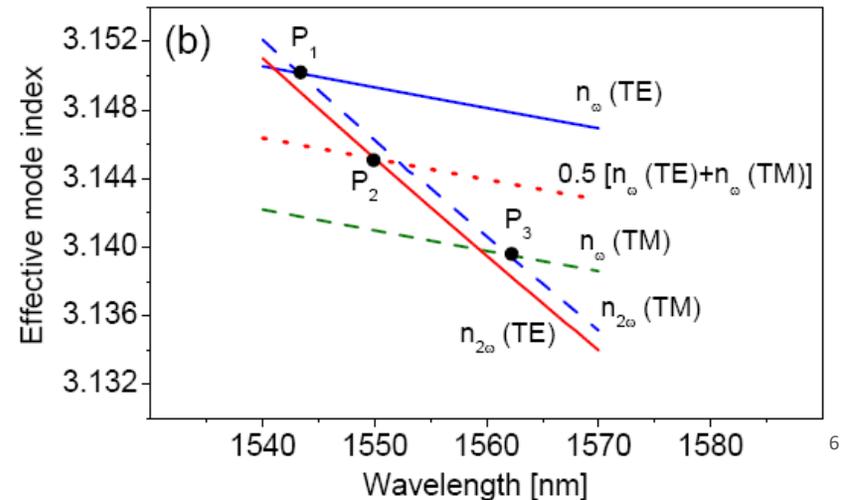
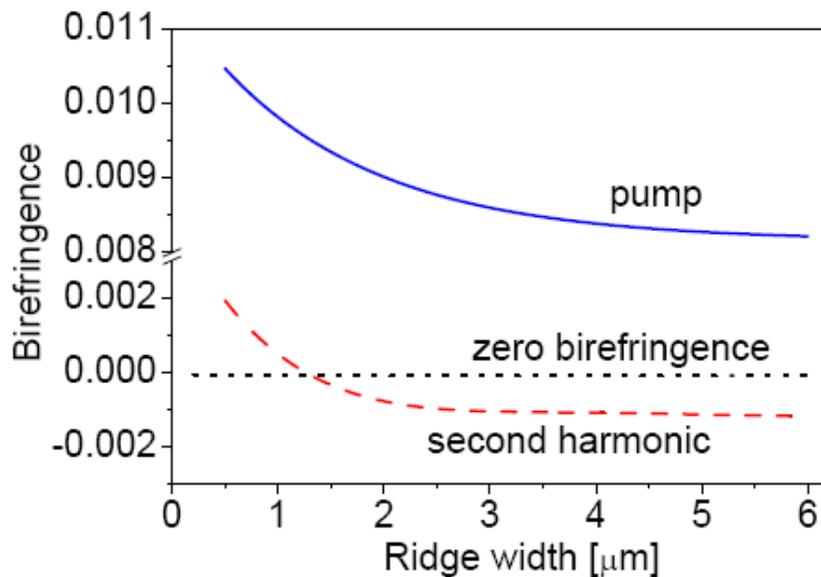
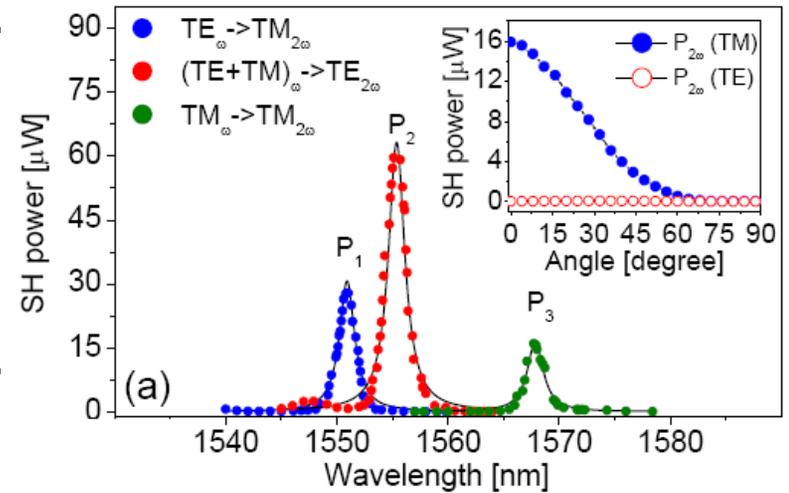


P. Abolghasem, *Opt. Express.* **35** (2010)

TYPE-0 SECOND HARMONIC GENERATION

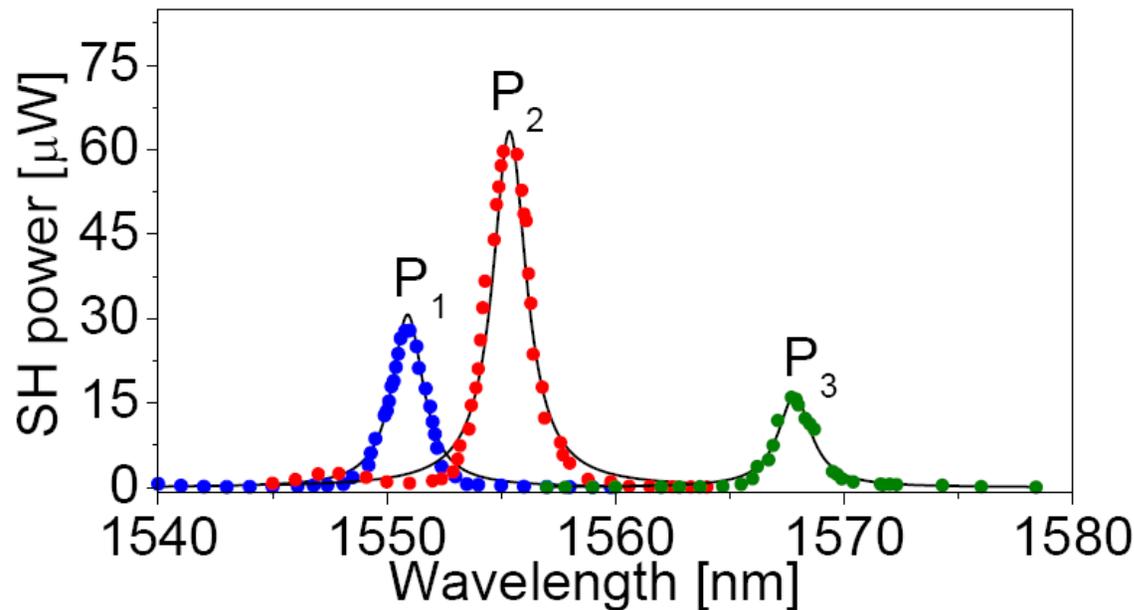
□ type-0 $TM_{\omega} \rightarrow TM_{2\omega}$ second-harmonic generation:

phase-matching scheme	$P_{2\omega}$ [μW]	λ_{PM} [nm]	efficiency [$\%W^{-1}\text{cm}^{-2}$]
$TE_{\omega} \rightarrow TM_{2\omega}$	28	1551	5.3×10^3
$TE_{\omega} + TM_{\omega} \rightarrow TE_{2\omega}$	60	1555	1.1×10^4
$TM_{\omega} \rightarrow TM_{2\omega}$	16	1568	2.8×10^3



BRW – CHIP BASED POLARIZATION-ENTANGLED PHOTONS

- Second harmonic generation



Definitions:

Type-I:

$$\text{TE}(\omega) + \text{TE}(\omega) \rightarrow \text{TM}(2\omega)$$

Type-II:

$$\text{TE}(\omega) + \text{TM}(\omega) \rightarrow \text{TE}(2\omega)$$

Type-0:

$$\text{TM}(\omega) + \text{TM}(\omega) \rightarrow \text{TM}(2\omega)$$

P. Abolghasem, et al, Opt. Express, 18, 12861(2009)

EXAMPLE OF AN ENTANGLED STATE

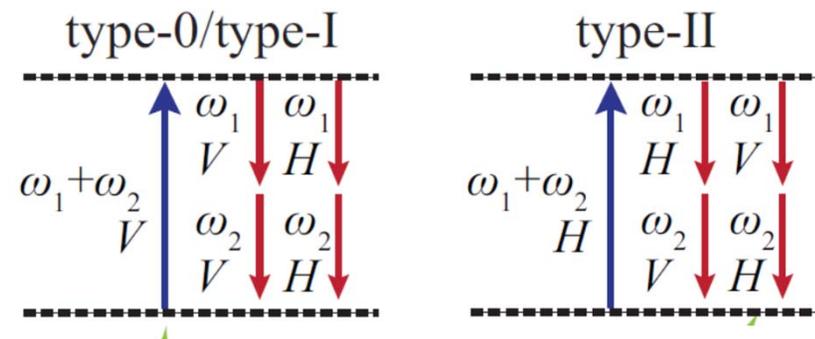
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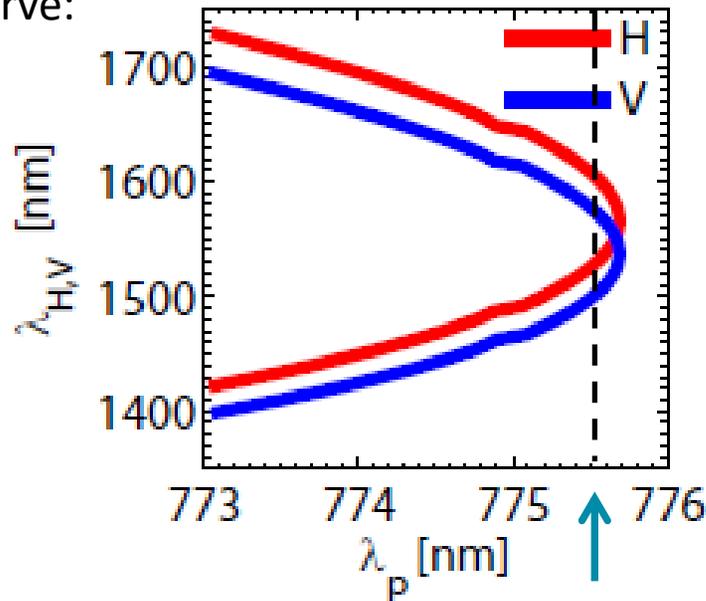
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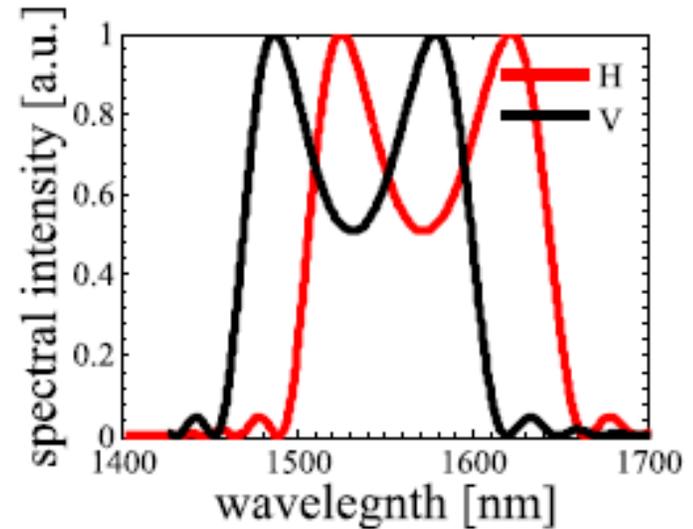
BRW – CHIP BASED POLARIZATION-ENTANGLED PHOTONS

