Silicon Nitride Waveguide Design for Linear Optical Entanglement Swap

Tyrel Boese[1], Neshat Sadafi[2], Matt Eichenfield[2]

[1]Colorado Mesa University
[2]University of Arizona

Correspondence:
tjboese@mavs.coloradomesa.edu

Center for Quantum Networks
NSF Engineering Research Center

Highlights

- Interpreted and designed photonic entanglement swap circuit
- Optimized waveguide material and design
- Simulated multimode interference coupler using COMSOL and numerical methods

Abstract:
We design an integrated photonic circuit based on double-stripe silicon nitride waveguide geometry to implement entanglement swapping for quantum networking applications. The objective is a scalable, low-loss platform for high-fidelity photonic interference. To evaluate performance, we employ the effective index method to simulate components and taper transitions with reduced computational cost. We achieve a simulated transmission rate of 46.75% through the circuit, demonstrating the feasibility of integrated entanglement-swapping architectures in silicon nitride photonics.

Background:

Optical Entanglement Swap Circuit

A qubit is the basic unit of quantum information, analogous to a classical bit, but can exist in a superposition of states: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad |\alpha^2| + |\beta^2| = 1$

Entanglement is when two qubits are linked such that one's state can be inferred from the other, for example this Bell state:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

If we have two pairs of photons entangled A with B, and C with D, we can remotely entangle A&D together by performing a bell state measurement on B&C. This is 'Entanglement Swapping. To perform this measurement, the photon qubit pairs must be indistinguishable, therefore the information of which path they came from must be erased. This is done through Hong-Ou-Mandel interference – when the pairs are incident on a 50:50 beam splitter, they interfere with one another resulting in both photons exiting the same side of the beam splitter, regardless of their starting path.

Implications

Through entanglement swapping, two distant qubits can be remotely entangled. This would allow for increased scalability of quantum computers through distributed computing, as well as increased scalability of quantum networks through quantum repeaters.

Theoretical Design

Entanglement can be achieved with photons through several degrees of freedom, such as spatially, temporally (or time-bin), or most commonly through polarization. This design focuses on photon pairs encoded through their polarizations, with states:

$$|H\rangle \qquad\qquad |V\rangle$$

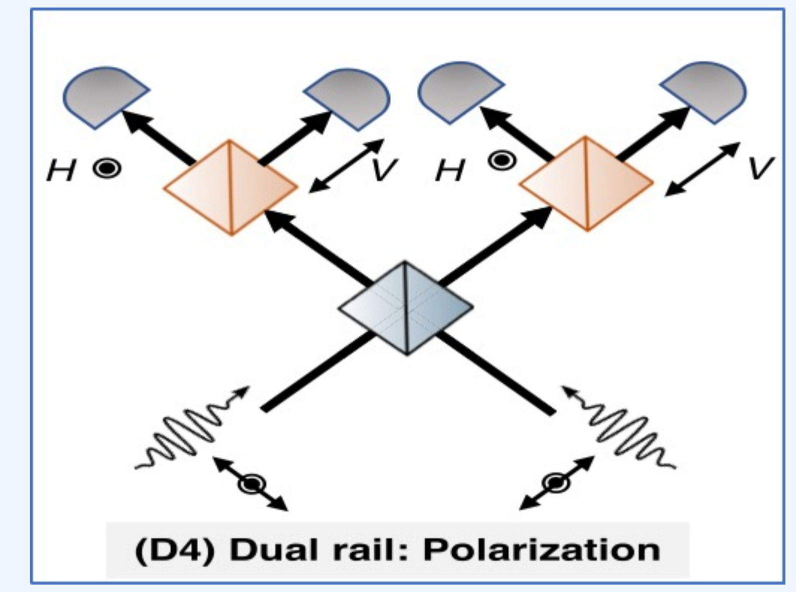
The qubit pairs are incident on a 50:50 beamsplitter, which leads them to polarizing beam splitters for measurement. The detectors give "click patterns" corresponding to the measurements – of 8 possible patterns, 4 of them correspond to a successful entanglement.

