Optical Circuit Switching/Multicasting of Burst Mode PAM-4 using a Programmable Silicon Photonic Chip

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Abstract: Aiming to facilitate increased intra-datacenter throughput and reconfigurability, the use of a programmable silicon photonic chip to achieve optical circuit switching and multicasting of 12.5GBaud burst mode PAM-4 is experimentally demonstrated for the first time.

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1. Introduction

Datacenters (DC) continue to grow in scale, handling ever increasing amounts of data traffic. The high demand for cloud based services fueled by advances in wireless and mobile technologies, means that much of this growth in traffic volume is taking place inside the DCs themselves [1]. This requirement – for large bandwidth data to be routed from server to server via intra-DC networks – cannot be handled efficiently by current Ethernet switching technologies [2] and so the use of optical routing, through wavelength division multiplexing (WDM), along with optical switching technologies such as wavelength selective switches (WSSs) [3] and micro-opto-electro-mechanical systems (MEMS) [4] have been proposed for use in DC networks. However these technologies are limited in terms of their switching speed, scalability and ability to handle a wide range of traffic flows in an agile manner [5-7] – a key requirement for future DC optical networks.

Silicon Photonic (SiP) technology has emerged as a means of producing cost effective, small footprint, photonic integrated circuits (PICs), which can provide a multitude of functionalities, and are compatible with complementary metal-oxide semiconductor (CMOS) processes [8]. In this work, a programmable SiP chip, based on eight cascaded micro-ring resonators (MRRs), is employed to perform reconfigurable wavelength routing (circuit switching), as well as optical multicasting – an essential operation in the physical layer of future DC networks [9]. Four level Pulse amplitude modulation (PAM-4) is used, as it facilitates a straightforward augmentation of the non-return-to-zero (NRZ) format/hardware currently employed in DCs, while doubling the throughput [10]. Recent work has demonstrated multicasting with a SiP chip based on Mach-Zehnder interferometers (MZIs) within a static data environment [11]. In this work we present a system capable of providing nanosecond-scale wavelength switching through the incorporation of a fast tunable sampled grating distributed Bragg reflector (SG-DBR) laser at the transmitter [12]. The rapid wavelength reconfigurability facilitates burst switching functionality. Additionally, an integrated software control plane has been developed to manage the SiP chip, demonstrating the systems' suitability in meeting the needs of future intra-DC software defined networks (SDN).

2. Programmable Silicon Photonic Chip

The SiP chip used for this work consists of eight cascaded MRRs, with one input port and eight output ports. The chip essentially acts as a reconfigurable 1×8 spatial switch, as each MRR exhibits wavelength selectivity which can be tuned (on µs timescales) in order to drop an incoming wavelength at a desired port. Additionally, the MRRs' passbands may be tuned to overlap so that the same incoming wavelength may be dropped at multiple ports – optical multicast. A software control plane based on a field programmable gate array (FPGA) was developed in order to provide user control of the spatial reconfiguration, including unicast and multicast operations [13]. It operates by using digital-to-analog converters (DACs) to provide voltages required to thermally tune the MMRs to various points across the C-band, in order to achieve the desired circuit switch functionality. The 3dB pass band of each ring is estimated to be 87GHz [13], and due to fiber grating alignment issues, the chip exhibits 20dB of loss.

3. Experimental Setup

The experimental setup is show in Fig. 1. A tunable SG-DBR is set to switch between two wavelengths (2dBm output power) by driving one of its grating sections with a clock signal. A continuous 12.5GBaud PAM-4 signal was generated by a Keysight M9502A arbitrary waveform generator (AWG) operating at 62.5GSa/s, amplified and used to modulated the optical switching signal via a Mach-Zehnder modulator (MZM); producing burst mode data in the optical domain. In order to compensate for the coupling losses caused by the fiber grating on the silicon photonic

