Efficient Free-Space Multi-Spatial-Mode Optical Communication

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Photons as Information Carriers

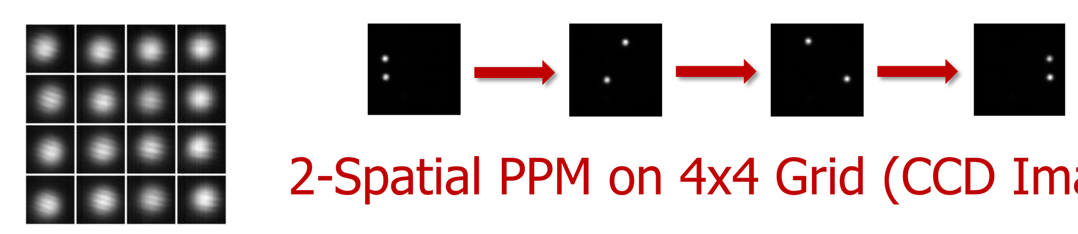
- Information can be stored and transmitted in the physical properties of light
- E.g.: polarization, frequency, time bins (pulses), spatial bins (pixels)
- Messages are sent by modulating this property and sending the photon through a physical channel
- E.g.: optical fiber, free space
- What is the information capacity of a photon?

Measures of Communication Efficiency

- Photon Information Efficiency (PIE): Information in a detected photon (in bits/photon)
- Spectral Efficiency (SE): Rate of information over limited bandwidth (in bits/s/Hz)
- Can we get both high PIE and high SE?

Spatial Pulse Position Modulation

- Use multiple spatial modes to increase information without using more spectral bandwidth
- Use fewer pulses (more SE), but use multiple spatial modes in each pulse (more PIE)
- The message is a train of time-modulated symbols
- The symbol is a grid of space-modulated pixels



2-Spatial PPM on 4x4 Grid (CCD Image)

Theoretical Possibilities [1]

- With 1.55 μm light and 7 cm apertures, this gives 10 bits/photon and 5 bits/s/Hz using 189 spatial modes and 200 MHz modulation
- This gives 1 Gbit/s with only 12.8 pW of power!

Requirements for Efficient Communication

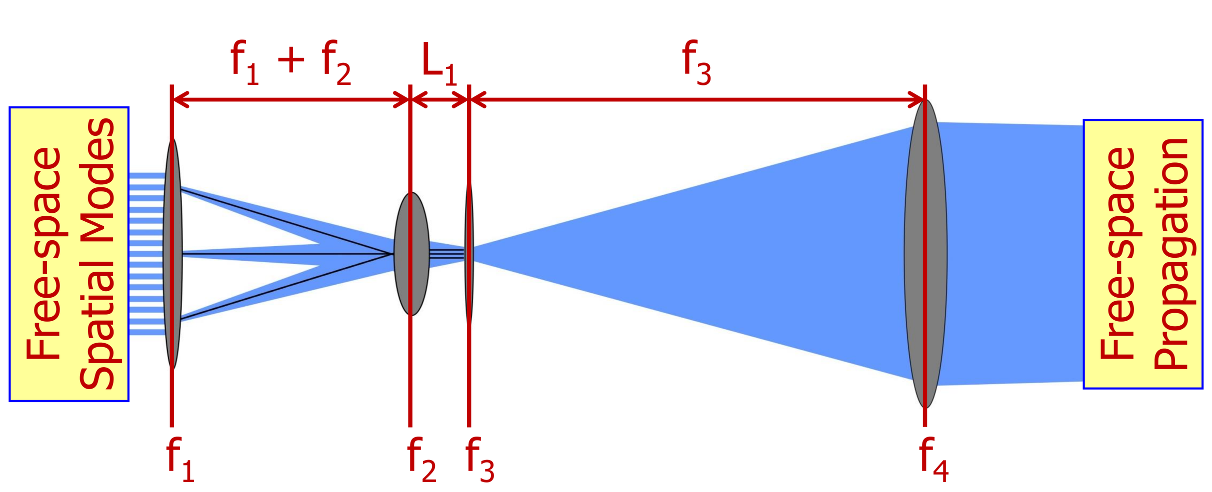
- Scalable transmitter design for transmitting single photons through large number of channels
- Scalable free-space optics design to image spatial symbol from transmitter to detector
- Scalable detector technology for large arrays that can detect single photons
- Dynamic switching to perform time modulation
- Error correcting codes to compensate for crosstalk, leakages, and loss