- Non-degenerate type-II process

Tuning curve:



Spectra intensity:

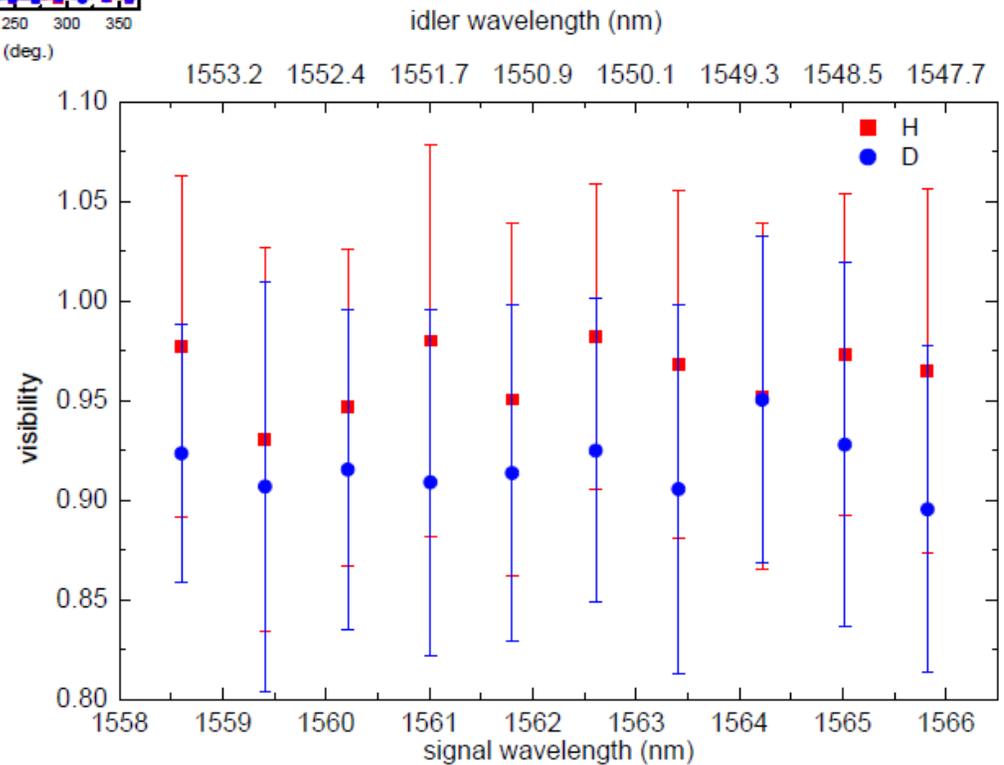
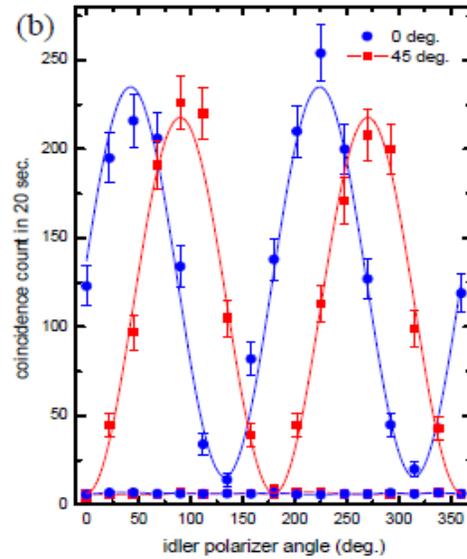
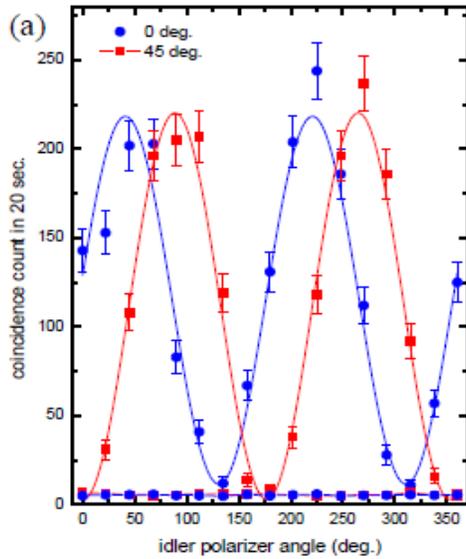


Generated state:

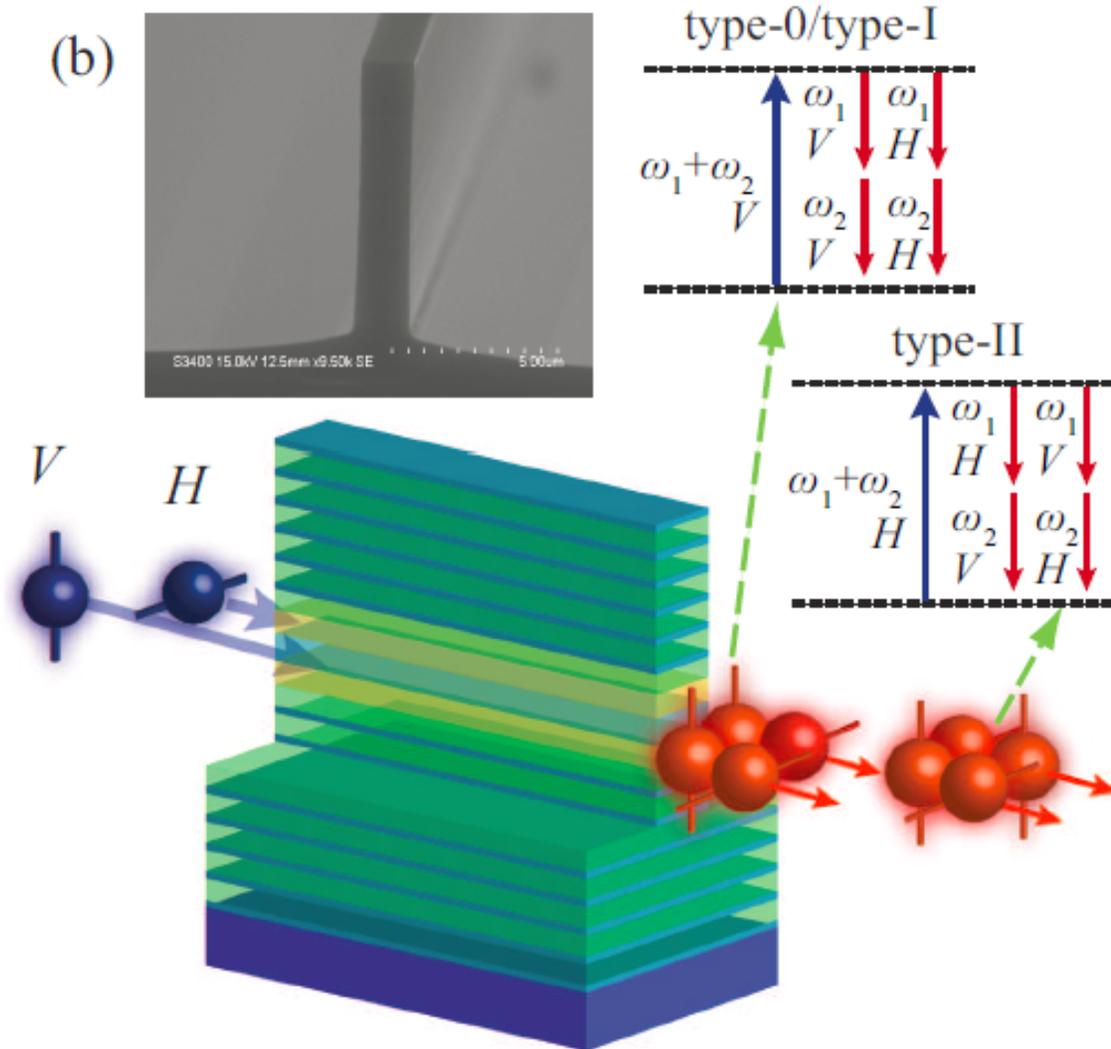
$$|\Psi\rangle = \int d\omega_1 d\omega_2 [A_{HV}(\omega_1, \omega_2) |\omega_1, H\rangle_s |\omega_2, V\rangle_i + A_{VH}(\omega_1, \omega_2) |\omega_2, V\rangle_s |\omega_1, H\rangle_i],$$

Not identical!

BRW – CHIP BASED POLARIZATION-ENTANGLED PHOTONS

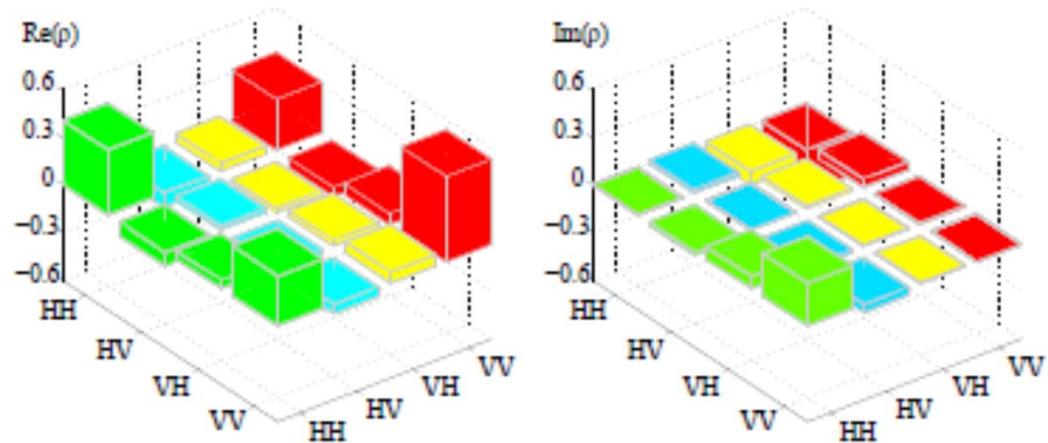


FURTHER CAPABILITIES OF THE PLATFORM

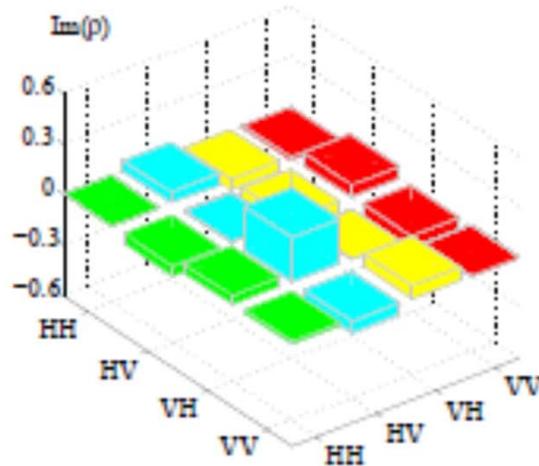
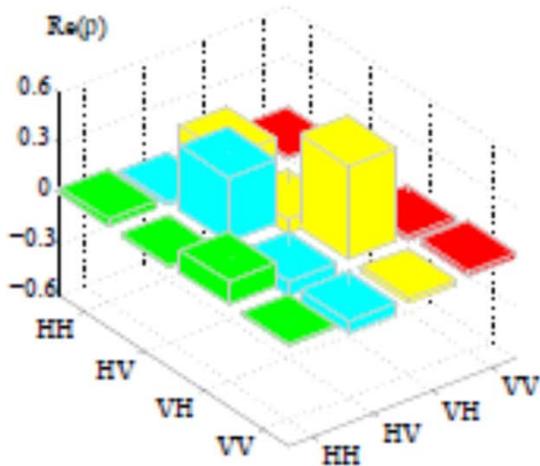


