Highly-integrated multi-functional optoelectronic chip for next generation optical networks

Hilmi Volkan Demir and Vijit Sabnis
Department of Electrical Engineering, Stanford University, Stanford CA, USA
Email: volkan@stanford.edu, vsabnis@stanford.edu

ABSTRACT

We introduce a novel, highly-integrated, multi-functional optoelectronic microchip that allows for unconstrained wavelength conversion, multi-wavelength optical signal regeneration and switching. This device replaces the existing optical-electrical-optical conversion for these applications, alleviating the problems of high component and packaging costs, large space and high power consumption, a lack of scalability, and high complexity due to combination of various functional elements. The main advantages of this technology are low cost fabrication, low optical and electrical power consumption, high-speed operation, scalability and electrical configurability.

KEYWORDS

Optical switch, wavelength conversion, optical regeneration

INTRODUCTION

The tremendous number of installed optical fibers has made an enormous aggregate transmission bandwidth available. The network nodes that currently interconnect these fibers only meet the current communication bandwidth demand and will soon become a bottleneck. To upgrade these nodes, service providers will require high-performance, cost-effective solutions. State-of-the-art network nodes require cascading discrete, bulky, optical, electrical and optoelectronic components to perform optical-electrical-optical conversion. The bundling of such discrete components imposes disadvantages: high component and packaging costs, large space and high power consumption, a lack of scalability, and high complexity. To overcome these disadvantages at a substantial cost savings and assist the realization of next generation optical networks, we invented a highly-integrated multi-functional optoelectronic chip that simultaneously performs unconstrained wavelength conversion, multi-wavelength optical signal regeneration, and routing [1-4].

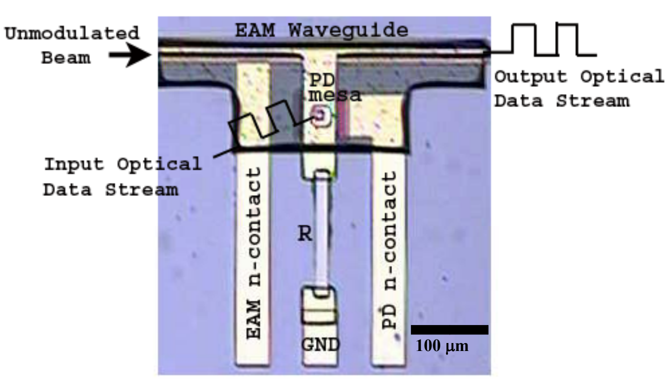

Figure 1: Top view picture of a fabricated optically controlled optical switch element

TECHNOLOGY

We present a novel, efficient optical-electrical-optical conversion technology alternative to the conventional approach. Our technology consists of an optoelectronic chip that transfers optical information from an input data stream to an output data stream, restoring the optical signal at a different wavelength than the input if desired. In Figure 1, we show a recently fabricated optically-controlled optical switch chip that includes a waveguide electroabsorption modulator (EAM) and a surface-normal illuminated photodetector (PD), monolithically integrated as a part of an indium phosphide (InP) circuit. It is compact and scalable into two-dimensional arrays. It operates at high speeds, consumes low electrical and optical power, and is enabled and disabled electronically. Figure 2 demonstrates the performance of a switch design operating at 40 Gb/s, the next generation telecommunication data rate.

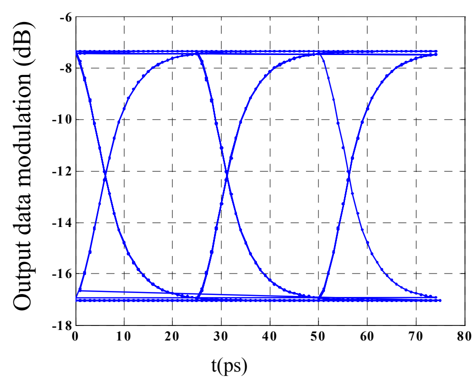

Figure 2: Simulated output data stream at 40 Gb/s

To realize a prototype, we developed a new, two-growth, ten-mask-step InP process, compatible with semiconductor laser fabrication. With this fabrication sequence, we incorporate separate layers for the photodiode and modulator on the same wafer as shown in Figure 3. This is one of the first demonstrations of on-chip integration of photodiode and modulator arrays, eliminating the use of discrete, bulky components.

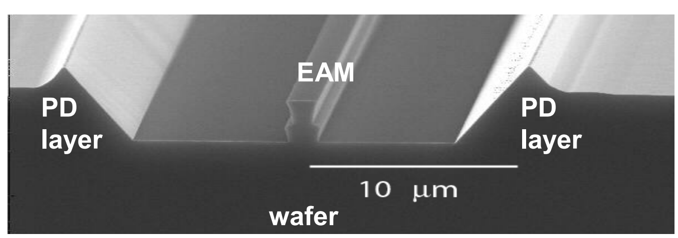

Figure 3: Picture of separately grown PD layers next to EAM

APPLICATIONS

• *Wavelength-converting optical crossbar switch array:* In Figure 4, we illustrate an exemplary crossbar switch matrix generated by arraying the individual switch element pictured in Figure 1. By electronically reconfiguring the cross nodes of the switch matrix, the chip routes each input channel to a selected output channel, possibly at a different wavelength. Since there is no limitation on the operating input and output wavelengths, the switch array achieves unconstrained wavelength conversion. This alleviates the problem of wavelength congestion in wavelength division multiplexed (WDM) networks. A large-scale array such as a 64x64-element switch is practically feasible, making a single chip suitable for handling dense WDM channels. Such a highly integrated switching chip will replace numerous electronic components as is necessary with conventional technologies.

