The Orbital Angular Momentum of Light for Ultra-High Capacity Data Centers

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ABSTRACT

The potential of orbital angular momentum (OAM) of light in data center scenarios is presented. OAMs can be exploited for short reach ultra-high bit rate fiber links and as additional multiplexing domain in transparent ultra-high capacity optical switches. Recent advances on OAM integrated photonic technology are also reported. Finally demonstration of OAM-based fiber links (aggregate throughput 17.9Tb/s) and two layers OAM-WDM-based optical switches are presented exploiting OAM integrated components and demonstrating the achievable benefits in terms of size, weight and power consumption (SWaP) compared to different technologies.

Keywords: orbital angular momentum, optical switching, space division multiplexing, data-center.

1. INTRODUCTION

The increasing demand of data-storage capacity in the data centres due to the diffusion of the Internet of Things, video streaming and social networking applications is pushing to the limit the performance of both the data centre communication links and switches. Optical technology can be a viable solution to overcome the power consumption, footprint and scalability issues [1]. Among the optical technologies, multi-domain multiplexing [2] and switching [3] are currently being investigated as effective approaches. In the last years the OAM of light has been proposed as further multiplexing domain, to be exploited in conjunction with wavelength, polarisation and time to improve the capacity of the point-to-point optical links. Short free-space [4] and kilometre-range optical fibre transmission [5] are demonstrated based on special fibres designed to support OAM modes propagation [2], [6]. OAM can be exploited also as switching domain to increase the scalability and the throughput of the optical switches [7]. In order to make the OAM-based multiplexing and switching solutions effective also on the size, weight and power consumption (SWaP) point of view, the exploitation of integrated technology is necessary. Most of the initial demonstrations have been carried out with bulk components as spatial light modulators (SLMs) [8]. These solutions allow for OAM mode order tuning, but with millisecond timescale and with large footprint. Integrated circuits for the generation and multiplexing of OAM beam on silicon platform have been demonstrated based on different approaches. The ones based on microrings are attractive for the low power consumption and fast reconfiguration time [9]. Nevertheless, the multiplexing of the OAM beams represents a major challenge that has been solved up to now with bulk or not tunable solutions.

Here we investigate the exploitation of the OAM of light in data-centers with two independent approaches: high-capacity OAM-wavelength multiplexed switch-to-switch links and high-performance (port number, power consumption, footprint) OAM-wavelength based switches. The proposed solutions can be exploited in actual data-center scenario and interfaced with standard data-center equipment, since Gaussian-to-OAM and OAM-to-Gaussian mode conversion is implemented at the OAM link and OAM switch edges, which allows signal processing with standard devices. We proposed an integrated solution for the combined generation and multiplexing of OAM modes based on concentric Omega (Ω)-shaped waveguides [10]. This solution allows the independent tuning of the OAM mode emitted by each waveguide and represents a compact way for Gaussian-to-OAM mode conversion and multiplexing. For the OAM demultiplexing we adopted an ultra-compact and passive solution based on cascaded refractive elements, which allows the contemporary spatial separation of beams carrying different OAM modes and their conversion to Gaussian. By exploiting a graded-index ring-core fibre (GIRCF), we demonstrate the transmission of 16 wavelength division multiplexing (WDM) channels multiplexed over 10 OAM modes over 1 km, with 16-quadrature amplitude modulation (QAM) modulated signals, reaching the total capacity of 17.9Tb/s. Moreover, a two-layer OAM and wavelength switch is demonstrated enabling 1.9Tb/s total throughput.

2. OAM-BASED MULTIPLEXING AND SWITCHING FOR DATA CENTERS

The typical data-centre architecture is a fat-tree as shown in Fig. 1 (a). Three levels (Top-of-rack, Aggregation, Core) of aggregation are present, each one formed by switches and optical links. The combination of OAM multiplexing and WDM can increase both the capacity of the links and the switch number of ports, thus improving the data-center scalability. A conventional fibre-based link can be replaced with an OAM fibre supporting N OAM modes as shown in Fig. 1 (b). MN signals at the switch (e.g. aggregation) output ports are mapped in N groups of M WDM channels (WDM mux) by electrical-to-optical (E/O) conversion. Then all the N Gaussian WDM channels groups are converted N OAM modes, multiplexed (OAM mux) and sent through the OAM fibre. At the destination switch (e.g. core) the N WDM channels groups are spatially separated depending on the OAM order and converted back to the Gaussian domain by an OAM demultiplexer (OAM demux). Then the M WDM channels are demultiplexed (WDM demux) and received by optical-to-electrical (O/E) conversion. With this approach the capacity of the single-fibre link is increased N times with respect to a link exploiting only M WDM channels. OAM fibres supporting up to 22 OAM modes have been developed up to now [2]. This approach could be in principle adopted together with a multi-core approach, giving rise to an even higher link capacity. The proposed OAM-multiplexed fibre link can be interfaced with standard data-center switches, since Gaussian-to-OAM and OAM-to-Gaussian mode conversion is implemented at the OAM fibre edges.

