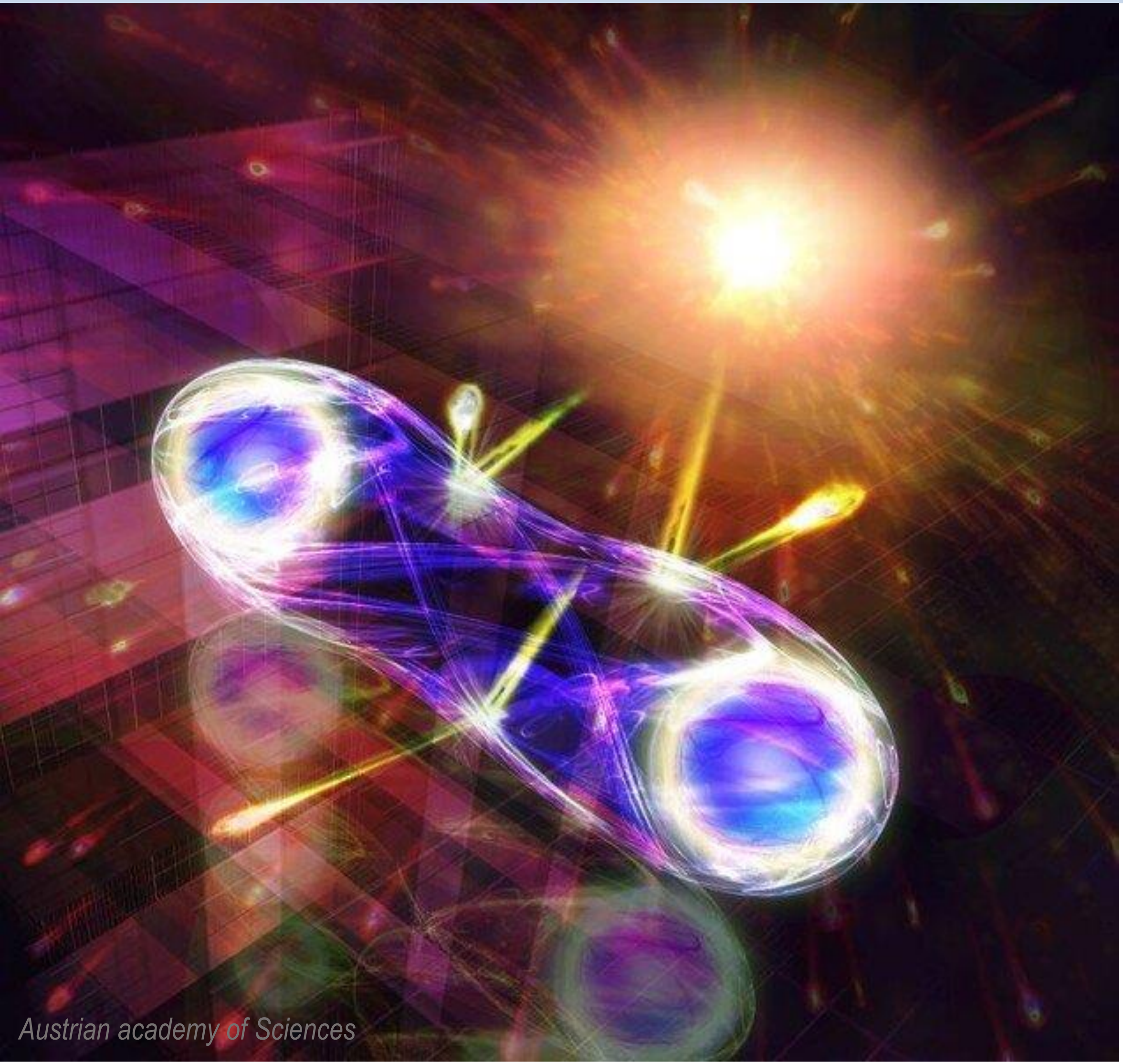
Entangled photon sources for free space and fiber based QKD

– Highlights from the Quantum Photonics Lab at IIT Delhi



Joyee Ghosh
Department of Physics, IIT Delhi

FIRST INTERNATIONAL QUANTUM COMMUNICATION CONCLAVE,
Vigyan Bhawan, 27-28 March 2023

