Applications of Silicon Nanophotonics: Space-division Multiplexing and Integrated Spectroscopy

A. Grieco*, B. Hong*, G. Porter**, Y. Fainman*

*Department of Electrical and Computer Engineering, University of California, San Diego, CA 92093-0407 USA (e-mail: agrieco@ucsd.edu; bjhong@ucsd.edu; fainman@eng.ucsd.edu).
**Department of Computer Science and Engineering, University of California, San Diego, CA 92093-0407 USA (e-mail: gmporter@cs.ucsd.edu).

ABSTRACT

Data center needs are evolving as more advanced optical transmission techniques are deployed. This presentation discusses recent technological developments pertaining to the scalability and characterization of the network fabric: space-division multiplexing on a chip, and integrated spectroscopy. Integrated space-division multiplexing (SDM) on a chip partitions the bandwidth utilizing the orthogonal degrees of freedom of the guided spatial modes in a multi-mode waveguide. This approach is tantalizing because it promises cost, complexity and scalability advantages by augmenting or replacing the existing wavelength-division multiplexing (WDM) technology. We discuss our experimental work on integrated periodically nanostructured resonant couplers that selectively transfer energy between arbitrary modes within a multimode waveguide. This coupler possesses advantages in terms of packing density, bandwidth, and tunability in comparison to alternative SDM schemes. Continuing the theme of datacenter telecommunications, we discuss our work on integrated spectroscopy. An integrated spectral analyzer is particularly interesting in this context, and would be invaluable in many portions of the photonic platform. Potential applications include the measurement of optical signals as well as the characterization of laser transmitters and other photonic link components. Naturally, these measurement needs also extend to intra data center traffic and maintenance of the carrier interface. We also discuss the broader implications of integrated spectroscopy in the chemical, biochemical, and medical fields.

Keywords: Bragg gratings, multiplexing, integrated optics, sectroscopy

1 INTRODUCTION

Networks must continue to scale with significant user demand increases, while minimizing cost and energy requirements low. One approach to meeting this challenge is the construction of hybrid networks [1]-[8], which include both electronic packet switches, and photonic circuit switches. The most advanced designs employ integrated photonics [9].

Miniaturization of these systems is difficult as a consequence of the stable operating environment required by the individual components. This problem is particularly severe in WDM devices due to presence of many lasers and transceivers operating on a closely spaced wavelength grid. Consequently, in the context of integrated photonic switches there is the impetus to consider SDM as an alternative to augment or replace WDM [10]-[13]. This reduces transceiver complexity and eases laser stabilization by multiplexing the data on the orthogonal spatial modes of a single wavelength supported by a multimode waveguide rather than relying on multiple wavelengths.

Generally, miniaturization of photonic systems results in additional cost and complexity in the final device, because the various environmental parameters must be actively monitored and controlled. Here we propose a design for an integrated spectrometer that would be useful in this context, and would be invaluable in many portions of the photonic platform. Potential applications include the measurement of optical signals as well as the characterization of laser transmitters and other photonic link components. Naturally, these measurement needs also extend to intra data center traffic and maintenance of the carrier interface. We also discuss the broader implications of integrated spectroscopy in the chemical, biochemical, and medical fields.

2 SDM DESIGN

The integrated SDM technology pioneered by our research group accomplishes the coupling between arbitrary spatial modes using nanostructured resonant waveguides [13]. A section of one such device is shown in Figure 1. The advantages of this approach include a small device footprint and high packing density, and bandwidth that may be arbitrarily tailored. The effect of periodically structuring may be described using electromagnetic coupled mode theory [14]-[17]. In summary, the effect of such structuring is to transfer energy between modes. However, the magnitude of this transfer is generally negligible, and only becomes significant when the difference between the wavenumbers of the interacting modes is matched to a spatial Fourier component of periodic dielectric perturbation. This phase matching condition is very stringent, and results in a stopband centered about a certain wavelength. The bandwidth of the stopband depends on the