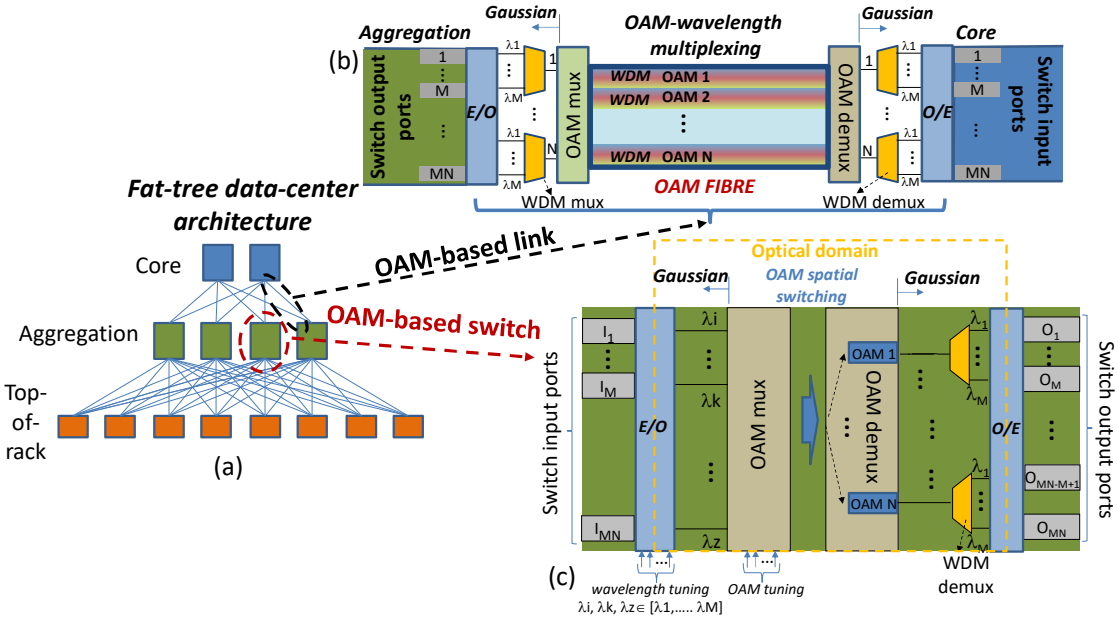

Figure 1: (a) Data center architecture. (b) Data-center fibre link based on OAM-wavelength multiplexing in OAM fibres. (b) Data-center switch architecture exploiting OAM and wavelength as switching domains.

The OAM-based switch can be implemented according to the scheme of Fig. 1 (c). The switch output ports are addressed by exploiting the OAM and wavelength domains. M wavelengths and N OAM modes can address MN output ports. The electrical signals at the switch input ports are converted to the optical domain, mapped onto a specific wavelength and OAM mode according to the destination port. The OAM mode mapping is done with a tunable OAM mux which also spatially multiplexes all the signals. The OAM demux spatially separates all the beams carrying different OAM and converts them back to the Gaussian domain. Then, N WDM demultiplexers separate all the M wavelength channels, which are then converted back to the electrical domain. Since the OAM switching is exploited in the switch core only, and Gaussian signals are present at the switch edges, they can be converted from/to the electrical domain with standard devices. This makes the proposed switch suitable to be employed in conventional data-center environment.

3. INTEGRATED TECHNOLOGY FOR OAM GENERATION AND MULTIPLEXING

We propose a new approach for the OAM modes generation and multiplexing based on concentric Ω-shaped waveguides. Each waveguide consists of a ring geometry with an aperture α that enables the integration of multiple coaxial rings without any crossings between the bus waveguides. Second-order Bragg gratings are patterned on the inner sidewall of the waveguide to scatter the confined whispering gallery modes (WGMs) to a vertically radiated OAM mode. The topological charge of the emitted OAM mode is $l=(2\pi-\alpha)Rn/\lambda-q$, where n is the effective refractive index of the Ω -shaped waveguide, R is the radius, α is the aperture angle, and q is the grating number. The grating profile has been designed with an exponential increase along the waveguide propagation direction to keep the vertical emission uniform along the azimuthal direction. The devices are 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 tune the radiated OAM mode