Joyee GHOSH

Associate Professor

Physics Department

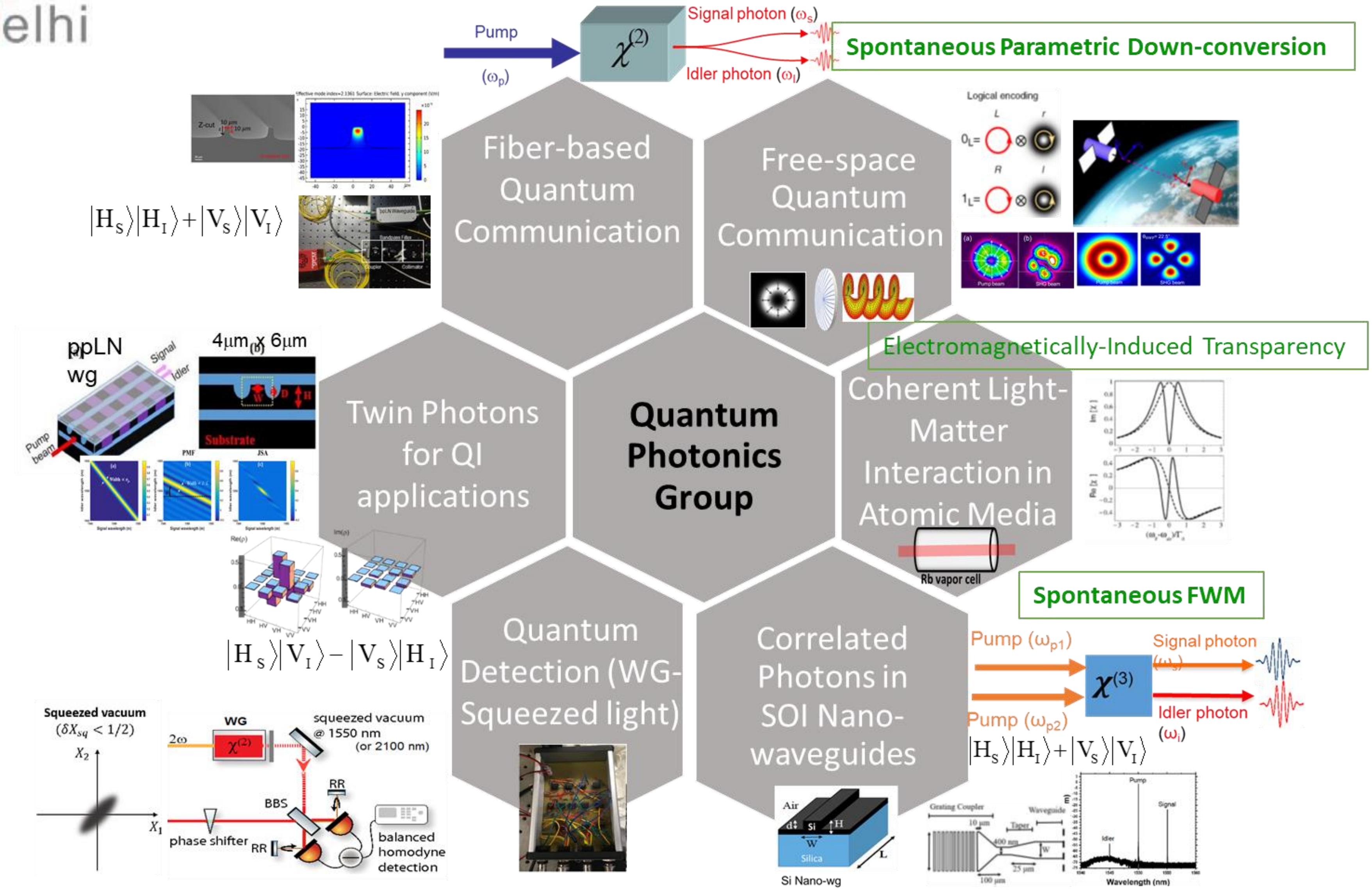
https://web.iitd.ac.in/~joyee/

iitdelhi

Quantum Photonics Group

Research interests: **Quantum & Nonlinear Photonics, Atomic Physics**

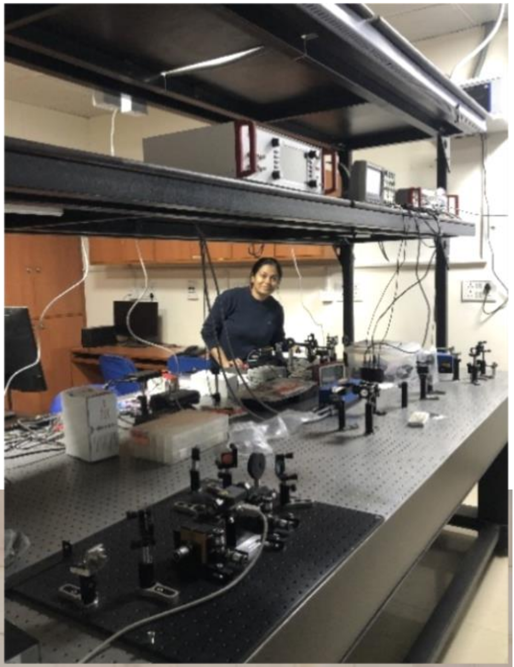
Quantum Technologies with "Single" and "Entangled" Photons



Quantum Photonics Group

Research interests: Quantum & Nonlinear Photonics, Atomic Physics
Quantum Technologies with “Single“ and “Entangled“ Photons

Faculty collaborator: **VV - Prof. Vivek Venkataraman** (EE, IITD)



<u>Group Members:</u>
- Shivani Sharma (JG+VV)
- Omshankar
- Rajni Bala (VV)
- Vikash Yadav (JG+VV)
- Akanksha Angural
- Bharti
- Vijay
- Kaustav Chatterjee
- Dr. Mitali Sisodia (postdoc)
- Dr. Vishal Sharma (postdoc)

Postdoc/ Past members:
- Dr Ingo Nosske (PTB Germany)
- Dr Arun Patel (Lecturer, DU)
- Dr. Ramesh Kumar (**PhD**, 2020, Asst. Prof. DU)
- Dr. Vineet Shukla (Asst. Prof. Raipur Engg. College)

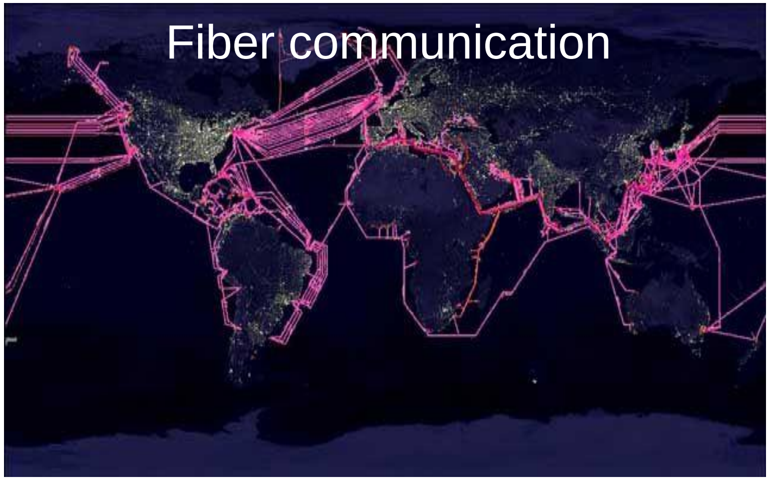
Quantum Communication

Optical band~700-850nm	Telecom band~1400-1600nm

- Free-space
- SPD: PMT (40%@500nm), Si-SPAD (80%@750nm), SNSPD (>90%): expensive

- Fiber-based
- SPD: PMT (2%@1550nm), InGaAs-SPAD (20%@1550nm), SNSPD (~90%@1550nm): expensive

https://in.pcmag.com

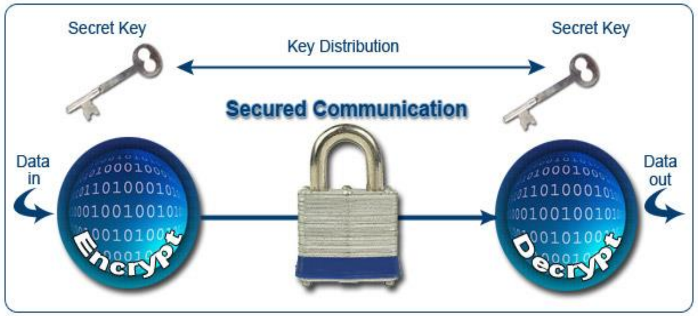


https://www.pinterest.com/pin/523965737871003374

Security Considerations in QKD

QKD protocols

C. H. Bennett and G. Brassard, Proc. IEEE Int. Conference on Computers, Systems and Signal Processing, Bangalore, India (IEEE Press, New York, 1984), 175.



No-cloning theorem

Measurement leads to state collapse

Measurements are irreversible

1) Prepare and Measure protocols (single-photon based)

- **BB84 Protocol (1984)** → Attenuated laser pulses
- **B92 Protocol (1992)**
- **4+2 Protocol (1995)**
- **Six- State protocol (1998)**
- **Decoy State Protocol (2003)**
- **SARG04 Protocol (2004)**

Attacks

- **PNS attack**
- **Intercept-resend attack**

2) **Entanglement based** protocols (entangled-photon based)

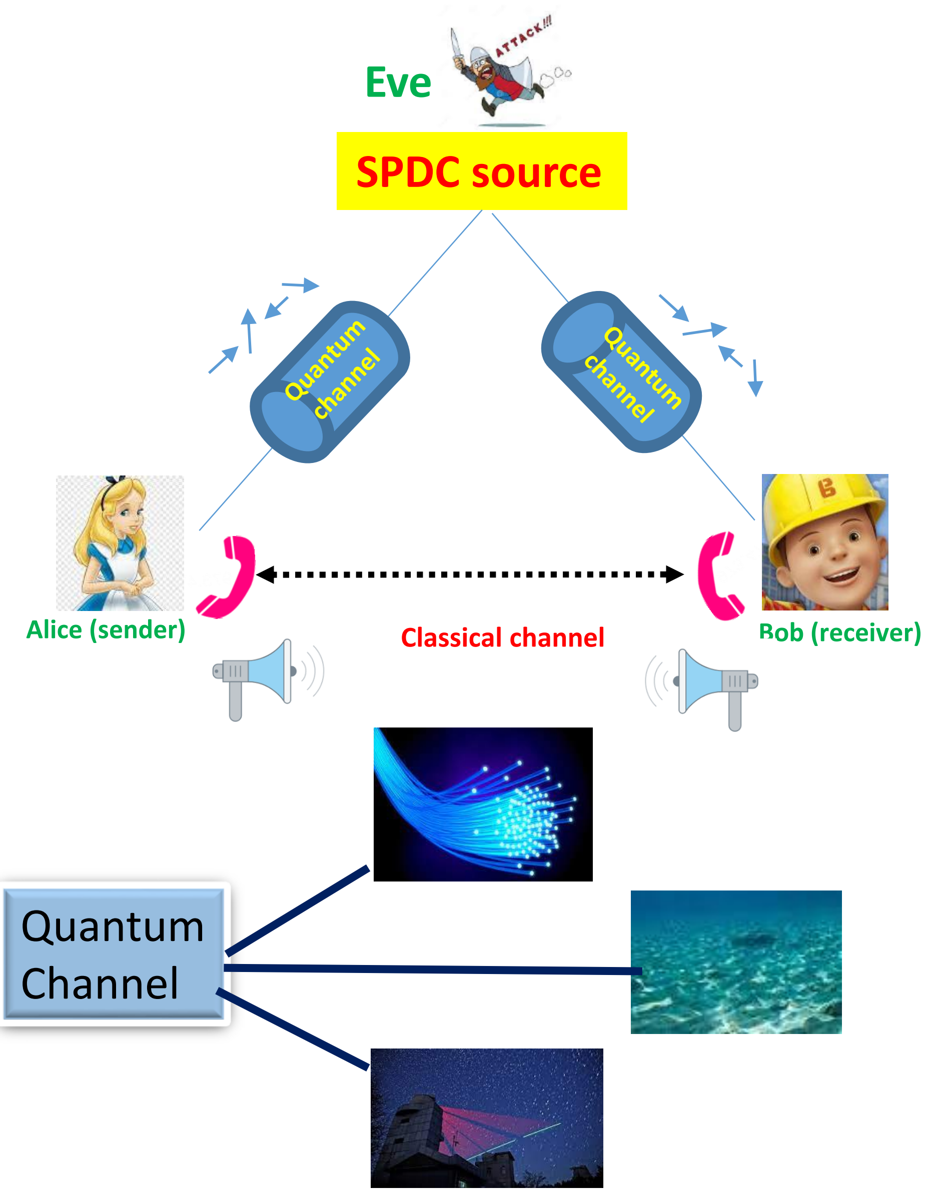
- **Ekert91 Protocol (1991)**
- **BBM92 Protocol (1992)**