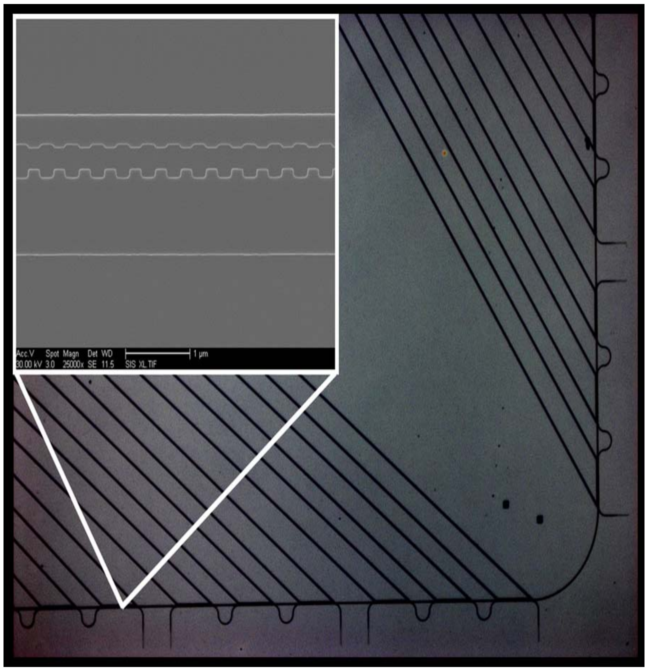

Figure 1: Microscope image of a periodically SDM device with integrated eaters. Note for scale that the bends have a 30 micron radius. Inlaid is an electron micrograph of a section of periodically structured mode selective coupler. The scale bar on the inlay reads 1 micron.

mutual overlap of the interacting modes and the dielectric perturbation, and may be increased or decreased very precisely by geometrically engineering the waveguides. Notably, since guided modes have exponentially decaying tails outside the waveguide core, it is possible to use this mechanism to couple energy between adjacent waveguides, as well as between modes within an isolated waveguide.

Our current research is focused on the demonstration of an optical switch architecture comprised of these SDM couplers. The first iteration of a three by three switch is shown in Figure 1. The device fabricated using standard silicon on insulator waveguide technology that has been well described in the literature [13]. This device is composed of unit cells that each contain three gratings designed to selectively couple into a distinct modes of a multimode waveguide. The center wavelength of each grating stopband can be selectively activated by thermally tuning the grating using integrated heaters. This initial design is the most naïve architecture possible architecture, however is it extremely robust with respect to environmental instability. The primary drawback is poor scalability. Future work will focus on completing the fabrication and characterization of the current prototype, as well as the development of more optimized architectures.

3 SPECTROMETER DESIGN

An integrated spectral analyzer would have a wide range of applications. It would be valuable in telecommunications for the characterization of lasers and other optical components, as well as maintenance of the carrier link. Similar metrology needs exist for complex integrated photonic circuits. Further applications include all of the areas where optical spectral analysis is conventionally employed such as chemical and biochemical sensing, medical analysis. The general benefits of this technological miniaturization include a more stable platform, improved power efficiency, and size and weight reduction.

We propose an integrated spectrometer design composed of a distributed Bragg reflectors [14]-[17] paired with a tunable index ring resonators [18]. In such a device the input signal is coarsely partitioned using the Bragg reflectors, which have bandwidth equal to the free spectral range of the resonators. The Bragg reflectors direct each