Functional Model

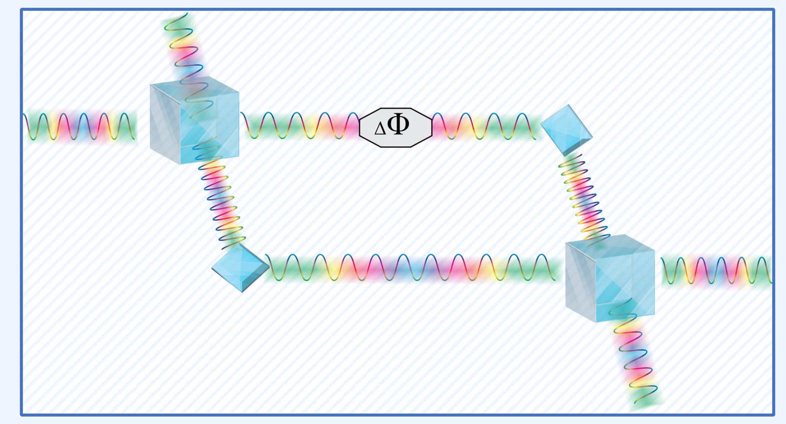
Integrated waveguides offer significantly lower optical losses and higher stability than bulk optics. Bulk optics components are translated to integrated photonic components; the beam splitters become multimode interference couplers.

Entanglement Swap Circuit [3]

- Two polarization entangled qubit sources are entangled with a Bell State Measurement after Hong-Ou-Mandel Interference.
- On successful entanglement, the two pairs will exit towards the same polarizing beam splitter, resulting in one of 4 click patterns, of a possible 8.



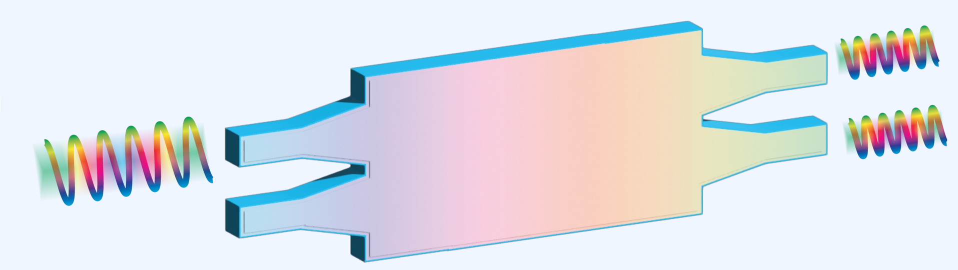
Mach Zehnder Interferometer (MZI)

