SAND2014-3023C

A silicon photonic channelized spectrum monitor for UCSD's multi-wavelength ring network

Ryan Aguinaldo,[1,*] Peter Weigel,[1] Hannah Grant,[1] Christopher DeRose,[2] Anthony Lentine,[2] Andrew Pomerene,[2] Andrew Starbuck,[2] Andre Tkacenko,[3] and Shayan Mookherjea[1,*]

[1] University of California, San Diego, Mail Code 0407, La Jolla, California 92093-0407 USA
2 Sandia National Laboratory, Applied Microphotonic Systems, Albuquerque, New Mexico 87185 USA
3 NASA Jet Propulsion Laboratory, Signal Processing Research Group 332C, Pasadena, CA 91109 USA
[*]Email: raguinaldo@ucsd.edu, smookherjea@ucsd.edu

Abstract: A compact silicon photonic channelized optical spectrum monitor is designed and realized, which can replace a large rack-mounted OSA's channel power monitoring functionality, and the signal processing algorithm underlying its operation is described.

OCIS codes: (230.3120) Integrated optics devices;

1. Introduction.

As part of our goal to replace conventional hardware by their functional equivalents in silicon photonics, here we describe the design, fabrication and measurement of an OSA-on-a-chip for MORDIA (Microsecond Optical Reconfigurable Datacenter Interconnect Architecture) which is a multi-wavelength, multi-port optical circuit-switched DWDM ring network, supporting upto 24 optical lambdas on the 100 GHz ITU-T grid in the C band, each carrying 10 Gbit/s data [1]. The OSA is used to read what are the optical power levels of the channels and our chip is also designed to provide that needed information, but with many orders-of-magnitude size, weight and power reduction, as well as the opportunity for monolithic integration with other silicon photonic components.

2. Device Architecture.

As shown in Fig. 1, our chip-scale architecture consists of 24 channels, where each channel consists of a 7th order microring drop filter, weakly coupled to the bus waveguide. We and others have previously demonstrated that coupled silicon microrings can achieve high extinction (>50 dB) and steep sidewalls (slope >100 dB/nm) in an ultra-compact footprint [2-4]. Single microrings are unsuitable since the relatively-broad single-pole Lorentzian lineshapes cause inter-channel crosstalk and degrade the transmitted light in the bus waveguide after only a few stages. The silicon photonic chip was fabricated using Sandia's Silicon Photonic Process (SPP1) using partially-etched silicon rib waveguides and adiabatically-widened microrings.

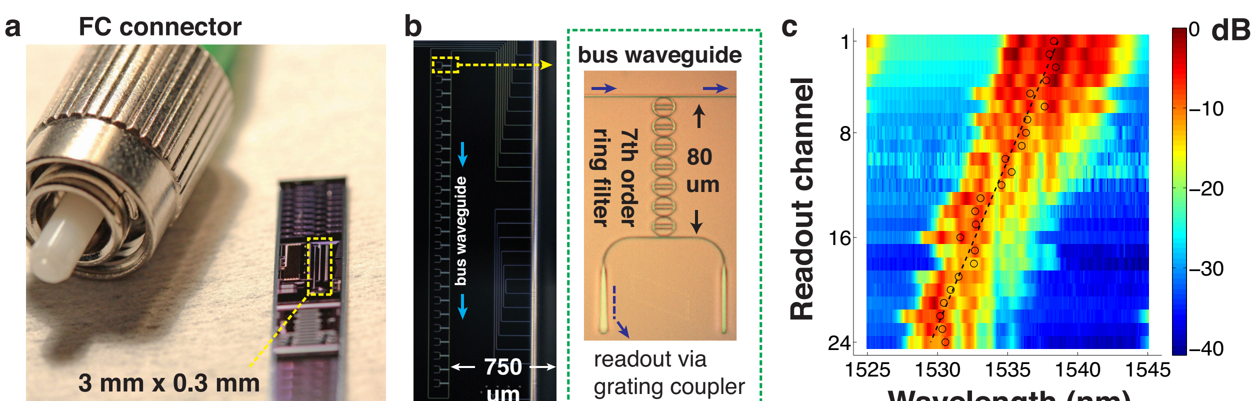

Fig. 1a, chip-scale spectrum monitor (size and comparison with FC connector shown), **b,** dark-field image of the 24 channels; inset shows one of 24 drop-filters, consisting of 7 cascaded microrings (image shows a partially-fabricated chip, without metallization). **c,** readout map (measuring the matrix **T**) for one band of wavelengths. The circles are the center wavelengths of each readout port; the dashed line is a visual guide (slope = 0.4 nm /channel).

On the reported chip, the channel-to-channel center spacing was about 0.4 nm, and the drop bandwidth of the channels (defined by the magnitude of the coupling coefficient between the microrings), was measured to be about 2 nm. The bandwidth was intentionally greater than the channel-to-channel spacing, so that multiple detector readouts are obtained for each lambda. The dropped channels feed into 24 detection ports; in the chip we report on here, grating couplers which lie in a linear array on a 125 μm pitch were used for off-chip detection using a high-sensitivity InGaAs photodiode. No thermal tuning of the microrings was performed. Fig. 1c shows the mapping between the detector ports and the input optical wavelength, measured using a narrow-band tunable laser at the input, and lensed tapered fibers for coupling to the input port (edge coupler) and detector port (grating coupler). We have verified that essentially the same information was obtained by coupling the output light to an InGaAs sensor array (in this case, all the output channels can be read out simultaneously). We label this matrix measured over a range of wavelengths as **T**.