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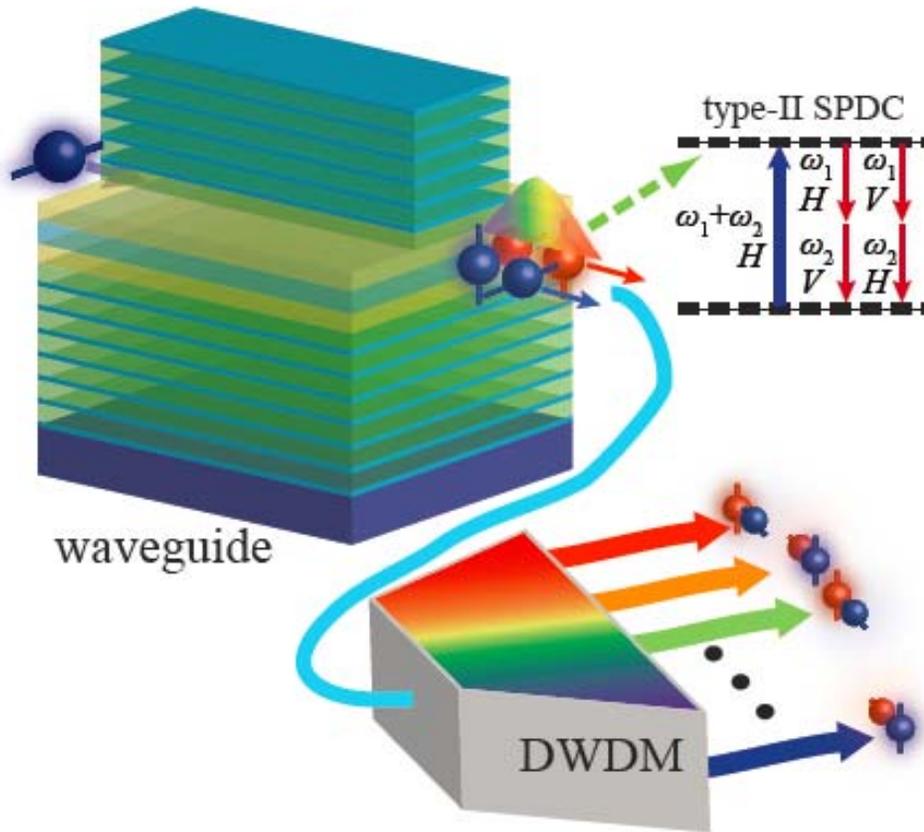
- Type-II measurements
 - Concurrence: 0.55
 - Fidelity 0.74 to a maximally entangled state



- Type-0/type-I measurements
 - Concurrence: 0.85
 - Fidelity 0.89 to a maximally entangled state



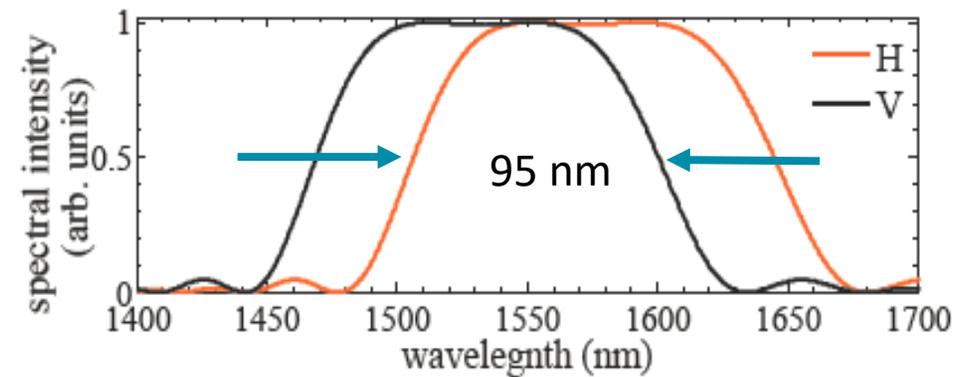
BROADLY TUNABLE ENTANGLED SOURCES



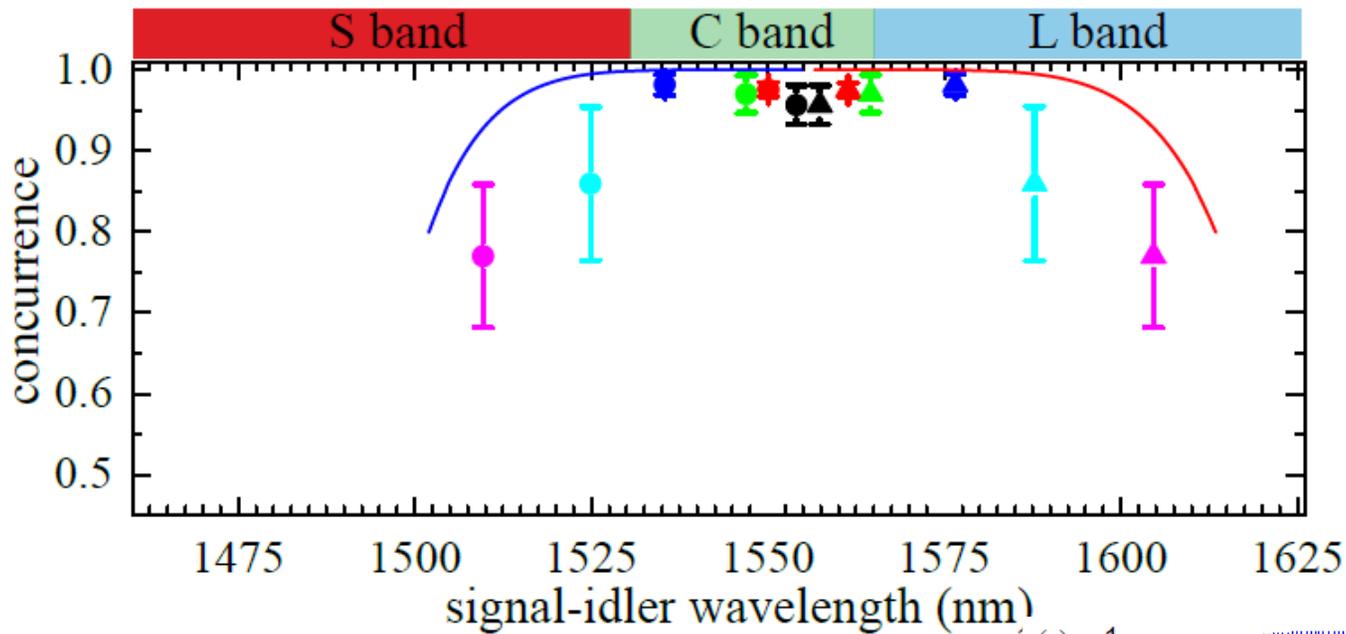
- Type-II Spontaneous Parametric Down Conversion in BRWs

$$|\psi_n\rangle = \frac{1}{\sqrt{2}} \iint_{B_n} d\omega_s d\omega_i [\Phi_{HV}(\omega_s, \omega_i) a_H^\dagger(\omega_s) a_V^\dagger(\omega_i) + \Phi_{VH}(\omega_s, \omega_i) a_V^\dagger(\omega_s) a_H^\dagger(\omega_i)] |vac\rangle,$$

