Deliverable Report

Deliverable No: D2.9

Deliverable Title: OAM waveguide transmission

Grant Agreement number: **255914**

Project acronym: **PHORBITECH**

Project title: **A Toolbox for Photon Orbital Angular Momentum Technology**

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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.	D2.9
Deliverable name	OAM waveguide transmission
WP no.	2
Lead beneficiary no.	4 (UNIVBRIS)
Nature	R
Dissemination level	PU
Delivery date from Annex I	Month 24
Actual delivery date	30 September 2012

D2.9) OAM waveguide transmission: Analysis of the achievable OAM transmission performances in waveguides. Assessment of the role of the waveguide transverse profile in determining the OAM preserving properties and the cross-talk, both in total-internal reflection and photonic-crystal bandgap confinement. Experiments with coherent beams and single photons. *Excerpt from the GA-Annex I describing the deliverables of WP2, page 17]*

We demonstrate ultra-compact vector optical vortex emitters based on the interaction of whispering gallery modes and angular gratings. The devices are fabricated on a silicon-on-insulator substrate. The smallest device is 3.9 micrometers in radius, three orders of magnitude smaller than previously reported devices. The wave-front of the emitted optical beams has been characterised by interference schemes with circularly polarised Gaussian reference beams, confirming that the emitted beams carry well-defined and flexibly reconfigurable orbital angular momentum. As a first step toward photonic integration of optical vortex devices, we further fabricate integrated emitter arrays and demonstrate simultaneous emission of multiple optical vortices. This work enables potential large-scale integration of optical vortex emitters on CMOS-compatible silicon chips for wide-ranging future applications. This device is presented within the context of deliverable 2.9, since it demonstrates a new device concept capable of generating (and detecting) OAM states of light within an integrated waveguide architecture. Although OAM is not within the waveguides (as was the original aim of this deliverable), we feel that this work falls within the scope of this deliverable, providing additional functionality for the generation, detection, control and manipulation of OAM using waveguide circuits, and thus adding to the PHORBITECH OAM toolbox.

Integrated Ultra-Compact Optical Vortex Beam Emitters and Arrays

1. Working principle

The working principle of the device is analogous to 2^{nd}-order grating structures (Fig. 1B) widely used in planar waveguides as input/output couplers (16). If the waveguide grating is now curved to form a loop, by way of Huygens' Principle, the wave-front of the radiated light is expected to skew in the azimuthal direction and transforms to a helix, which suggests the creation of an OAM-carrying beam (Fig. 1C).

The radiated beams are vector vortices with topological Pancharatnam charge equal to $l=p-q$, where p is the the order of the WGM involved or the number of optical periods around the resonator and q the number of grating elements around the resonator. The topological Pancharatnam charge, similar to the topological charges of scalar vortices, is directly related to the OAM of vector vortices, and the amount of OAM carried by the radiated beam is $l\hbar$ per photon. For a fabricated device, q is a constant while the value of p can be changed by exciting selected WGMs. Therefore variable OAM can be generated by simply tuning the injected laser wavelength to various cavity resonances, or alternatively tuning cavity resonances with respect to a fixed injection wavelength by changing the refractive index of the cavity material.