Why?

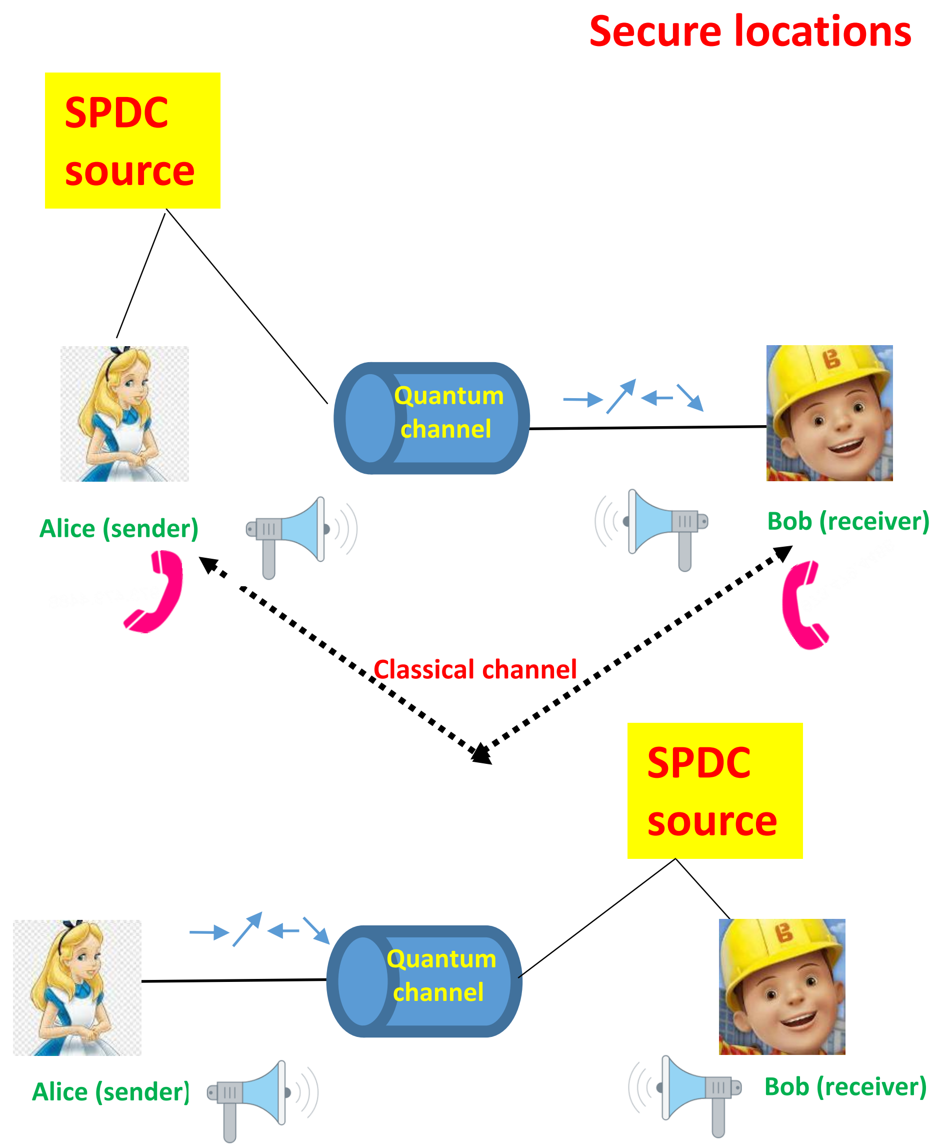
- True single/ entangled photon source
- Eavesdropping attacks
- Inherent randomness
- Longer transmission paths
- Inherent source-independent security
- Bell's inequality test

Entanglement - based QKD

Source in the middle



Source at Alice's or Bob's side

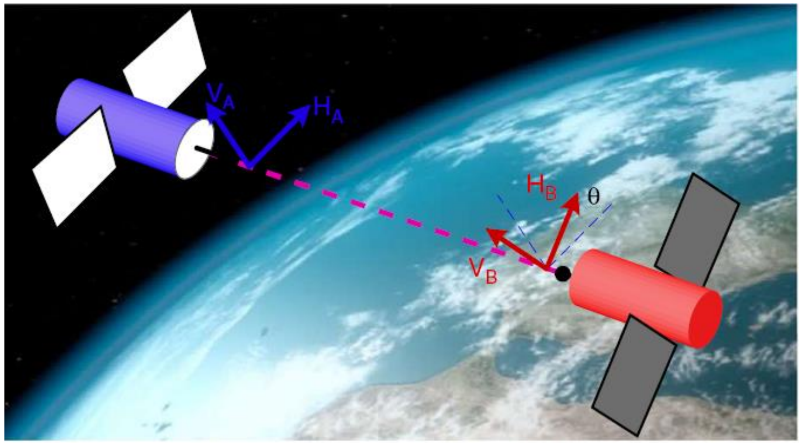


Quantum Technologies using Hybrid Photons for Secure Communication & Quantum Information

DRDO/DIA-CoE

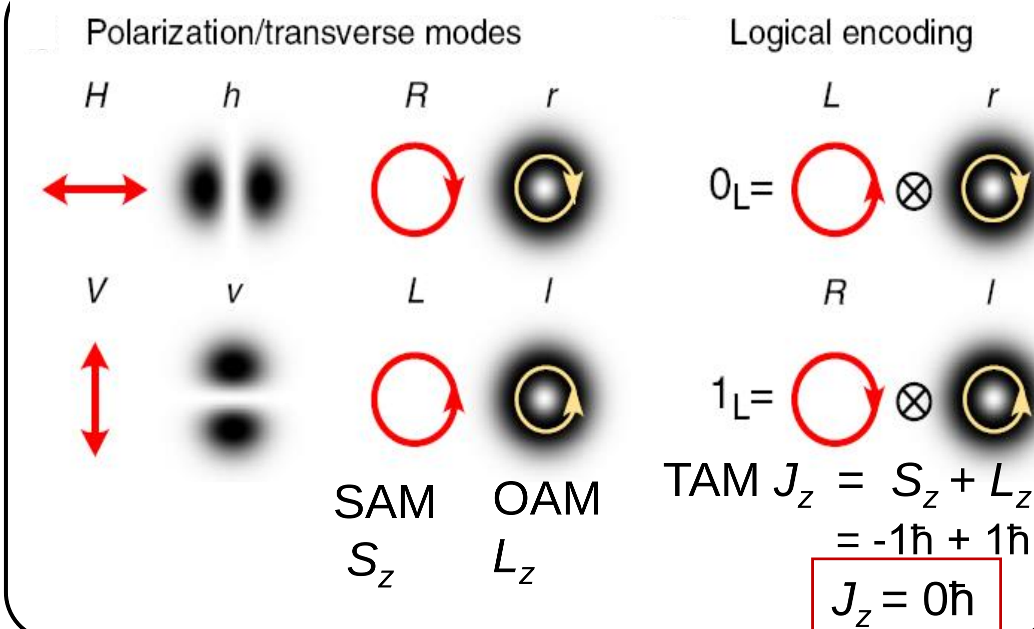
IITD

PI: Joyee Ghosh



Nature Communications 3, 961 (2012)