- Spectra of photon pairs



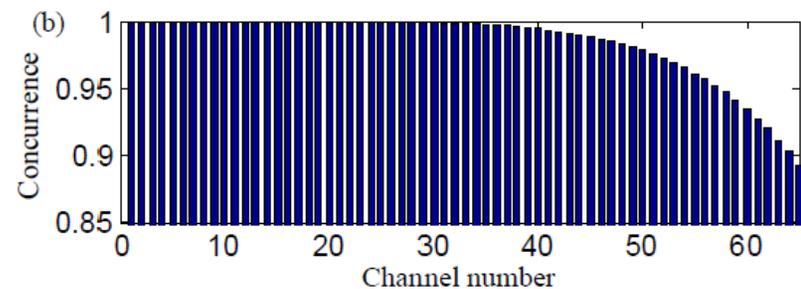
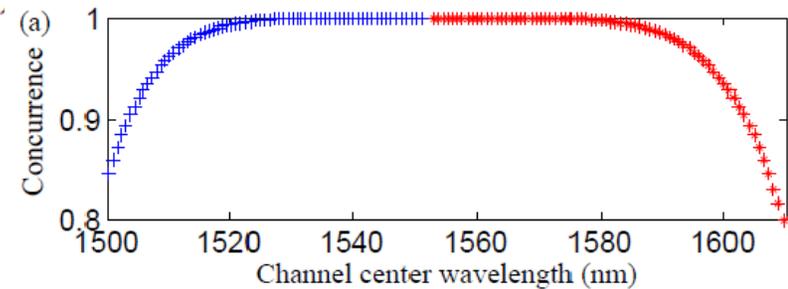
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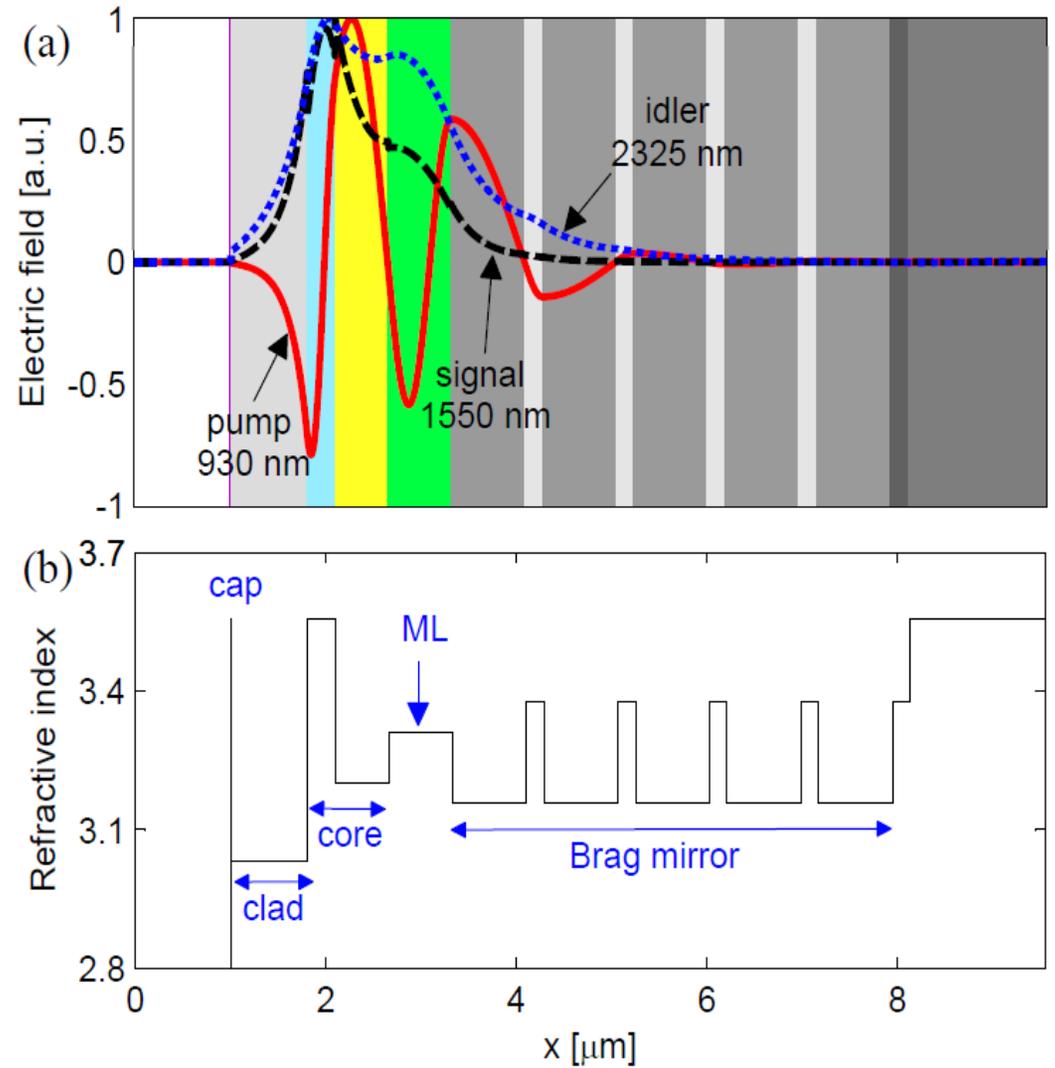
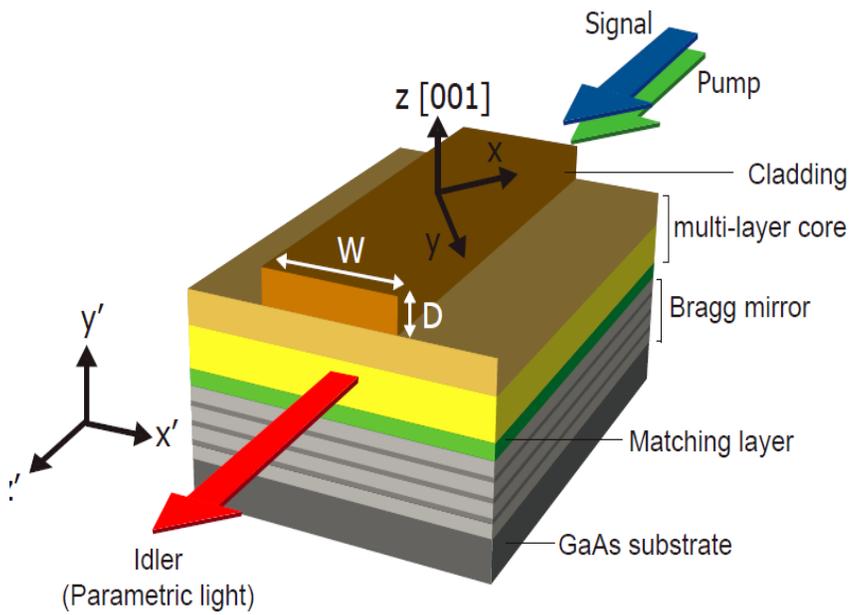
Peak concurrence
 0.98 ± 0.01

Concurrence at least
 0.96 ± 0.02 in 40 nm

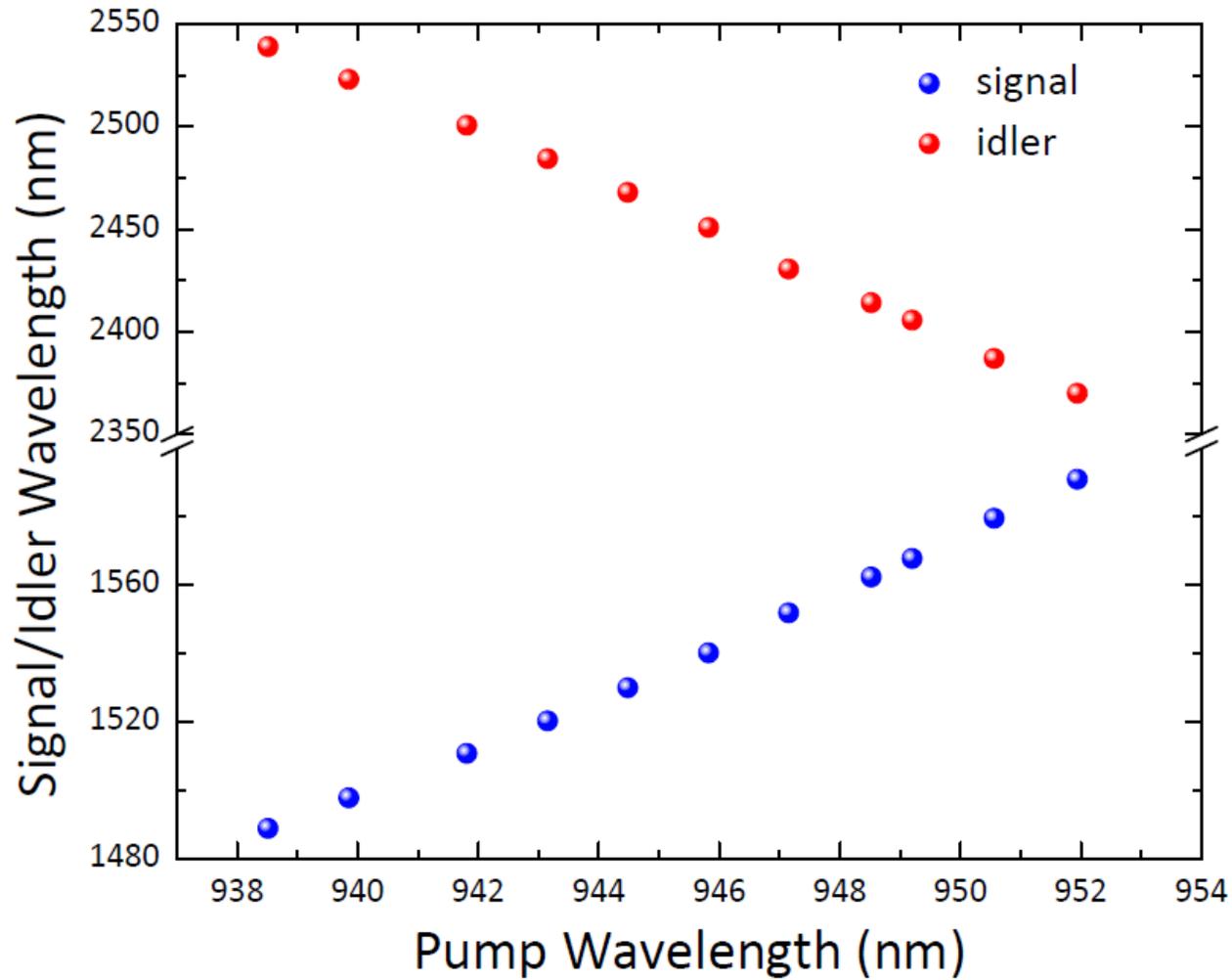
Concurrence at least
 0.77 ± 0.09 in 95 nm



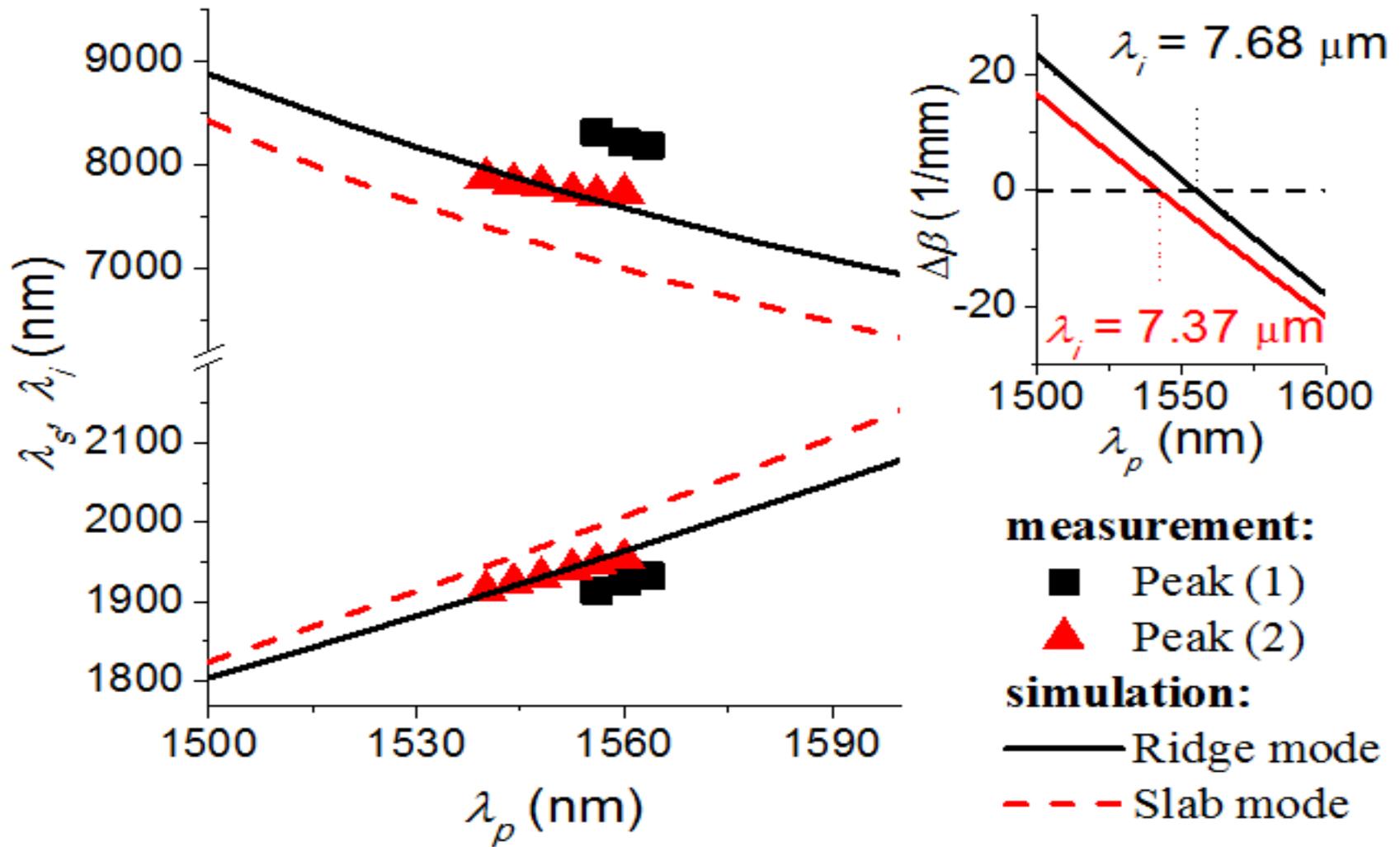
FURTHER CAPABILITIES OF THE PLATFORM – IR TUNING



