Tunable Orbital Angular Momentum (OAM) Conversion on 100Gb/s Real Data Traffic by Exploiting Concentric Waveguide Emitters

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Abstract *We propose an OAM converter exploiting an innovative integrated OAM multiplexer based on concentric omega-shaped waveguides. The OAM converter, which can operate on signals multiplexed both in OAM and wavelength domain, is successfully tested up to 100Gb/s with real data-traffic.*

Introduction

The orbital angular momentum (OAM) of light can be exploited together with the more consolidated multiplexing domains such as wavelength and polarisation to increase the capacity of optical communication channels[1]. An OAM beam has an azimuthal phase equal to $\varphi(\phi)=\exp(i \cdot l \cdot \phi)$, where ϕ is the azimuthal angle and l is the topological charge of the OAM state, i.e. the OAM order. OAM conversion, i.e. the capability to change the order l of an optical beam carrying OAM, is a required functionality for increasing the flexibility of the communication systems[2,3]. Up to now OAM conversion was demonstrated with bulk devices such as SLMs[4] and a cascade of OAM multiplexers and demultiplexers based on hybrid 3D photonic integrated circuits[5].

Here we propose a compact implementation exploiting an OAM demultiplexer/demodulator based on cascaded refractive elements[6], coupled to an innovative OAM modulator/multiplexer based on a single chip with integrated concentric omega (Ω)-shaped waveguides. The proposed scheme can convert the OAM of signals multiplexed both in the OAM and wavelength domain with only two OAM-processing devices. Moreover, in the proposed solution the order of the converted OAM mode can be easily tuned by applying a proper voltage to each independent Ω-shaped waveguide. Successful operation up to 100Gb/s is demonstrated with commercial network cards generating coherent QPSK polarisation-multiplexed real data traffic.

Working principle

The working principle of the OAM converter architecture is shown in Fig. 1 (left). The scheme is suitable for independent conversion of the OAM order of signals multiplexed both in the OAM and wavelength domain. An incoming beam

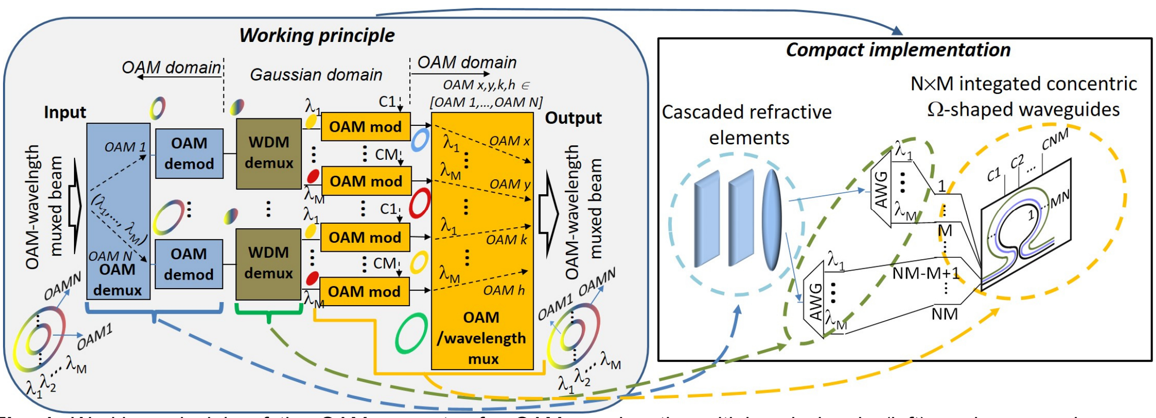

Fig. 1: Working principle of the OAM converter for OAM-wavelength multiplexed signals (left), and proposed compact implementation (right).

composed by N×M channels multiplexed over N OAM modes and M wavelengths is sent to an OAM demultiplexer (OAM demux) which spatially separates all the OAM modes. Each mode is fed to an OAM demodulator (OAM demod) converting the OAM mode to Gaussian mode, regardless of the wavelength. Different wavelengths are then separated with a wavelength demultiplexer (WDM demux). Each channel at each wavelength is then converted back to the OAM domain with an OAM modulator (OAM mod). Since the OAM conversion operation must be flexible, i.e. all the channels should be convertible into any of the N OAM modes, each OAM modulator must be tunable, i.e. the order of the emitted OAM mode can be changed by acting on a control signal *Ci*. Following the OAM modulator, the OAM signals are then spatially multiplexed (OAM mux), to generate an optical beam in which all the signals are multiplexed in the OAM and wavelength domain. The OAM converter can be realized with the compact implementation shown in Fig. 1 (right). The OAM demux and the N OAM demod can be implemented with a single device based on cascaded refractive elements[6], the WDM demux with an arrayed waveguide grating (AWG), the N×M OAM mod and the OAM/wavelength mux with a single integrated device based on N×M independently tunable concentric Ω-shaped waveguides. The number of Ω-shaped waveguides should be equal to the number of multiplexed channels at the OAM converter input.