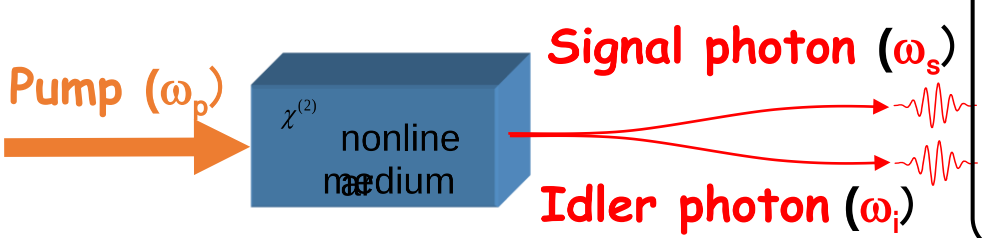
Rotationally-invariant Hybrid photons



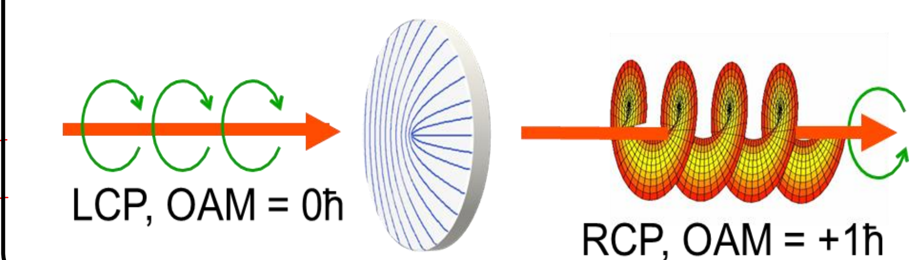
Generation of entangled photon pairs

→ Spontaneous Parametric Down-Conversion

→ simple, highly efficient, spectrally bright



OAM manipualtor → Encoder & Decoder



P2QP-7: Quantum Technologies using Hybrid Photons for Secure Communication & Quantum Information

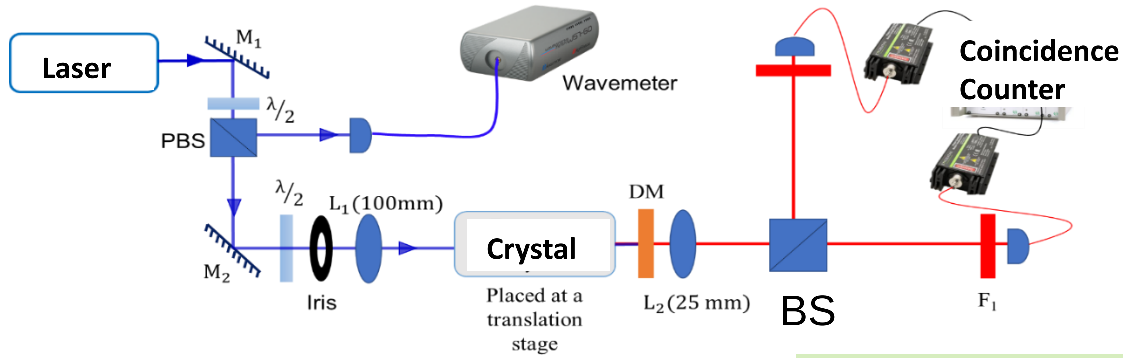
DRDO/DIA-CoE

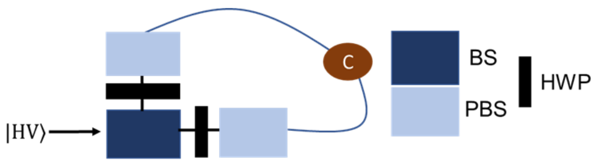
IITD

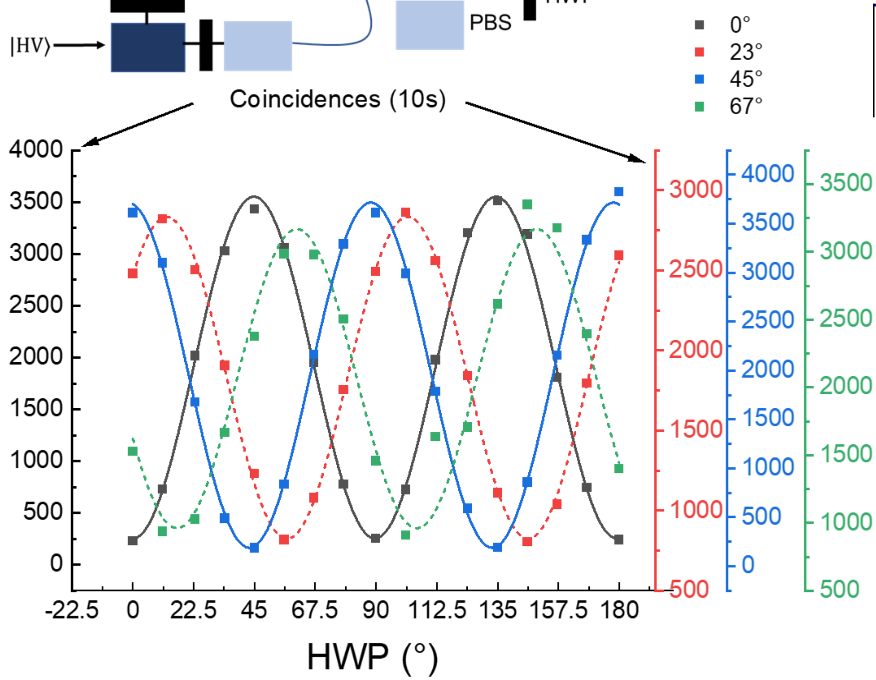
PI: Joyee Ghosh

Polarization-entanglement

$$|H_S\rangle|V_I\rangle + |V_S\rangle|H_I\rangle$$

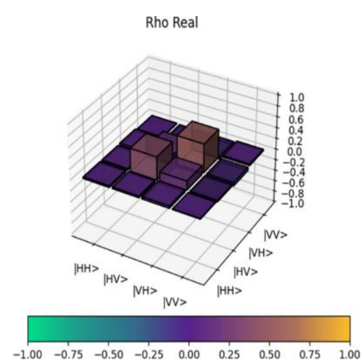






Max counts $\Delta\theta_{HWP} = 45°, 135°$

Min counts $\Delta\theta_{HWP} = 0°, 90°, 180°$



Publications:

1. **Journal of Optics (2023)** https://doi.org/10.1088/2040-8986/acc672
2. **Physical Review A 102,** 033722 (2020)
3. **Optik 247** 167970 (2021)
4. **Applied Physics B 127,** 167 (2021)

- Polarization entanglement → needs to be improved
- *Next steps*
  → Hybrid-Entanglement
  → Entanglement-based QKD