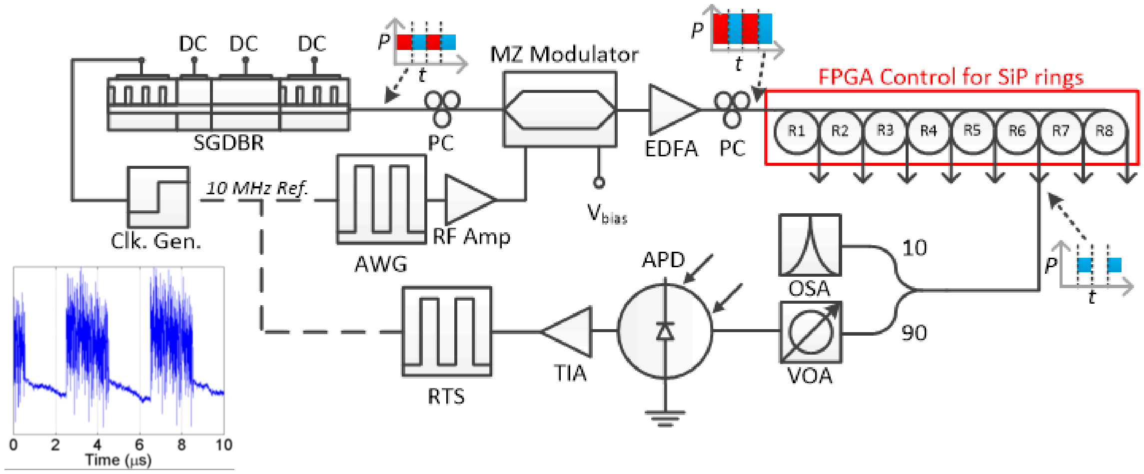
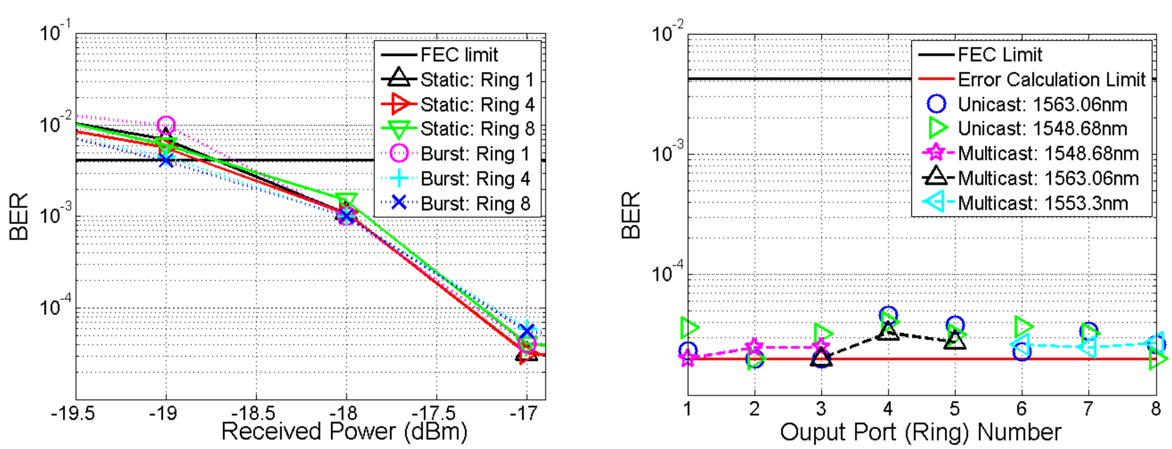


Fig. 1. Experimental setup including figurative representations of the switching/routing operations. The inset shows example received 2μs bursts at the RTS.

chip, an erbium doped fiber amplifier (EDFA) was used to amplify the signal from -8 to 12dBm. Through the FPGA control plane, one (unicast) or more (multicast) rings were tuned to drop one of the incoming wavelengths. The optical power at the output of the SiP chip varied between -10 and -15dBm depending on system configurations, and a variable optical attenuator (VOA) was used to restrict the maximum input power at the avalanche photodiode (APD) receiver to -15dBm. The received burst signal was sampled at 25GSa/s by a Tektronix MSO71254C real time oscilloscope (RTS). In order to avoid signal distortion from the AC coupled photo-receiver, a relatively short clock period of 4μs was used, resulting in a burst length of 2μs on either wavelength. Digital processing of the received signal (resampling, normalization, adaptive equalization, symbol synchronization and decoding) were performed offline using Matlab. The adaptive equalizer was a 13 tap finite impulse response (FIR) filter, and the tap weights were updated using a decision-directed least-mean square (DD-LMS) algorithm [14]. The symbol synchronization was performed with the aid of a training sequence which consisted of 32 PAM-4 symbols.