3. Signal processing for spectral reconstruction.

The transceivers have a known (Lorentzian) lineshape S(λ), and the center wavelengths of the channels used in MORDIA are known to be on the 100 GHz grid. What are unknown are the amplitudes of these channels. The reconstruction algorithm is based on finding the optimal solution in the least squares sense as defined by the Frobenius norm. For example, suppose that we measure the matrix $\mathbf{T}^{24x171}$ whose *rows* represents the transfer functions of each of the 24 detector ports over 171 wavelengths within the range of wavelengths 1528 nm to 1545 nm with step size 0.1 nm. Now, within this spectral range, there are 23 channels on the ITU-T 100 GHz grid, and the spectrum of the source (e.g., XFP+ module) is known, labeled S(λ). We construct a matrix $\mathbf{S}^{171x23}$, in which each *column* is S(λ) centered at the corresponding ITU-T channel's wavelength. Any misalignment between the (discrete) frequency axes which define the rows of the **T** matrix and the columns of the **S** matrices must be measured accurately. Next, a new matrix $\mathbf{V}^{24x23}$ is defined as **T**×**S**; unlike the "fat" matrix T, which does not have a left-inverse, the matrix **V** is "skinny", is of full column rank, and does have a left-inverse. The problem becomes that of estimating the channel amplitudes $\mathbf{C}^{19x1}$ from the detector amplitudes $\mathbf{D}^{24x1}$ which are related by the equation **D** = **V**×**C**. The optimal least-squares solution is provided by the Moore-Penrose pseudo-inverse of **V** [5], i.e., we uniquely obtain the estimates $\mathbf{C} = \mathbf{V}^{-1}\times\mathbf{D}$, from which the measured spectrum can be reconstructed using the known lineshape of the transceivers S(λ).

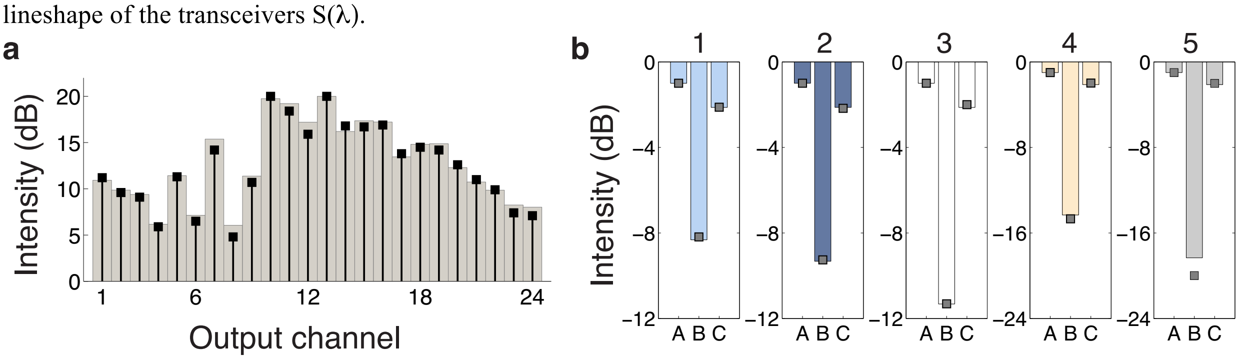

Fig. 2a, 24 detector outputs for a representative input spectrum, with bars representing the expected readouts (based on the spectrum measured using a conventional OSA) and stems showing the actual readouts from the chip. The intensity scale in dB has an arbitrary zero reference. **b,** Comparison of actual (bars) and reconstructed amplitudes (squares) for three channels at A: 1533.593 nm, B: 1558.909 nm and C:1568.169 nm combined with non-uniform amplitudes and input to the chip. Five different test cases are measured, numbered 1 to 5, corresponding to changing the amplitude of only channel B. Notice the change in vertical scale for the last two panels. The intensity scale in dB has an arbitrary zero reference (common to the five panels).

Fig. 2 shows an example of a three-channel reconstruction, using three lasers at 1533.593 nm, 1558.909 nm and 1568.169 nm. Fig. 2a shows the expected detector amplitudes $\mathbf{D}^{24x1}$ for this composite spectrum, and the actual readouts. Next, the amplitude of only the second laser was changed and the reconstructed readout was able to track the amplitude changes (despite the presence of two other tones) over a wide dynamic range. Further improvements can be expected by accurately aligning the three lasers to a common frequency grid. Here, as a test case, we have used very narrow linewidth lasers (<100 MHz est.), which is more demanding than, for example, when using XFP transceivers (~10 GHz spectral width). Also, the wavelengths used span a wider range than shown in Fig. 1c.

The authors are grateful to the CIAN ERC EEC-0812072 and NSF MRI ECCS 1229677. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

[1] N. Farrington, et al. ACM SIGCOMM Computer Commun. Rev. Vol. 42, No. 4, pp. 95–96 (2012).
[2] J. R. Ong, R. Kumar and S. Mookherjea, IEEE Photonics Technology Letters Vol. 25, No. 16, pp. 1543-1546 (2013).
[3] F. Xia , M. Rooks , L. Sekaric and Y. Vlasov , Opt. Express, Vol. 15, No. 19, pp. 11934 -11941 (2007).
[4] X. Luo, et al., IEEE Photon. Technol. Lett., Vol. 24, No. 10, pp. 821–823 (2012).
[5] R. A. Horn and C. R. Johnson, *Matrix Analysis* (Cambridge University Press, Cambridge, UK, 1985).