CMOS compatible optical Isolator with tandem Ring Modulators

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***Abstract*—Integrated optical isolators to date have relied on bonded magnetic materials for isolation $>$ 30 dB. However, such materials are incompatible with CMOS processes. We propose a tandem ring modulators to achieve high-isolation and a small footprint. It uses plasma dispersion effect, thus achieving low-insertion loss and high-speed modulation.**

***Index Terms*—Optical Isolator, plasma dispersion, Ring Modulator**

I. INTRODUCTION

Optical isolators are an essential component for any optical system operating with a laser. Back reflections into the laser, create chaos in the cavity. Optical isolators prevent any back reflection into the laser, thereby preventing the degradation of laser Relative Intensity Noise (RIN). Several options have been proposed to break the lorentz reciprocity, namely the use of a bonded magnetic-optic material [1], non-linear resonators [2] or a material with time and spatially varying index of refraction [3].

Use of magneto-optic garnet materials has been extensive since they provide low loss and high isolation at telecom wavelengths. However, it is often difficult to integrate these garnets with CMOS compatible materials. Second option is to use nonlinear resonators for optical isolation, but this method requires either high field enhancement or high input power. This makes the isolator input power dependent. Thus, the final option is to use material index that varies both spatially and temporally. These isolators have been implemented in CMOS platforms and show the most promise for on-chip integration. However, due to complicated modulations schemes, such isolators provide low optical isolation.

Recently, it was proposed by Doerr and colleagues that by arranging two p-n phase shifters in tandem, one can provide isolation for a narrow band of frequencies. These phase shifters occupy large footprint on chip and are undesirable. In this work, we propose to replace these phase shifters with a compact Ring modulator and calculate the obtained isolation. Our results show that isolation $>$ 40 dB can be obtained, limited only by the on-off extinction ratio of the ring modulator.

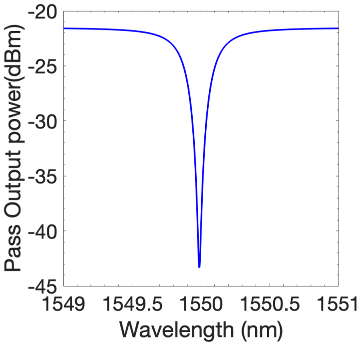

Fig. 1. Pass spectrum of a ring modulator used in this work.

II. THEORY

We will consider an all-pass ring for the discussion. Equation representing this modulator is given by

$$E_t[V(t)] = E_i e^{i(\frac{2\pi n_{eff}[V(t)]L}{\lambda}+\pi)} \left(\frac{a[V(t)] - r e^{-i\frac{2\pi n_{eff}[V(t)]L}{\lambda}}}{1 - a[V(t)] r e^{i\frac{2\pi n_{eff}[V(t)]L}{\lambda}}} \right) \quad (1)$$

$E_t[V(t)]$ is the voltage dependent Electric field output, E_i is the input electric field into the resonator, $n_{eff}[V(t)]$ is the voltage dependent effective index change in the ring modulator, L is the circumference of the ring modulator,λ is the operating wavelength, $a[V(t)]$ is the voltage dependent round trip loss of the ring and r is the coupling coefficient of the ring to the bus waveguide. Numerical value of parameters are given in Table I. A typical spectrum based on (1) is given in Fig. 1. The on-off extinction ratio for this ring modulator is 22 dB. The architecture of a time modulated isolator is borrowed from [3]. However, a major difference is in the fact that [3]

TABLE I
FITTED PARAMETER FOR THE RING MODULATOR EQUATION

Parameter	Value
E_i	8.4×10^{-5} V/m
a	0.9782
r	0.9814
n_{eff}	2.6
n_g	3.8

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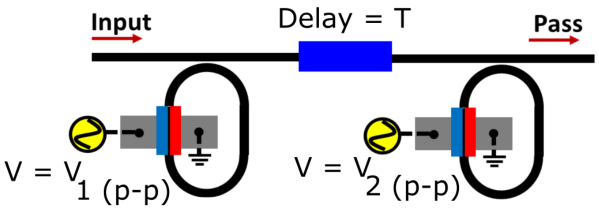

Fig. 2. Schematic of our proposed tandem ring modulator based isolator.