Department of Science and Technology (DST)

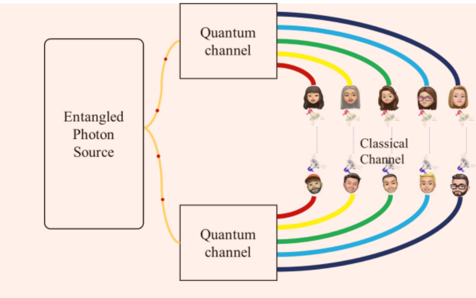
DST

Q-62: Integrated sources of entangled photons for quantum communication and quantum information applications

IITD

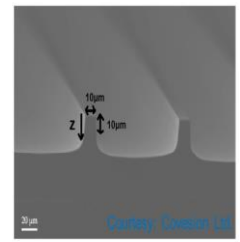
DST-QuEST

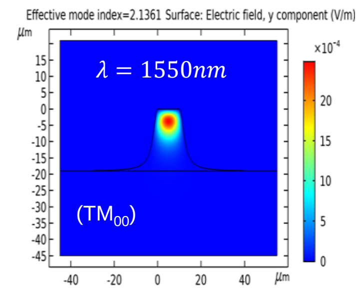
***PI:* Joyee Ghosh,** *Quantum Photonics Lab, Department of Physics, IIT Delhi*



All-fiber-integrated, WDM-based source of entangled photons towards multiuser QKD

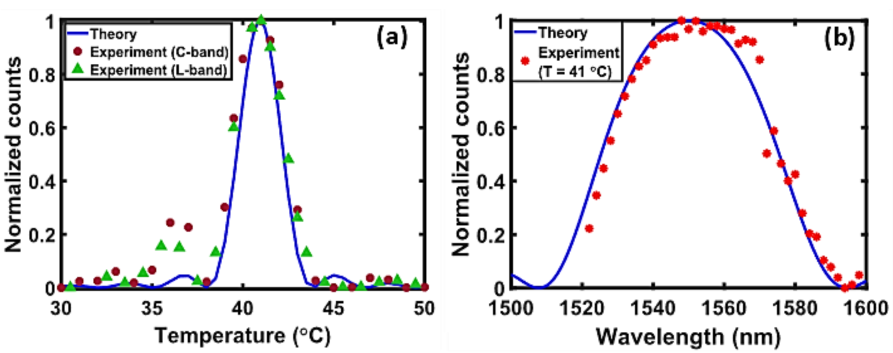
Zn-indiffused MgO:ppLN waveguide



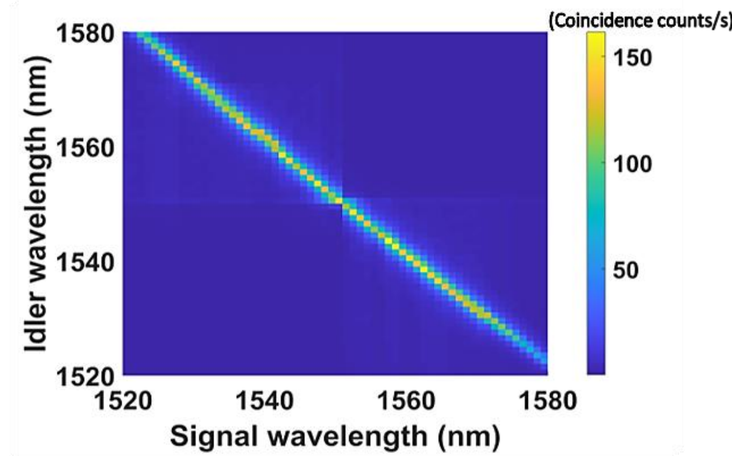


Broadband Telecom photons@1550nm

Generated Brightness ~ 10^7 pairs/s/mW/nm



Joint Spectral Intensity of Photon Pairs



হ্যাকারদের হারানো যাবে? কেলাস, লেজার রশ্মির খেল বাঙুরের মেয়ে জয়ীর -- সুজয় চক্রবর্তী কলকাতা ০২ ফেব্রুয়ারি ২০২১ ১০:২৯

Research highlight:
ABP news *(Ananda Bazar Patrika)* 2 Feb 2021:
https://www.anandabazar.com/science/dsts-quest-joyee-ghosh-using-crystal-laser-ray-to-make-hacking-free-telecommunication-dgtlx/cid/1263771

Publications:

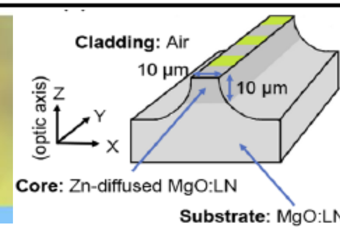
1. **Applied Physics B 126**, 186 (2020)
2. **Physical Review A 102** (3), 033722 (2020)
3. **Optik 247** 167970 (2021)
4. **Applied Physics B 127**, 167 (2021)
5. **Optics Letters 47(19)** 5132 (2022)

Happy to share Research Highlights in 2022 from the Quantum Photonics Lab at Physics, IIT Delhi. https://web.iitd.ac.in/~joyee/

Optics Letters 47(19) 5132 (2022)

5132 Vol. 47, No. 19 / 1 October 2022 / *Optics Letters* **Letter**

Optics Letters

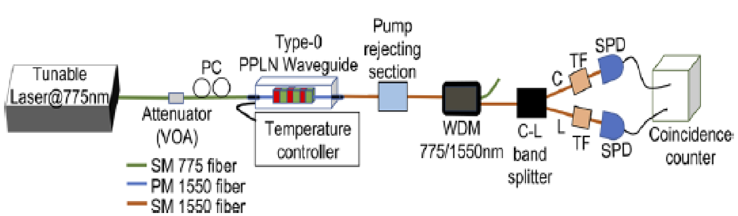


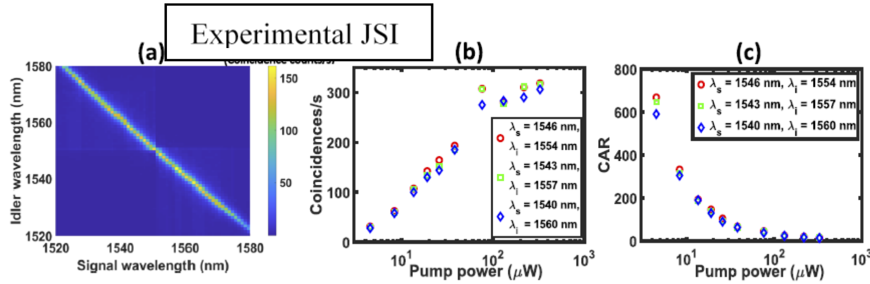
https://doi.org/10.1364/OL.472045

Broadband telecom photon pairs from a fiber-integrated PPLN ridge waveguide

Vikash Kumar Yadav,[1] Vivek Venkataraman,[1,2] AND Joyee Ghosh[1,*]

Experimental demonstration of a spectrally correlated photon-pair source at telecom wavelengths (FWHM > 45 nm spanning across the S-, C-, and L-bands), based on SPDC in a WDM based, all-fiber integrated PPLN ridge waveguide. Efficient photon-pair generation with a coincidence-to-accidental ratio (CAR) ~1322 and spectral brightness ~2.5×10^7 pairs/s/mW/nm. Such sources can be employed in wavelength division multiplexed (WDM) quantum key distribution (QKD) over existing fiber-optic networks.