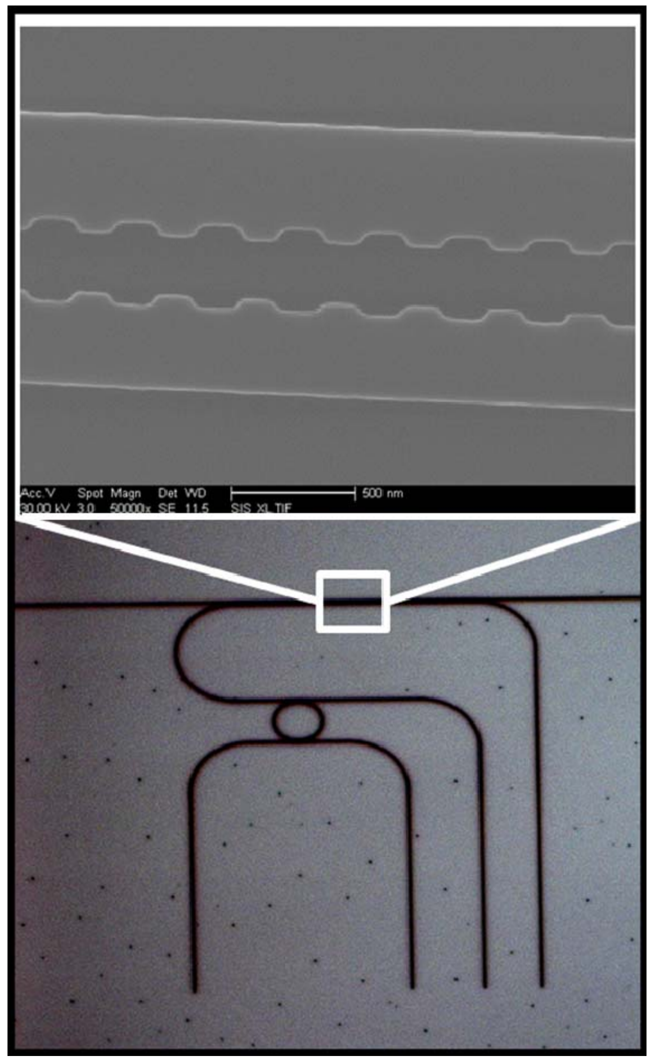

Figure 2: Microscope image of an integrated spectrometer unit cell. Note for scale that the ring resonator has a 10 micron radius. Inlaid is an electron micrograph of a section of periodically structured mode selective coupler. The scale bar on the inlay reads 500 nm.

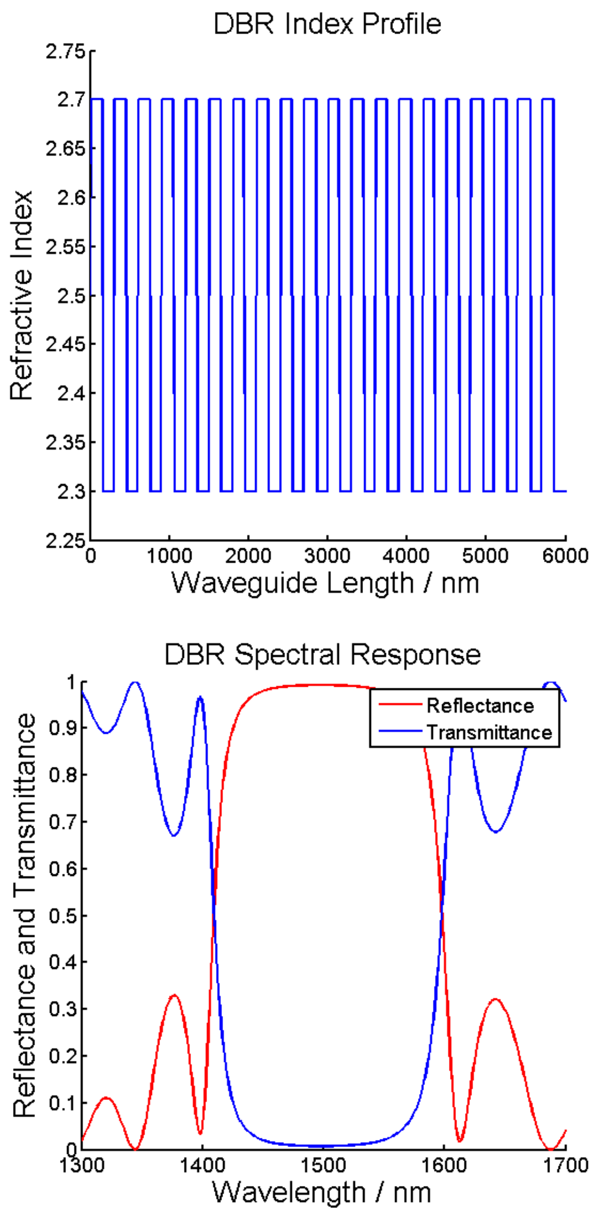

Figure 3: Refractive index profile (top) and layer stack model spectral response (bottom) of an unapodized Bragg reflector.