Experimental Goals

- Design transmitter and free-space optics
- Characterize errors and crosstalk
- Implement efficient codes with dynamic switching
- Test communication efficiency against theoretical predictions using single-photon receivers

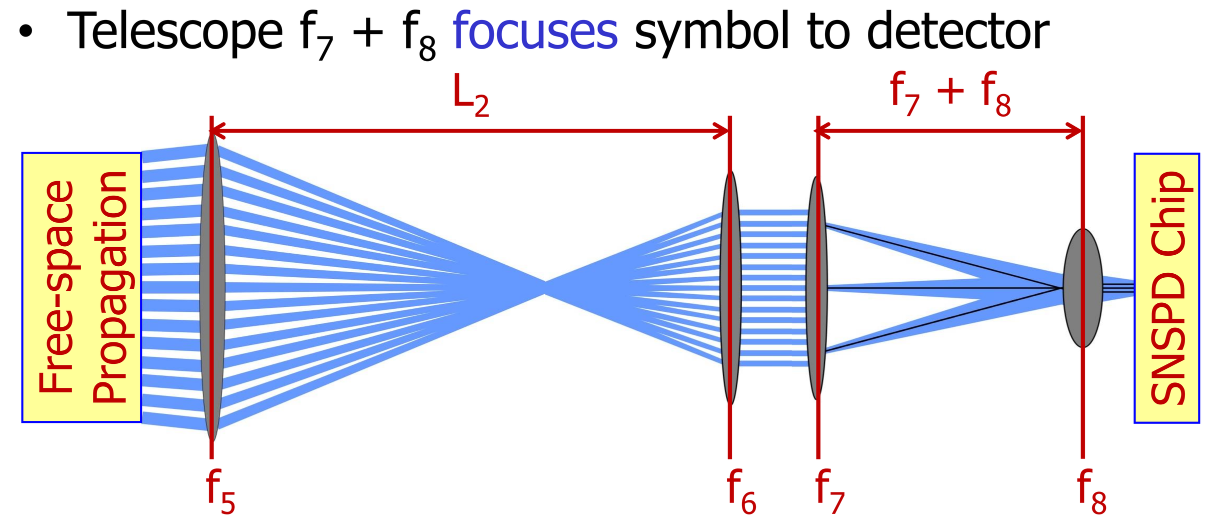
Transmitter-side Design

- Assume source of many spatial modes
- Telescope $f_1 + f_2$ demagnifies image by f_1/f_2
- Lens f_3 bends rays inwards to a point at f_4; beams expand to fill aperture lens f_4
- At transmitter aperture lens f_4, beams are large, centered, and overlapping, with different angles
- Lens f_4 sends output towards receiver
- Adjustable length L_1 used to adjust output collimation to focus at receiver



Receiver-side Design

- Beams arrive at receiver aperture lens f_5 separated and at different angles
- Adjustable length L_2 used to make beams parallel
- Telescope $f_7 + f_8$ focuses symbol to detector