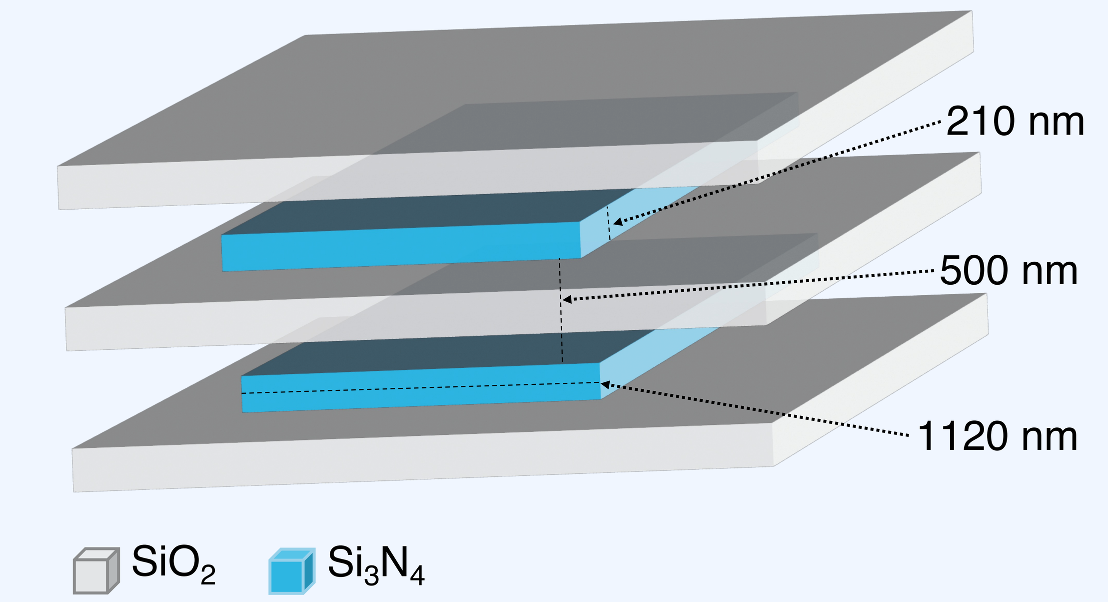


- Incoming light is split, a change in phase is caused in one arm, and then the light is recombined in another splitter.
- By controlling phase, one can mitigate the effects of manufacturing tolerance in a single input splitter, to maintain high fidelity.

Multimode Interference Coupler (MMI)

- Replaces the beam splitter in the design
- Uses the self-imaging effect to split power between its outputs
- Can also split polarizations of inputs using the birefringence of the material

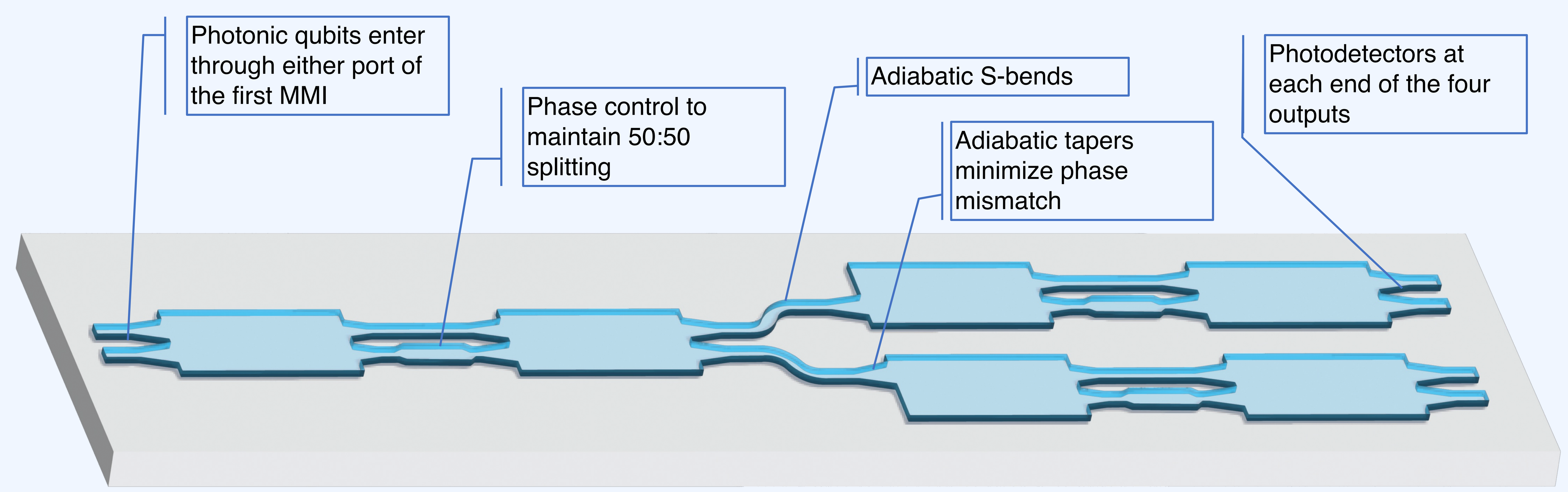




Dual Layered Silicon Nitride:

