Deliverable Report

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Name, title and organisation of the scientific representative of deliverable's lead beneficiary (task leader):

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Deliverable table

Deliverable no.	D2.4
Deliverable name	OAM waveguides
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Lead beneficiary no.	5 (UNIVBRIS)
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CONTENTS

We investigated different routes for OAM encoding in waveguides. One approach will utilise the recent results of UGLAS [1] demonstrating phase unfolding which projects the azimuthal phase dependence of OAM states onto a linear coordinate which can be injected into an array of single mode waveguides. We studied the evolution of large superposition states in waveguide array structures [3, 4] and conducted a theoretical study of mode coupling in single mode waveguides which is crucial for further applications of single mode as well as multimode waveguides.
In [2] we show high control over single phonon and two-photon states in a reconfigurable integrated quantum photonic circuit. This opens the prospect to manipulate path encoded OAM states within the waveguide structure.
Besides encoding in single mode structures multimode structures are an interesting approach for encoding. Light propagates in multimode devices as superpositions of Hermite-Gaussian modes and using the self imaging principle provides prospect of transmitting OAM states.
We fabricated in cooperation with different partners (University of Twente, Jena University, TOSHIBA) waveguide structures in SiON [3, 4], fused silica, and silicon-on-insulator (SOI) and characterised them with classical light as well as with correlated photons testing their stability concerning quantum interference effects.

1. Single mode structures [3]

We theoretically studied mode coupling in arrays of single mode waveguides and experimentally measured the evolution of single photons as well as two indistinguishable photons in an array of 21 evanescently coupled waveguides in SiON.

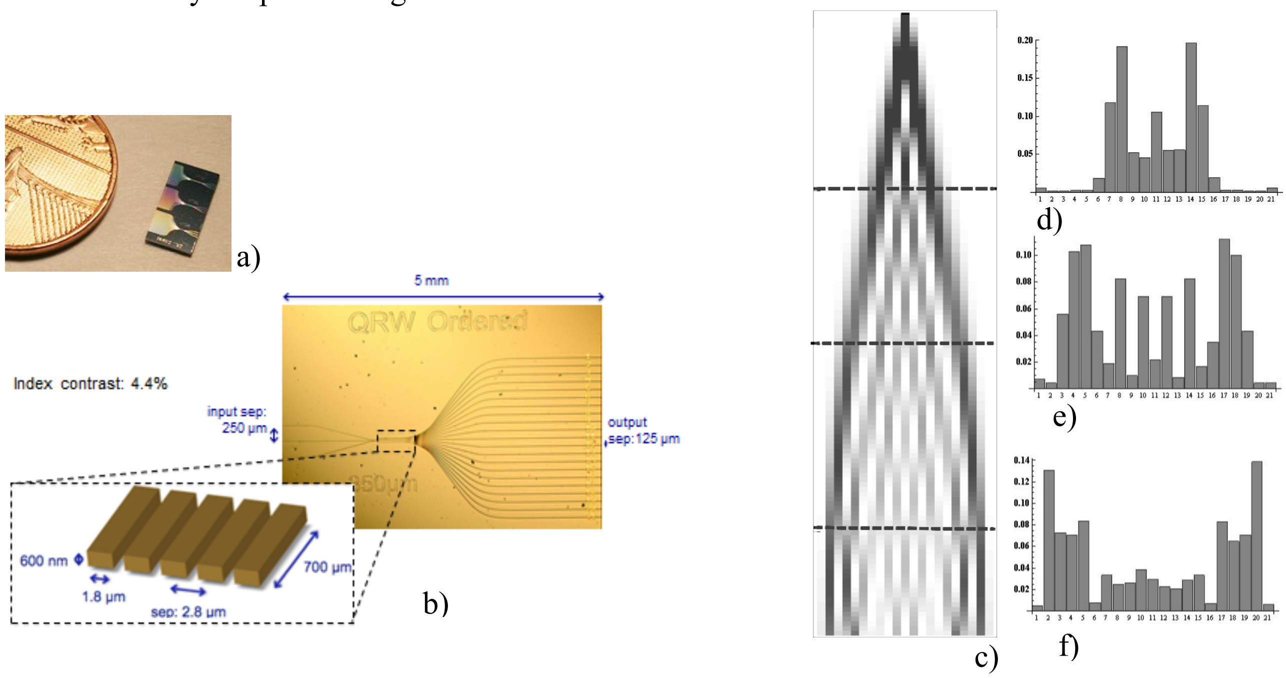

Figure 1: a) shows SiON chip with three array structures of different lenght with waveguide dimensions stated in b). The simulated evolution of a single photon propagation in the array is shown in c) together with the measured time steps corresponding to the three different devices: d) array of 350 micons, e) array of 700 micons, f) array of 1050 micons.