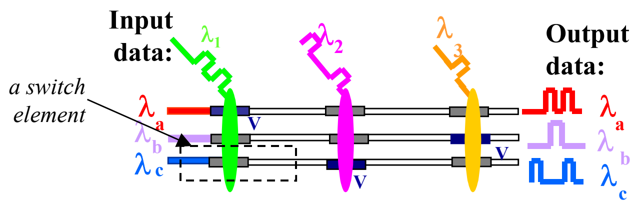

Figure 4: Schematic diagram of a crossbar switch array

• *Multi-wavelength signal regeneration:* The optical signal is reshaped while switching because of the nonlinear transmission of the switch, correcting for the distortion and suppressing the noise inherent in the fiber optic system. It is also possible to retime the signal by using a synchronized short pulse train instead of the unmodulated beam, which compensates for the undesired fiber dispersion effects. Furthermore, operating a switch element in the gain mode, the signal is reamplified, offsetting fiber transmission losses. By combining these functions, all WDM channels can simultaneously undergo signal restoration with a single switch array chip, replacing conventional regenerators for each channel.

IMPACT ANALYSIS

• *Impact on existing infrastructure—Cost reduction:* Using today's technology, wavelength conversion, signal restoration and routing require combining separate optical-electrical-optical conversion equipment. One such setup made of discrete components costs on the order of $10K-20K per channel, the total cost becoming excessive for a single typical multi-channel network node and growing proportionally with the complexity of the overall fiber network. We have spoken with several leading photonics companies and concluded that it is viable to produce our integrated switch array for several hundred dollars, resulting in individual channel costs on the order of tens of dollars for the modules replaced by on-chip integration. Such a significant component and packaging cost reduction will allow current optical networks to be upgraded economically when the bandwidth demand increases.

• *Impact on next generation optical networks—Enabling new technologies:* The highly-integrated nature of this device creates possibilities for new system-level technologies. For instance, we proposed the use of our switch array chip at the heart of an unprecedented 100 Tb/s multi-channel optical router and also for optical clock generation with optical heterodyne mixing. These new technologies are currently in the research phase and will likely lead to exciting applications.

INNOVATION

Our work has been innovative in three major directions:

• The first is the invention of a *new integrated photonic device*, based on the idea of confining high-speed electrical signals in a lumped-element optoelectronic circuit. Thus, the optical switching is localized, requiring low optical and electrical powers for high-speed switching and avoiding microwave packaging. To our knowledge, this is the first proposal of scalable two-dimensional optically controlled optical crossbar switch architecture.

• The second thrust of innovation is in the *fabrication process* of such an integrated optoelectronic circuit. We developed a selective area regrowth technique that allows the close integration of different optoelectronic diodes made of distinct layers. We also developed a new wafer-level processing technique to interconnect optoelectronic diodes with other circuit elements in a compact area.

• Third, we propose *new applications* enabled by the sophisticated functionality of our high-speed photonic device, which can perform simultaneous wavelength conversion, signal restoration and routing for multiple WDM channels on a single chip. This work stands as one of the first attempts for a "smart" photonic device with several functions, traditionally performed by external control electronics, sprinkled in its internal functionality.

We have filed for an U.S. patent for the device concept, implementation and applications [1], and are in the process of filing for another related to our novel wafer-level processing in collaboration with Intel Corporation.

DEVELOPMENT TIMELINE

We have demonstrated different implementations of such optically controlled optical switches over the last 5 years [2-4]. We established a world-class telecommunication test bed worth $1M and will start system-level testing in Spring 2003. We expect to demonstrate functional switch arrays in 2004.

Acknowlegments

We would like to thank our supervisors Prof. Miller and Prof.Harris of Stanford University for their valuable guidance, and our collaborators O. Fidaner and Dr. Yairi from Stanford, Dr. Zheng from Intel Strategic Technology, and Dr. Li from OEPIC for their contributions. We would also like to acknowledge Intel Corporation for funding our research.

References

[1] H.V. Demir, V. Sabnis and D. A. B. Miller, "Semiconductor device for rapid optical switching by modulated absorption,' *US patent application number 10/075921.*

[2] M. Yairi, H.V. Demir, and D. A. B. Miller, "Optically-controlled optical gate with an optoelectronic dual diode structure—theory and experiment,' Special issue on Components for Ultrafast Communications, Journal of Optical and Quantum Electronics, 33(7-10), pp. 1035-1054 (2001).

[3] V. Sabnis, H.V. Demir, M. Yairi, J.S. Harris, Jr., and D. A. B. Miller, "Observation of wavelength-converting optical switching at 2.5 GHz in a surface-normal illuminated waveguide," Proceedings of the 14th IEEE Lasers and Electro-Optics Society Annual Meeting, San Diego, CA pp. 362-363, (2001).

[4] H. V. Demir, "Ultrafast optoelectronics for switching and wavelength conversion", Annual Meeting of Stanford Photonics Research Center, Stanford, CA (2001)(Invited talk)