Experimental setup and results

The OAM converter is tested with the setup shown in Fig. 2. An on-off keying (OOK) 20Gb/s pseudo-random bit sequence (PRBS) is generated, amplified with an erbium doped fibre amplifier (EDFA), filtered (BPF) and sent through a collimator to a commercial spatial light modulator (SLM) for mapping an OAM onto the input signal. The OAM order is selected by loading a proper phase mask on the SLM. The

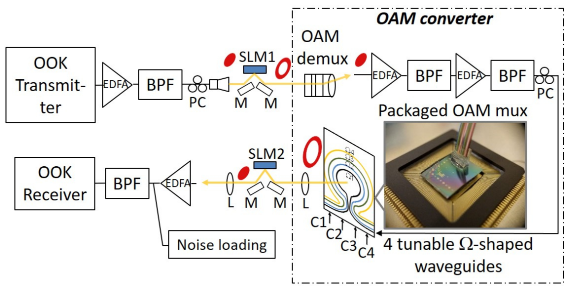

Fig. 2: Experimental setup. EDFA: Erbium doped fibre amplifier; BPF: band pass filter; PC: polarisation controller; M: mirror; SLM: Spatial light modulator; L: lens; Ci: control signal; Inset: Packaged OAM mod/mux.

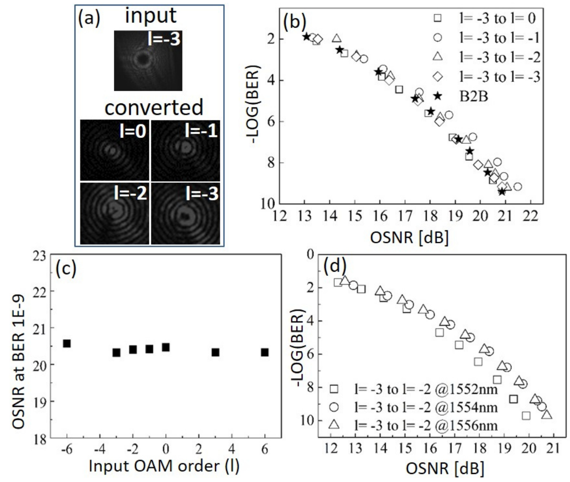

Fig. 3: Experimental results. (a) Intensity profile of the OAM beam before and after the conversion. (b) BER vs. OSNR for different orders *l* of the converted OAM mode. (c) OSNR vs. order of the OAM beam to be converted. (d) BER vs. wavelength of the OAM beam to be converted.

generated OAM beam is fed into the OAM converter. The OAM demux transforms the input OAM modes into plane waves, with different phase tilts depending on the OAM mode order. The OAM demux output plane wave is coupled into a single mode fibre (SMF), and amplified before being coupled to one of the four concentric Ω-shaped waveguides of the packaged OAM mux. The four-layer Ω-shaped waveguides with radius ranging from 21.96μm to 43.92μm and out-coupling efficiency ranging from 15% to 20% are patterned coaxially to the generated multiplexed OAM modes. The device is fabricated on a silicon-on-insulator (SOI) wafer with a 220nm-thick silicon core and a 2μm-thick buried oxide. Metallic heaters are defined in close proximity to each Ω-shaped waveguide to independently tune the radiated OAM mode with an efficiency of approximately 18mW per OAM mode. We packaged the silicon chip in a ceramic chip carrier with bonded electric wires to tune the waveguides and a pigtailed fiber array to couple the light (see inset in Fig. 2). The converted OAM beam, vertically emitted with respect to the Ω-shaped waveguides plane, is collimated towards a second SLM to be converted to a Gaussian mode and coupled into an SMF, preamplified and received. In the first characterisation, the input signal wavelength is set to 1552.33nm and OAM order is *l*=-3. The signal is then converted to OAM order *l*=0,-1,-2 and -3. The total number of converted OAM modes is limited to four by the maximum voltage applicable to the heater contacts. Fig. 3 (a) shows the intensity profile of the OAM beam before and after the conversion in the different cases. The diameter of the intensity doughnut profile increases by increasing the absolute value of the converted OAM beam

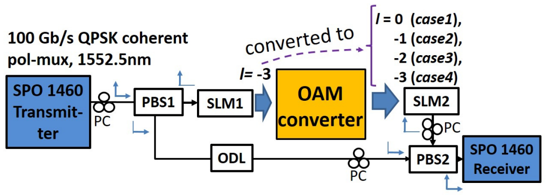

Fig. 4: Field trial setup. PBS: polarisation beam splitter; SLM: spatial light modulator; ODL: optical delay line.