4. Results

Figure 2(a) gives the bit error rate (BER), for various received powers, of received burst data at 1548.68nm, dropped at a single output port/ring (unicast operation). Static results were also recorded to provide a baseline performance comparison. In order to obtain burst mode measurements, the laser was set to switch between 1548.68nm and 1553.3nm and, via the software control plane, rings 1, 4 and 8 were, in turn, tuned to route bursts on the 1548.68nm wavelength to the photo receiver where they were captured for analysis. The quality of the data bursts were evaluated given a 10ns settling period after a laser switching event [12]. In this case the results show that there is no performance penalty in the burst mode cases, compared to static cases. The results also show that the performance remains the same from ring to ring in both static and burst mode cases. A BER of around 1×10^{-3} was recorded for a received power of -18dBm in all cases. The forward error correction (FEC) limit shown is 4.2×10^{-3}.



(a) (b)

Fig. 2. (a) Received power versus BER for wavelength 1548.675nm, dropped at rings 1, 4 and 8, for both static and burst modes, and (b) calculated BERs for burst mode unicast and multicast operations, for various wavelengths.

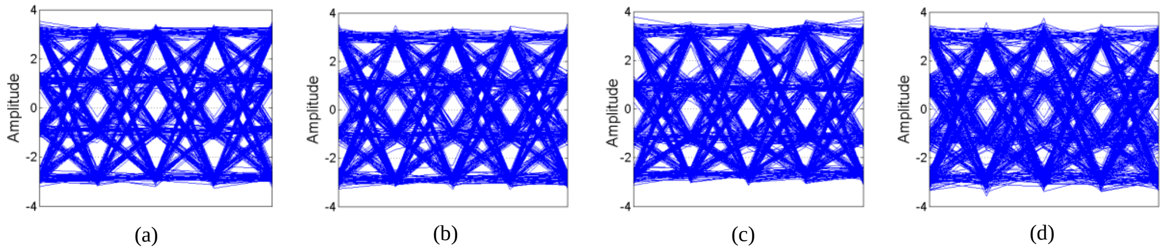


Fig. 3. Sampled PAM-4 eye diagrams corresponding to bursts on (a) 1563.06nm, unicast through ring 1, BER = 2.3×10^{-5}, (b) 1553.3nm multicast operation through ring 8 BER = 2.3×10^{-5} , (c) 1548.68nm, unicast through ring 4, received power of -17dBm, BER = 6.0×10^{-5} and (d) 1548.68nm, unicast through ring 8, received power of -18dBm, BER = 1×10^{-3}.

Figure 2(b) shows BERs for burst mode data, at a received power of -15dBm, for various wavelengths at all output ports. The figure also gives results where optical multicasting is employed on up to three rings (indicated by dashed lines between values in the figure). BER values equaling the error calculation limit (2×10^{-5}) indicate results where a reliable BER calculation could not be performed due to the lack of measured bit errors. Nevertheless, good performance was achieved in all cases where similar BER values, ranging from 2×10^{-5} to 4×10^{-5}, were obtained. In order to implement multicast functionality with the SiP chip, the passbands of up to three rings were thermally tuned to overlap such that equal power was dropped from each port. As the optical signal is now split into three paths rather than one, the output power from each ring drops by 4.8dB, in this case to around -15dBm. Since the APD receiver gives optimum performance at -15dBm, it follows that no discernable difference in performance can be observed, between unicast and multicast data, in Fig. 2(b). However this fact does highlight the need for appropriate network planning where SiP multicast operations are envisioned.

Fig. 3(a), (b), (c) and (d) show sampled PAM-4 eye diagrams for various configurations indicated in the caption. Fig. 3(b) is taken from a detected burst through ring 8, which was also multicast through rings 6 and 7.

5. Conclusion

For the first time, the transmission of burst mode PAM-4 data, through a MMR based SiP has been experimentally demonstrated. Furthermore, optical multicasting has been achieved on up to three output ports without penalty, with near uniform BERs achieved for all output ports across a range of wavelengths.

The inclusion of a fast tunable SG-DBR in the system allows for burst switching on nanosecond time scales, and in combination with the circuit switching offered by the programmable SiP chip, represents a subsystem capable of handling short term, long term and ill-behaved data flows – a critical requirement for future DC networks which will provide a plethora of services. Another crucial element for future reconfigurable DC networks is the ability to support SDN. The use of an FPGA based control plane in this work highlights SiPs potential for use with SDN applications and adds greatly to the flexibility of the system to meet user demands

Lastly, advances in SiP technology will allow for MRR based devices to be manufactured with narrower passbands and lower coupling losses, facilitating WDM networking between servers with much higher granularity, and in a more efficient manner.

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