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Optical Isolator Design Aspects with Silicon Photonics -A Review

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***Abstract*: --- The advancement in silicon photonics especially for Photonics Integrated Circuits design has generated a requirement for modelling all optic components accurately and effciently.Optical isolator desing is based on Faraday roation principle. This has posed design challenges with respect to complexity and efficiency.The back reflection of light in photonics device diminishes the performance of the whole system.An effective design of an optical isolator becomes crucial for system design.The electro optic and magneto optic techniques are used to analyze and solve the transverse electric and magnetic fields.The main goal is to have desired isolation.The nonlinear Kerr effect occuring in optical devices is recently adopted so as to achieve optical isolation with the help of mixing of wavelengths. This paper reviews different methods and experiments specifically for designing an optical isolator for silicon photonic devices.**

***Keywords* — FWM,interference,modes,MZI,optical-isolator,photonics,TE,TM..**

I. INTRODUCTION

The silicon photonics design is being researched over a decade alongwith its integration of photonics devices on silicon platform. This takes advantage of CMOS facilities and high performance optical systems. The silicon photonics uses optical interconnect so as to replace electrical communication links with optical links. Beyond optical communication photonics devices are used in industrial drive for applications such as spectroscopy, sensors etc. However functionally electronics and photonics behave as a single entity. One of the crucial aspect of Photonics Integrated Circuit design is an optical isolator. The main aspect isolator design is to reduce the backscattering of light wave in the circuit through destructive inference. For decades, researchers have contributed towards specific design on an isolator using imperative techniques. This paper focuses on the review of few different approaches for designing [1].

II. OPTICAL ISOLATOR

The very purpose of optical isolator is to block the unwanted rear reflections or transmission which is polarization independent. The implementation of the basic isolator includes two bifringent plate and a Faraday rotator wheel which acts as a link between two walk off polarizer. When light passes through these optical component, they propagate separately as o-ray (ordinary ray) and e-ray (extraordinary ray).Isolation becomes crucial when a photonic circuit has optical amplifiers and/or lasers connected to the fiber network. To design isolator one of the classical approach is to use magneto optic material. Here the challenging part is to deposition polycrystalline films as well as bonding of crystals. The magneto optics works well with transverse magnet polarized light whereas photonics integrated circuits works with transverse electric polarized light [2].

III. MAGNETO-OPTICAL APPROACH

Optical isolator is fabricated using magneto-optical material.Here the symmetry of time reversal breaks down due to which the transmission in forward direction is not as same as the backward reflection.Author S.Ghosh in his paper discusses design of optical isolator for TE polarized light (as PIC works with same polarization)with magento-optical material.In the design two common methods to implement silicon on insulator are die-to-wafer bonding and another is magentron sputtering deposition. This is also known as pulsed laser deposition on the top layer of silicon waveguide circuits.[2][3].The improvement in properties of material and integration process on semiconductor substrate by forming thick layer on top of seed layer has reduced thermal expansion mismatch and losses due to scattering which otherwise reduces performance[2][3].The author further explains about the material which is typically used in Faraday rotator medium is yttrium iron garnet (YIG). .However it creates challenges in phase matching of TE and TM modes[2][8].The solution to this particular problem is known as non reciprocal phase shift (NRPS) [2][8]. The mathematical formulation of NRPS is as follows.

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$$\varepsilon = \begin{bmatrix} n^2 & 0 & j\varepsilon_{xz} \\ 0 & n^2 & 0 \\ -j\varepsilon_{xz} & 0 & n^2 \end{bmatrix} \quad (1)$$

Here is the dielectric permittivity tensor which is non symmetrical and results in non reciprocal behaviour , n is the refractive index and [2][8]. is related to the Faraday rotation as [2][8]. The NRPS is calculated as follows

$$NRPS = -j\omega\varepsilon_0 \frac{\iint \varepsilon_{xz}(x,y) E_x^0 E_z^0 \, dxdy}{\iint [E_x^0 H_y^0 - E_y^0 H_x^0] dxdy} \quad (2)$$

where is radial frequency, is free space permitivity, are field amplitudes of permittivity.

