

# Demonstration of a Ce:YIG/SOI isolator by BCB bonding

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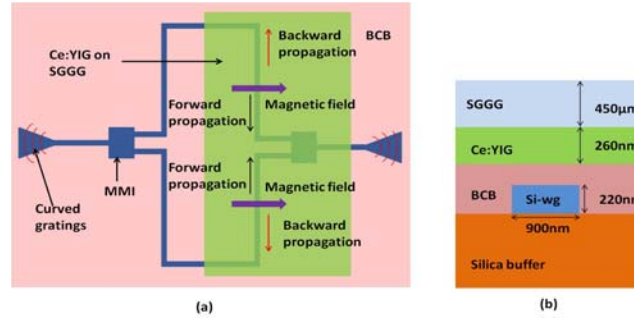
*We demonstrate an optical isolator on a Silicon-on-insulator platform realized by adhesive BCB bonding. A Ce:YIG die was manually bonded on top of a Mach-Zehnder interferometer (MZI) using a 100nm thick BCB bonding layer. Experimentally a maximum isolation of 25dB was obtained. The insertion loss of the bonded device is about 8dB. The nonreciprocal phase shift (NRPS) induced by the Ce:YIG with the aid of an external magnetic field matches with simulation. The simulation, design and experimental results are presented in this paper.*

## Introduction

Of-late many active optical components have been realized on the III-V/Silicon-on-insulator (SOI) platform, and as time goes on, the number of components in an optical circuit increasing. As a result there are several potential sources of back reflection in such a circuit. Specifically lasers realized on the above mentioned platform are sensitive to back reflections. To achieve stable laser operation an optical isolator is highly desirable, integrated on the same platform. An optical isolator can be realized by incorporating a non-reciprocal material on silicon waveguide circuits. A magnetic medium can serve this purpose with the aid of an external magnetic field. Ferrimagnetic materials, such as Yttrium Iron Garnet (YIG) or Ce substituted YIG can be used as magneto-optic material. There are two straightforward approaches already proposed in literature to integrate the magneto-optic material on a silicon waveguide platform: one is bonding of the magnetic material on the silicon waveguide circuit [1], while the other one is sputter deposition of a polycrystalline thin film [2]. The deposition approach is a wafer-scale approach but the deposited film suffers from reduced Faraday rotation and high optical loss. In this work we adopt an adhesive die-to-wafer bonding technique using BCB to integrate Ce:YIG on the silicon waveguide. While the bonding approach was already demonstrated using direct molecular bonding [1, 3], here we focus on the use of adhesive bonding technique [4], since this approach is very promising for integrating the optical isolator after the heterogeneous laser integration process on the same platform as in this case surface roughness and contamination requirements to achieve good bonding are not stringent.

## Design & Simulations

Commercially available fiber-pigtailed bulk isolators use the longitudinal Faraday effect in which isolation is realized by polarization rotation of incident light induced by YIG in combination of two polarizers with polarization axes offset by  $45^\circ$ , with an external magnetic field applied parallel to the light propagation direction. High index contrast silicon waveguides are birefringent and to achieve maximum isolation, the phase matching condition between TE and TM modes needs to be satisfied. The form-birefringence is strongly dependent on the waveguide geometry and it is very difficult to control the exact geometry for optimal performance. The device presented in this paper works on the basis of the non-reciprocal phase shift (NRPS) experienced by TM polarized light propagating through a Ce:YIG covered silicon waveguide in the presence of an external magnetic field applied transverse to the light propagation direction. A Mach-Zehnder interferometer (MZI) is used to observe the NRPS in terms of non-reciprocal power transfer. The schematic of the layout of the bonded device is shown in the figure 1a.



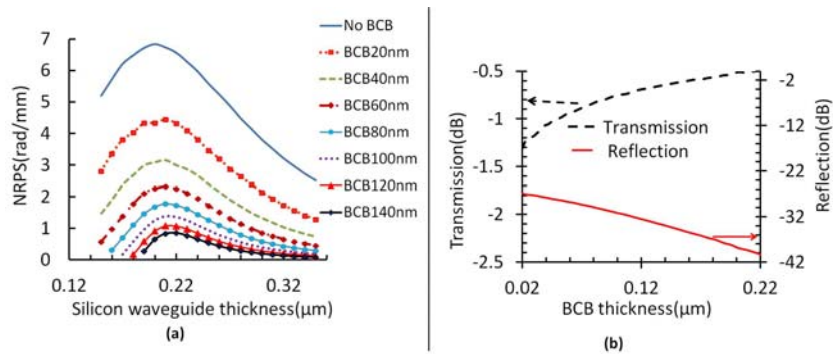
**Figure 1: (a) Schematic layout of the Ce:YIG/SOI optical isolator (b) waveguide cross-section**

