Quantum walk and bend-free coupling in commensurable waveguide arrays

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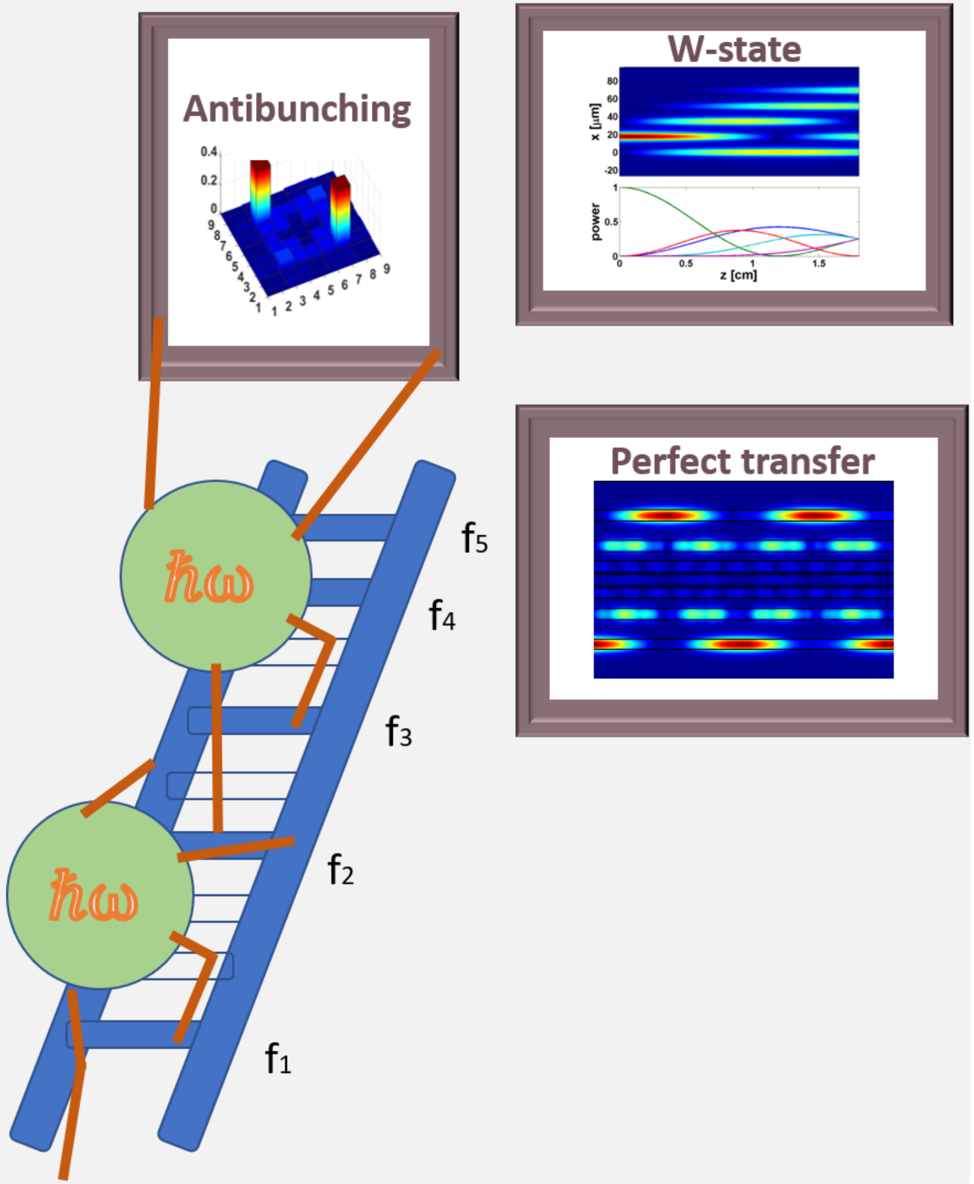
Problem:
If the quantum photonic integrated circuits (PICs) could be constructed solely of waveguide arrays, how would their building blocks look like?

