ARTICLE IN PRESS

Optics Communications ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Interconnection network architectures based on integrated orbital angular momentum emitters

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ARTICLE INFO

Keywords:
Orbital angular momentum multiplexing
Optical switching
Interconnection network
Optical integration

ABSTRACT

Novel architectures for two-layer interconnection networks based on concentric OAM emitters are presented. A scalability analysis is done in terms of devices characteristics, power budget and optical signal to noise ratio by exploiting experimentally measured parameters. The analysis shows that by exploiting optical amplifications, the proposed interconnection networks can support a number of ports higher than 100. The OAM crosstalk induced-penalty, evaluated through an experimental characterization, do not significantly affect the interconnection network performance.

1. Introduction

The scalability of the current electrical interconnection networks for data center connectivity is hampered by several challenging technological issues as power consumption and footprint [1,2]. An effective solution to overcome these issues is represented by optical interconnection networks based on optical switching [3]. By exploiting simultaneously different switching domains, a further enhancing of scalability and total capacity can be obtained [4]. The orbital angular momentum (OAM) of light can be exploited as further switching domain, together with the more traditional domains as e.g. wavelength, time and frequency, to increase the scalability of the optical interconnection networks. An optical beam with OAM of order l, where l is an integer, has an azimuthal phase term $exp(i \cdot l \cdot \theta)$, where θ is the azimuthal angle. Beams with different OAM order are orthogonal, i.e. they can propagate together ideally without crosstalk [5]. Optical beams carrying OAM can be generated by exploiting bulk components as spiral phase plates [6] or spatial light modulators [5]. Integrated devices such as microrings with super-imposed grating [7,8] circular grating couplers cascaded to star couplers [9] and hybrid 3D integrated circuits [10] have been demonstrated as a more compact alternative to the generation of light carrying OAM.

The OAM of light has been successfully exploited both in transmission and switching experiments. OAM multiplexing has been demonstrated both for free-space [5,11] and fiber transmission [12,13]. OAM switching has been demonstrated based on spatial light modulators in [14–16].

A two-layer OAM and wavelength based switch architecture has been presented in [17], based on a single and not tunable OAM emitter with multiple superimposed gratings.

Here we present three novel interconnection network architectures based on integrated concentric OAM emitters/modulators, which can be independently tuned, thus making the network completely flexible over the two layers, i.e. OAM and wavelength. We analyze the scalability of the architectures in terms of OAM emitters/modulators general characteristics and perform a power budget and optical signal to noise ratio (OSNR) analysis. The physical parameters exploited for the analysis are experimentally measured.

2. Two-layer interconnection network architectures

A possible scheme for a two-layer interconnection network exploiting both OAM and wavelength as switching domains is shown in Fig. 1. The switch has a total number of $M \times N$ optical inputs and $M \times N$ optical outputs. The ports are logically grouped in N subsets, corresponding to the number of cards of an Ethernet switch. Each set of ports represents the number of I/O ports of a card in an Ethernet switch architecture. The ports of the same subset are addressed by the wavelength domain, while the different sets of ports (i.e. cards) are addressed by the

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http://dx.doi.org/10.1016/j.optcom.2017.08.024
Received 23 May 2017; Received in revised form 8 August 2017; Accepted 11 August 2017
Available online xxxx

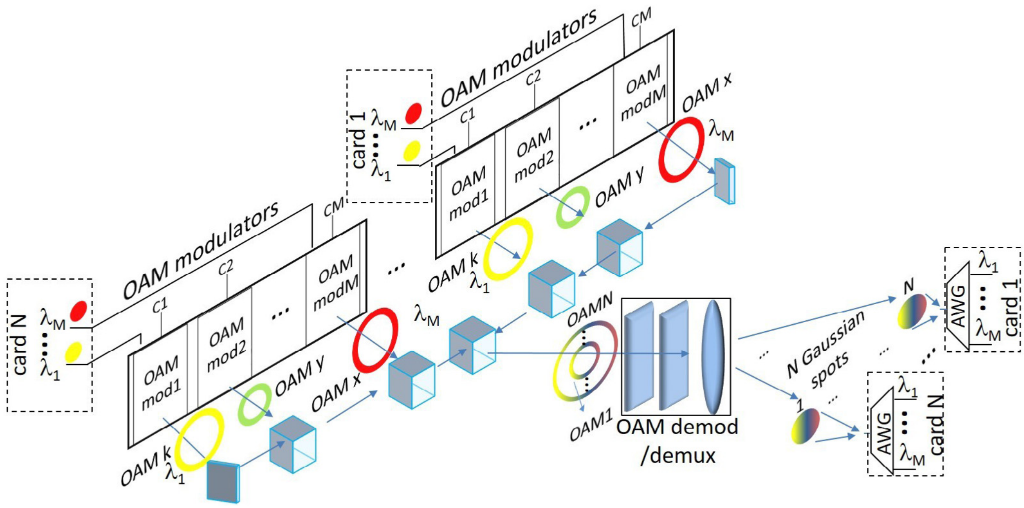

Fig. 1. Two-layer interconnection network architecture based on parallel integrated OAM emitters/modulators.