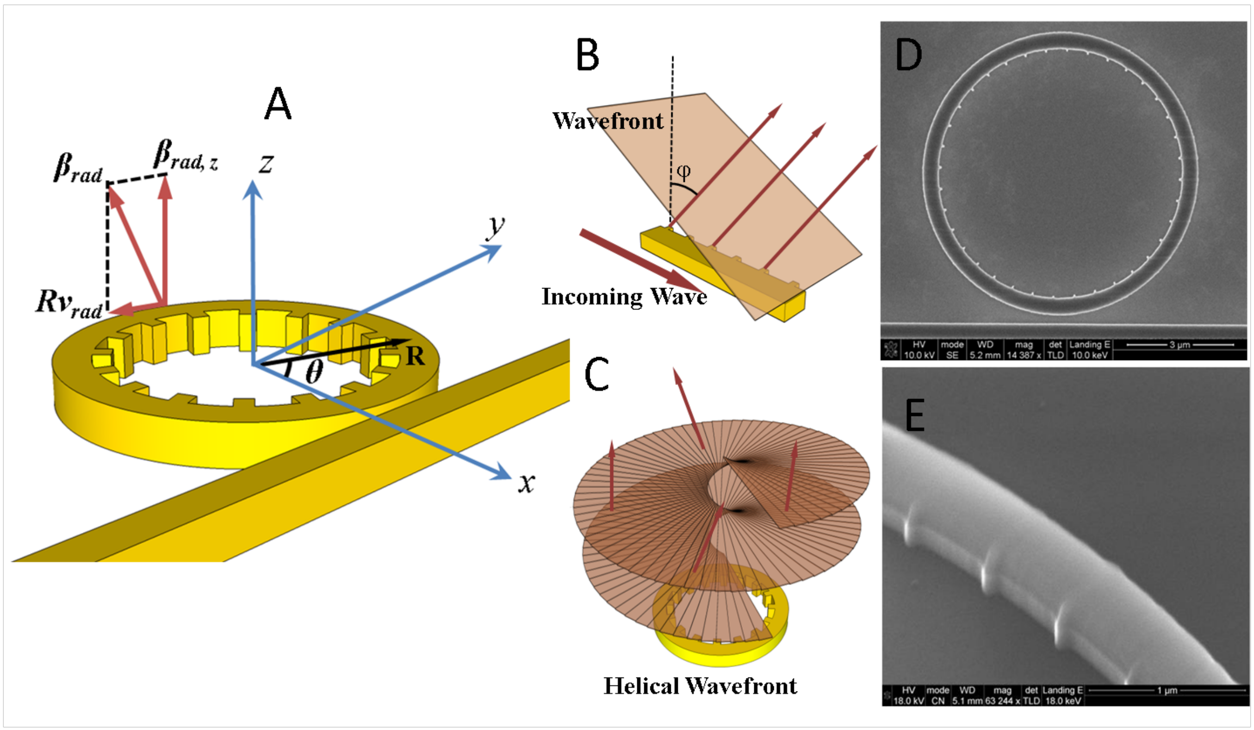
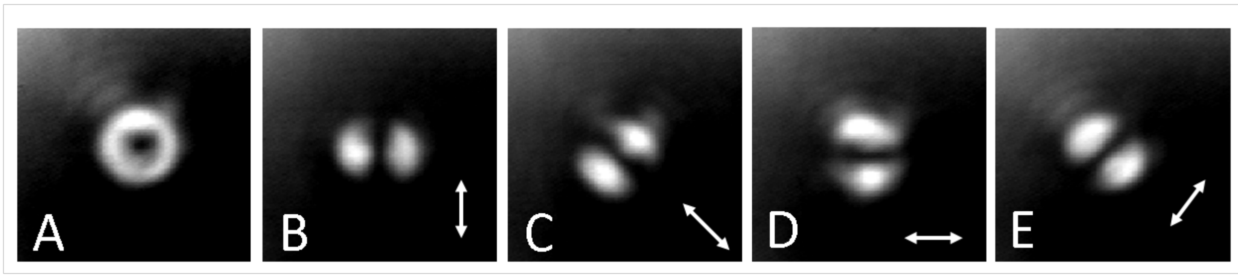


Figure 1: (A) Schematic of the device with angular grating patterned along the inner wall of a micro-ring resonator which is coupled to linear waveguide for optical input. (B) Schematic illustration of a linear waveguide with gratings. The guided wave is scattered by the grating elements collectively acting as a phased radiation source array, and a significant fraction of power is diverted to a certain direction φ, in which constructive interference occurs. The wave-front of the total radiated field is a plane with titled angle of φ. (C) Schematic illustration of angular grating together with the helical wave-front of the radiated beam. (D), (E) SEM images of a fabricated device (*R*= 3.9 µm).

2. Experimental results

Two types of micro-ring devices were designed and fabricated (R=3.9 µm, q=36 and R=7.5 µm, q=72) on the same SOI chip (*17*). The devices have been designed so that the resonance associated with zero OAM quantum number (l=0) is around the centre of our tunable laser's wavelength range (1470-1580 nm). Fig. 1E-F show the scanning electron microscopy (SEM) images of a device with R=3.9 µm.