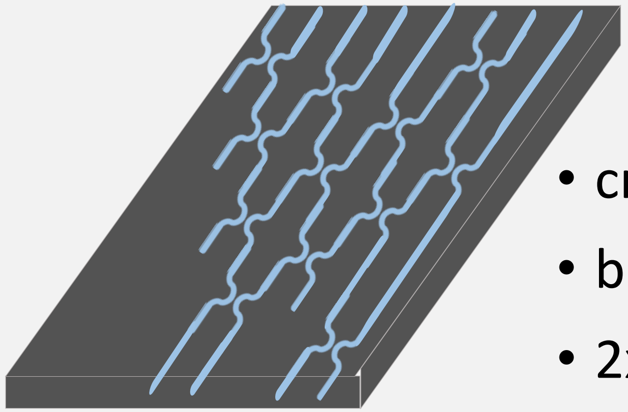
Method:
It is argued that the waveguide arrays with commensurable eigenfrequencies satisfy requirements for the basic passive building blocks.

Results and discussion:
Different Wannier-Stark ladder climbing strategies are employed to construct interconnects and couplers capable of the high-fidelity coherent transfer and entanglement generation.



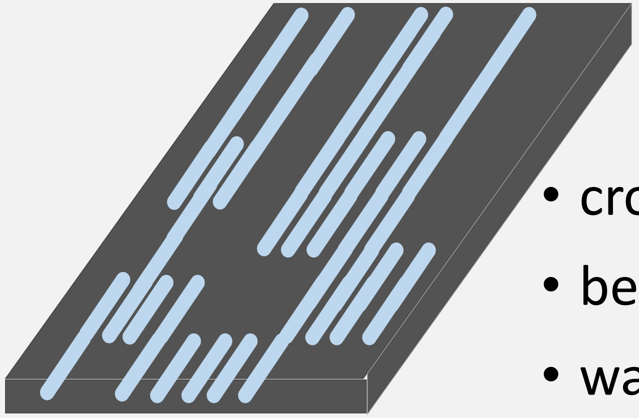
Bend-free photonic integrated circuits

State-of-the-art



- crosstalk scrambling
- bend-induced losses
- 2x2 directional couplers

Vision



- crosstalk leverage
- bend-free
- waveguide arrays (WGA)

Building blocks

- Interconnects
- Splitters
- Couplers
- Quantum-state generators

← Unrestricted AI-aided design

← **Restricted exact solutions**

Functional requirements

- Perfect transfer of information
- Meaningful splitting ratios
- Entanglement preservation
- Coherence preservation
- Scalability

WGAs with commensurable spectra

- A possible solution are WGA with commensurable eigenspectra.
- They guarantee periodic light propagation that fulfils the functional requirements.

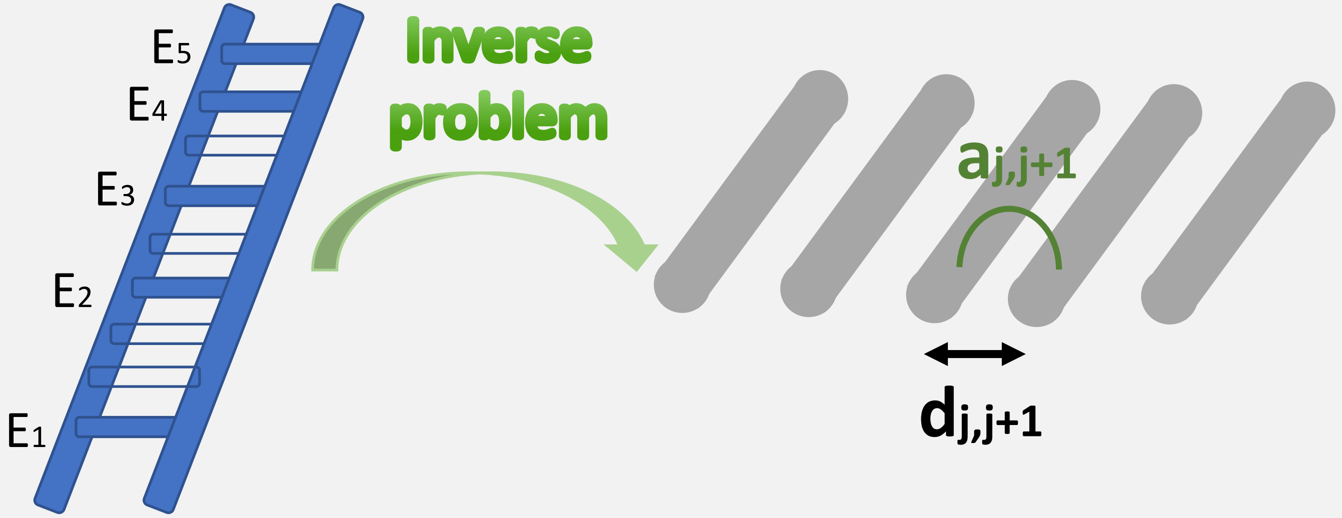
WGA spectrum is chosen as a combination of eigenvalues from the equidistant Wannier-Stark ladder.

