Cryogenic integrated optical modulators for classical and quantum computing

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ABSTRACT

In recent years, standard CMOS microprocessors have approached their maximum power dissipation per unit area, effectively placing a limit on computational power. This highlights the urgent need to explore alternative technologies. One promising avenue is the use of superconductors, which demonstrate zero resistivity below a critical temperature. However, circuits based on superconductors necessitate the use of cryostats to maintain low temperatures, presenting challenges in data transfer with the room temperature environment. While coaxial cables are often employed for this purpose, they suffer from limited data transfer rates and contribute significantly to heat load. On the contrary, photonics integrated circuits (PICs) coupled with optical fibers present a viable solution. They enable scalable, cost-effective, and power-efficient optical interconnections capable of supporting high data transfer rates while minimizing heat transfer. In this presentation, We will discuss the latest advancements in cryogenic PICs, focusing on their application in interfacing with cryogenic computing systems such as single-flux-quantum logic circuits and superconducting qubits.

Keywords: photonic integrated circuits, cryogenic devices, electro-optic modulator, magneto-optic modulator

1. INTRODUCTION

As we approach the saturation of Moore's Law for CMOS electronics, it is becoming increasingly critical to find alternative solutions that meet the ever-growing demand of computing power from artificial intelligence.[1,2] Among the plethora of possible approaches, superconducting integrated circuits (ICs) stand out as a promising technology for both classical[3,4] and quantum applications.[5,6] The lack of resistance in superconducting ICs makes them ideal for significantly reducing energy dissipation, a major limitation in CMOS electronics. However, this advantage comes with the cost of operating at cryogenic temperatures.

A major challenge in connecting low-temperature systems to room-temperature environment is data transferring. Current data links from cryogenic systems rely on coaxial cables, which are not scalable and cause unwanted heat transfer into the cryostat. Additionally, the limited bandwidth of electrical cables further hampers data transmission rates.

Optical data links using fiber optics can overcome the limitations of coaxial cables.[7,8] Optical fibers are two orders of magnitude smaller, act as excellent thermal insulators, and offer a channel capacity more than 100 times greater than electrical cables. These characteristics enable higher data transmission rates without introducing significant heat load.

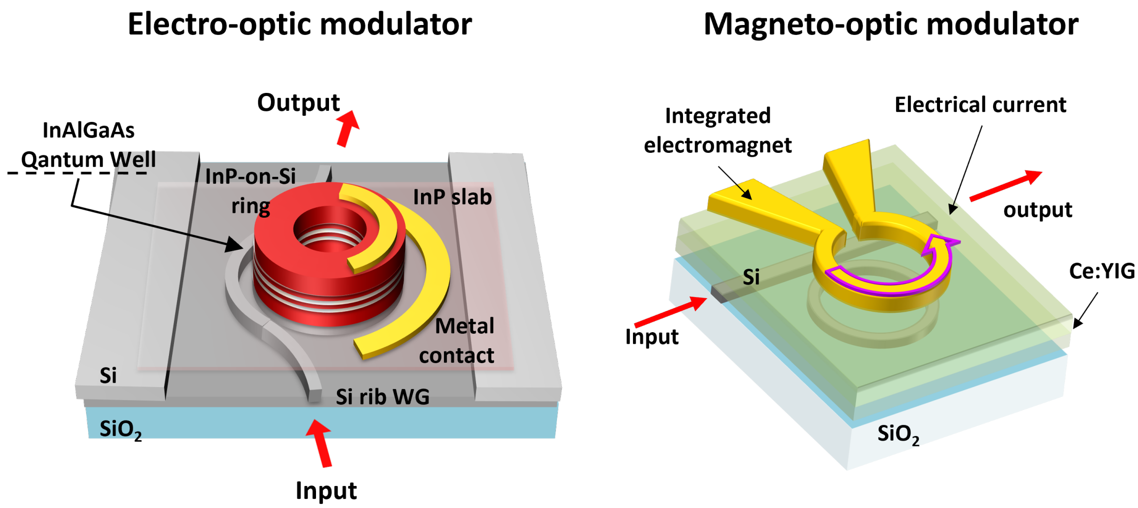

Figure 1. Proposed ring-based electro-optic modulator[16] and magneto-optic modulator[17] for data-link from cryogenic to room-temperature enviroment.

2. CRYOGENIC INTEGRATED OPTICAL MODULATORS

To implement fiber-optic links, optical modulators are required to convert an electrical signal into an optical carrier. In the last decade, integrated modulators have been demonstrated to operate at temperatures as low as 4 K using various photonic platforms to perform egress optical data link.[8–15] Figure 1, shows two approaches we have explored to demonstrate low driving-voltage and energy efficient cryogenic modulators.

The two proposed solutions are based on electro-optic effect and magneto-optic effect. While the two devices use different material systems, they share the same configuration based on an all-pass ring resonator. The use of a resonant cavity is instrumental to have a device more sentive to the variation of the refractive index variation, resulting in a lower driving voltage for modulation.

The electro-optic (EO) modulator is constructed using a stack of 15 quantum wells made from Indium Aluminum Gallium Arsenide (InAlGaAs), bonded onto a silicon ring resonator. Electro-optic effects are induced in InAlGaAs by operating the device under reverse bias conditions. III-V materials, like InAlGaAs, exhibit multiple electro-optic effects, including the free carrier effect (plasma effect), the band-filling effect (Burstein-Moss effect), and the quantum confined Stark effect (QCSE). The advantage of using this class of materials compared to other EO modulators is evident from Table 1, which compares the voltage–length product, a commonly used figure of merit for EO efficiency. Given the same footprint (i.e., the same length), the voltage required to achieve a phase shift of π is the lowest in InAlGaAs, making it an excellent material for modulators with small driving voltage and, consequently, the low power consumption.

