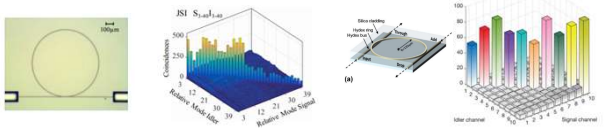
Randomized Tomography of On-Chip Biphoton Frequency Combs

Presenter: Karthik Myilswamy (Purdue) **PI:** Andrew M. Weiner (Purdue), Joseph M. Lukens (ORNL)

Motivation

- Generation of high-dimensional quantum states using microrings in a compact fashion



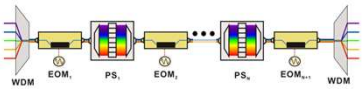
Silicon Nitride
50 GHz FSR

Imany, P., et al. Opt. Express **26**, 1825-1840 (2018)

Hydex
200 GHz FSR

Kues, M., et al. Nature **546**, 622-626 (2017)

- Frequency bin encoding allows versatile state manipulation with Quantum Frequency Processor (QFP)



Lu, H. H., et al. IEEE Photon. Technol. Lett. **31**, 1858-1861 (2019)

Previous Approaches

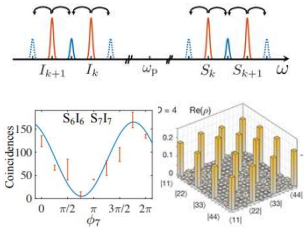
- Requires active mixing of frequency bins to quantify entanglement
- Tomography of higher dimensional states is challenging

Projective Measurements

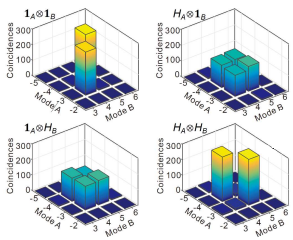
- Electro-optic modulation (EOM) used to generate overlapping sidebands
- Higher dimensions require aggressive amplitude filtering – reducing efficiency

Quantum Gates

- Synthesis of full quantum gates using QFP
- Higher-dimensional gates require many optical elements



Imany, P., et al. Opt. Express **26**, 1825-1840 (2018)



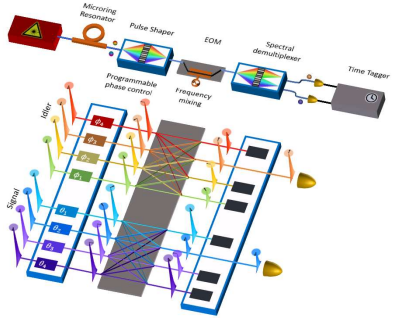
Kues, M., et al. Nature **546**, 622-626 (2017)

Lu, H. H., et al. Optica **5**, 1455 (2018)

- Both approaches are ill-suited to single-frequency EOM

Our Method: Randomized Measurements

- Our approach leverages complex EOM mixing to realize randomized measurements



Randomized Operation

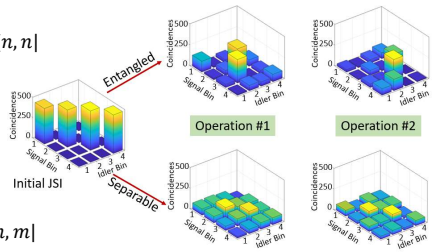
Consider our input state with 2d frequency bins (d=4 in illustration)

- Apply random, spectral phase functions with a pulse shaper
- Apply a single-tone, sinusoidal modulation with an EOM with a random modulation depth δ
- Collect coincidence counts between all d^2 frequency bin-pair combinations.

Bayesian Reconstruction

- Separable and entangled states result in strikingly different joint spectral intensity (JSI) patterns after a randomized operation

$$\rho_{ent} = \frac{1}{d}\sum_{m,n=1}^{d} |m,m\rangle\langle n,n|$$



$$\rho_{sep} = \frac{1}{d}\sum_{m=1}^{d} |m,m\rangle\langle m,m|$$

- **Bayes' Rule:** Given the set of quantum operations applied and their correlation measurements, we employ Bayesian estimation techniques to reconstruct the density matrix

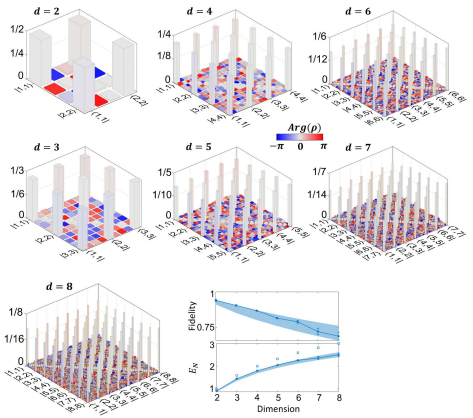
$$\Pr(x|\mathcal{D}) = \frac{\Pr(\mathcal{D}|x)\Pr(x)}{\Pr(\mathcal{D})}$$

- x: unknown parameters used to characterize density matrix
- $\mathcal{D}$: A set of observations
- $\Pr(\mathcal{D}|x)$: Incorporates the physical model
- $\Pr(x)$: Any prior information about x

Lukens, J. M., et al., New J. Phys. **22**, 063038 (2020)

Results: Reconstructed Density Matrices

- Reconstruction performed up to d=8 (record high in frequency encoding)



- E_N : Log-Negativity (an entanglement metric)
- Shaded region – theoretically estimated

Conclusion

- In summary, we have completely characterized on-chip biphoton frequency combs generated from a Si_3N_4 microring resonator, up to record-high dimensions, using a novel measurement technique and Bayesian inference.

Refer to our article for detailed discussions:
"**Bayesian tomography of high-dimensional on-chip biphoton frequency combs with randomized measurements**" *arXiv preprint arXiv:2108.04124* (2021).

Acknowledgements

- Collaborators (Si_3N_4 MRR Fabrication): Junqiu Liu, Tobias Kippenberg (EPFL)
- Team Members: Hsuan-Hao Lu (Purdue), Ryan Bennick (ORNL), Suparna Seshadri (Purdue), Mohammed Alshaykh (Purdue)
- Sponsors:

National Science Foundation WHERE DISCOVERIES BEGIN