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Novel optically-controlled optical switch based on intimate integration of surface-normal photodiode and waveguide electroabsorption modulator for wavelength conversion

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Current optical-electronic-optical conversion (o-e-o) technology [1] requires propagating high-speed signals in the electronic domain and cascading separately packaged electronic and optoelectronic devices, resulting in increased cost, size, weight, power consumption, and heat radiation. For o-e-o conversion without the use of conventional electronics, we introduce a novel, highly-integrated, chip-scale, optically-controlled optical switch that incorporates a surface-normal photodiode (PD) and a waveguide electroabsorption modulator (EAM) on the same substrate, as shown in Fig. 1. [2] Such an integrated optical switch avoids the difficulties and the limitations of ordinary o-e-o conversion, and eliminates the need for separate packaging of its individual parts.

Featuring a unique circuit configuration as sketched in Fig. 2, the tight, on-chip integration of PD and EAM enables the localization of the high-speed electrical signals in the switch, allowing for high-speed, low-power operation with the switching bandwidth set by the internal device RC time constant and without requiring conventional high-speed electrical signal propagation and impedance matching. With its ability to transfer optical information from an input optical data stream at λ_1 onto another incident optical beam at λ_2, the optically-controlled optical switch serves as a wavelength converter as depicted in Fig. 1. There are essentially no limitations on the choice of λ_1 and λ_2 since the photodetector detects a broad range of wavelengths and the modulator input need only fall within the modulation band of the modulator, which can likely cover the C-band. Hence, the device offers truly arbitrary wavelength conversion. The additional advantages of our device include low-cost fabrication, small size, low power consumption, high-speed operation, scalability, an absence of interferometric structures, electronic configurability and compatibility with tunable laser diode fabrication. The combination of these device features and its surface-normal input configuration potentially enables the two-dimensional, dense integration of our switches into a large-scale, electrically-reconfigurable, wavelength-converting, optical crossbar switch.

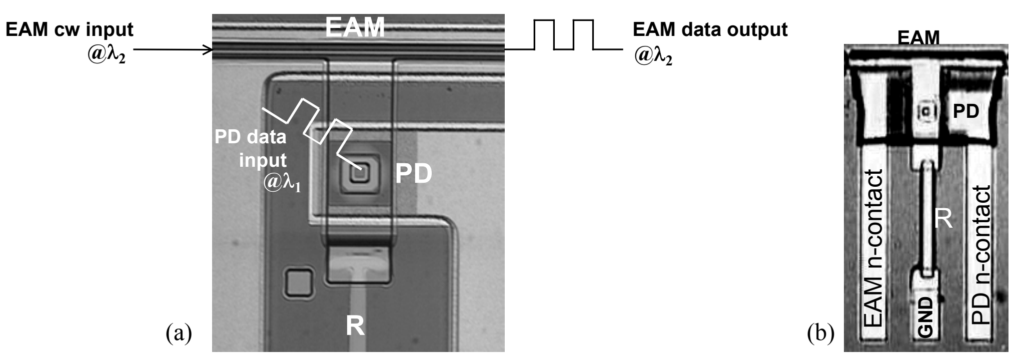

Fig. 1. Plan view of a fabricated device: (a) before final metallization, (b) after completion of fabrication

Fig. 1 shows a fabricated device that embodies a PD mesa and an EAM waveguide monolithically integrated on an InP substrate along with an on-chip TaN thin-film resistor (R). The PD, EAM and R are very tightly integrated in the simplified circuit configuration as presented in Fig. 2 with an overall circuit size of 300 μm by 300 μm. Two optical inputs to the device are shown in Fig. 1: an optical input data stream at λ_1 is incident on the PD mesa from the input fiber above, and a continuous-wave (cw) beam of light at λ_2 is coupled horizontally from a fiber into the EAM waveguide. The device output is the EAM output beam that is coupled into the output fiber. The optical switch imprints the PD input data stream at λ_1 on the EAM output at λ_2 by directly, and very locally, driving the

EAM with the PD. To operate the switch, the PD and EAM are separately DC-biased through a pair of bypass capacitors connected to two external power supplies. With a properly chosen bias, the EAM initially heavily absorbs at the incident cw beam wavelength. When a binary one of the optical input data stream at λ_1 arrives at the PD, its resultant photocurrent generates an almost instantaneous voltage drop across the local R, reducing the voltage across both the PD and EAM. Consequently, the EAM transmits its input beam at λ_2, resulting in a binary one at its output. The intimate PD-EAM integration in a scale size much smaller than the wavelength of any electrical signal at the switching frequencies allows for the lumped element operation. The by-pass capacitors confine the high-speed signals in the switch and prevent loading from the DC biasing circuit.

