Photonic Non-Volatile Memory Devices

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With the ability to convert electrical to optical signals, Electro-Optic Modulator (EOM) as an electronic device is an increasingly important component for emerging technologies that includes optical sensors, photonic neural networks [1], quantum-information processing [2], and future possibilities of inter-chiplet optical interconnect networks through a photonic interposer [3]. With high-conversion-efficiency due to Pockel's effect, electro-optic materials like Lithium Niobate (LN) and Barium Titanate (BTO), the intimate integration of photonics and electronics will enable exciting functional and compact devices by heterogeneous integration, beyond co-packaged optics. Among such new class of devices are non-volatile memory functional photonic devices.

Realizing electro-optic memories has been a fundamental challenge. Lacking a high-density native photonic memory solution, photonic compute systems will need to shuttle data continuously between electronic memories and photonic components, leading to significant energy costs that impact power-performance of systems like photonic neural networks [4]. We have proposed new devices that combine high-efficiency thin-film LN EOM and Ferroelectric HZO Non-Volatile Memory (NVM) Capacitor [5] (Fig. 1). The resultant integrated Electro-Optic Modulator and Memory (EOMM) allows electronically encoded analog memory states to be translated into high-speed optical transmission and phase modulations in a single compact device. Such a device would enable new possibilities for dynamically reconfigurable photonic systems. Among which is the potential for optical interposers with reconfigurable photonic interconnects that can scale beyond future connection bottleneck (Fig. 1). Photonic interconnect sharing through dynamic run-time reconfigurability overcomes the optical interconnect density shortcomings, relative to electrical interconnects, due to the relatively large optical devices and floor-planning restrictions to manage thermal crosstalk due to the lasers.

Beyond NVM-enabled reconfigurable photonics, can photonics enable Compute-in-memory (CIM) architectures and what would be the benefits? For resistive-based CIM systems, the array scalability is inevitably limited by IR losses with increasing error accumulation due to the increasing wire resistance as arrays grow in size. We have recently proposed an electro-optic memory array with an optical bitline (BL) that circumvents the BL IR loss and capacitive loading issue (Fig. 2). By implementing a two-transistor-one-modulator (2T1M) memory cell, the matrix dot-products can be performed by FeFET memories, operated in sub-threshold region, while the accumulation is summed through phase modulation of an optical signal through a LN capacitive modulator. The photonic waveguide BL read-out is achieved through pairs of shared Mach-Zender Interferometers (MZI) to maximize column layout efficiency. By eliminating IR loss on the BL, we can enable up to 3750kb array size and achieving up to 45% inference accuracy improvement even on a large-scale transformer model compared to conventional CIM arrays [6].