independently. The OAM multiplexer design is shown in Fig. 2 (a). It is composed by four concentric Ω-shaped waveguides with radius from 21.96µm to 43.92µm. The power for the tuning between two consecutive OAM modes is 23 mW. The emission efficiency, i.e. the ratio between the power injected into the waveguides and the emitted power is 20%. The waveguides are packaged in a square ceramic chip carrier (16mm x 16mm) with bonded electric wires for OAM tuning and a pigtailed fibre array to couple the light into the device as shown in Fig. 2 (b). The switching time between two consecutive OAM modes is measured to be 10µs and can be reduced to hundreds of nanoseconds with an improved heaters design. With this tuning speed, the OAM mux is suitable for data center scenarios, in particular for long-life traffic applications. The integrated OAM mux is employed to demonstrate a two-layer switch.

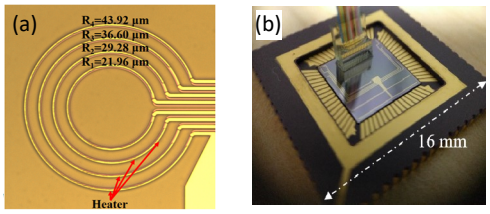

Figure 2: (a) Four-waveguides integrated OAM mux microscope images. (b)Packaged OAM mux with input fibre array and wire bonding.

4. 17.9 TB/S OAM-WAVELENGHT MULTIPLEXING IN FIBRE

We demonstrate here the transmission of 16 WDM channels multiplexed over 10 OAM modes through 1 km special OAM fibre, i.e. graded-index ring core fibre (GIRCF). 4x4 Multi-input multi-output (MIMO) processing is applied at the receiver. Fig. 3 illustrates the measured bit error rate (BERs) vs. optical signal to noise ratio (OSNR) of all 10 modes over one of the 16 WDM channels (1554.1 nm) carrying 28 Gbaud quadrature phase shift keying (QPSK) modulation. All channels show BER performance below the soft-decision forward error correction (SD-FEC) limit. The power penalty is <5 dB. The modulation format is then changed to 16QAM. The output 16QAM constellation is recovered and BER up to 10^{-3} measured. Fig. 4 shows the constellations for multiplexed OAM modes of group l=5 (a), l=4(b) and l=3 (c). The exploitation of integrated OAM multiplexers to generate and multiplex OAM beams in OAM fibres is under investigation. Recent experiments demonstrated the coupling of the OAM beam emitted by an integrated microring to a few-mode fibre [11], showing the feasibility of compact solutions.

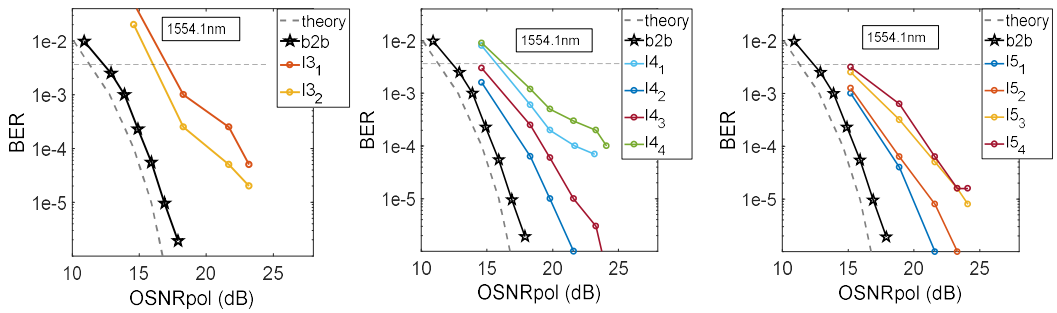

Figure 3: BER vs OSNR at 1554.1 nm for all the 10 OAM modes.