Thus with the above mathematical formulation the basic compnents of the proposed Machâ€"Zehnder interferometer (MZI) isolator design subsits polarization rotator, silicon waveguide covered with Ce:YIG used as nonreciprocal phase shifter,fiber-to-chip grating couplers for TE polarization [2].

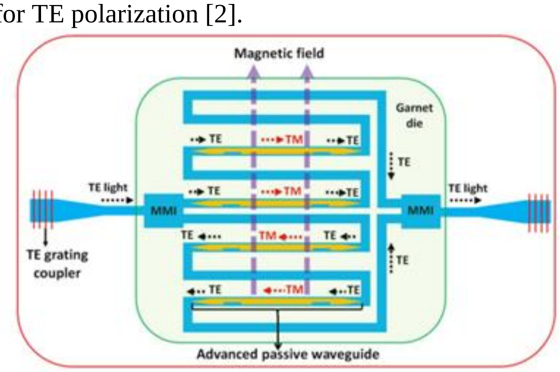

Fig.1: Design of Optical Isolator

The NRPS configuration can be realized using Mach-Zehnder Interferometer (MZI) as shown in figure 1 proposed by author [2]. A magneto optical garnet on silicon waveguide can be achieved either by direct bonding and epitaxial layer [5].

IV. ELECTRO-OPTICAL APPROACH

The author C. R. Doerr has broached electro-optic method to use a tandem arrangement of two phase modulators in order to reduce the insertion loss with the help of two short modulators [4].Thus in the underlying scheme of tandem phase modulator, one modulator is driven by a sine wave at frequency and another by a cosine wave also at frequency. The dual phase modulator combination are distant by waveguide propagation distance of where is group velocity in waveguide.When the signal transmits from left to right in the top arm, the transmission is represented as follows.

$$e^{jA\sin[2\pi f(t-\Delta T)]} e^{jA\cos(2\pi ft)} = 1 \quad (3)$$

where $\Delta T = 1/(4f)$ is time delay amidst the phase modulators. Similarly right to left transmission is represented by

$$e^{jA\cos[2\pi f(t-\Delta T)]} e^{jA\sin(2\pi ft)} = e^{j2A\sin(2\pi ft)} \quad (4)$$

Thus above two equations shows that the forward signal will not have effect of backward energy.The only issue with this design is isolation will be narrow band since the backward propagating light gets distributed to other frequencies which causes to fail to achieve isolation in case broadband device is applied [4]. To overcome this problem the interferometer called as N- arm interferometer is upgraded by adding above discussed narrow-band isolator in each arm. Here each arm is driven by different overall RF phase.[4]. The analogus RF phase in arm n is while optical phase remains same in all the arms.As a result of this in backward direction the different RF phases generated sidebands interfere destructively and broadband isolation can be accomplished.The figure 2 shows the proposed arrangement by the author [4].

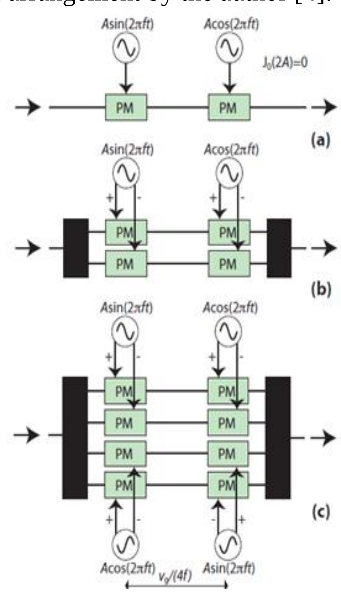

Fig.2: Tandem Phase Modulator. (a) single arm (b) two arm (c) four arm

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V. MULTIMODE INTERFERENCE BASED APPROACH

Photonic devices based on Multimode Interference (MMI) has opened up wide range of applications. This based on properties of performance,size,and fabrication fortitude [6].The author Zhuromskyy has proposed MMI based isolators for TE modes with magnetic domain structure [6].Fabrication of MMI based isolator on InP subsrate was experimented by Yang and. Keyi has demonstrated TM mode MMI isolator design on Silicon on Insulator (SOI) waveguide[6].