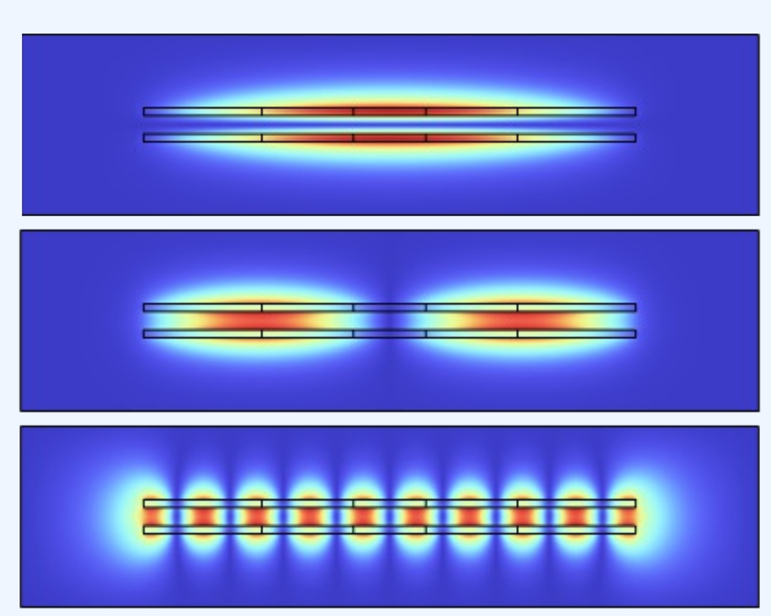
- Silicon Nitride (Si_3N_4) core layers inside of a Silicon Dioxide (SiO_2) Cladding.
- Low loss and CMOS compatible.
- Birefringence between transverse electric (TE) and transverse magnetic (TM) modes is low.

The refractive index of a material describes the speed of light in a material as compared to vacuum. Birefringence describes a difference in the effective refractive index of a material applied to different polarizations. This must be minimized in this design to maintain indistinguishability of the photon pairs for successful entanglement.

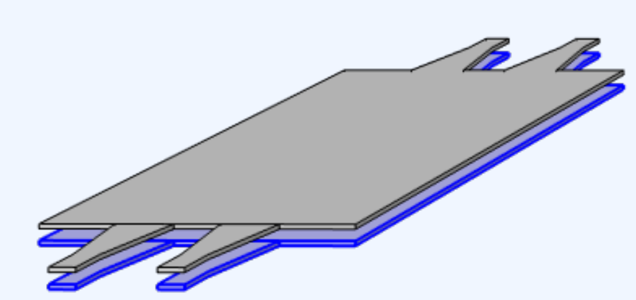


Photonic Circuit Design

- The theoretical design is implemented using Mach-Zehnder Interferometers built from multimode interference couplers.
- Dimensions of the couplers are separately optimized for polarization-insensitive splitting, and polarization sorting.



- COMSOL is used to simulate and visualize light propagation through the proposed multimode interference coupler.



Multimode interference Coupler COMSOL Simulation

- The Effective index method is used to approximate the behavior of the multimode interference coupler
- Transverse cross sections are simulated at key lengths to get an effective index of refraction.
- Using an interpolated function of these indices of refraction, an index is set for the longitudinal cross section simulation.

Results

- Using Effective Index Method, Transverse Electric (TE) electromagnetic waves in the fundamental mode (TE0) are found to have:

➢ **Transmittance: 46.75%**

Future Work

- Simulate both TE & TM modes in the multimode interference coupler
- Optimize dimensions for balanced 50:50 splitting as well as polarization splitting
- Simulate full circuit structure
- Fabricate the circuit and experimentally verify results

References

- [3]Dhara, P., Englund, D., & Guha, S. "Entangling quantum memories via heralded photonic Bell measurement." Physical Review Research (2023).
- Soldano, L. B., & Pennings, E. C. M. "Optical multi-mode interference devices based on self-imaging: Principles and applications." IEEE Journal of Lightwave Technology (1995).
- Chen, C.-L. "Foundations for guided-wave optics." (2006)

Acknowledgements

- The authors gratefully acknowledge financial support from NSF grant #1941583

Arizona · MIT · Harvard · University of Maryland · University of Massachusetts Amherst · BYU · University of Chicago · Howard University · Northern Arizona University · University of Oregon