सत्यमेव जयते
Department of Science and Technology (DST)
DST
DST-QuEST

Q-62: Integrated sources of entangled photons for quantum communication and quantum information applications

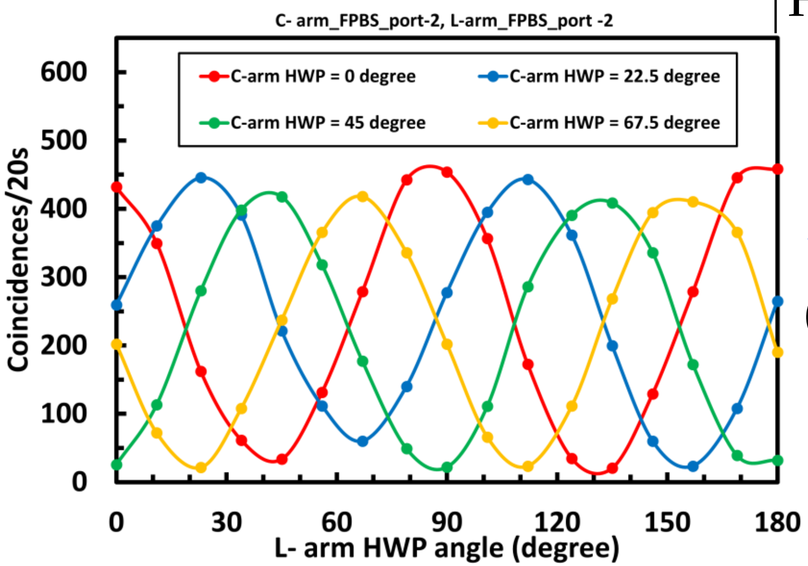
IITD

PI: Joyee Ghosh

$P_{in1} = P_{in2} \sim 5\mu W$
$\lambda_p = 775$ nm

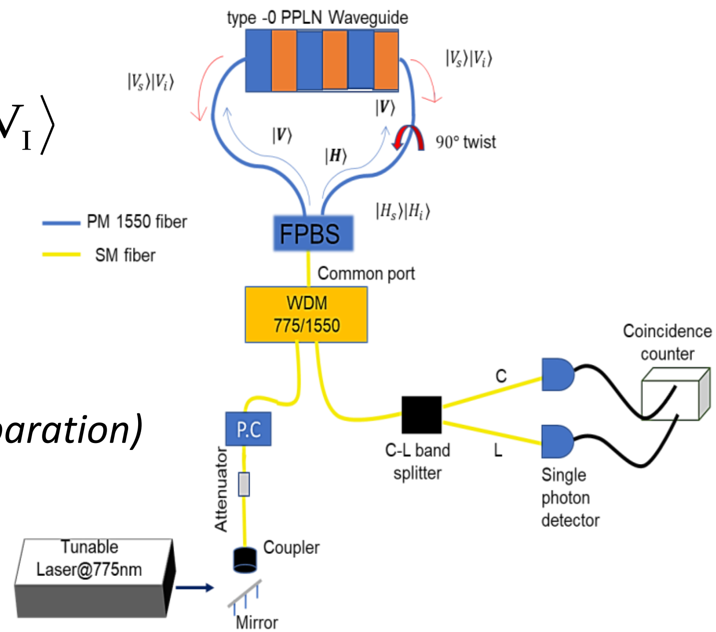
Polarization entanglement

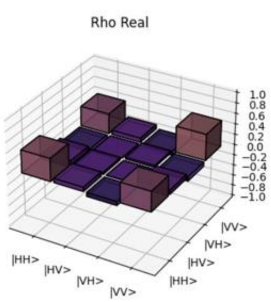
$$|H_S\rangle|H_I\rangle + |V_S\rangle|V_I\rangle$$

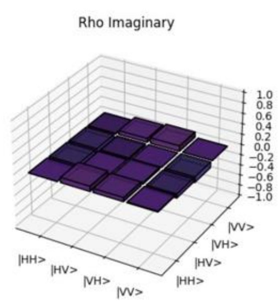


V. Yadav et al

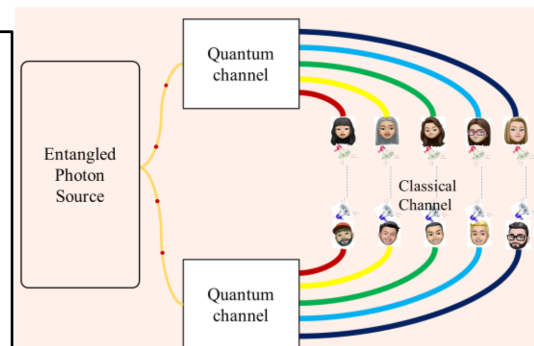
(manuscript in preparation)





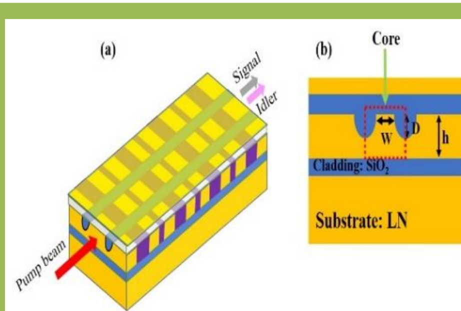


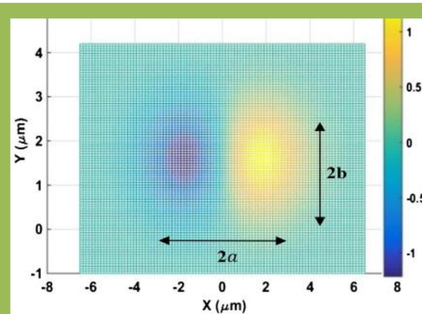
- Polarization entanglement → *achieved*
- Broadband & Individual channel entanglement → achieved
- *Next steps*
  → Entanglement-based QKD
  → Multi-user QKD



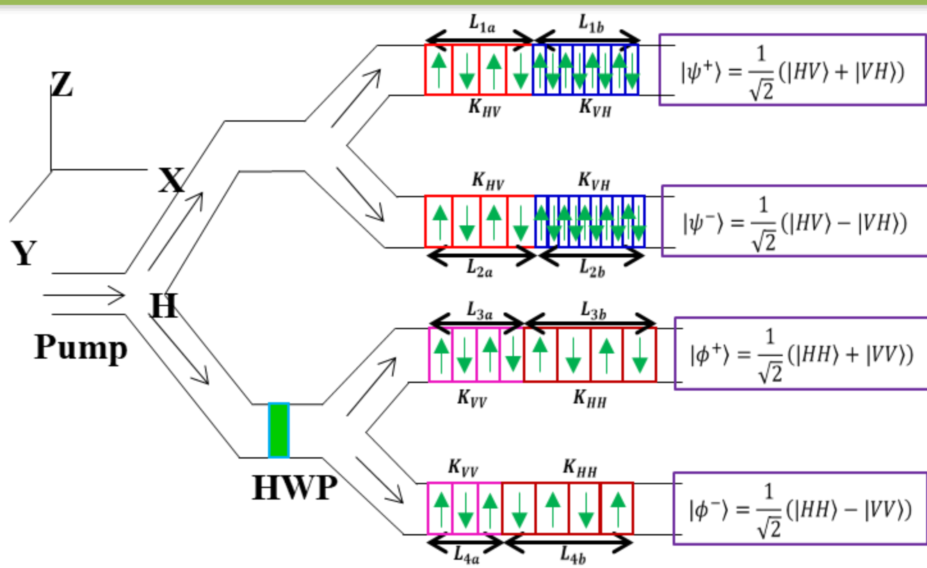
All-fiber-integrated, WDM-based source of entangled photons towards multiuser QKD

Integrated architectures in ppLN and ppKTP for generating entangled and hyperentangled photons