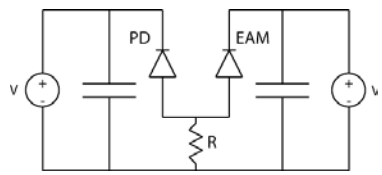

Fig. 2. Simplified circuit diagram of the device

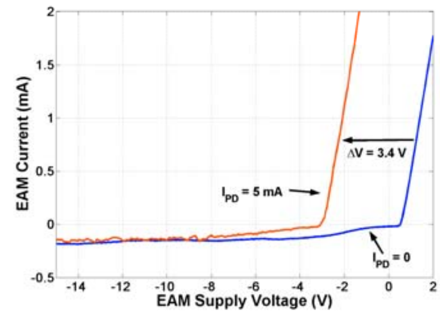

Fig. 3. Optically-shifted EAM IV with an incident PD beam

Fig. 3 shows the EAM current as a function of the EAM power supply voltage with and without a cw PD beam. The measured IV curve in the presence of the PD beam is shifted by 3.4 V with respect to the IV in the absence of the PD beam. This optically-induced 3.4 V shift agrees well with the expected voltage drop due to 5mA of photocurrent from the photodiode passing through the 650 ohm on-chip R. This experimentally confirms the functionality of the switch circuit. Such an optically-induced voltage swing is sufficient for modulation of the EAM transmission at >10dB extinction ratio. Fig. 4 shows the experimental optical switching bandwidth of the device for three different sets of device parameters along with our theoretical predictions. The good agreement of the theoretical simulations with the experimental data verifies the AC circuit model. The optical 3-dB bandwidths are 0.8 GHz, 1.1 GHz and 2.0 GHz for the three sets of switch designs. Fig. 5 illustrates an open eye diagram of the EAM output at 1530 nm with a ~15 dB contrast ratio and ~11 signal-to-noise ratio when a 1Gb/s photodiode input data stream at 1550 nm is incident. This demonstrates a proof-of-principle wavelength conversion from 1530 nm to 1550 nm.

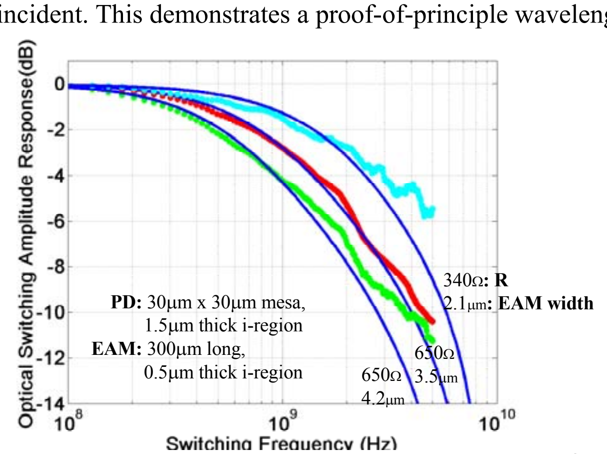

Fig. 4. Experimental and theoretical optical switching transfer functions for three sets of tested devices

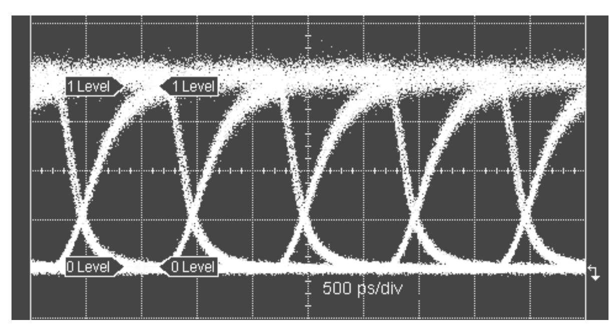

Fig. 5. Eye diagram at 1Gb/s

In summary, we demonstrate a novel, proof-of-principle, low-power, compact, wavelength-converting optical switch, while avoiding the use of conventional o-e-o conversion. Based on our results, we anticipate that our device can be scaled to 10 Gb/s operation by appropriate reduction of the on-chip resistor and progressive scaling of the device capacitances. Moreover, we believe our device is well-suited to further integration into a large-size, two-dimensional, optical crossbar switch.

References

[1] S. J. B. Yoo, "Wavelength conversion technologies for WDM network applications," IEEE J. Light. Tech., 14 (6), pp. 955-966, (1996).

[2] V. Sabnis, H.V. Demir, O. Fidaner, J.S. Harris, Jr., D. A. B. Miller, J-F. Zheng, N. Li, T-C. Wu, and Y-M. Houng "Optically-switched Dual-diode Electroabsorption Modulator" OSA Integrated Photonics Research Meeting, 2003, IMB3.