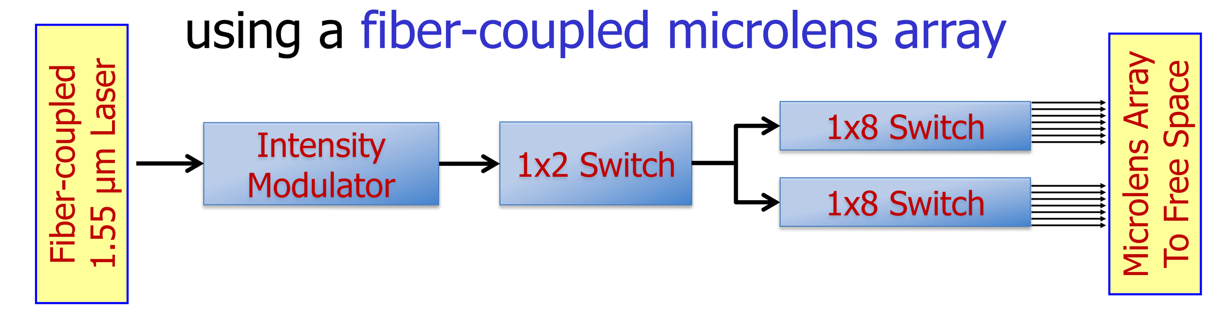


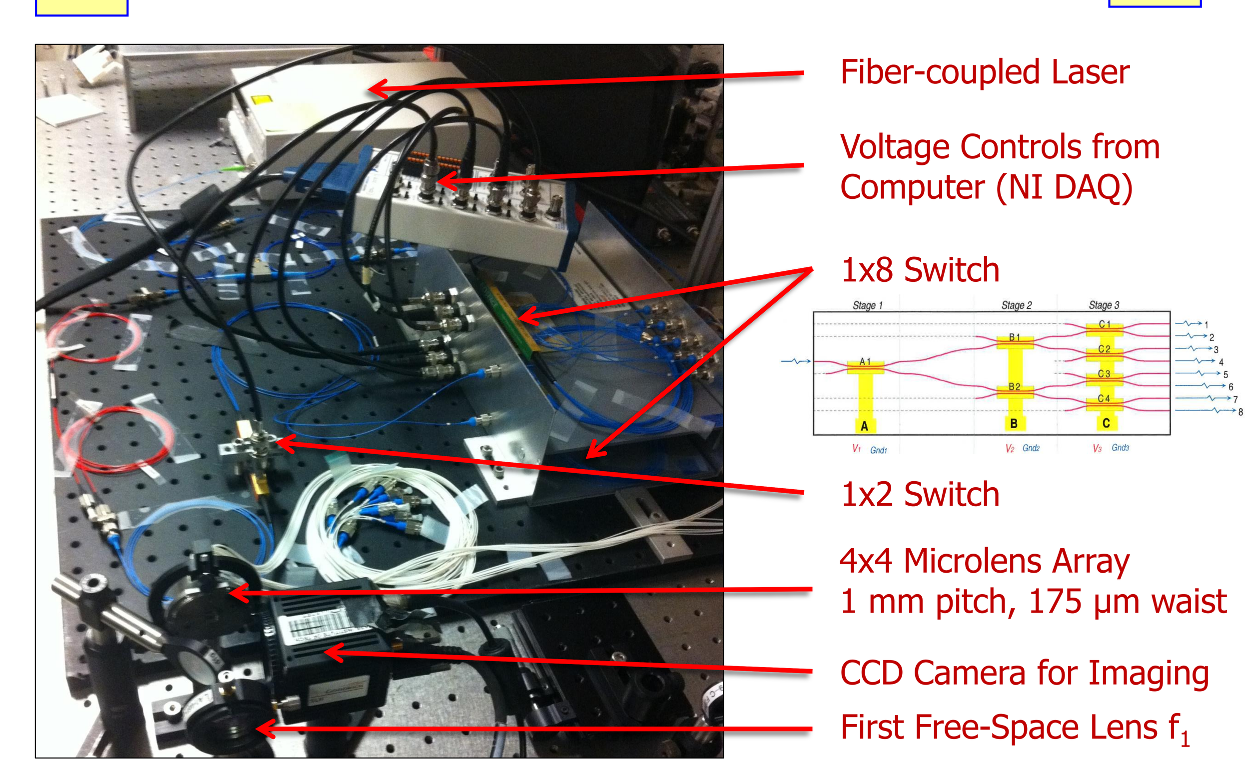
Detector Array Technology

- Need an array of efficient photon detectors to resolve spatial modes
- Solution: superconducting nanowire single photon detector (SNSPD) arrays

