Data Transmission using Orbital Angular Momentum Mode Multiplexing and Wavelength Division Multiplexing with a Silicon Photonic Integrated MUX Chip

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Abstract *We present a simultaneous WDM and orbital angular momentum (OAM) mode photonic chip multiplexer, and demonstrate data transmission of 8xWDM channels on 2xOAM modes, each carrying 10-Gbit/s OOK data through an 800-m ring-core OAM fiber. All 16 channels attain BERs below the 7% FEC limit.*

Introduction

The demand for data transmission capacity is increasing and consequently, new technologies are continuously being developed. With the matured use of time, wavelength, and polarization-division multiplexing (MUX), as well as higher order modulation formats, the attention has turned towards space-division multiplexing (SDM)[1]. Besides using multi-core/few-mode fibers supporting LP modes, another promising path is to use orbital angular momentum (OAM) modes for spatial mode-division multiplexing (MDM), since it provides a large number of stable eigenstates[2]. A key component to allow for effective OAM multiplexed data transmission is an OAM multiplexer, which is truly orthogonal to multiplexing in wavelength simultaneously. Some suggested approaches to OAM multiplexing have limited feasibility for WDM[3], [4], by e.g. converting WDM to OAM. We recently designed a WDM-compatible chip that enables multiplexing of OAM modes from L=-7 to L=+7 over a broad wavelength range, designed to cover the full C-band. The initial characterization results of the OAM performance are presented in [5], [6], though without an experimental demonstration of the WDM compatibility.

In this paper, we demonstrate the capability of simultaneously multiplexing WDM and OAM channels using our OAM MUX chip. We transmit 16 10-Gbit/s OOK channels distributed on 8xWDM channels and 2xOAM modes, L = -5 and -7, through an 800-m OAM-supporting ring-core fiber[7]. All channels are below the 7% forward error correction (FEC) limit, demonstrating the OAM-chip's crucial compatibility with WDM fiber-based systems.

OAM MUX chip

Figure 1 shows an image of the silicon-on-insulator (SOI) MUX chip[5]. The total dimension is 11.7 mm x 2.3 mm. It consists of three parts. On the left, are 15 input grating couplers each with a 500-μm adiabatic taper. The channel spacing of the input couplers is 127 μm, which is compatible with commercial fiber arrays. In the middle, is a star coupler that generates 2πL phase difference across the 26 output waveguides[8], where L is an integer between -7 and 7 depending on the choice of input waveguide, hereby providing the required phase shift for generation of OAM modes from L=-7 to L = +7. To the right, a ring of 26 output grating couplers emits the phase delayed light into free space. However, one of the output gratings has 20 dB higher loss than the others due to a

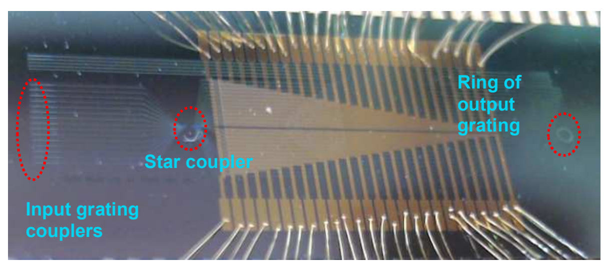

Fig.1: Image of the fabricated chip with a ring of 26 output grating couplers

fabrication error. In order to account for phase errors introduced by fabrication imperfections, there are thermal heaters on top of each waveguide between the star coupler and output grating couplers. These enable optical path length compensation by changing the refractive index of the waveguides. The total loss of the chip, including input coupling loss, is around 20 dB. We expect this could be reduced to 10 dB

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through design improvements. The current designed chip can, as mentioned, in principle excite and multiplex all OAM modes from L=-7 to L=+7 over a large wavelength range. The fabricated chip, however, suffered some faulty phase-shifters, which we believe can be easily fixed in future iterations, and it was still possible to demonstrate the essential functionality of the OAM-MUX chip by simultaneously exciting two modes (L= -5,-7) for eight different wavelengths with data transmission characterization.