A coupling matrix is inverse designed from the spectrum.

Petrovic and Veerman,
Ann. Phys. **392**, 128 (2018)

The corresponding WGA is implemented by adjusting waveguide spacings $d_{j,j+1}$.

Bellec, Nikolopoulos, Tzortzakis
Opt. Lett. **37**, 4504 (2012)



$$d_{j+1,j+2} = d_{j,j+1} + \frac{1}{\alpha} \ln \frac{a_{j,j+1}}{a_{j+1,j+2}}$$

Functional requirement

✓ Scalability

Interconnects for high-fidelity transfer

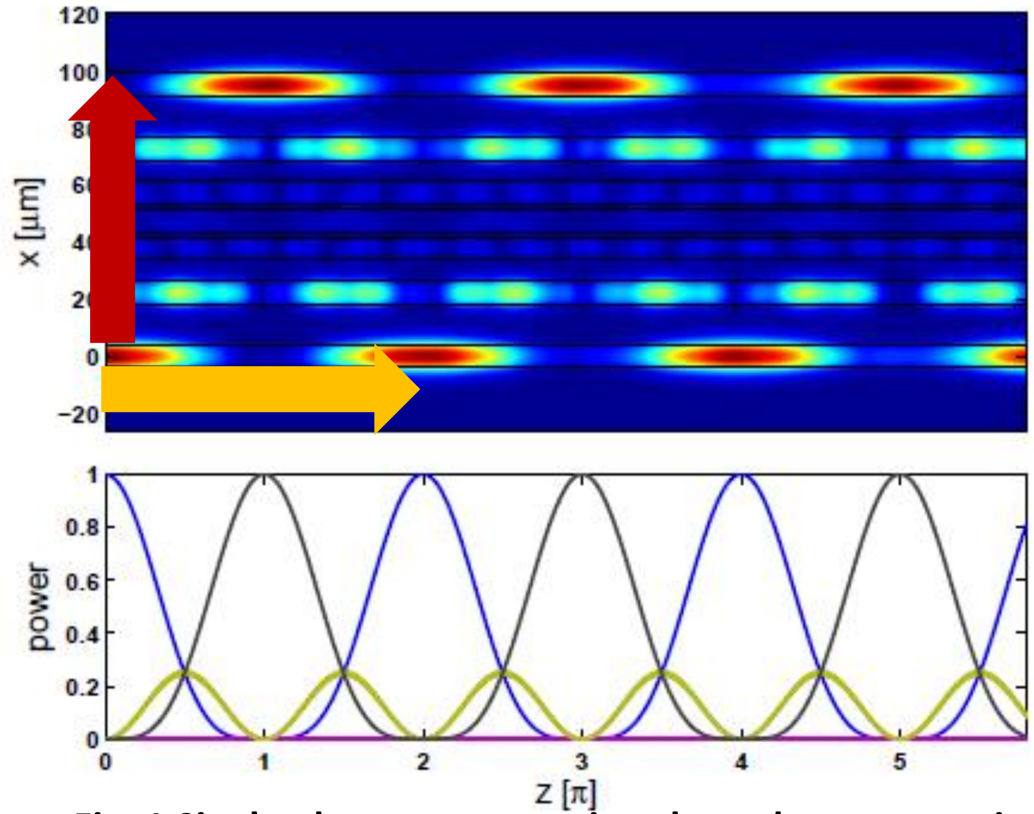


Fig. 1 Single photon propagation through a symmetric WGA with 7 WGs with eigenvalues 0, ±1, ±100, ±10001.