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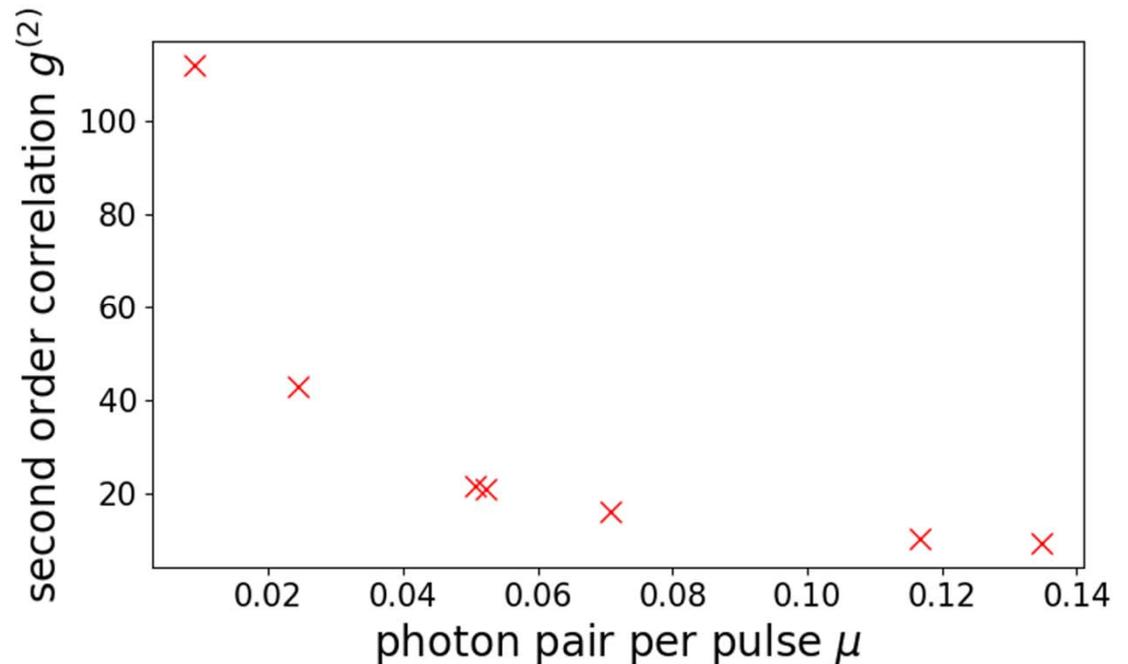


FURTHER CAPABILITIES OF THE PLATFORM – IR TUNING



FURTHER CAPABILITIES OF THE PLATFORM – FLUX VS HERALDING

- Flux available from single element sources can be $\sim 1 \times 10^8$. This can be scaled up in an integrated setting with ease.
- The level of pumping be it high or low pumping regimes play a role in defining the $G(2)$ and Flux relation



- **Definition**

- $g^{(2)} = \langle N_s N_i \rangle / \langle N_s \rangle \langle N_i \rangle$ where N_s and N_i are the photon number operator on the signal and idler mode.

FURTHER CAPABILITIES OF THE PLATFORM – DISPERSION

phase-matching scheme	Type-I	Type-II	Type-II
ridge width	677 nm	677 nm	375 nm
group velocity dispersion	-7.6×10^{-4} ps ² /m	—	—
group velocity mismatch	—	-0.34 ns/m	-2.92 ns/m
pump wavelength	677 nm	706 nm	944 nm
SPDC bandwidth	61 THz (456 nm)	869 GHz (5.7 nm)	101 GHz (1.2 nm)
Temporal correlation	15 fs	1.2 ps	10 ps

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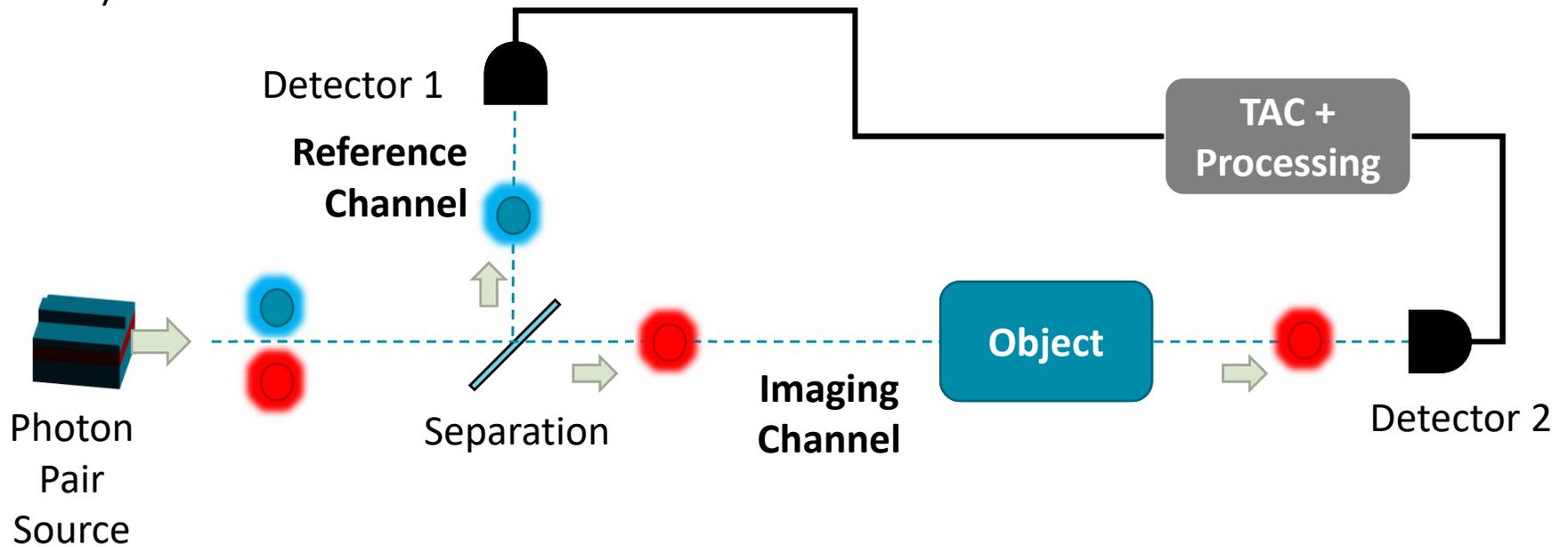
SUMMARY



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QUANTUM INSPIRED TARGET DETECTION

- Generate entangled twin-photons: one gives a reference, the other is sent towards object.
- Allows you to better separate the useful image from unwanted noise in the collected light.
- Entangled pairs will lead to synchronized detections; noise photons will not (core idea)



QUANTUM ENHANCED TARGET DETECTION

- Several advantages over their classical counterparts:
 - **Improved SNR** for the detection of low-contrast objects
 - High resilience to environmental **noise**
 - High resilience to environmental **loss**
 - **Sub-shot-noise** performance
 - Operation at **low illumination levels**

S. Lloyd, *Science* **321**, 1463–1465 (2008)

S.-H. Tan et al., *Phys. Rev. Lett.* **101**, 253601 (2008)

INTENSITY CORRELATION TARGET DETECTION SCHEME

- Definitions:

- Target detection scheme with intensity correlation

$$S = N_p N_r - \langle N_p \rangle \langle N_r \rangle$$

Where S is the signal, N_p and N_r are photon number operator of the probe and reference mode.

- When the target object is absent, the intensity correlation S must be zero in average, since environmental noise photon could not be correlated with the reference photon. The presence of the target is asserted if the measured correlation S is large than a certain threshold.

- Figure of Merit:

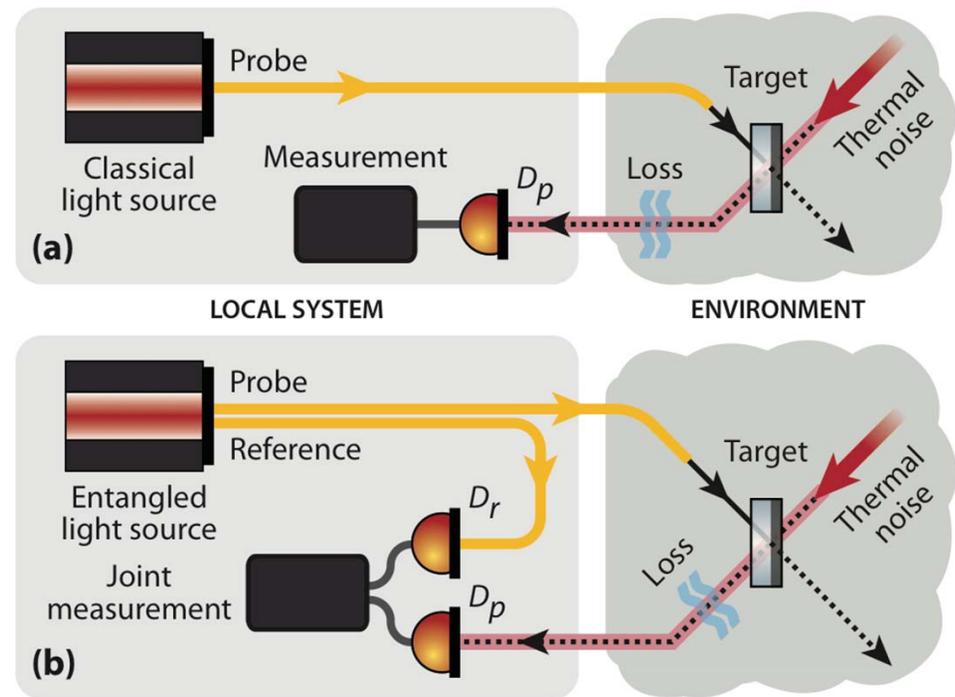
- Since the intensity correlation based target detection scheme is a threshold detection of intensity correlation signal S , then it is nature to define the figure of merit as the (normalized) fluctuation of the correlation signal S (called the visibility in the MS):

$$\mathcal{E} = \frac{\langle S_{\text{in}} \rangle - \langle S_{\text{out}} \rangle}{\sqrt{\langle \delta^2 S_{\text{in}} \rangle + \langle \delta^2 S_{\text{out}} \rangle}}$$