In cooperation with University of Jena we measured a structure of 9 waveguides fabricated in fused silica by direct-write technique. This technique allows three-dimensional waveguide structures, the refractive index contrast can be varied by changing the writing speed and by multiple writing processes. We measured single photon propagation as well as two-photon correlations shown in figure 3.

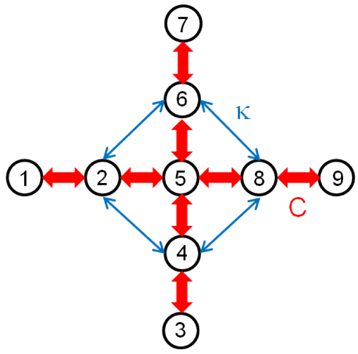

Figure 2: Structure of 9 waveguides coupled horizontally and vertically (C) as well as diagonally (k).

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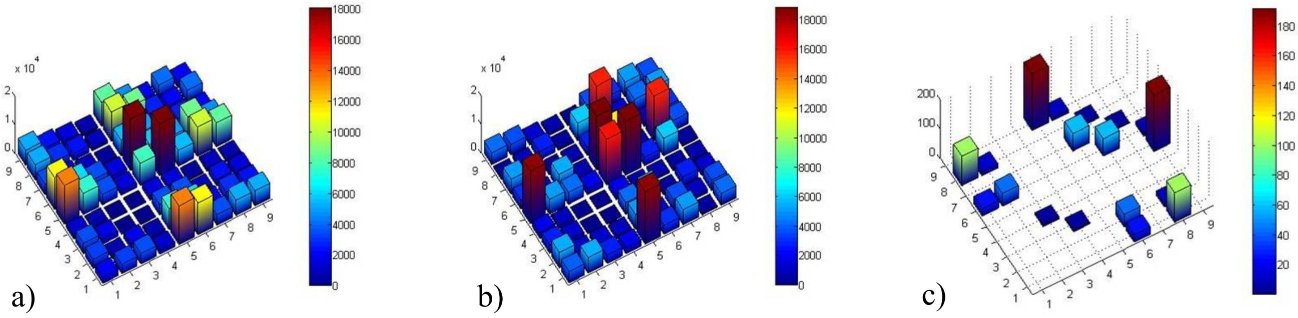

Figure 3: Measured corretation function a) for input of two distinguisable photons in waveguides number 1 and 7, b) indistinguisable photons and the violations of a classical inequality in standard deviations c).

2. Multimode encoding

We designed multimode mode encoding devices (MME) (Fig. 4) adapting existing designs [5] to the technology that we used. In order to test those structures we have made two types of circuits:

-An MME followed by an adiabatic output taper with seven waveguides acting like a 7 pixel one dimensional CCD. This circuit should allow us to check the behaviour of the designed MMC.

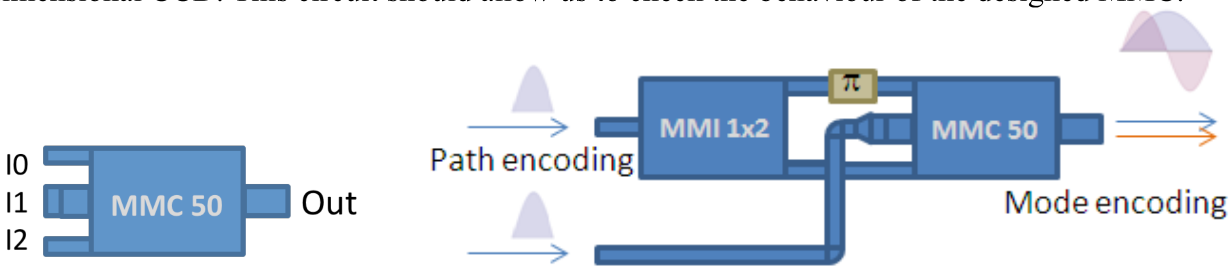

Figure 4: Left: 50% efficiency path to mode converter. Right: 100% efficiency path to mode converter. The MMC 50 component maps the side inputs (I0 and I2) into the 1st order mode of the output. But if the light is launched only from one side, then the conversion efficiency into the first order mode is only 50%. The remaining power is lost. To get 100% efficiency, the light has to be launched from both sides. We therefore use a 1x2 MMI splitter with a phase correction on one arm before. If the mode at the input I1 is the 0 order mode, this mode is

self imaged at the output. The 0 order mode is launched by adiabatically tapering the standard waveguide used in path encoding to match the size of I1. [5]