Parallel transfer via full state revival

Condition: Commensurable eigenspectrum

Perfect transfer via mirroring between waveguides *j* and *n+1-j*

Additional conditions:

- Odd number of waveguides
- Mirror symmetry
- Alternating eigenvalue parity

Functional requirement

✓ Perfect transfer of information

Transfer fidelity = 1.

Fidelity is highly sensitive to deviations of waveguide spacings from the design values.

Equal-energy splitters as entanglement generators

An example of an equal-energy splitter

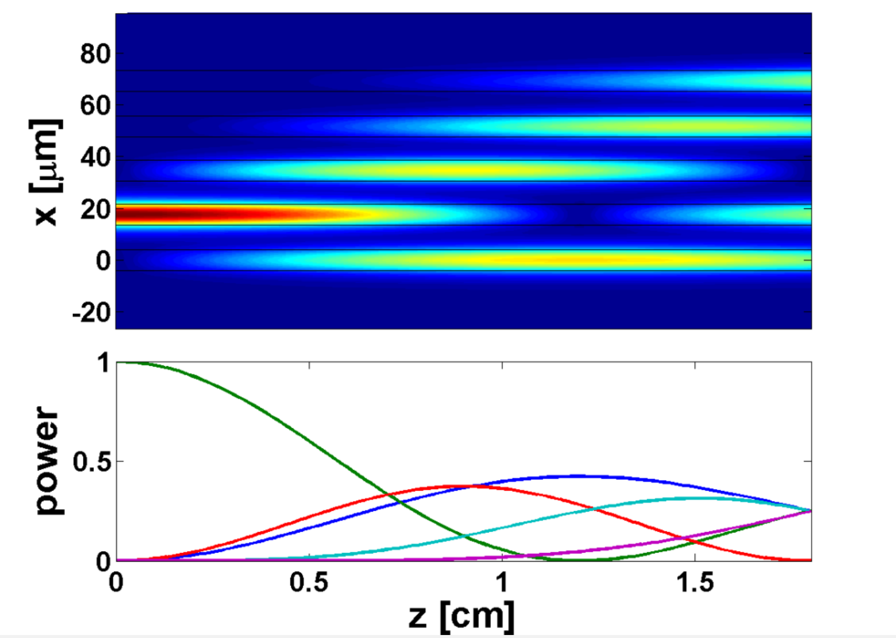


Fig. 2 Single photon evolution through a WGA with 5 WGs and equidistant eigenvalues. The simulation was performed with single-mode fibre SMF-28 parameters.

Petrovic, *Opt. Lett.* **40**, 139 (2015)

W-state generation

$$|W_4\rangle = \frac{1}{\sqrt{4}} \big(e^{i\pi/2} |1000\rangle + e^{i\pi} |0100\rangle + e^{i\pi} |0010\rangle + e^{-i\pi/2} |0001\rangle \big)$$

The *n* non-zero ports deliver path-entangled W-state in the basis truncated to *n*.

$$|W_n\rangle = \frac{1}{\sqrt{n}} \sum_{k=1}^{n} \hat{a}_k^\dagger |0\rangle$$

Also combiners

2:1, 3:1, etc.