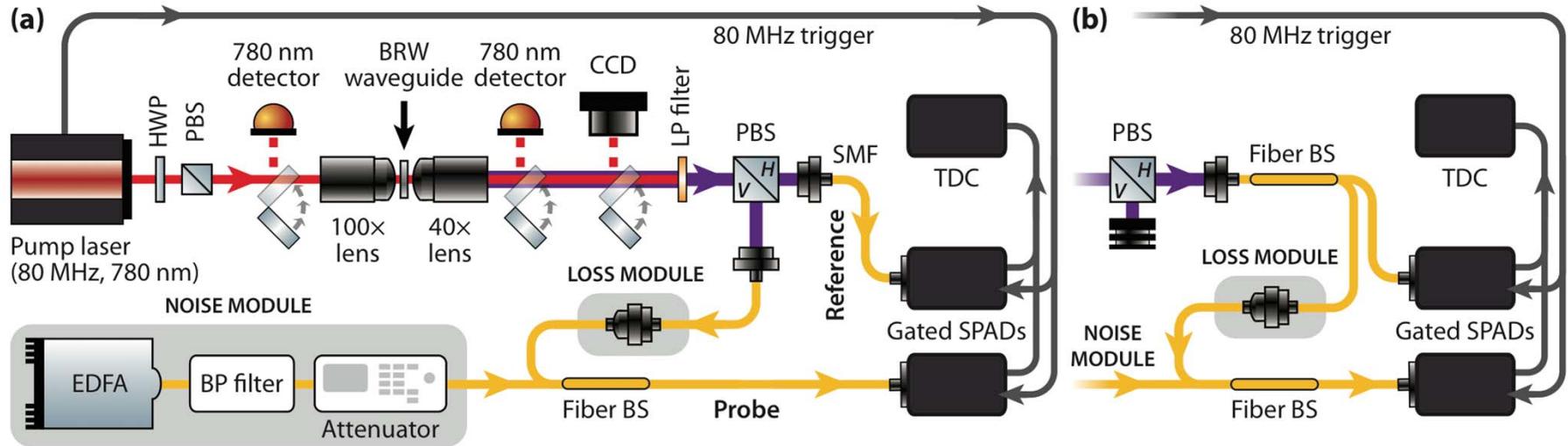
- The subscript in and out denote the presence and the absence of the target.

INTENSITY CORRELATION TARGET DETECTION SCHEME

- Intensity correlation based scheme with SPDC source(ICQ):
 - Probe-reference photon pair generated through SPDC source are highly correlated because they are always generated in pairs.
- Intensity correlation based scheme with correlated thermal state source (ICC):
 - Two correlated thermal state split from a single thermal state beam are classically correlated and is optimal for classical Intensity correlation target detection scheme [Lopaeva et al PRL].

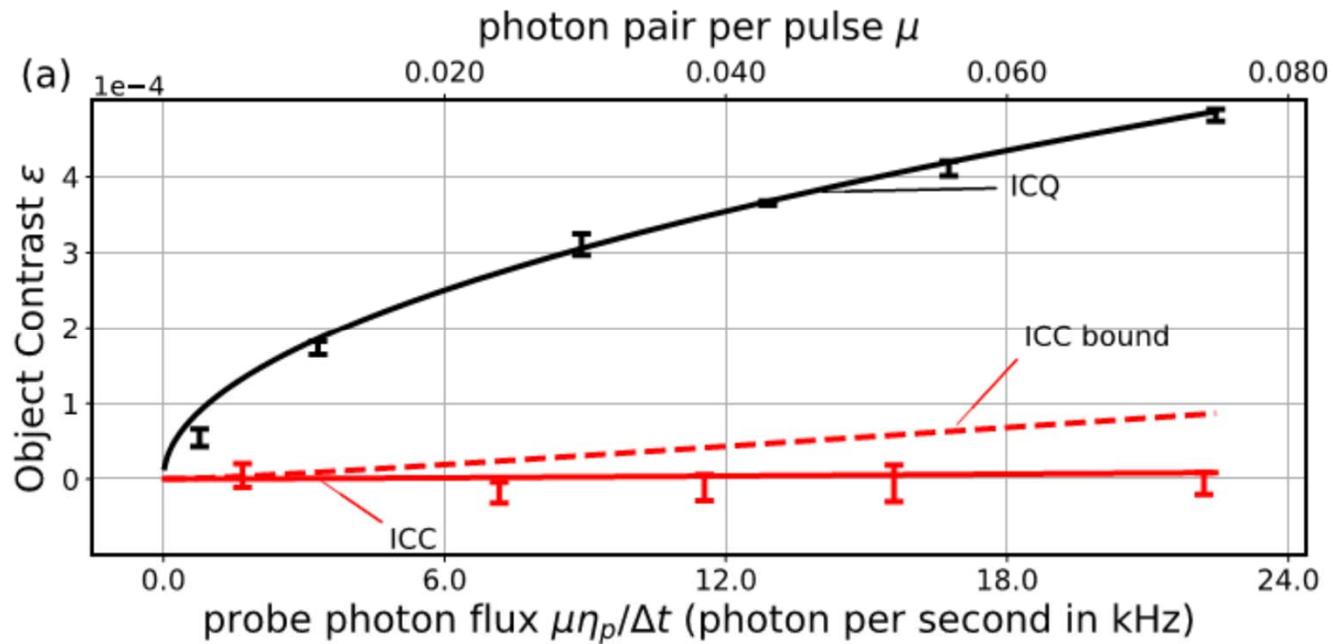


QUANTUM ENHANCED TARGET DETECTION

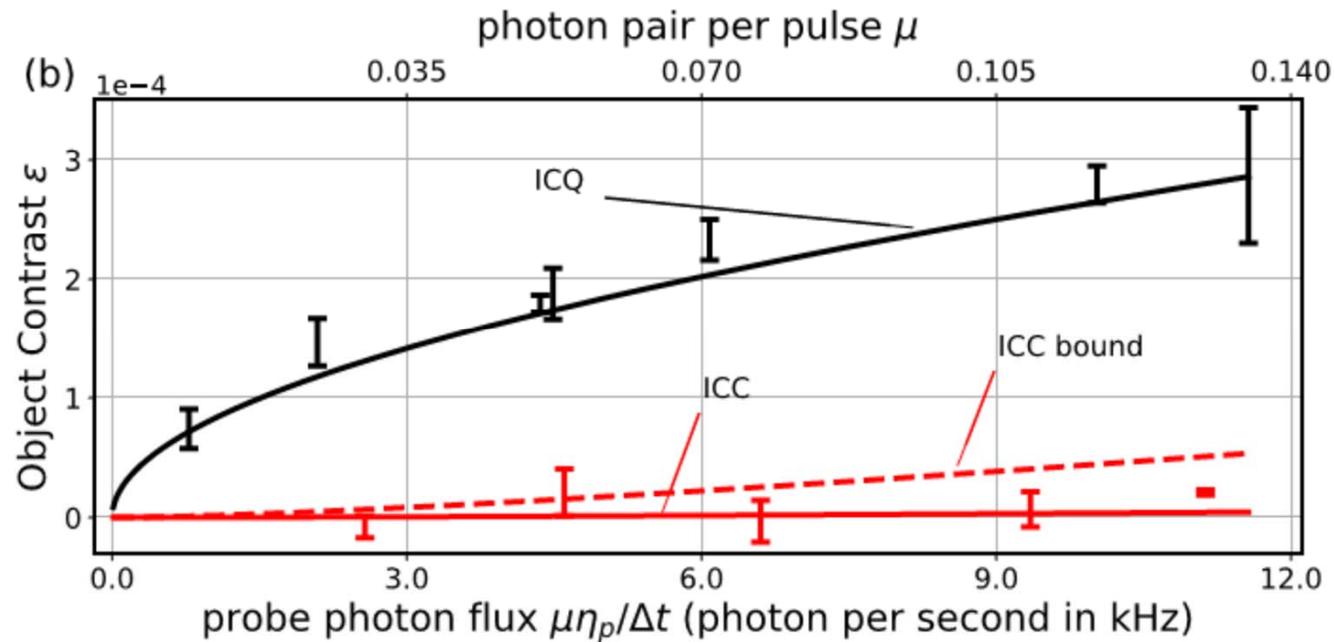


The H-polarized photon in each photon pair produced by type-II SPDC is used as a reference beam; the V-polarized photon is used as a probe beam. HWP: half-wave plate; PBS: polarizing beam splitter; BS: beam splitter; BRW: Bragg reflection waveguide; LP: long-pass; BP: band-pass; SMF: single-mode fiber; SPAD: single-photon avalanche diode; TDC: time-to-digital converter