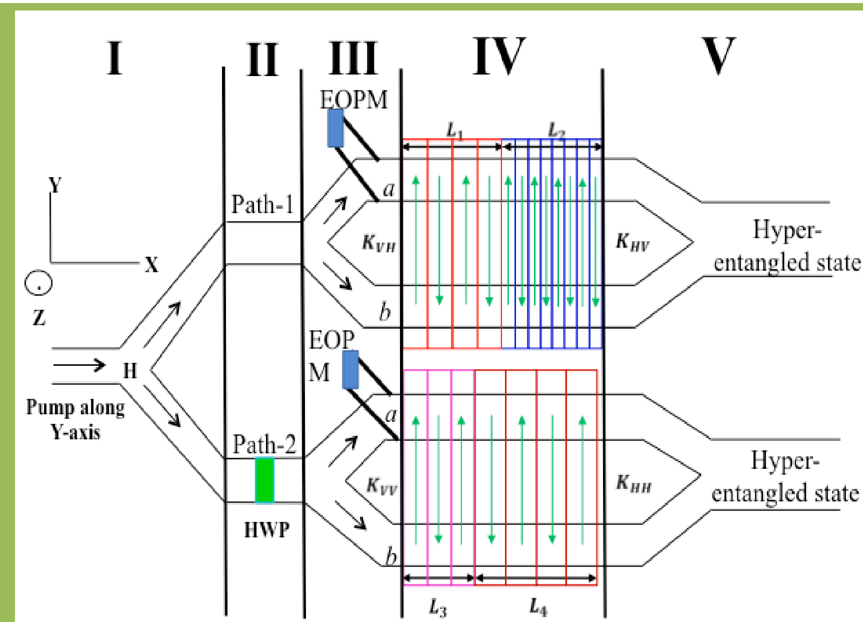




- ***Postselection-free***, ***hyperentangled*** *photon pairs in a* ***ppLN ridge waveguide***: ***Physical Review A*** **102, 033722 (2020);** Ramesh Kumar, V. K. Yadav and **Joyee Ghosh**
- *SPDC Photon Pairs Using a Spatially Anti-symmetric Pump Beam in a ppLN Ridge Waveguide*: ***Applied Physics B****: Lasers and Optics* **126**, **186 (2020);** Ramesh Kumar and **Joyee Ghosh**



- ***All-optical Bell states through a multi-poled, integrated*** *waveguide device:* **OPTIK 247, 167970 (2021):** Vineet K. Shukla & **Joyee Ghosh**
- *Polarization-entangled biphoton states: a comparison of biperiod waveguides in* ***KTP*** *and* ***LN***: **Applied Physics B: Lasers and Optics 127, 167 (2021)**; Vineet K. Shukla & **Joyee Ghosh**



- ***Waveguide-based swappable hyperentangled photon states*** *in a multi-period, postselection-free device:* ***Optik–J. Light and Electron Optics 262, 169304 (2022),*** **Vineet Kumar Shukla, Omshankar & Joyee Ghosh**

FWM: Si and SiN nano-waveguides

Telecom-Band Quantum Light Sources Using Dispersion-Engineered SOI Waveguides

Broadband photon pair generation: Spontaneous Four Wave Mixing

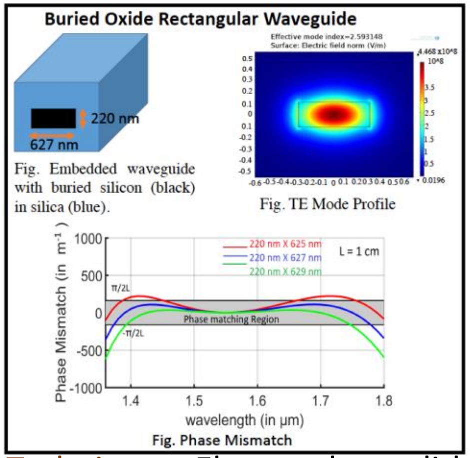
•*Spectrally-pure integrated telecom-band photon sources in silicon*, Shivani Sharma, Vivek Venkataraman, and Joyee Ghosh*, (**communicate**d 2021).

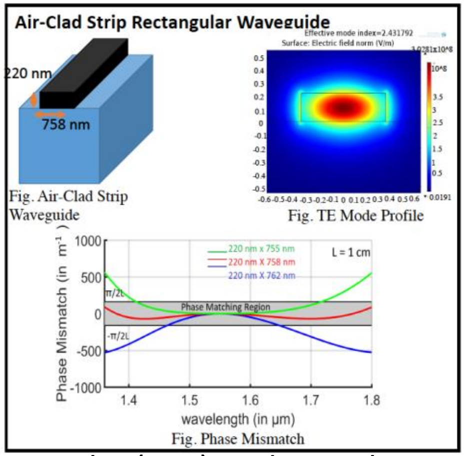
•Frontiers in Optics + Laser Science 2021 Technical Digest Series (Optica Publishing Group, 2021), paper JW7A.74 •https://doi.org/10.1364/FIO.2021.JW7A.74

• **IEEE Journal of Quantum Electronics 56**, No. 5, 8400508 (**2020**) *Nanowaveguide Designs in 220-nm SOI for Ultra-Broadband FWM at Telecom Wavelengths* -- Shivani Sharma, VB, PR, J. Ghosh & V. Venkataraman

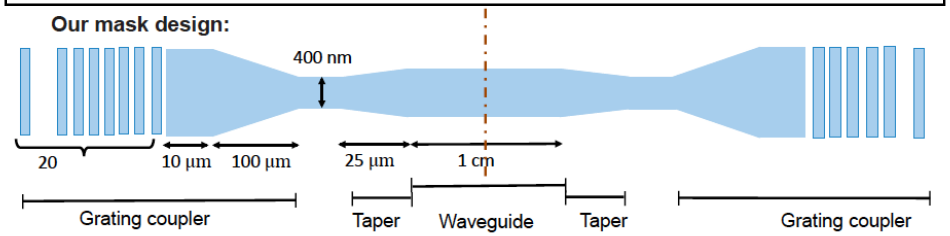
• OSI International Symposium on Light - IIT Kanpur (2018); **Photonics 2018** – IIT Delhi -- *Silicon Nanowaveguide Designs for broadband photon pair generation* Shivani Sharma, Vivek Bharadwaj, Pravin Rawat, V. Venkataraman & Joyee Ghosh

• **ICOL 2019, IRDE** Dehra Dun, paper FIN-pp-30 -*Telecom-Band Wavelength Conversion in Air-Clad Silicon Waveguides*, **Shivani Sharma**, A. Goswami, Joyee Ghosh, Vivek Venkataraman, Bijoy K. Das

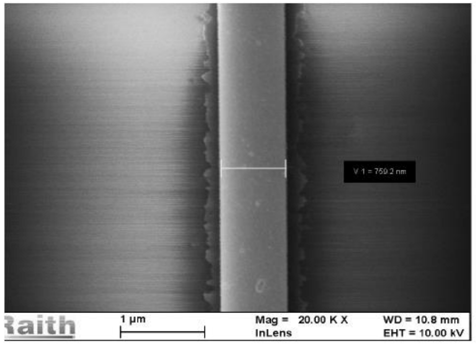




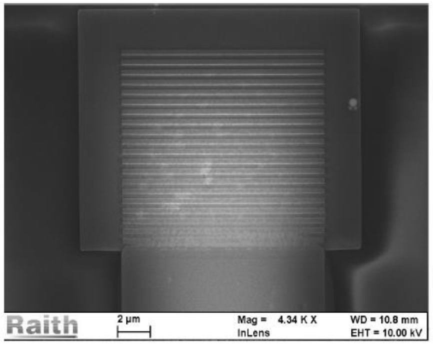
Techniques: Electron beam lithography (EBL), Inductively coupled plasma reactive ion etching (ICP-RIE)



Adiabatic taper: To ensure that only fundamental TE mode propagates



Waveguide with width W = 759.2 nm



Grating coupler

In collaboration with Prof. B. K. Das (IIT Chennai) & Prof. V. Venkataraman (EE, IIT Delhi)

A special tribute to this year's Nobel prize in Physics for **Entangled Photons**, from us!

