Photonic Integrated Devices for Exploiting the Orbital Angular Momentum (OAM) of Light in Optical Communications

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Abstract *We discuss the development of silicon photonic microring resonators for the emission of optical vortex beams. These devices offer great potential for high capacity short-reach optical interconnects thanks to their compactness, low power consumption and fast reconfigurability.*

Introduction

Orbital angular momentum (OAM) offers an additional degree of freedom of light beams with potential applications in micromanipulation, microscopy[1] and free-space communications[2]. OAM beams consist of *l*-fold spiral phase fronts with a singularity in the central axis. OAM modes with different modal index *l* form an orthogonal base and can therefore be effectively exploited to enhance the capacity of an optical communication link through mode division multiplexing (MDM)[3].

In the vast majority of the experiments reported so far, OAM beams were generated using free-space optical components such as spatial light modulators[2], q-plates[4], or digital micro-mirror devices (DMD)[5]. The use of bulk optic components makes these approaches unsuitable for optical communications because of the large size of the devices and the slow switching speed between OAM modes, which is limited to a few kHz. In the last few years, a number of groups have demonstrated integrated optical devices for the generation and manipulation of OAM carrying beams[6,7,8]. Such devices are mechanical robust, cheap to manufacture and can be integrated in dense arrays with footprints as small as a few tens of micrometers. A key feature of using integrated circuits is the potential for fast on-chip tunability, which offers novel opportunities for switching of OAM data channels and OAM routing flexibility.

Here, we discuss recent research progress on the development of an ultra-compact tunable integrated OAM device fabricated on a silicon photonic technology. We show how the devices can be engineered for fast switching of the OAM modes, on-chip manipulation of the emitted polarisation state and multi-wavelength and multi-OAM state emission. Initial experiments on a transmission link into a few mode fibre (FWF) will also be discussed.

Device geometry

The devices make use of the resonant condition of microring resonators incorporating periodic scattering elements that couple the waveguide propagating beams to vertically emitted beams. The generated OAM mode order, *l*, is defined by the resonant order, *p*, and the number of scattering elements in the ring, *q*, as:

$$l = sign(p) \times (|p| - q) \qquad (1)$$

where *p* is taken as a positive or negative value depending on the direction of propagation inside the resonator (i.e. clockwise or counter-clockwise). The device is extremely simple as it only requires a ring resonator and a bus waveguide for coupling the input optical signal. Different OAM mode orders can be addressed by aligning the input wavelength to different resonances of the device.

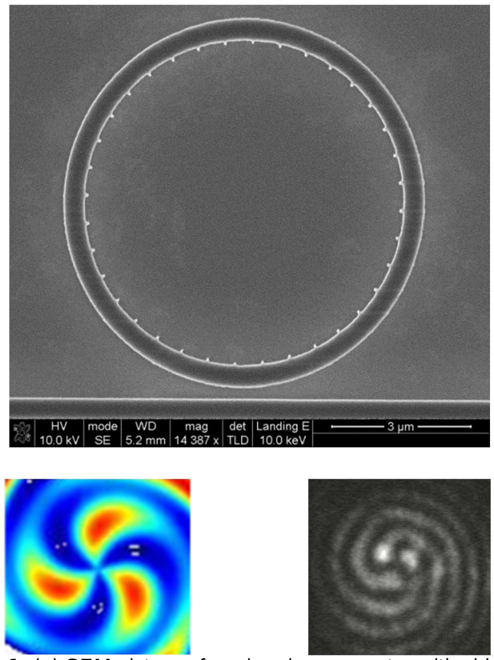


Fig. 1: (a) SEM picture of a microring resonator with sidewall gratings. (b) Simulated and (c) measured interference pattern of an emitted beam with *l*=3

Switching of OAM modes

The OAM mode order of a single wavelength signal can be actively modulated by tuning the effective index of the waveguide via thernal[9] or carrier-induced effects[10]. Although slower than carrier-induced tuning, thermal tuning retains the essential simplicity of the emitter as it only requires a single electrical connection, allowing for the design of complex multi-emitter architectures. Devices with concentrical metal resistive lines were developed to create a thermal change of refractive index in the waveguide core, and hence tune the resonant order and the emitted OAM mode (see Fig.2).

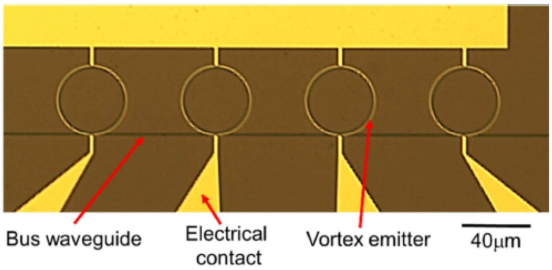
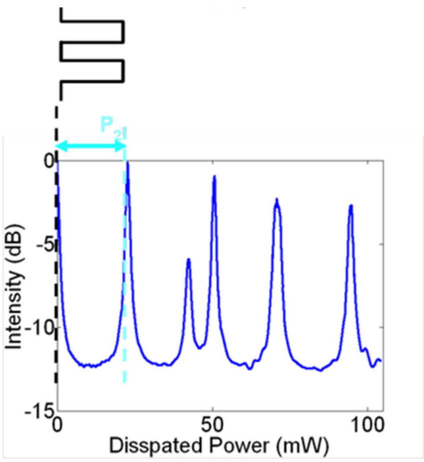


Fig. 2: Optical picture of an array of OAM emitters with individually addressable heaters for OAM switching and reconfigurability

Fig. 3 shows an example of real-time switching between the OAM modes. A fixed input wavelength resonant to the *l*=-2 mode is coupled into the microring resonator and the dissipated power on the heather is modulated so as to tune the resonant wavelength between the *l*=-2 and *l*=-1 mode. The switching time between OAM modes is of the order of a few μs, only limited by the thermal response time of the system. This device geometry can be used to address as many as 10 different OAM modes.