Both types of devices have been characterised by launching continuous-wave light from a tunable laser into the access waveguide to excite quasi-TE mode. The near field intensity distribution of the radiated beam from the devices, with *l*=0, is annular with a dark centre, as imaged on an infrared camera (Fig. 2A), and indeed is predominantly azimuthally polarized (Fig.2B-E). The emission spectrum of the device with R=7.5 µm is shown in Fig.3A.



b) c)

Figure 2: (A) Measured near field intensity distribution of the radiated beam with *l*=0. (B)-(E) Measured intensity distributions after the polarizer for the directions indicated by the arrows. A two-lobe intensity pattern arranged orthogonal to the polarizer axis is obtained. When the polarizer is rotated, the two-lobe pattern rotates in the same manner, confirming that the radiated beam is a CV beam with azimuthal polarization. standard waveguide used in path encoding to match the size of I1. [5]

The wavefront of the radiated beams, revealed by interference with co-propagating RHCP and LHCP Gaussian reference beams (Fig 3.B-C), indeed has spiral arms equal to *l*-1 (RHCP) or *l*+1 (LHCP and the sign of the topological charge is indicated by the chirality of the pattern. For example, the beam associated with the special case of *l*=0 can be decomposed into two scalar waves with topological charges of ±1, which is confirmed by the left- and right-handed single-arm patterns. The nine resonances therefore correspond to *l*=0, ±1, ±2, ±3, ±4.