Happy to share Research Highlights in 2022 from the
Quantum Photonics Lab at Physics, IIT Delhi. https://web.iitd.ac.in/~joyee/

Silicon photonic wires for broadband polarization entanglement at telecommunication wavelengths -- **Physical Review Applied 18,** 044043 (**2022**)

-- *selected as an Editors' Suggestion*. https://doi.org/10.1103/PhysRevApplied.18.044043


PHYSICAL REVIEW APPLIED

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Editors' Suggestion

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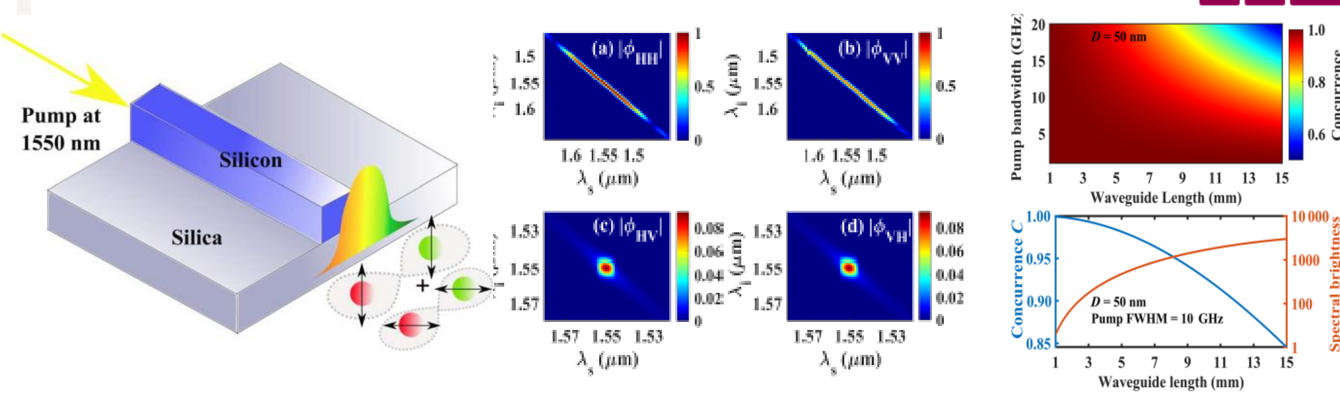
Silicon Photonic Wires for Broadband Polarization Entanglement at Telecommunication Wavelengths

Shivani Sharma, Vivek Venkataraman, and Joyee Ghosh
Phys. Rev. Applied **18**, 044043 – Published 18 October 2022

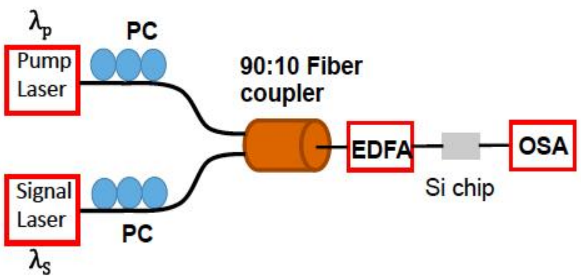
More

DOI:https://doi.org/10.1103/PhysRevApplied.18.044043

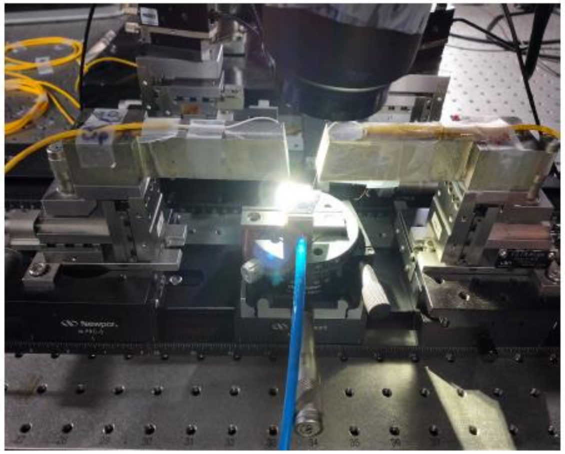


Selected as an Editors' Suggestion: Compact and scalable sources of broadband polarization entanglement at telecommunication wavelengths based on silicon photonic integrated circuits (Si PICs) will pave the way for multi-user long-distance quantum communication at enhanced data rates over the existing optical fiber network via WDM protocols. Progress towards this goal using the conventional silicon-on-insulator (SOI) platform has been hindered due to the large birefringence in such nano-waveguides. This work theoretically shows this limitation can in fact be overcome via careful dispersion engineering to achieve optimum waveguide dimensions that directly generate high-quality *polarization-entangled photon pairs using nonlinear wave-mixing* over a broad range of wavelengths, yielding sources operating across ~80 pairs of channels on the ITU (International Telecommunication Union) grid. Also demonstrated that the bandwidth of the input pump light needs to be limited to avoid degradation in the degree of entanglement due to PMD within the SOI nano-waveguide.

Experimental result: FWM signals

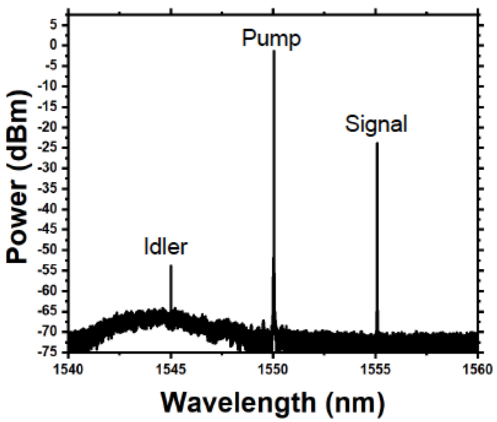


PC: Polarization controllers
EDFA: Erbium doped fiber amplifier
OSA: Optical spectrum analyzer

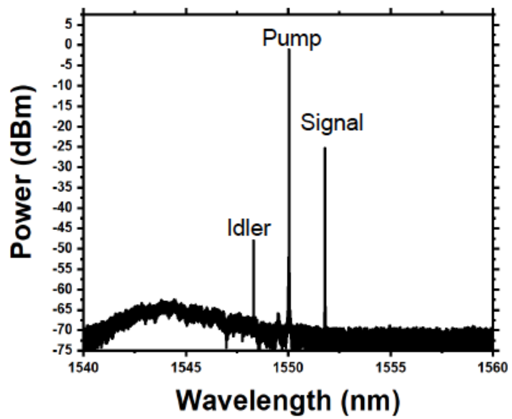


OSA output with tapered waveguide # 6

520 mW after EDFA
Detuning= λ_p-λ_s= 5 nm



900 mW after EDFA
Detuning= λ_p-λ_s= 1 nm



Telecom-Band Wavelength Conversion in Air-Clad Silicon Waveguides,
Shivani Sharma, Arnab Goswami, Joyee Ghosh, Vivek Venkataraman, Bijoy K. Das, ICOL 2019, IRDE Dehra Dun, paper FIN-pp-30.

Theory & Simulations

1. *Nanowaveguide Designs in 220-nm SOI for Ultra-Broadband FWM at Telecom Wavelengths* - Shivani Sharma, Vivek Kumar, Pravin Rawat, Joyee Ghosh, and Vivek Venkataraman, **IEEE Journal of Quantum Electronics 56**, No. 5, 8400508 **(2020**).

2. *Spectrally-pure integrated telecom-band photon sources in silicon*, Shivani Sharma, Vivek Venkataraman, and Joyee Ghosh **IEEE- Journal of Lightwave Technology,** 10.1109/JLT.2022.3188526, **(July, 2022).**

3. *Silicon photonic wires for broadband **polarization entanglement** at telecommunication wavelengths* -- Shivani Sharma, Vivek Venkataraman, and Joyee Ghosh, **Physical Review Applied 18**, 044043 (2022) – selected as Editor's Choice

Thank you for staying tuned!