Generating Multiple Spatial Modes

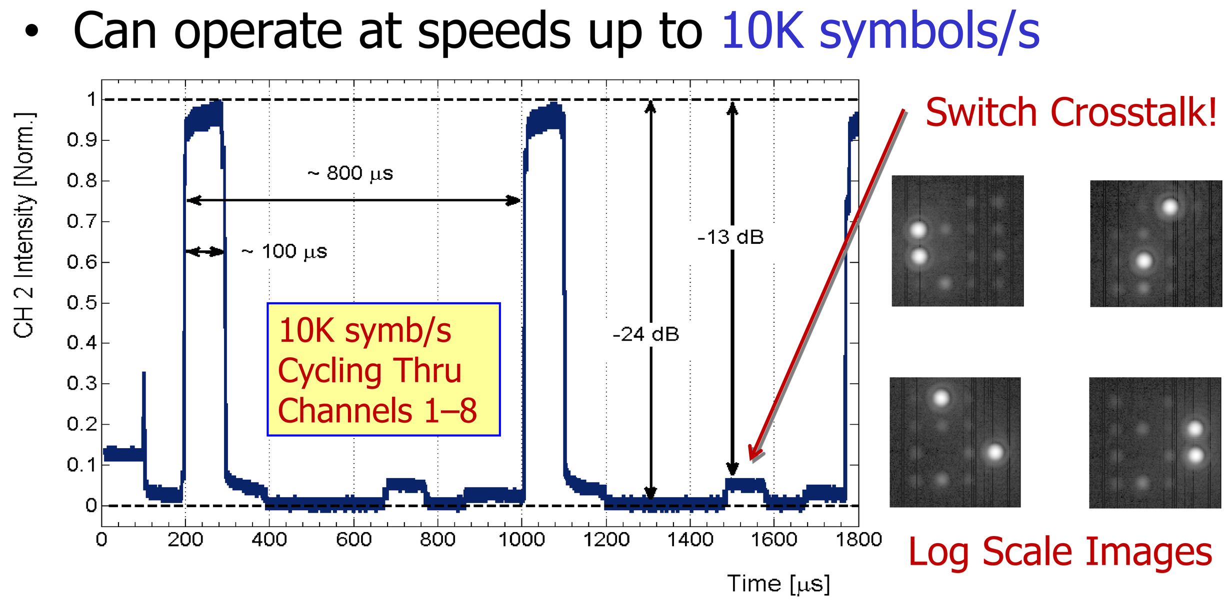
- In-fiber optical switching, then send to free space using a fiber-coupled microlens array





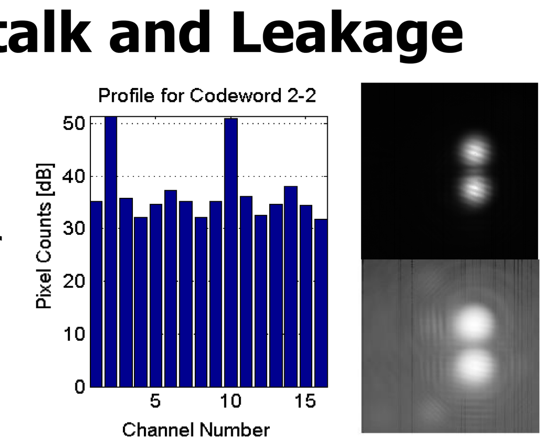
Dynamic Switching

- Control switch voltages using NI DAQ cards
- Can operate at speeds up to 10K symbols/s