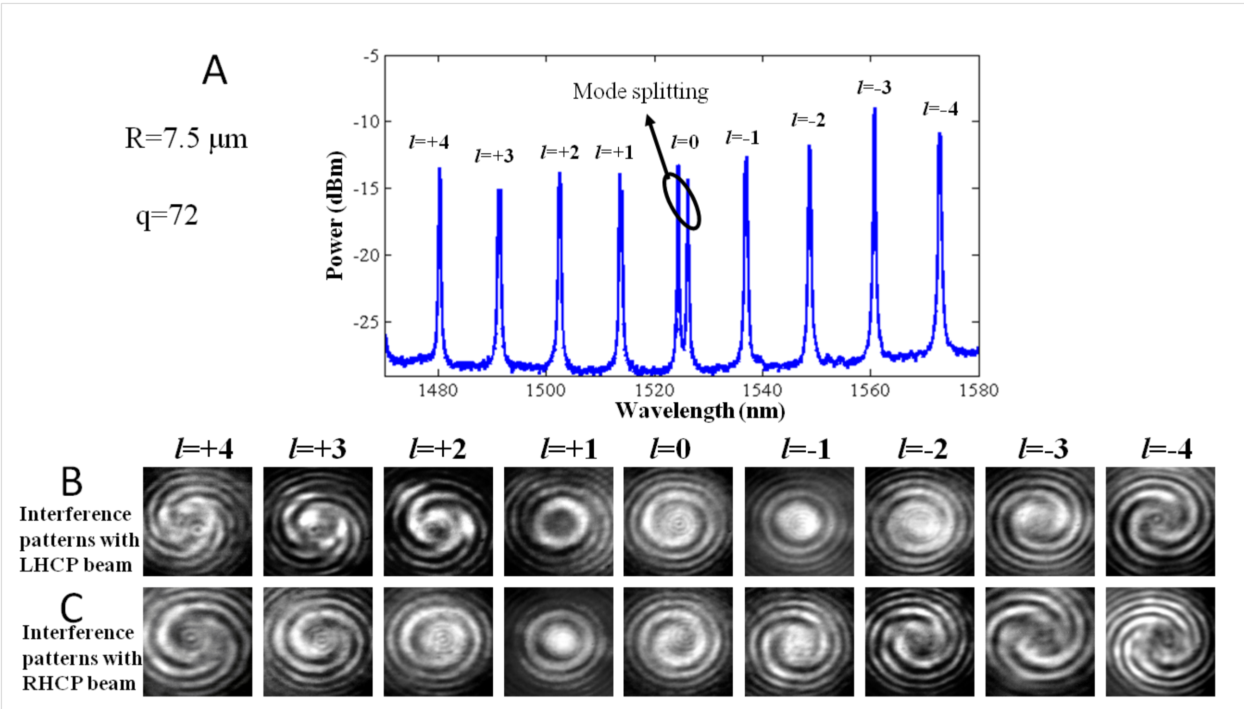


Figure 3: (A) Measured radiation spectrum for a device with R=7.5 μm. The *l*=0 wavelength is about 1525 nm. (B)-(C). Interference patterns with LHCP and RHCP reference beams. Each pattern in Fig. 3 B has *l*+1 spiral arms while each pattern in Fig. 3 C has *l*-1 spiral arms.

Furthermore, to demonstrate the potential of photonic integration, we fabricated OAM emitter arrays which consist of up to four identical emitters coupled to the same access waveguide (Fig.4 A). Simultaneous emission of identical vortices has been verified as shown in Fig. 4B and Fig. 4C. The spiral patterns rotate synchronously when the phase of the reference beam is changed.

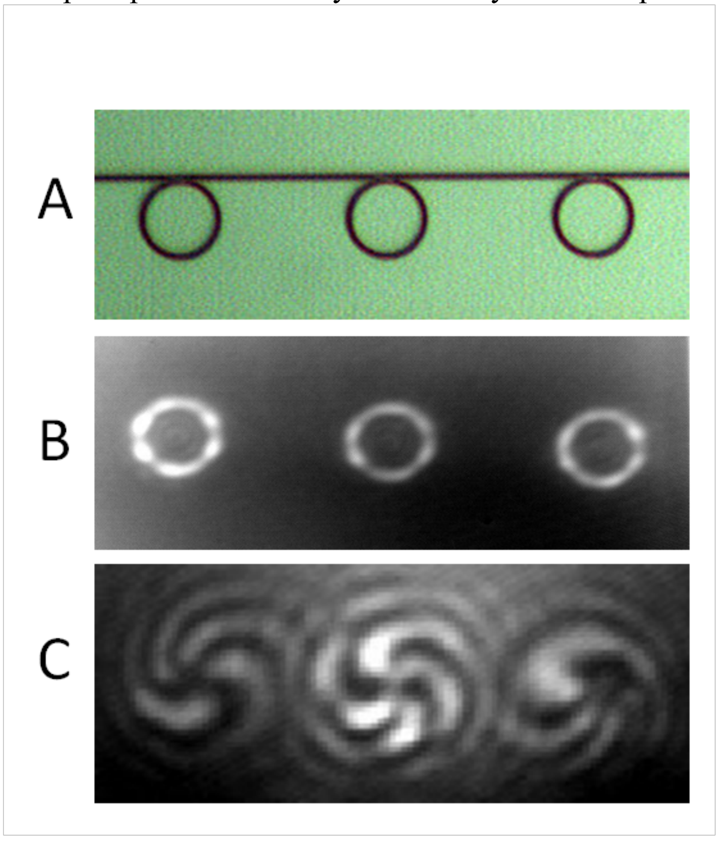


Figure 4: (A) Part of an array consisting of four identical emitters, zoomed-in for clarity. (B) Near field intensity patterns emitted from the array. The difference in their brightness is attributed to slight differences in their resonance peaks due to fabrication variations. (C) An example of interference pattern between the emitted beams from the array and co-propagating RHCP Gaussian beam. All beams have the same OAM order (*l*=-3). In (17) all 4 emitters are shown to emit simultaneously.

PHORBITECH contribution to this deliverable

This work is presented in part as a contribution to the PHORBITECH project, with efforts from Janwei Wang, Mark Thompson and Jeremy O'Brien. It should be noted that this work also contains substantial contributions from non-PHORBITECH partners from the University of Bristol (Xinlun Cai and Siyuan Yu) and the University of Glasgow (Michael Strain and Marc Sorel).

PHORBITECH contributors to this deliverable

<u>UNIVBRIS</u>: Janwei Wang, Mark Thompson and Jeremy O'Brien

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