The magneto-optic (MO) modulator is fabricated by bonding a thin film of Cerium-doped Yttrium Iron Garnet (Ce:YIG) onto a silicon all-pass ring resonator. A gold coil, aligned with the silicon microring, serves as an integrated electromagnet. When a current is injected into the coil, it generates a magnetic field, inducing a nonreciprocal phase shift in the Ce:YIG. Similar to the parameter V_π used for electro-optic modulators, we define I_π as the current that induces a phase shift of π in the magneto-optic modulator. For comparison, the equivalent $V_\pi \cdot L$ values for the magneto-optic modulator are shown in Table 1.

3. RESULTS

The performance of the device are tested at cryogenic temperatures in a closed-cycle cryostat (Montana Cryostation s200) at a temperature of 4 K. Figure 2 shows the eye diagrams measured for both the electro-optic and magneto-optic modulators at a data rate of 1 Gbps.

Table 1. Comparison of $V_\pi \cdot L$ in integrated optical modulator.

Material platform	Temperature	$V_\pi \cdot L$	Dominant EO effects
InAlGaAs[17]	4 K	0.2 V·cm*	free carrier, band-filling, QCSE
InAlGaAs[18]	300 K	0.2 V·cm*	free carrier, band-filling, QCSE
LiNbO3[15]	4 K	4.2 V·cm	Pockels
LiNbO3[19]	300 K	1.7 V·cm	Pockels
BaTiO3[10]	4 K	5.0 V·cm	Pockels
BaTiO3[20]	300 K	0.45 V·cm	Pockels
Ce:YIG[17]	4 K	0.04 V·cm†	Nonreciprocal phase shift
Ce:YIG[17]	300 K	0.03 V·cm†	Nonreciprocal phase shift

*Concentrations of In, Al, and Ga must be adjusted to achieve 0.2 V·cm. These concentrations differ at 4 K and 300 K.
†For the magneto-optic modulator, the equivalent value of V_π is calculated as the product of I_π and the resistance of the coil.

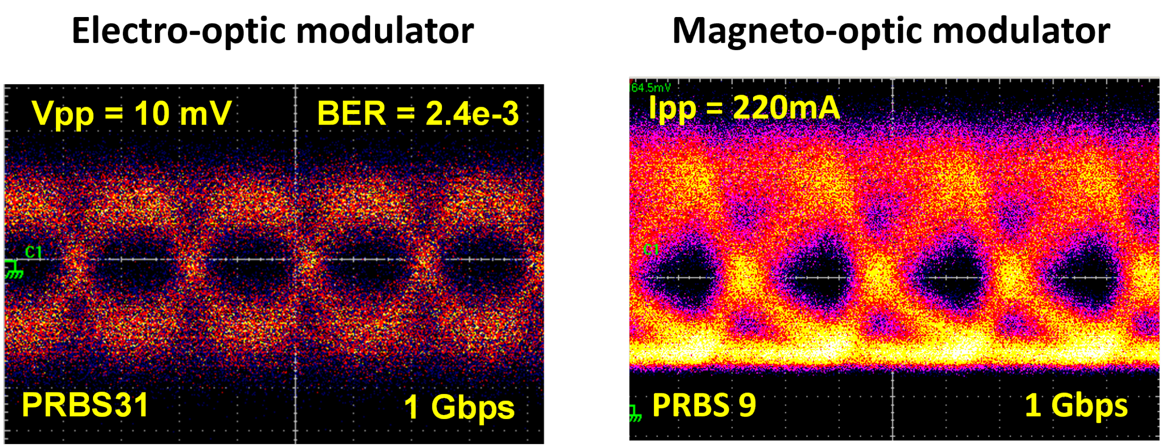

Figure 2. Eye diagram at 4 K of the electro-optic modulator (left) and magneto-optic modulator (right).

The electro-optic modulator is biased at a voltage of -2 V, resulting in a bias current of 0.14 nA. The eye diagram was measured using a peak-to-peak voltage of 10 mV. With a capacitance of 400 fF, the energy consumption of the device is as low as 10.4 aJ/bit, making it, to the best of our knowledge, the most efficient cryogenic modulator.

For the magneto-optic modulator, the eye diagram was measured with a current varying between $\pm$110 mA. With an impedance of 0.3 nH and a resistance of 350 mΩ, the estimated energy consumption is 6 pJ/bit. Although this value is relatively high, it can be significantly reduced through improved device fabrication. Enhancing the quality of the deposited gold in the coil and decreasing the distance between the coil and the waveguide could potentially lower the energy consumption below 50 fJ/bit, making this approach more competitive.

For both devices, the data rate of 1 Gbps is near the maximum modulation rate. In the magneto-optic modulator, this rate is close to the ferromagnetic resonance frequency of the Ce:YIG, imposing a material limit. In the electro-optic modulator, while the large quality factor of the resonator (Q $\simeq$ 53,000) makes it more sensitive to the driving voltage, it also limits the maximum modulation rate.

4. CONCLUSIONS

In this work, we have demonstrated two classes of cryogenic modulators, based on the electro-optic and magneto-optic effects, that can be used for interfacing with superconducting circuitry. These solutions offer benefits such as reduced driving voltage and lower energy consumption, presenting the potential for efficient data transfer in both cryogenic classical and quantum computing systems.

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