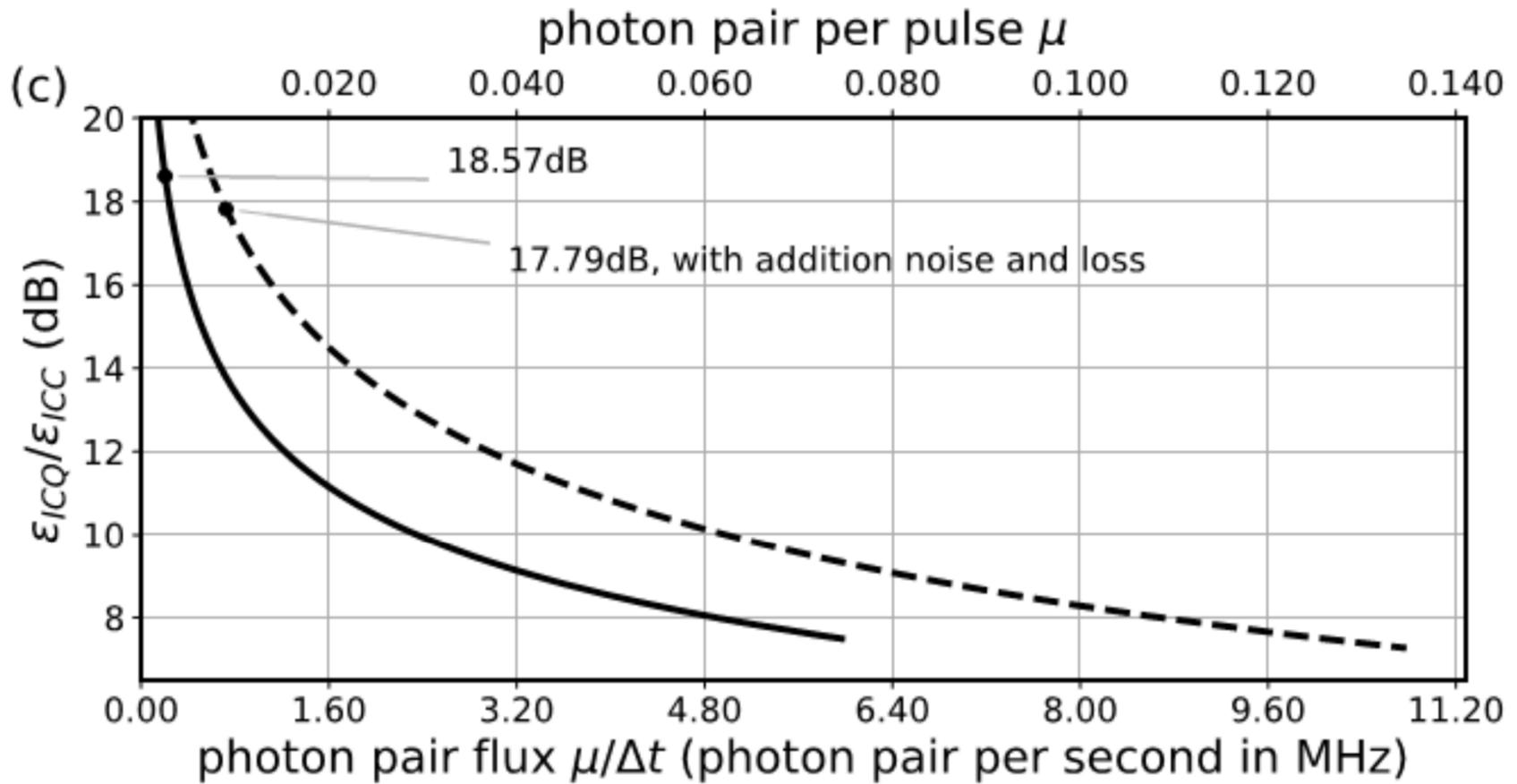
VISIBILITY AND POWER



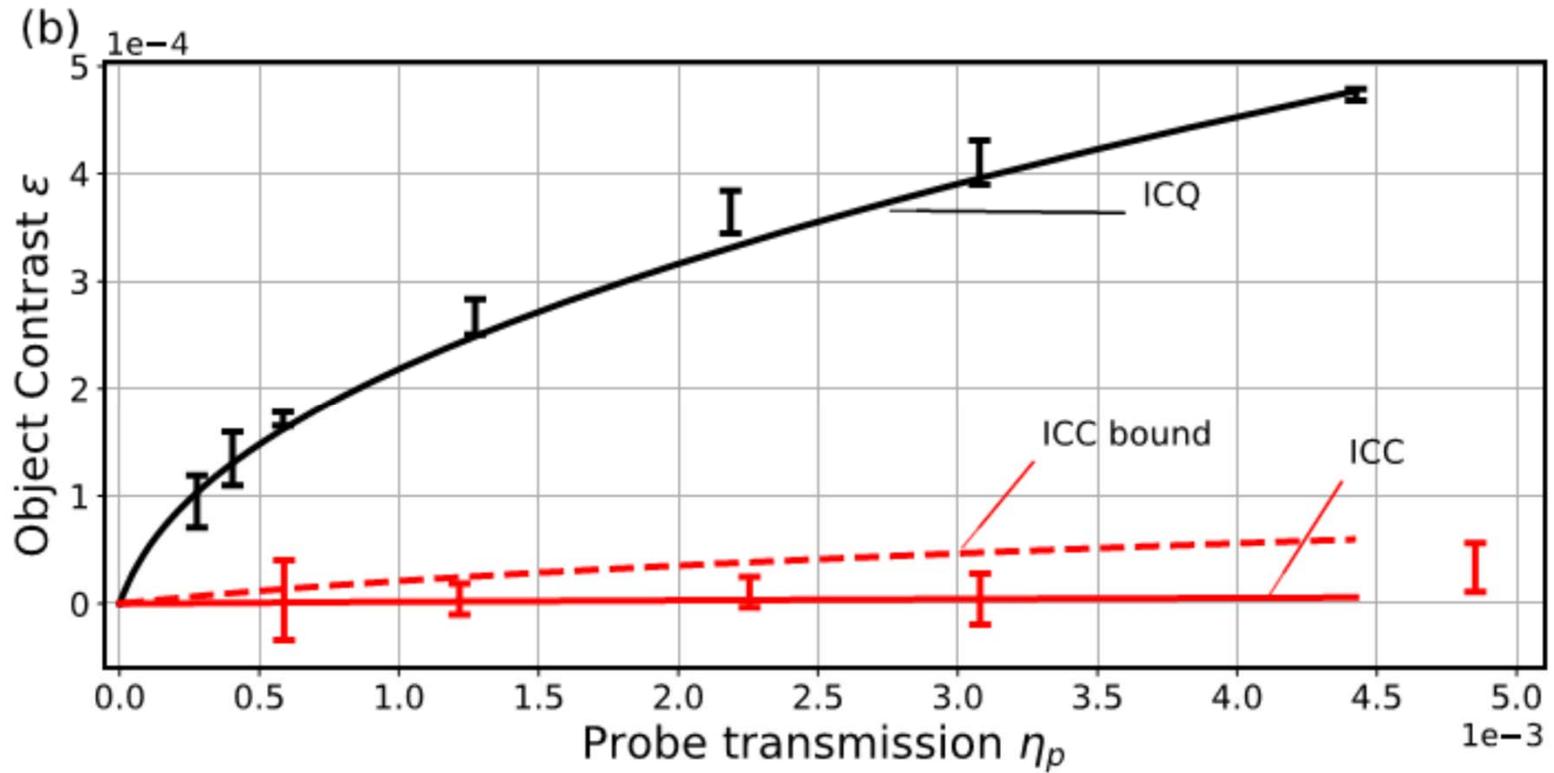
VISIBILITY AND POWER WITH ADDITIONAL LOSS