Experimental setup

The experimental setup is shown in Fig. 2. Eight CW lights, from eight distributed feedback (DFB) lasers, at wavelengths between 1547.2 nm and 1554.2 nm, with a 1 nm spacing, are sent to two intensity modulators. One wavelength at a time is used as the test channel, while the other 7 wavelengths are used as dummy channels. The test channel is modulated with a 10 Gbit/s on-off keying (OOK) signal, generated from a bit-pattern generator (BPG), while the dummy channels are modulated by the inverted OOK signal for de-correlation from the test channel. An erbium-doped pre-amplifier (EDFA) with 20-dB amplification is employed to compensate for the loss in the dummy channels so that each of them has comparable power to the test channel. A tunable band stop filter (BSF) with a bandwidth of 0.8 nm generated by a wave shaper is employed to suppress the ASE from the pre-amplifier at the wavelength of the test channel. After aligning the state of polarization (SoP) to the test channel, the dummy channels are combined with the test channel using a 3 dB coupler. An EDFA amplifies the total power to +32.5 dBm. A 3 dB-coupler splits the light into inputs for OAM L=-5 and -7 generation. A 100-m long single mode fiber (SMF) is added in order to de-correlate the data and eliminate interference between OAM channels. Since the input grating couplers on the chip is polarization sensitive, polarization controllers (PCs) are used before coupling light into the OAM MUX chip. Additionally, a variable optical attenuator (VOA) is applied for OAM L=-5 for power equalization. The multiplexed signals are coupled into an 800-m long ring core fiber by a free-space lens system. A quarter wave plate is employed to convert the linearly polarized output from the chip to circular polarization. After transmission through the OAM fiber, the light is converted to linear polarization and sent to a spatial light modular (SLM) for de-multiplexing (DEMUX) and mode filtering. The topological charge of light is altered by using a reversed phase pattern, which enables the conversion from a specific OAM mode to a Gaussian beam. The Gaussian beam is then coupled into an SMF, whereas the other modes that remain as OAM modes, are spatially filtered out. A tunable optical filter is used to select the wavelength of the test channel and to filter out ASE noise after a pre-amplifier. The filtered optical signal is then sent to the receiver and the bit-error-rate (BER) is measured using an error detector.

Results and discussions

The OAM-MUX chip works well, and is successfully able to generate the two desired OAM modes simultaneously for all 8 wavelengths, confirmed by BER measurements (Fig. 3(b)). Figure 3(a) top shows the spectra of the input WDM channels to the OAM chip. Figure 3(a) bottom shows the output spectra of the OAM MUX/DEMUX system when OAM L = -

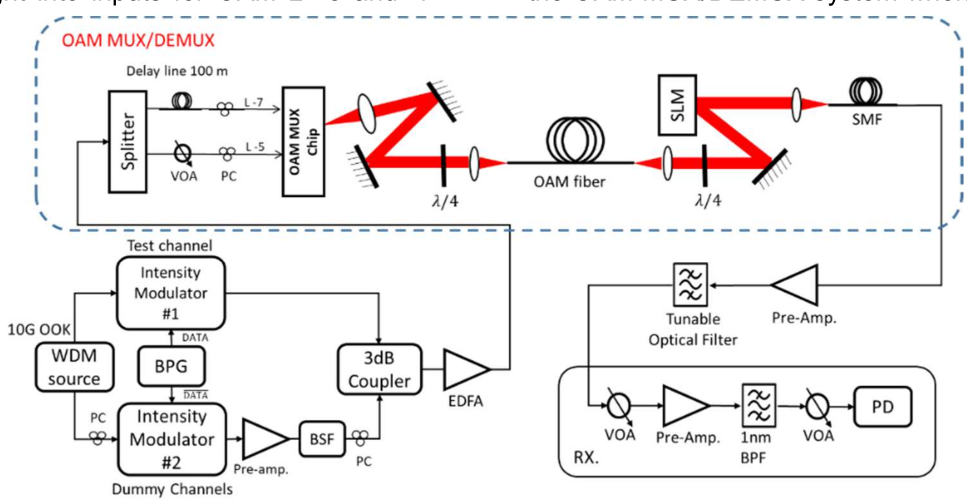

Fig.2: Schematic of the experimental setup for the chip-based OAM-WDM data transmission