For TM modes, NRPS result can be accomplished by expanding layers of different material with an external magnetic field applied at right angle to the wave vector. The propagation constants contrasts in forward and backward direction.

The output power equation of MMI waveguide can be indicated as linear combination of all the guided modes as follows [6]

$$P(L) = \omega_0^2 + \omega_1^2 + 2\omega_0\omega_1 cos((\beta_0 - \beta_1)L) \quad (5)$$

In above equation $P(L)$ represents power transmission at device length of L. β_0, β_1 represents propagation constant for TM00 and TM01 modes and ω_0, ω_1 represents power coupling efficiency respectively. Variation in the length L of the waveguide produces harmonic variation in the power.The crucial length of MMI isolator where the minimum backward output and maximum forward output occurs can be expressed with following equation.

$$L_{mmi} = \frac{\pi}{(\beta_{f0} - \beta_{f1}) - (\beta_{b0} - \beta_{b1})} = \frac{\pi}{(\beta_{f0} - \beta_{b0}) - (\beta_{f1} - \beta_{b1})}$$
(5)

From equation (5) , it can be observed that power output P diminishes to null if and only if $\omega_0 = \omega_1$. This condition does not saisfy when a symmetric mode in single-mode waveguide is used to excite a symmetric and an asymmetric mode [6].But on other hand large isolation can be realized with the help of progressively cascade structure.The performance of an MMI isolator was calculated based on Finite Element Method (FEM) simulation.Thus to achieve 20 dB isolation the author used six MMI isolators for cascaded structure.The following figure 3 shows the sketch of the MMI isolator introduced by author [6].

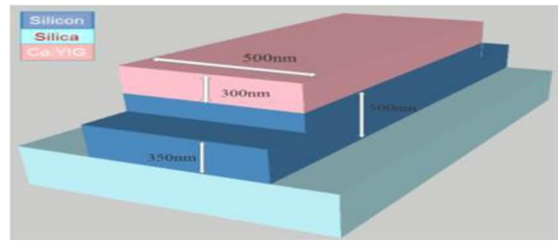

Fig.3: Sketch of MMI Isolator

VI. FOUR WAVE MIXING BASED APPROACH

Off late, Silicon photonics development based on nonlinear optical effect is one of the prominent design approaches. The reason for same is their material compatibilty,planar integration,easy fabrication and operation.Ke Wang has proposed a Nonlinear effect method called Four Wave Mixing (FWM) [1]. FMW is a typical optical Kerr effect.It arises when three different wavelengths of light are launched into the fiber [7]. The phenomenon uses Bragg scattering FWM process where pump wave progresses in the backward direction and weakens the backward signal.The forward propagation of pump wave assures better performance.With the help of phase matching condition in case of FWM the codirectional signal the pump brings about productive wavelength conversion and differing directional signals are separated by wavelength filtering [1].FWM mode optical isolators are are able to perform concurrent operations in both directions by resolving the issue of dynamic reciprocity constraints and manages to accomplish practical solution.In the proposed design of the author isolation loss is cruically reduced by raising the power level [1].

The fundamental structure introduced by Ke Wang as shown in figure involves two indistinguishable filters and a strip waveguide needed to convert FWM wavelength [1].The filter is realized with coupled grating structure that has two gratings with similar period, however their refractive indices are unequal.The proposed filter satisfies coupled Bragg condition with simultaneous back coupling of optical signals with the wavelengths as well as trasnmitting others.The Figure shows the transmission and back coupling spectrum.Filter 1 is used in transmission mode and filter 2 is used in back coupling mode [1].

In the introduced design the optical pump with wavelength λ_P progresses in leading direction through the integrated isolator along with forward signal of wavelength λ_S .The range of transmission band of filter 1 comprises wavelengths of pump and signal i.e. λ_S and $\lambda_P < \lambda_1$ or λ_S and $\lambda_P > \lambda_2$. In next step the idle wave which is wavelength shifted replica of original signal is engendred by FWM by satisfying coupled Bragg condition $\lambda_1 < \lambda_{FWM} < \lambda_2$. Thus at Port 3 the original signal and pump lights are terminated and degrades back reflection [1]. In reverse direction wavelength of reflected signal becomes λ_{FWM} travels from port 2 to port 1 towards long strip waveguide. The reversed optical signal does not interact with forwarding pump as FWM needs phase matching. In this way non reciprocity is achieved in both the direction concurrently[1].