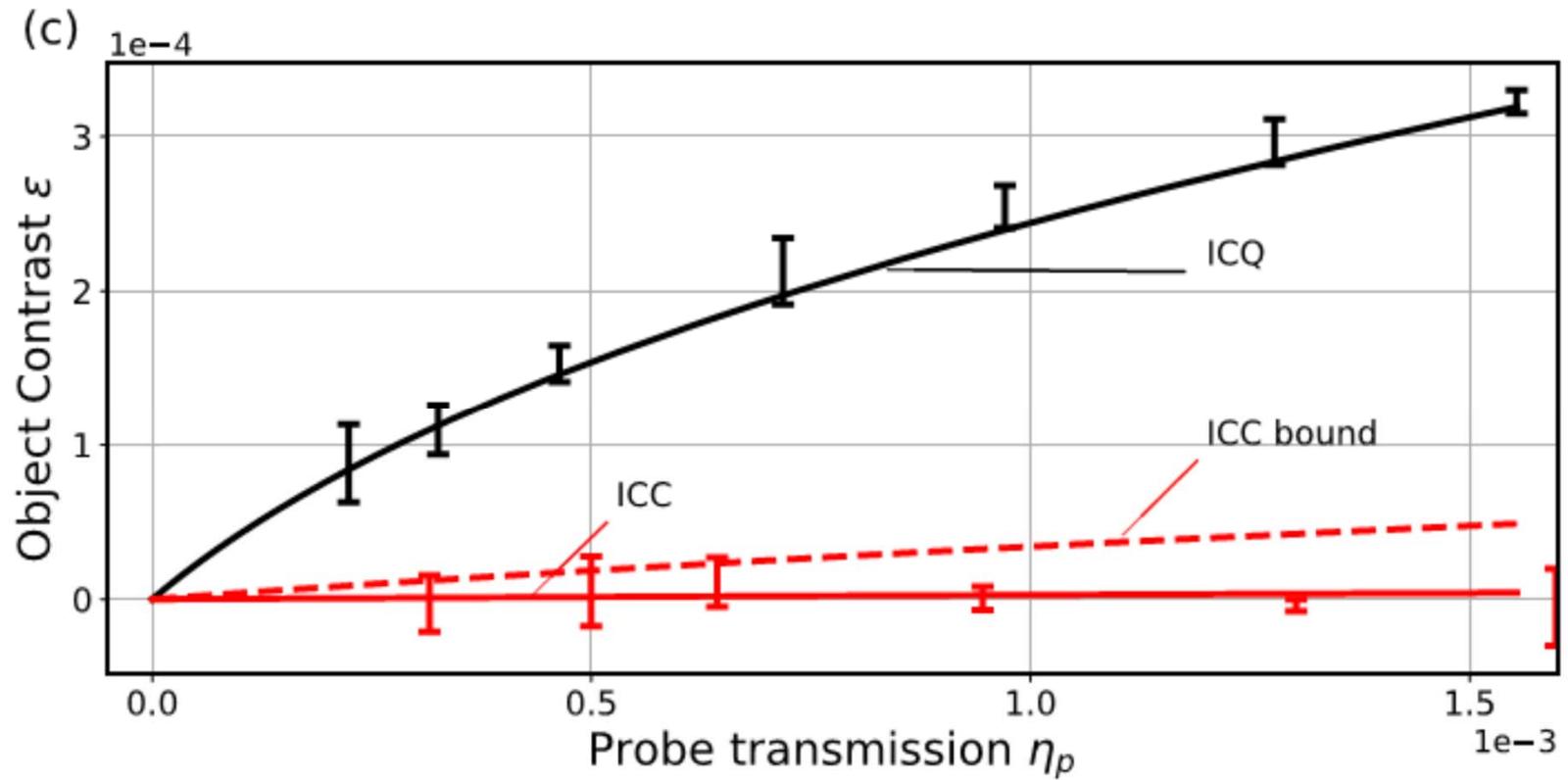
VISIBILITY RATIO AND POWER



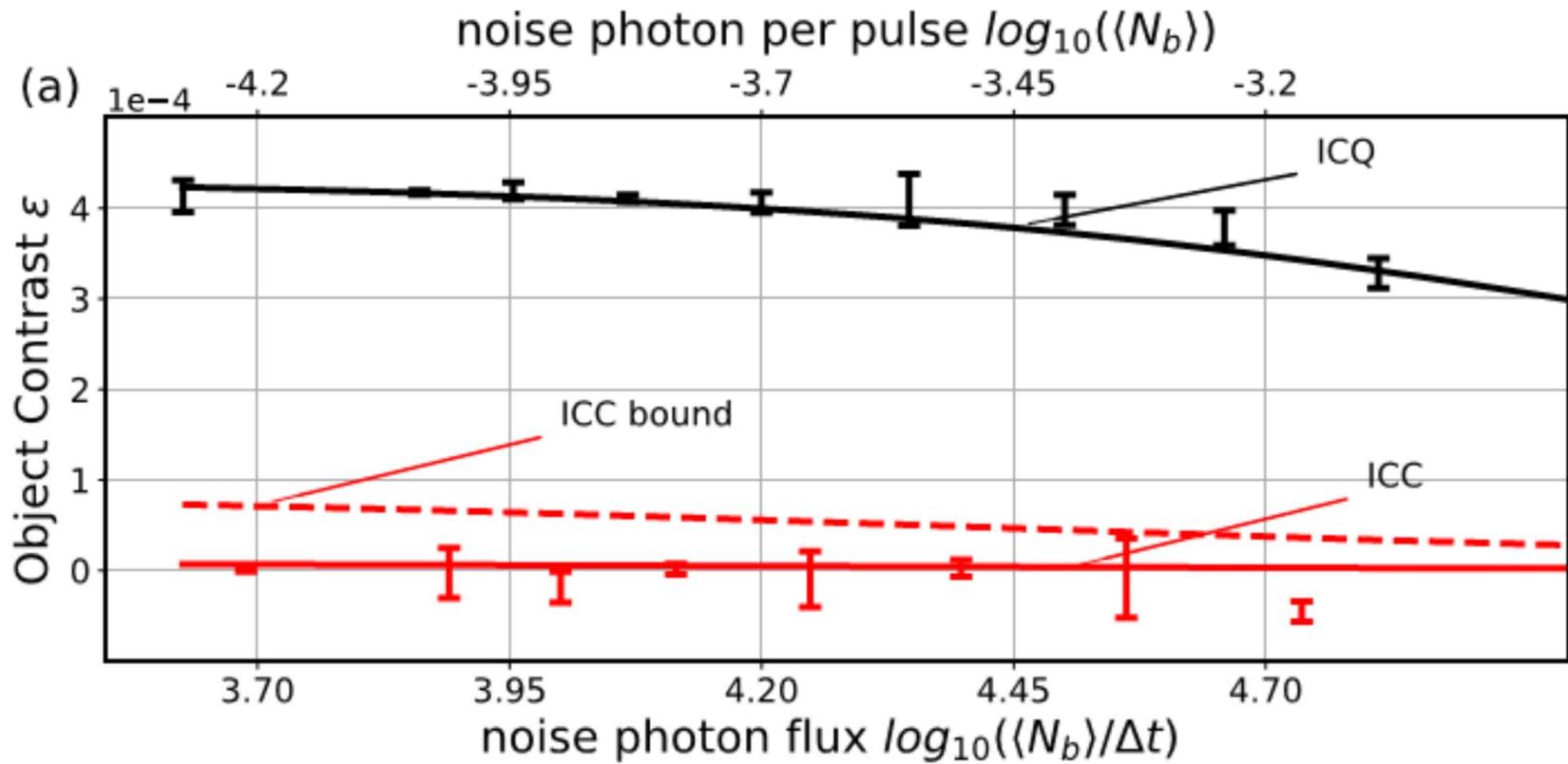
VISIBILITY AND LOSSES



VISIBILITY AND LOSSES WITH ADDED NOISE

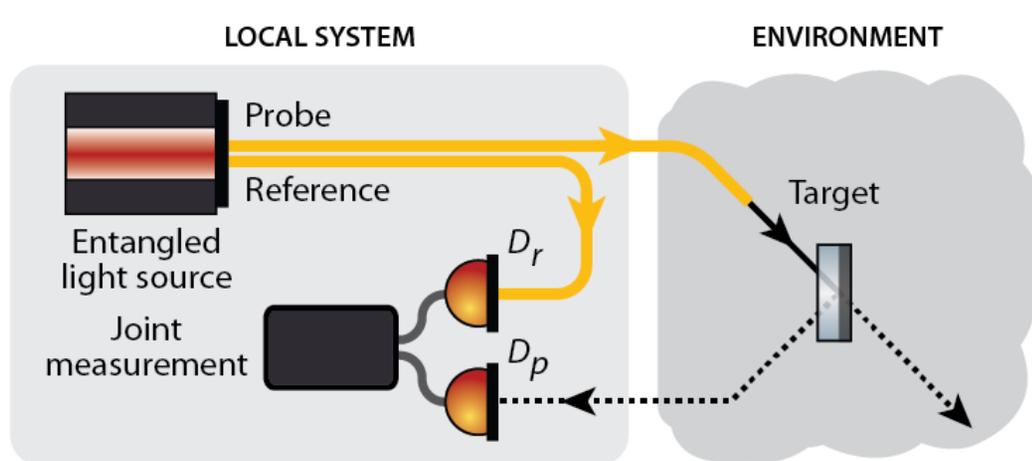


VISIBILITY AND NOISE

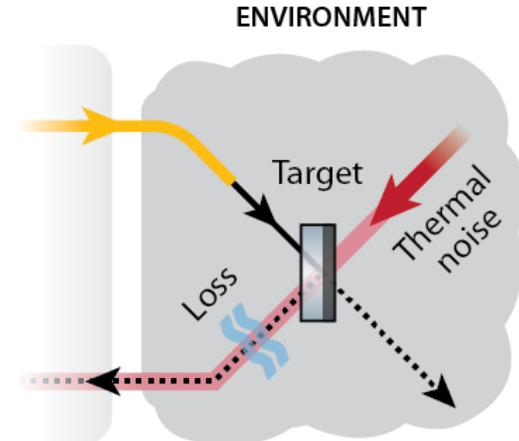


INTENSITY CORRELATION TARGET DETECTION SCHEME

- Performance comparison:
 - The ICQ scheme with photon pair source have significant advantage over the ICC scheme with correlated thermal source, in the low flux regime. The performance advantages persist even if there are high level of loss and noise.



18.57 dB quantum advantage over best theoretical CI scheme with no additional noise and loss
Background/signal = 7.66 dB



29.69 dB loss

13.40 dB noise

17.79 dB quantum advantage
(Noise + background)/signal = 13.40 dB

NON CLASSICAL SOURCE REQUIREMENTS

- What does quantum enhanced target detection tell us about the performance metrics from integrated sources
 - High Flux
 - Power handling capabilities of integrated sources
 - Compact sources or ones that can be efficiently connected to optical fibers
 - Non degenerate or Ghost imaging
 - High Heralding Efficiency
 - Usually tenable at low flux
 - Highly tunable and non-degenerate sources
 - Ghost imaging

TALK OUTLINE

GROUP STRATEGY

- TECHNOLOGY PLATFORM

SOURCES AND CIRCUITS FOR QUANTUM APPLICATIONS

- NON-CLASSICAL SOURCES

QUANTUM-ENHANCED TARGET DETECTION

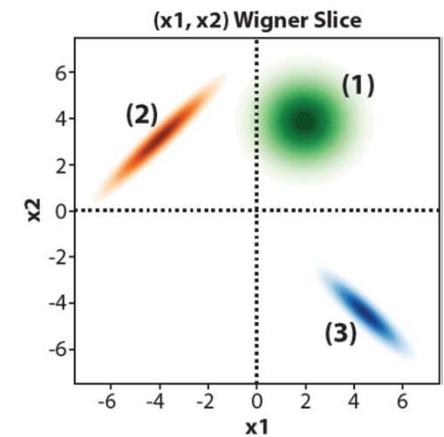
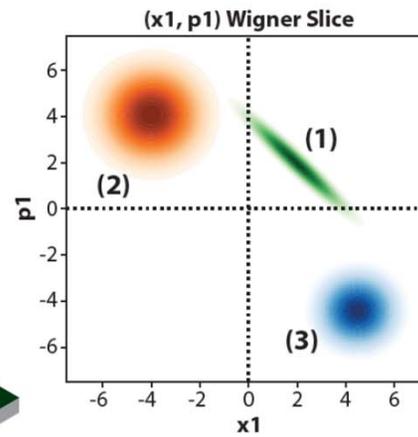
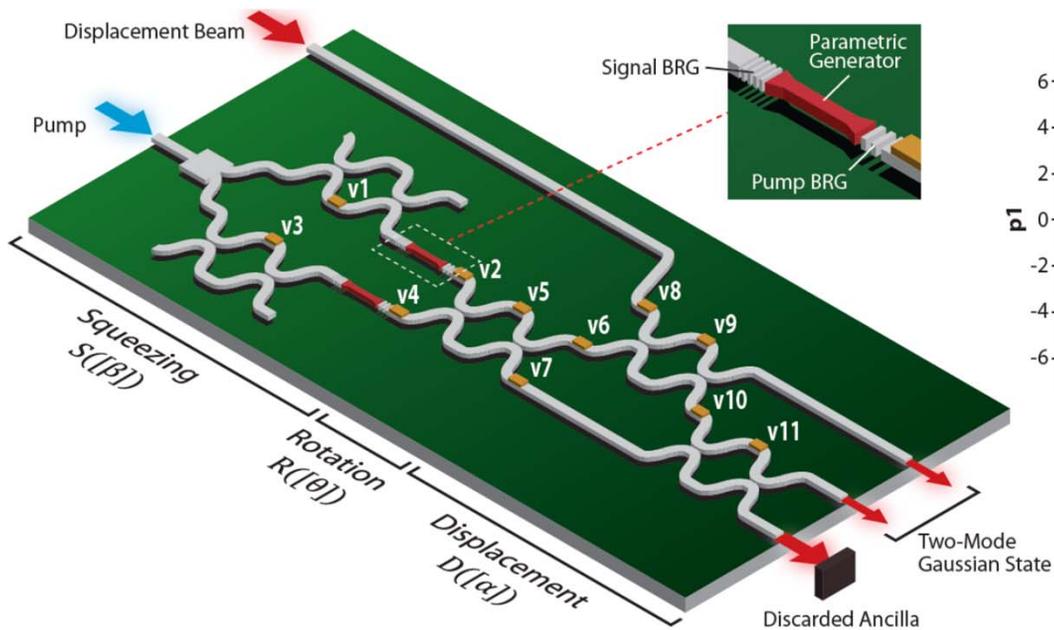
- PERFORMANCE AND FIGURES OF MERIT

SUMMARY



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FURTHER CAPABILITIES OF THE PLATFORM – CIRCUITS



Normalized Electrode Bias Voltages

State	v1	v2	v3	v4	v5	v6	v7	v8	v9	v10	v11
(1)	1	0.75	1	0.25	0	0	0	-0.25	0.25	-0.5	0.75
(2)	1	0.25	1	0.25	0.5	0	0	-0.75	0.75	0.5	0.5
(3)	0.75	0.25	0.75	0.25	0.5	0.5	0.5	0.25	1	0.5	1

SUMMARY AND OUTLOOK

- Provided an over view of the capabilities of this platform for quantum photonics circuits
 - The wealth of functional integration, scalability and efficiency are the highlights of the platform, but losses and in/out coupling remain a challenge.
- Demonstrated the performance of these sources in target detection applications
 - Enabled by long range loss behaviour