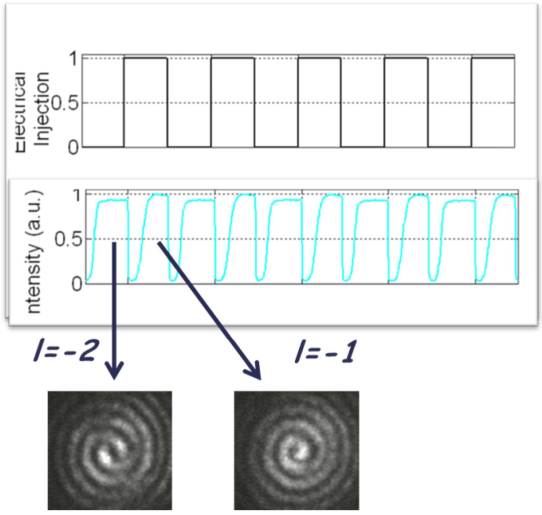


Fig. 3: The device can be switched between two different OAM modes by modulating the dissipated power on the heaters. The measured rise-time and fall-time of the modulated trace (bottom) are 10 μs and 1.4 μs, *respectively.*

Polarisation and wavelength control

In the initially demonstrated geometry the grating was defined on the waveguide sidewalls and the radiated near field was predominantly azimuthally polarised when a quasi-transverse electric (quasi-TE) mode propagated in the waveguide[8]. OAM beams with radial polarisation can be emitted from gratings that are defined on the top of the waveguide. The emission of any state of polarisation as a superposition of the two orthogonal azimuthal and radial states of polarisations can then be achieved by placing two sets of gratings at different positions to intercept locally dominating field components at different relative phase.

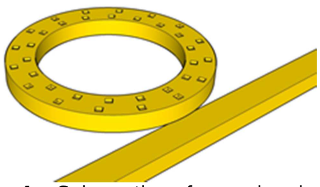


Fig. 4: Schematic of a microring resonator with top waveguide gratings for the emission of radially polarised beams. Any polarisation state can be generated by combining sidewall and top waveguide gratings.

A similar design strategy can be adopted for the generation of multiple OAM states at a single wavelength by superposing gratings with different periods and coupling strengths so as to provide accurate control of the OAM spectrum in both the relative weight and phase of the OAM states. The flexibility of this approach is shown in Fig 5 where a silicon waveguide with a superposition of sidewall relief grating functions is used to construct arbitrary combinations of eight-basis filter responses[11].

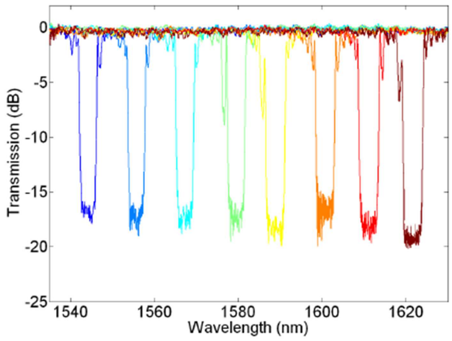


Fig. 5: Output spectrum from a silicon waveguide with 8 superimposed gratings spaced by 10 nm in wavelength

A key functionality for optical communications is the conversion of multiple input beams, each carrying different information, to different OAM states (i.e., multiplexing), as well as to separate them after transmission (demultiplexing). The use of multiple microring resonator emitters concentrically integrated can fulfil these tasks. Such geometry requires a dual-core structure where the access waveguides are defined on the lower layer, with vertical light coupling between waveguides and resonators (see Fig. 6).

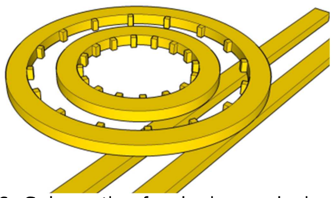


Fig. 6: Schematic of a dual-core device for multiplexing and demultiplexing of multiple OAM states.

The potential of these devices for short-reach optical interconnects is currently being assessed on few mode fibre (FWF) optical links. Initial experiments were carried out with two emitted eigen-modes that were modulated at 1Gbit/s with on-off keying (OOK) modulation. Propagation through a 1.1 km of fiber shows OSNR penalties of less than 2 dB.

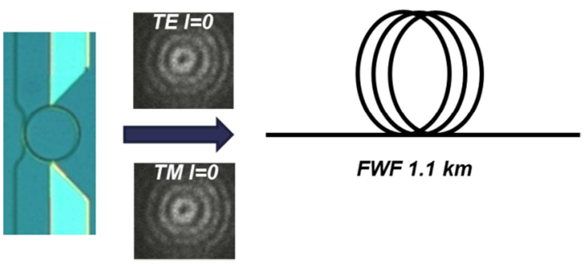


Fig. 7: Two eigen-modes (TE *l*=0 and TM *l*=0) are coupled and propagated through a 1.1 km of FWF for evaluating the device performance on short link interconnects.

Conclusions

Integrated photonic circuits offer a very promising solution for the generation and manipulation of OAM beams thanks to their unique potential for integrating several functionalities on a single chip. OAM states with good modal purity can be effectively emitted with simple geometries combining a microring resonator and a second order grating. We briefly reviewed some of the recent progress on the development of these devices and discussed how the geometry can be engineered to provide OAM mode tunability, control over the emitted polarisation state, emission of multi-OAM and multi-wavelength beams, as well as multiplexing and demultiplexing functionalities. Preliminary assessments on a few mode fibre optical link confirm the potential of this approach for short link optical interconnects.

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