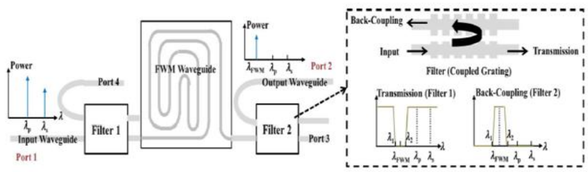

Fig.4: FWM Based Silicon Integrated Isolator

VII. CONCLUSION

In conclusion , different methods of designing the optical isolators with silicon photonics have been discussed.In case of mangeto optical approach the NRPS effect is taken into account to achieve non reciprocity. This resolves the phase matching problems of TE and TM mode.One of the technique used in electro optical approach is tandem phase modulator where one modulator is driven by sine function and another by cosine function.The narrow band problem for tandem phase modulator device is solved by N-arm interferometer where RF phase in the arm 'n' is altered while optical phase remains unchanged. This results in broadband isolation.In case of MMI based isolator design the TE and TM modes are solved using FEM solvers.Here power coupling is calcualted as a linear combination of variation in length of waveguide and propagation constants of different modes.To obtain higher isolation gain and to avoid issues with symmetric & asymmetric modes cascade structured design is implemented. Finally the recently proposed FWM based isolator design takes the non linear effects approach.This intoduces two filter in the range of pump wavelength and forward signal. The idler wave generated by FWM satisfies coupled Bragg condition. The reverse optical signal does not interact with forward pumping thus gaining the non reciprocity.

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REFERENCES

[1] Ke Wang,Shitao Gao,Yang Wang,Ampalavanapillai Nirmalathas,Christina Lim,Kamal Alameh and Efstratios Skafidas Four-Wave-Mixing-Based Silicon Integrated Optical Isolator With Dynamic Non-Reciprocity, Vol.28,No.16. 1em plus 0.5em minus 0.4em IEEE Photonics Technology Letters,August 15, 2016..

[2] S.Ghosh,S.Keyvaninia,Y.Shirato,T.Mizumoto,Optical Isolator for TE Polarized Light Realized by Adhesive Bonding of Ce:YIG on Silicon-on-Insulator Waveguide Circuits , Vol.5,No.3. 1em plus 0.5em minus 0.4em IEEE Photonics Journal,June 2013.

[3] S. Ghosh, S. Keyvaninia, W. Van. Roy, T. Mizumoto, G. Roelkens, and R. Baets, Ce:YIG/Silicon-on-Insulator waveguide optical isolator realized by adhesive bonding, Vol.5,No.3. 1em plus 0.5em minus 0.4em Optics Express, Jan. 2012.

[4] C. R. Doerr, L. Chen, and D. Vermeulen, Tandem-Phase-Modulator-Based Optical Isolator in Silicon. 1em plus 0.5em minus 0.4em 39th European Conference and Exhibition on Optical Communication (ECOC 2013) .

[5] Y.Shoji, A.Fujie, and T.Mizumoto Silicon Waveguide Optical Isolator Operatingfor TE Mode Input Light, Vol.22,No.6. 1em plus 0.5em minus 0.4em IEEE Journal of Selected Topics in Quantum Electronics, Nov./Dec. 2016.

[6] Keyi,Shui,L.Deng and L.Bi Multimode interference isolator on Silicon-on-Insulator platform,IEEE International Nanoelectronics Conference (INEC),2016.

[7] O.Aso,M.Tadakuma and S.NamikiFour Wave Mixing in Optical Fibers and Applications, No.19, 1em plus 0.5em minus 0.4em Furukawa Review, 2000.

[8] M.Soljacic,C.Luo,and J.D.Joannopoulos,Nonlinear photonic crystal microdevices for optical integration,Vol.28 No.8, 1em plus 0.5em minus 0.4em Optics Letters,April 2003.