use p-n phase shifter waveguides to achieve isolation while we replace the phase shifters with a ring. This simple substitution has many implications for the performance of the isolator. Firstly, for a ring modulator both amplitude and phase change are coupled in a nonlinear fashion. This provides complex voltage solution for the isolation. Thus, the actual isolation from a tandem ring modulator has to be evaluated numerically. Schematic of a proposed setup is give in Fig. 2. Setup consists of two all pass ring modulators, connected together by a delay line with **Delay** $= T$. First ring is modulated by a signal $V(t) = V_1(t)$ while the second ring is modulated by a signal $V(t) = V_2(t)$ When the optical field passes from Input to pass port, the forward transmitted field is given by

$$E^{Forward}(t) = E_t^1(V_1(t)) \times E_t^2(V_2(t-T)) \qquad (2)$$

The backward reflected field is given by

$$E^{Backward}(t) = E_t^2(V_2(t)) \times E_t^1(V_1(t-T)) \qquad (3)$$

The isolation ratio (IR) can be written as the ratio of fourier spectrum of forward and backward signal

$$IR = \mathcal{F}(E^{Forward}(t))/\mathcal{F}(E^{Backward}(t)) \qquad (4)$$

Equation (2) and (3) are non-identical if $T \neq 0$ and $V_1 \neq V_2$. Here E_t^1 and E_t^2 are the electric fields at input of each ring modulator. If T, V_1 and V_2 is chosen properly, we can maximize the isolation. We choose $V_1(t) = V_0 \sin(2\pi f t)$ and $V_2(t) = V_0 \cos(2\pi f t)$ to maximize isolation at the targeted wavelength. The delay phase can be written as $\phi^{delay} = \frac{2\pi f T}{c}$ and our goal is to calculate the optimum value of ϕ^{delay} and V_0 for which the isolation ratio (IR) is maximized.

III. RESULTS

We calculate IR under two scenarios. In Scenario 1, wavelength is fixed to the resonance dip frequency of the spectrum , while the modulation voltage amplitude V_0 and ϕ^{delay} are varied (by varying the length of the delay line). Results are given in Fig. 3. The isolation ratio is maximized for a $\phi^{delay} = \frac{\pi}{2}$ and $V_0 = 1.8$ V. This corresponds to a delay time $T = \frac{c}{4f}$. The drive voltage $V_0 = 1.8$ V is small enough to be supplied by a conventional CMOS driver. Our estimates suggest that with a delay line of group index $n_g = 3.8$ and length $L^{delay} = 2.5cm$ we can achieve a target modulation frequency $f = 789$ MHz. This value is much smaller than the typical -3 dB bandwidth of ring modulators ($\approx 30-40$ GHz). Obtained IR is 50 dB at the optimal point. The above mentioned IR is calculated at a single wavelength of operation.

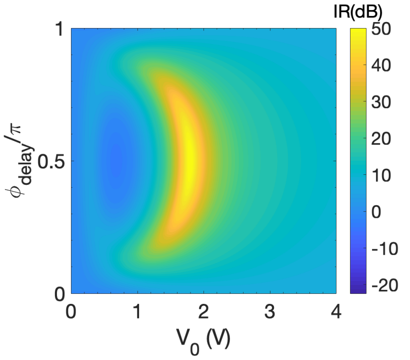

Fig. 3. Isolation ratio in decibels with variable modulation voltage and the phase of delay line. Wavelength is fixed to $\lambda = 1550nm$.

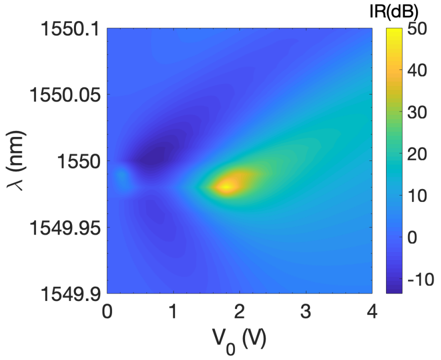

Fig. 4. Isolation ratio in decibels with variable input wavelength and the modulation voltage. Phase of delay line is fixed to $\phi^{delay} = \frac{\pi}{2}$.

Since, ring modulator is a resonant device, it only operates in a narrow range of wavelength. To quantify the bandwidth of this isolator, we perform simulations for Scenario 2, wherein we fix $\phi^{delay} = \frac{\pi}{2}$. Input wavelength and modulation amplitude is varied along each axis to find the bandwidth over which IR remains with 3 dB of the maximum value. From Fig. 4, we observe that the maximum IR of 50 dB occurs at 1550 nm and the IR>30 dB for a bandwidth of 1.87 GHz. Thus, a laser with linewidth less than 1.87 GHz can be easily isolated with the tandem ring modulator based isolator.

IV. CONCLUSION

In conclusion, we have numerically demonstrated a ring based optical isolator that can achieve a maximum isolation ratio of 50 dB and can maintain the isolation ratio greater than 30 dB for a bandwidth of 1.87 GHz.

REFERENCES

[1] B. J. H. Stadler, and T. Mizumoto, "Integrated magneto-optical materials and isolators: a review," IEEE Photonics Journal, vol. 6, pp. 1-15, December 2014.

[2] L. Bi *et al.*, "On-chip optical isolation in monolithically integrated non-reciprocal optical resonators," Nature Photonics, vol. 5, pp. 758762, November 2011.

[3] C. R. Doerr, L. Chen, and D. Vermeulen, "Silicon photonics broadband modulation-based isolator," Opt. Express, vol. 22, pp. 4493-4498, February 2014.