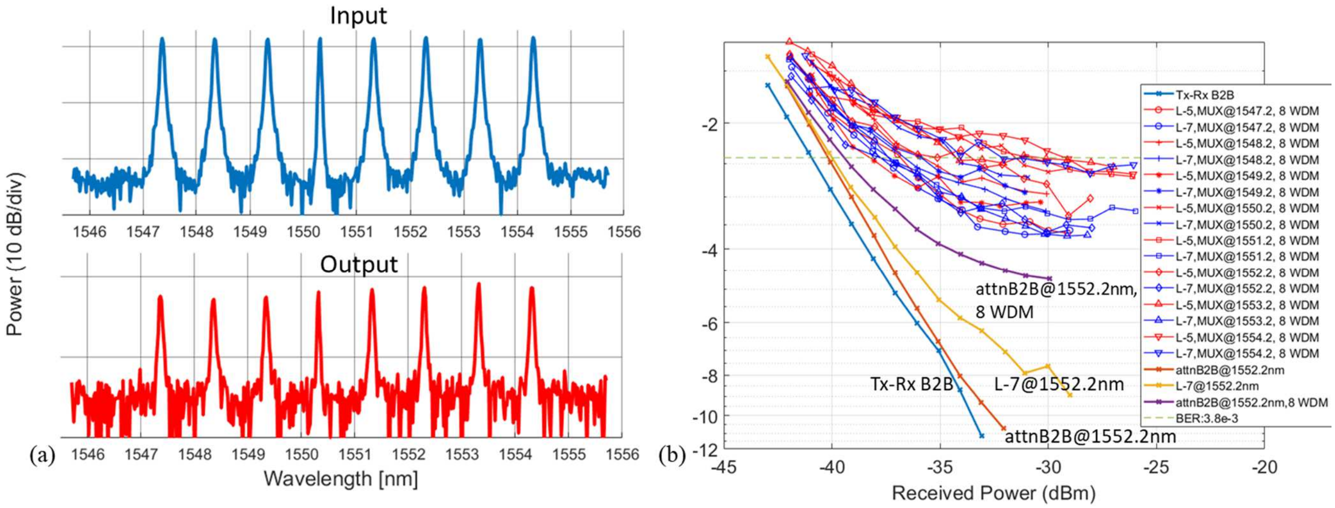

Fig.3: (a) Input and output spectra of 8 WDM channels of OAM MUX/DEMUX. (b) BER vs received power curves of two OAM modes over eight wavelengths as well as back-to-back measurements

7 is excited. In this example, the test channel is at 1550.2 nm. The dummy channels have wider spectra because of pre-amplification. Figure 3(b) shows the BER performance of OAM L=-5 and L=-7 for the 8 wavelengths from 1547.2 nm to 1554.2 nm, with all channels attaining better BER than the FEC limit. The blue curve at the bottom left is the back-to-back (B2B) curve for the test channel at 1552.2 nm, which characterizes the performance of the transmitter (intensity modulator #1) and receiver. The curve 'attnB2B@1552.2nm,8 WDM' (violet curve) is the B2B measurement at 1552.2 nm with eight WDM channels, where the system inside the dashed box in Fig. 2 is replaced by an attenuation of 59.5 dB, which corresponds to the loss of the OAM MUX/DEMUX system, in its present fabrication state. The curve 'attnB2B@1552.2nm' (orange curve) is the same case as that of the violet curve, but with only one wavelength channel at 1552.2 nm. There is about 1 dB penalty between the orange and violet curve at the FEC limit, and the violet curve has a BER error floor around 2e-5. This is because more WDM channels share the amplifier output power, and thus reduce the optical signal-to-noise ratio (OSNR), due to the low available power of each wavelength channel for the orange case. The curve 'L-7@1552.2nm' (green curve) is the BER performance when only the OAM L=-7 mode is transmitted at only one wavelength channel. It is very close to 'attnB2B@1552.2nm' (orange curve) at the FEC limit, and able to reach a BER of 1e-9, which confirms that the chip can indeed generate high purity OAM modes. The remaining red and blue curves with eight different marker types indicate the BER performance of OAM L=-5 and L=-7 modes at different wavelengths. Although all channels reach a BER below the 7% FEC limit (3.8e-3), the penalties with regards to 'L=-7@1552.2nm' (green curve) are large. They mainly come from the high loss and low power in each wavelength channel as well as some induced crosstalk between OAM L = -5 and L =-7. We believe that by improving the fabrication quality of the chip and the free-space coupling, it is possible to reduce the loss and reduce the penalty. The BER performance of the L=-5 mode is generally slightly worse than the L = -7 mode, which indicates that excitation of the L=-5 mode in the OAM fiber is not optimal. Future work aims to improve the system by applying more appropriate heater settings for phase error compensation using intelligent optimization algorithms and machine learning.

Summary

For the first time, to the best of our knowledge, we demonstrate data transmission of two orbital angular momentum (OAM) modes over eight WDM channels multiplexed by an OAM MUX chip. OAM modes of L = -5 and -7, each carrying 10 Gbit/s OOK data are multiplexed over wavelengths between 1547.2 nm and 1554.2 nm and transmitted through an 800 m ring-core OAM fiber. BER below 7% FEC limit is obtained for all data channels.

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