OAM domain. Each port of the OAM switch accepts a Gaussian signal, i.e. with the phase front having a Gaussian spatial distribution, at a wavelength within the allowed set of M wavelengths ($\lambda 1, \ldots \lambda M$). For each input port, an OAM modulator converts the signal onto an OAM mode, i.e. with a phase front with an helical spatial distribution, of order l among a set of N OAM modes (OAM 1, ..., OAM N) depending on the targeted output ports subset. The OAM modulator can be implemented with single integrated microrings with a superimposed grating, which emits the OAM beam in a direction orthogonal with respect to the microring plane [18]. The order of the converted signal is set with a control signal (Ci) by thermal tuning [19]. All the emitted OAM modes are multiplexed by free-space multiplexing based on beam combiners. All the OAM and wavelength multiplexed beams are then sent to the OAM demodulator/demultiplexer which at the same time spatially separates the OAM modes and converts them to a wavelength-multiplexed Gaussian spot. The OAM demodulator/demultiplexer can be implemented with a passive device build with two polymethyl methacrylate (PMMA) free-space diffractive optical elements suitably patterned followed by a lens as demonstrated in [20], or with a commercial multiplane light converter [21]. Then the M wavelength are separated with an arrayed waveguide grating (AWG). This scheme allows a relatively simple technological implementation of the OAM emitters, since they can be integrated as a parallel of microrings, but introduces losses due to free-space beam combining. The maximum loss $L0$ experienced by the signals due to the free-space coupling is:

$$L0 = 1/2 \cdot \lceil (N \cdot M - 1)/2 \rceil \tag{1}$$

where $N \cdot M$ is the total number of input ports (supposed to be even).

The number of couplers of the architecture of Fig. 1 can be reduced with an approach based on concentric OAM emitters/modulators as the one shown in Fig. 2. Here the $N \times M$ OAM emitters/modulators are concentric, i.e. the OAM signals coming out from the OAM emitters propagate coaxially, thus being spatially multiplexed. The multiplexed OAM beams are directed to the OAM demultiplexer/demodulator which spatially separates all the OAM modes of different orders and at the same time converts them to Gaussian modes, which can be propagated e.g. through a waveguide or an optical fiber. All the M wavelengths are demultiplexed, i.e. spatially separated, by an AWG and directed to the corresponding output port. This scheme is very compact since the functionalities of modulation and multiplexing are implemented with a single integrated device. The number of OAM modulators that can be integrated on the same OAM mod/mux limits the number of input ports.

An hybrid approach which combines the architectures of Figs. 1 and 2 is shown in Fig. 3. This alternative architecture is based on parallel concentric OAM emitters/modulators (OAM mux). All the M signals coming from each of the N cards are coupled to an OAM mux implemented with M concentric OAM emitters/modulators independently tunable. The emitted OAM signals are collimated and coupled with (N-1) free-space beam combiners and sent to the demodulation/demultiplexing part, which is equal to the demodulation/demultiplexing part shown in Fig. 2. This implementation reduces the number of concentric OAM emitters/modulators that need to be integrated on the same OAM mux, at the expenses of losses due to the free-space coupling.

3. Scalability analysis

In order to investigate the potential of the proposed interconnection networks, a scalability analysis is developed and detailed in the following. The analysis is carried out for the two architectures shown in Figs. 2 and 3, which are more promising in terms of balancing between losses and number of ports.

In the architecture shown in Fig. 2, the total number of ports corresponds to the number of concentric OAM emitters/modulators that can be integrated on the same chip. This number is limited by the maximum allowed size (e.g. diameter) of each OAM emitter/modulator, which influences the OAM beam divergence-induced losses, and by the minimum allowed distance between two concentric emitters/modulators. The beam emitted by the concentric OAM emitters/modulators is collimated by a lens and, according to the ray optics laws, diverges depending on the diameter of the OAM emitter/modulator (D) and the collimator focal length (f). The OAM beam divergence should be limited in order to keep the beam spot size smaller than the aperture of the OAM demod/demux (T). For a fixed maximum allowed T, it becomes:

$$Dmax < T \cdot f / L \tag{2}$$

where L is the distance between the collimator and the OAM demod/demux. Table 1 shows *Dmax* vs. f and L for $T = 10$ mm, which represents a safe limit for standard optical free-space devices.

The smaller is the distance between the collimator and the OAM demod/demux, the higher is the size allowed for the largest OAM emitter/modulator. Considering a collimator with high numerical aperture, e.g. $NA = 0.5$, with $f = 10$ mm, for a distance $L < 200$ mm, *Dmax* > 500 μm. The maximum number of concentric emitters in the OAM mux is:

$$K = (Dmax - Dmin)/(2 \cdot S), \tag{3}$$

where S is the minimum separation among two concentric OAM emitters and *Dmin* is the minimum diameter of the OAM emitter. Table 2

Please cite this article in press as: M. Scaffardi, et al., Interconnection network architectures based on integrated orbital angular momentum emitters, Optics Communications (2017), http://dx.doi.org/10.1016/j.optcom.2017.08.024.