References

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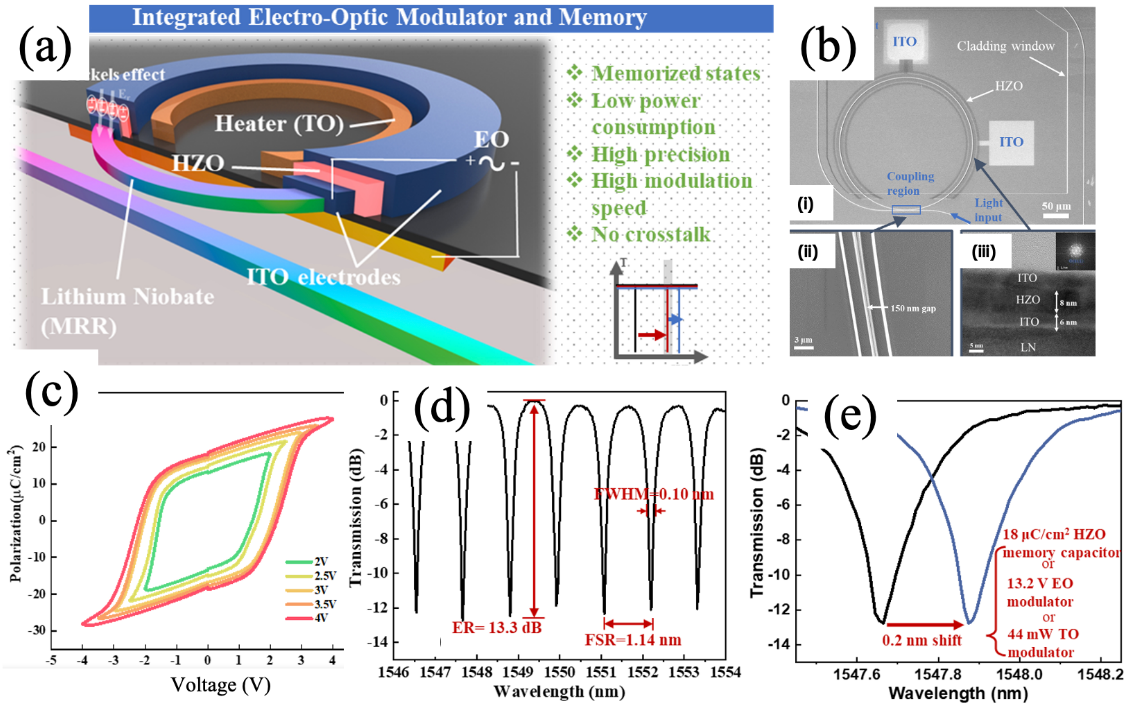
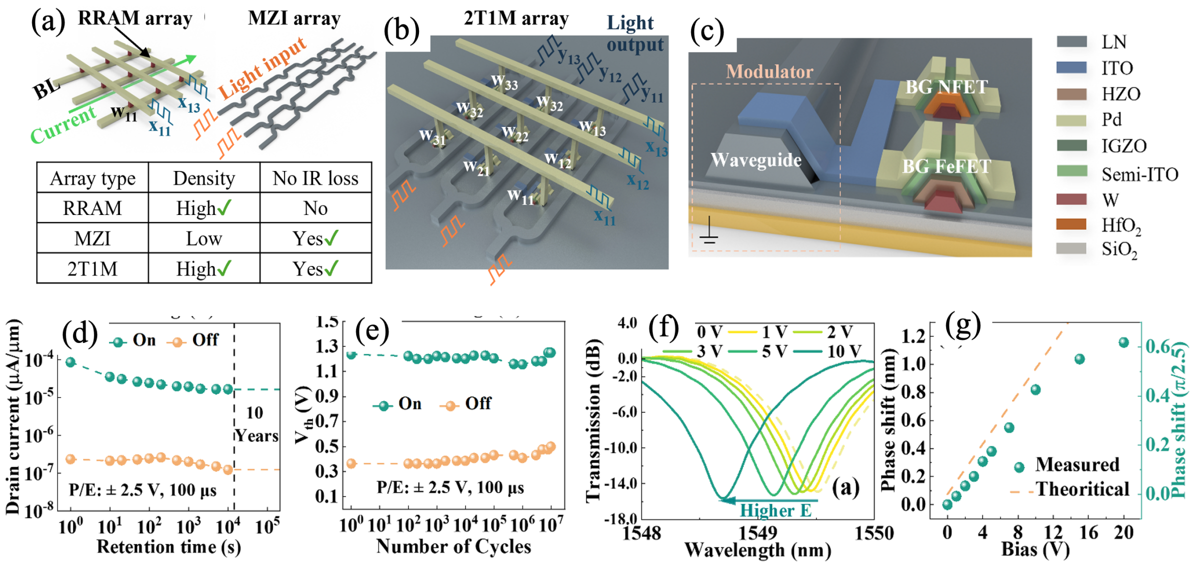


Fig. 1 (a) Illustration of Ferroelectric HZO-integrated thin-film LN Micro-Ring Resonator (MRR), (b) – i) SEM of the fabricated HZO-integrated MRR, ii) Ring-waveguide gap, iii) Cross-section TEM of ITO-HZO Ferroelectric capacitor on Lithium Niobate (LN). (c) PV loop of ITO-HZO of ferroelectric capacitor, (d) Transmission spectrum of NVM-MRR with Q = 1.6E4, (d) Resonance shifts of MRR due to ferroelectric-induced switching.



Array type	Density	No IR loss
RRAM	High✓	No
MZI	Low	Yes✓
2T1M	High✓	Yes✓

Fig. 2 (a) Illustrations comparing RRAM CIM Vs. all-photonics CIM circuits. (b) Illustration of 2T1M Electro-Optic CIM circuit with MZI-based bitline (c) the 2T1M illustration showing the ferroelectric and non-ferroelectric IGZO transistors (2T), (d) The retention characteristic of the ferroelectric IGZO transistor (FeFET), (e) The memory cycling endurance of the FeFET, (f) MZI transmission spectrum under different bias, (g) Phase shifts of optical signal modulated by the ITO-LN capacitor.