Functional requirements

- ✓ Meaningful splitting ratios
- ✓ Entanglement generation

Periodic bunching and coincidence revivals

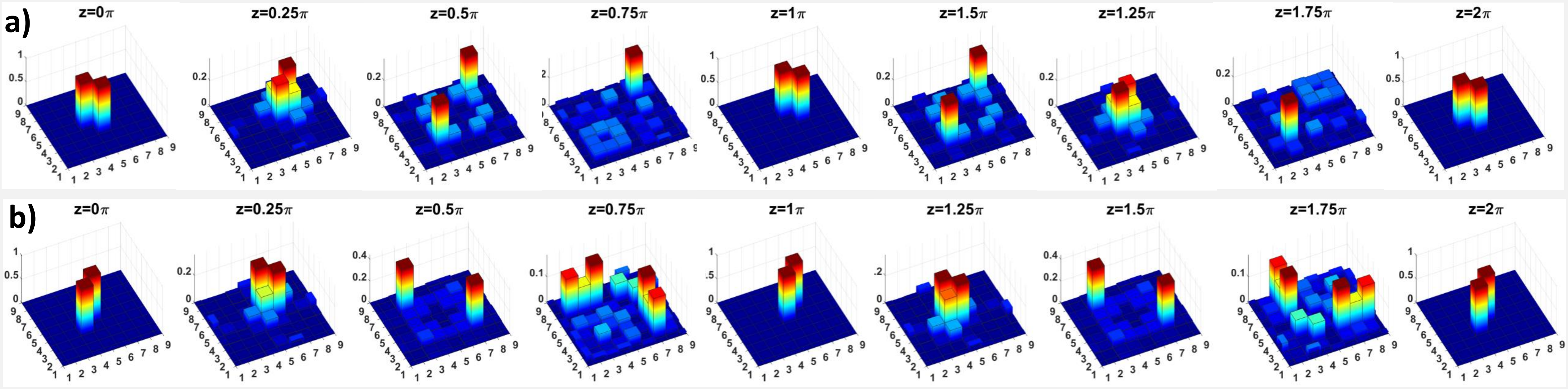
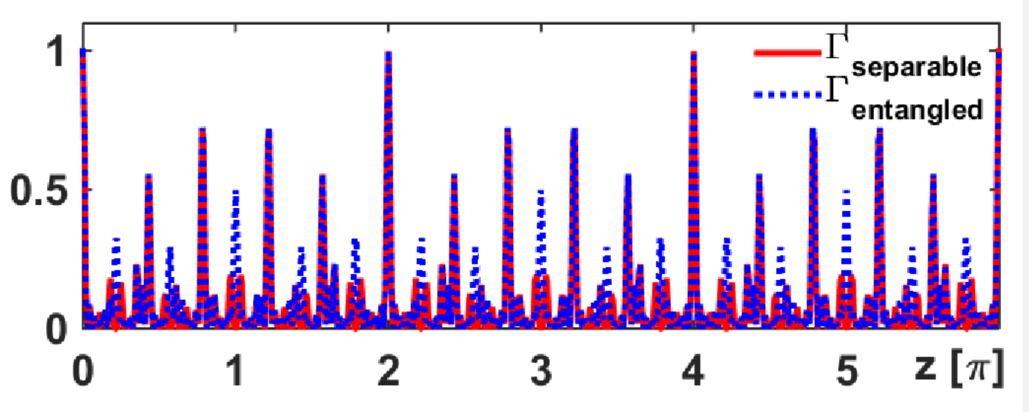


Fig. 3 Coincidence maps at the output of a WGA with 9 WGs and eigenvalues 0, ±1, ±4, ± 9, ±14. A photon pair enters at ports 4 and 5. a) Separable photons. b) Entangled photons.

Fig. 4 Evolution of photon correlations represented by the similarity measure:

$$\frac{\left(\sum \sqrt{\Gamma_{j,k}(z)\Gamma_{j,k}(0)}\right)^2}{\sum \Gamma_{j,k}(z) \sum \Gamma_{j,k}(0)}$$



Conclusion

The proposed WGAs fulfil the functional requirements for bend-free PICs:

- ✓ Scalability
- ✓ Coherence preservation
- ✓ Perfect transfer of information
- ✓ Meaningful splitting ratios
- ✓ Entanglement preservation