order. Fig. 3 (b) shows the bit error rate (BER) vs. the optical signal to noise ratio (OSNR) for different orders of the converted OAM mode. At BER 10^{-9} the maximum OSNR penalty with respect to the back to back is <1dB. Fig. 3 (c) shows the OSNR penalty at BER 10^{-9} for a converted OAM beam of order *l*=-2 vs. the order of the OAM beam to be converted. The maximum OSNR variation is <0.3dB. The OAM converter is then tested at different input wavelengths. The order of the OAM beam to be converted is fixed to *l*=-3 and the order of the converted OAM beam is fixed to *l*=-2. The wavelength of the OAM beam to be converted is set to 1552, 1554 and 1556nm. BER curves, displayed in Fig. 3 (d), show OSNR variations <1dB at BER 10^{-9}.

OAM conversion field trial

The OAM converter is tested with real data traffic at 100Gb/s according to the field trial setup displayed in Fig. 4. The 100Gb/s coherent polarization-multiplexed traffic at 1552.52nm generated by a commercial network card (Ericsson SPO 1460) is split into orthogonal polarizations (PBS1). A polarization is coupled to the OAM converter input, and the other one is orthogonally coupled to the signal coming from the OAM converter output (PBS2). SLM1 maps an OAM onto the coherent 100Gb/s signal and SLM2 converts to Gaussian the converted OAM signal before coupling it into the receiving card for performance measurements. An optical delay line (ODL) is used to synchronise the 100Gb/s traffic not travelling through the OAM converter with the one travelling through the OAM converter. The OAM converter input signal is

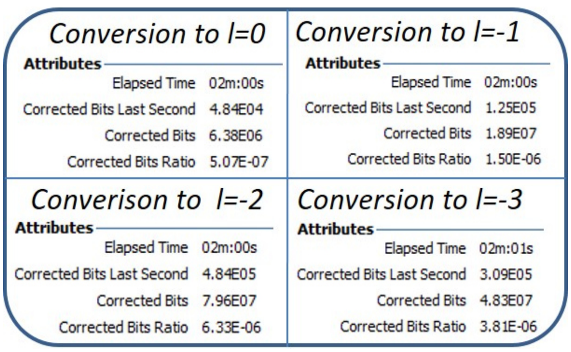

Fig. 5: OAM converter performance with coherent 100Gb/s QPSK pol-mux real data traffic. The input signal (OAM order *l*=-3) is converted to order *l*= 0:-1:-2:-3.

mapped onto OAM order *l*=-3 and converted to four different OAM orders *l*= 0, -1, -2, -3. Fig. 5 shows the performance displayed by the SPO 1460 software interface. In all cases, the system recovers all the errors, demonstrating the operability with 100Gb/s coherent real data traffic equipment after OAM conversion.

Conclusions

We presented a new scheme for converting the order of OAM beams based on an OAM mux implemented with integrated tunable concentric Ω-shaped waveguides. The scheme allows to implement with only two devices, an integrated OAM mux and a refractive elements-based OAM demux, OAM conversion of a bundle of signals multiplexed both in the OAM and wavelength domain. A four-Ω-shaped waveguides integrated OAM mux is designed, fabricated, packaged and tested within the OAM converter. Performance at 20Gb/s show a maximum OSNR penalty<1dB at BER 10^{-9}. The scheme is tested for different wavelengths, demonstrating operability over signals multiplexed both in the OAM and wavelength domain. The effectiveness of the proposed OAM conversion scheme is proved also in a field trial with 100Gb/s QPSK pol-mux real data traffic generated with a commercial network apparatus which confirms that the system can operate over different configurations of the OAM converter.

Acknowledgements

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References

[1] H. Huang et al., "100 Tbit/s free-space data link enabled by three-dimensional multiplexing of orbital angular momentum, polarization, and wavelength", Vol. **39**, no. 2, p. 197 (2014).

[2] A. E. Wilner et al., "Orbital-angular-momentum-based reconfigurable optical switching and routing", Photonic Research, Vol. **4**, no. 5, p. B5 (2016).

[3] M. Scaffardi et al., "A Silicon Microring Optical 2x2 Switch Exploiting Orbital Angular Momentum for Interconnection Networks up to 20Gbaud", J. Light. Tech., 2016.

[4] Y. Yue et al., "Reconfigurable Orbital-Angular-Momentum-Based Switching among Multiple 100-Gbit/s Data Channels", OFC, OM2G.1, Anheim, (2013).

[5] C. Quin et al., "Demonstration of Orbital Angular Momentum State Conversion using Two Hybrid 3D Photonic Integrated Circuits", OFC, OTh4A.1, San Francisco (2014).

[6] G. C. G. Berkhout, et al., "Efficient sorting of orbital angular momentum states of light," Physical Review Lett., Vol. **105**, 153601 (2010).