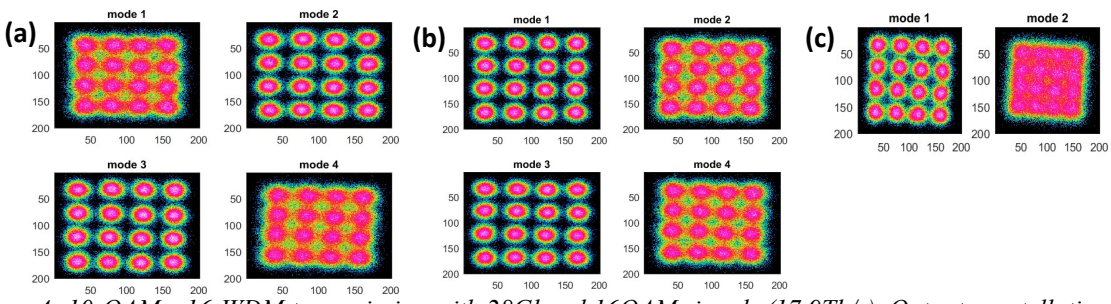

Figure 4: 10-OAM x 16-WDM transmission with 28Gbaud 16QAM signals (17.9Tb/s). Output constellation for the 10 multiplexed OAM modes of group l=5 (a), l=4 (b) and l=3(c).

5. OAM-WAVELENGTH SWITCH DEMONSTRATION

A two-layer switch exploiting OAM and wavelength as switching domains is demonstrated with the cascade of an OAM mux based on 4 integrated Ω-shaped waveguides and an OAM demux based on refractive elements.

The switch scheme is shown in Fig. 5 (a). Ω4, Ω3 and Ω2 are fed with a 30 Gbaud 16QAM signal at 1555.7, 1548.5, and 1552.8nm, respectively, and Ω1 with a 30 Gbaud OOK signal at 1556.5nm, in order to evaluate the performance under mixed data traffic. In a first switch configuration Ω4, Ω3, Ω2 and Ω1 emit an OAM beam of

order l=-5, l=-2, l=-3 and l=-4 respectively. Then Ω4 and Ω2 are switched to l=-2, i.e. on the same OAM order of the beam emitted by Ω3. As shown in Fig. 5 (b), the performance is almost independent of the switching configuration. The inset shows the good performance of the OOK signal. Considering a maximum power consumption for each Ω emitter of 70mW, the switch total power consumption/(Gb/s) <0.6mW for the tuning of the whole OAM multiplexer. The results show that the OAM-WDM switch based on integrated Ω-shaped waveguides multiplexer with 1.9Tb/s throughput is enabled.

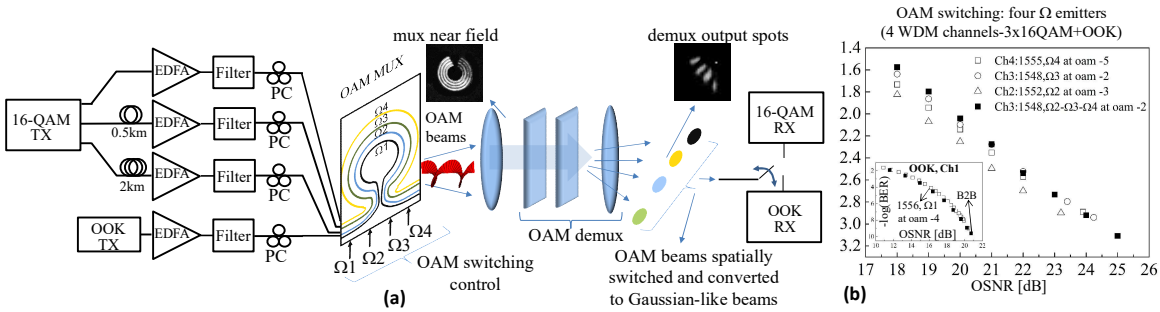

Figure 5: (a) Experimental setup. (b) BER vs switched OAM mode (4 WDM channels - 3x16QAM+OOK).

6. CONCLUSIONS

The OAM of light is exploited as multiplexing and switching domain, in conjunction to the wavelength, to increase the fibre-based links capacity and the switches scalability in data-center applications. An innovative integrated device is demonstrated for OAM modulation and multiplexing based on concentric Ω-shaped waveguides. Each waveguide can be independently tuned in a tens of microsecond timescale. Special GIRCF fibres supporting OAM modes are exploited to implement a 1km-long transmission of 16 WDM channels multiplexed over 10 OAM modes, to obtain a total aggregate bit rate of 17.9 Tb/s. Since Gaussian-to-OAM and OAM-to-Gaussian conversion is implemented at the fibre link edges, this approach can be exploited in actual data center scenario, since the OAM fibre link can be connected to standard devices. The integrated OAM multiplexer is used in conjunction with ultra-compact passive OAM demultiplexer to demonstrate a two-layer OAM-wavelength switch. The OAM domain is exploited in the switch core only, while Gaussian signals are present at the switch input-and output ports. This makes the switch suitable to be interfaced with standard data-center enviroment.

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