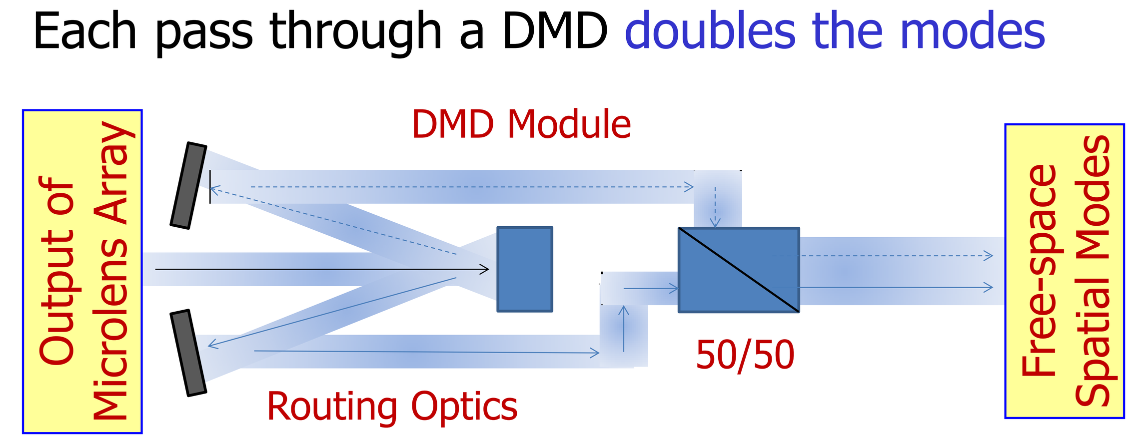
Characterizing Crosstalk and Leakage

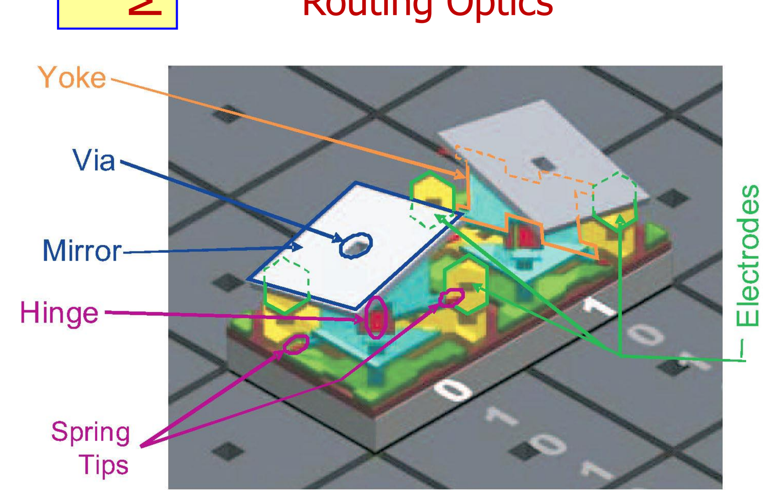
- Use CCD camera as spatial power meter
- Investigate tight packing of spatial modes: leakages



Scalable Multi-Mode Systems

- Fiber-coupled microlens arrays are effective but not scalable in cost for a large number of modes
- Solution: digital micromirror devices (DMDs)
- Each pass through a DMD doubles the modes





DLI 4130 (0.7" XGA)

Res: 1024 x 768
Pitch: 13.6 μm
Angle: ±12°
92% fill factor

Ongoing Research Goals

- Design DMD-incorporated transmitter system
- Implement FPGA dynamic control of switching
- Implement error-correcting coding to correct for crosstalk, leakages
- Perform bright-light testing of coding efficiency by simulating single-photon detection
- Demonstrate free-space coupling between transmitter and SNSPD receiver with 32 spatial modes at the single photon level
- Use two DMDs to go up to 64 spatial modes

References and Acknowledgement

[1] Guha, S., Dutton, Z., and Shapiro, J.H., "On quantum limit of optical communications…," Digest of the 2011 IEEE Internat. Sympos. on Inform. Theory, pp. 274–278 (IEEE, 2011).

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