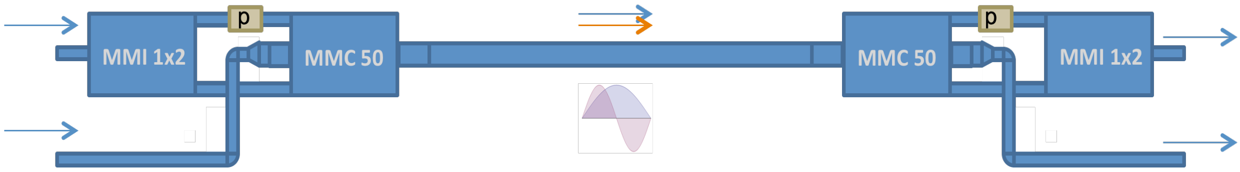

Figure 5: Mode encoding/decoding circuit.

-An encoding/decoding circuit (Fig. 5) with a first MMC to convert from path to mode encoding, a straight line which propagates the two modes together, ad finally another MMC circuit which converts back from mode to path.

The devices were fabricated by TOSHIBA in a silicon-on-insulator (SOI) chip with an index contrast of ~2.0. Some processing issues induced large losses which prevented us to test those devices. This batch will be rerun and we expect to get new devices.

3. Multimode Interference devices [3]

We fabricated MMI devices in silicon oxynitride (SiON) with a high refractive index contrast providing a compact and highly stable platform for interference of multiple modes. We achieve in this structure non-classical interference with a visibility of up to 99% of the theoretical maximum for a range of splitting rations.

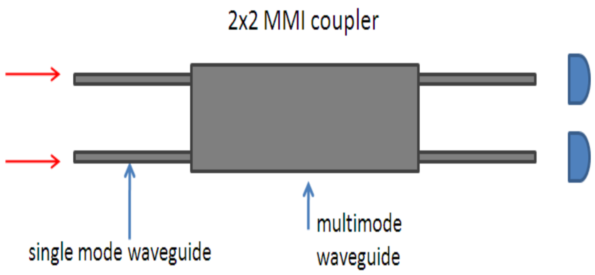

Figure 6: Schematic view of a 2x2 MMI device, mapping two input modes onto two output modes.

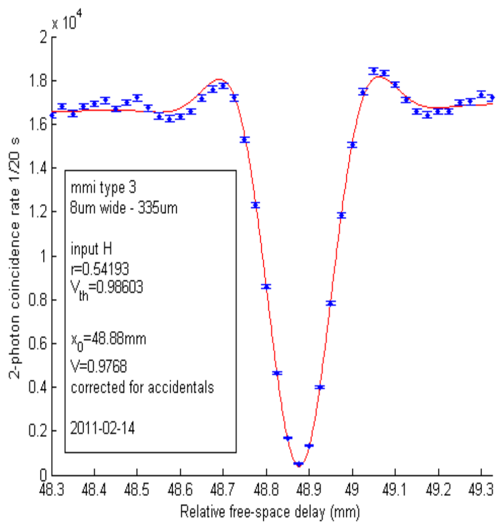

Figure 7: Measured HOM dip showing high visibility non-classical interference of two indistinguishable photons in a 2x2 MMI device.

[1] G. C. G. Berkhout, M. P. J. Lavery, J. Courtial, M. W. Beijersbergen, and M. J. Padgett, *Efficient Sorting of Orbital Angular Momentum States of Light*, Phys. Rev. Lett. **105**, 153601 (2010)
[2] P. J. Shadbolt, M. R. Verde, A. Peruzzo, A. Politi, A. Laing, M. Lobino, J. C. F. Matthews, J. L. O'Brien, *Generating, manipulating and measuring entanglement and mixture with a reconfigurable photonic circui,* Nature comm., arXiv:1108.3309v1
[3] J. D. A. Meinecke, K. Poulios, A. Politi, J. C. F. Matthews, N. Ismail, K. Wörhoff, M. G. Thompson, and J L. O'Brien, *Coherent Time Evolution and Boundary Conditions of Two-Photon Quantum Walks,* in preparation
[4] K. Poulious, D. Fry, A. Politi, M. Tompson, J. L. O'Brien, *Two-photon quantum interferrence in integrated multi-mode interference devices*, in preparation
[5] Leuthold et al., *Multimode interference couplers for the conversion and combining of zero-and first-order modes. Lightwave Technology*, Journal of (2002) vol. 16 (7) pp. 1228-1239