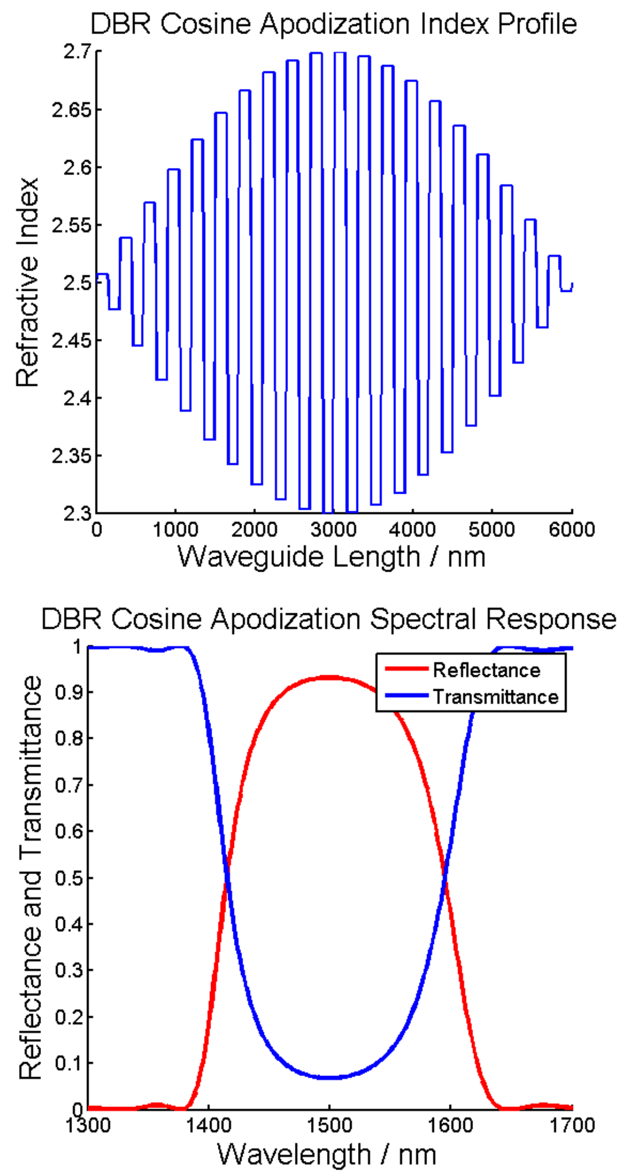

Figure 4: Refractive index profile (top) and layer stack model spectral response (bottom) of an apodized Bragg reflector.

spectral partition to a tunable ring resonator with a narrow transmission resonance. One ring resonator is paired with each Bragg stopband partition, and by tuning the ring resonators the spectral content of the input signal can be determined. The layout of such a spectral partition unit cell is displayed in Figure 2. Multiple unit cells can be employed in series to analyze large swaths of spectra.

A number of design considerations are crucial to this approach. In particular, achieving a reflector stopband with high rejection and a steep transition is critical for combining unit cells without gaps. In particular, Bragg reflectors are known to have sidelobes associated with the stopband that would be problematic in this context. To resolve this issue it is possible to apodize the Bragg structures in a way that minimizes these sidelobes. To visualize this effect Figure 3 and Figure 3 show a comparison of a layerstack model [19] of an unapodized structure with an apodized structure.

4 CONCLUSION

In conclusion, technological developments such as integrated periodically nanostructured resonant couplers that selectively transfer energy between arbitrary modes within a multimode waveguide and scalable integrated spectormeters based on a combination of ring resonators and Bragg reflectors are potential solutions to the scalability and characterization problems posed by future demands of the network fabric. Applications include augmentation or replacement of conventional multiplexing schemes, as well as measurement of photonic link components.

REFERENCES

[1] H. Bazzaz, M. Terwari, G. Wang, G. Porter, E. T. S. Ng, D. G. Andersen, M. Kaminsky, M. A. Kozuch and A. Vahdat, "Switching the Optical Divide: Fundamental Challenges for Hybrid Electrical/Optical Datacenter Networks," in Proceedings of the ACM Symposium on Cloud Computing (SOCC), Cascais, Portugal, 2011.

[2] K. Chen, A. Singlay, A. Singhz, K. Ramachandranz, L. Xuz, Y. Zhangz, X. Wen and Y. Chen, "OSA: an optical switching architecture for data center networks with unprecedented flexibility," in NSDI'12 Proceedings of the 9th USENIX conference on Networked Systems Design and Implementation, San Jose, CA, 2012.

[3] N. Farrington, G. Porter, S. Radhakrishnan, H. H. Bazzaz, V. Subramanya, Y. Fainman, G. Papen and A. Vahdat, "Helios: A Hybrid Electrical/Optical Switch Architecture for Modular Data Centers," in SIGCOMM'10, New Delhi, India, 2010.

[4] N. Farrington, Y. Fainman, H. Liu, G. Papen and A. Vahdat, "Hardware Requirements for Optical Circuit Switched Data Center Networks," in Optical Fiber Communication Conference (OFC/NFOEC), Los Angeles, CA, 2011.

[5] G. Wang, D. G. Andersen, M. Kaminsky, K. Papagiannaki, T. S. E. Ng, M. Kozuch and M. Ryan, "c-Through: Part-time Optics in Data Centers," in SIGCOMM’10, New Delhi, India, 2010.

[6] N. Farrington, G. Porter, Y. Fainman, G. Papen and A. Vahdat, "Hunting Mice with Microsecond Circuit Switches," in ACM HotNets, Redmond, WA, 2012.

[7] N. Farrington, G. Porter, P.-C. Sun, A. Forencich, J. Ford, Y. Fainman, G. Papen and A. Vahdat, "A Demonstration of Ultra-Low-Latency Datacenter Optical Circuit Switching," in ACM SIGCOMM, Helsinki, Finland, 2012.

[8] G. Porter, R. Strong, N. Farrington, A. Forencich, P.-C. Sun, T. S. Rosing, Y. Fainman, G. Papen and A. Vahdat, "Integrating Microsecond Circuit Switching into the Data Center," in ACM SIGCOMM, Hong Kong, China, 2013.

[9] Y. Fainman and G. Porter, "Directing Data Center Traffic," Science, vol. 342, pp. 202-203, 2013.

[10] K.-P. Ho and J. M. Kahn, "Mode Coupling and its Impact on Spatially Multiplexed Systems," in Optical Fiber Telecommunications VI, Amsterdam, Elsevier, 2013, pp. 491-568.

[11] L.-W. Luo, N. Ophir, C. P. Chen, L. H. Gabrielli, C. B. Poitras, K. Bergmen and M. Lipson, "WDM-compatible mode-division multiplexing on a silicon chip," Nature Communications, vol. 5, p. 3069, 2014.

[12] S. O. Arik, J. M. Kahn and K.-P. Ho, "MIMO Signal Processing for Mode-Division Multiplexing: An overview of channel models and signal processing architectures," Signal Processing Magazine, vol. 31, pp. 25-34, 2014.

[13] A. Grieco, G. Porter and Y. Fainman, "Integrated Space-division Multiplexer for Data Center Networks," IEEE Journal of Selected Topics in Quantum Electronics, vol. accpeted for publication, 2016.

[14] A. Grieco, B. Slutsky and F. Yeshaiahu, "Characterization of waveguide loss using distributed Bragg reflectors," Applied Physics B, vol. 114, pp. 467-474, 2014.

[15] A. Yariv and P. Yeh, Optical Waves in Crystals: Propagation and Control of Laser Radiation, Hoboken, NJ: John Wiley & Sons, 2003.

[16] H. Kogelnik, "2. Theory of Dielectric Waveguides," in Integrated Optics (Topics in Applied Physics), Berlin, DE, Springer-Verlag, 1975, pp. 13-81.

[17] D. J. Richardson, J. M. Fini and L. E. Nelson, "Space-division multiplexing in optical fibres," Nature Photonics, vol. 7, p. 94, 2013.

[18] A. Yariv and P. Yeh, Photonics: Optical Electronics in Modern Communications, 6th ed., Oxford: Oxford university Press, 2007.

[19] P. Yeh, Optical Waves in Layered Media, Hoboken, NJ: John Wiley & Sons, 2005.