The fundamental TM mode is excited by curved diffraction gratings [5] in a 900nm wide and 220nm thick silicon waveguide. The MZI consists of two multimode interferometers (MMI) connected through two single mode optical waveguides of width 900nm and thickness 220nm. The magnetic material is covering half of the MZI in such a way that the device operates in push-pull manner when a transverse magnetic field is applied. In push-pull mode the NRPS experienced by TM light in the upper branch is opposite to that of lower branch. The waveguide cross-section for the garnet covered part is shown in figure 1b. The NRPS per unit length for different BCB thicknesses can be calculated by a perturbation formula using a 2D full-vectorial simulation model.

$$NRPS = -j\omega\epsilon_0 \frac{\iint g(x,y) E_x^0 E_z^0 dx dy}{\iint [E_x^0 H_y^0 - E_y^0 H_x^0] dx dy}$$

where  $E_i^0$  and  $H_i^0$  ( $i = x, y, z$ ) are the unperturbed optical field amplitudes and  $g(x,y)$  is the gyrotropy constant related to the Faraday rotation coefficient ( $\theta_F$ ) of the nonreciprocal material by  $g(x,y) = n\lambda\theta_F/\pi$ , in which  $n$  is the refractive index of the

nonreciprocal material and  $\lambda$  is the wavelength. The resulting NRPS is shown in figure 2a for a 260nm thick Ce:YIG layer ( $\theta_F$ :  $-4500^0/\text{cm}$  at  $1.55\mu\text{m}$ ,  $n$ : 2.2) on a substituted Gadolinium Gallium Garnet (SGGG) substrate ( $n$ : 1.94) transferred to an SOI waveguide circuit. The graph shows that for a compact isolator a thin BCB layer is desirable but on the other hand for higher BCB thicknesses the device will be very tolerant. Since there is a mode mismatch at the interface between plain BCB covered SOI and garnet covered SOI, insertion loss and parasitic reflection can be expected at that interface. The simulated transmission and reflection is shown in figure 2b as a function of BCB thickness.



**Figure 2: (a) NRPS per unit length as a function of BCB bonding layer thickness and silicon waveguide thickness (b) insertion loss and reflection at the BCB covered SOI/ Ce:YIG covered SOI interface as a function of BCB bonding layer thickness**

It is clear from figure 2b that there is a trade-off between device length and insertion loss.

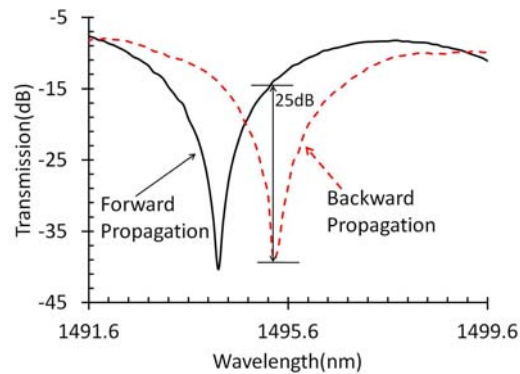
## Fabrication

The SOI waveguide circuits were fabricated in a CMOS pilot line using 193nm deep UV lithography and dry etching. After device fabrication, the SOI die was cleaned by following a standard SC-1 cleaning procedure. Then sequentially AP3000 and mesitylene diluted BCB (1:3 v/v) was spin coated on the SOI die at 5000rpm for 50 seconds. After that, the spin coated SOI die was kept on the hot plate at  $150^0\text{C}$  for 3-4 minutes to evaporate the solvent. Epitaxially grown Ce:YIG on SGGG substrate is cleaned by acetone and isopropylalcohol (IPA). Then, the garnet die was positioned on top of the MZI as depicted in figure 1a. Finally the bonded SOI is cured for about 3 hours following a standard BCB curing recipe. The BCB layer thickness is expected to be around 100nm for the given BCB dilution and spin coating parameters.

## Experimental results

The designed MZI has free a spectral range of about 7.5 nm. To avoid any radiation loss in the garnet covered silicon waveguide the bend radius was designed as  $60\mu\text{m}$ . In the experiment a stack of three small Neodymium alloy (Nd-Fe-B) permanent magnets are

positioned on top of the garnet die to provide the required transverse magnetic field. Transmission measurements were carried out both in forward and reverse directions to characterize the nonreciprocal phase shift. Light was coupled in and coupled out by focusing TM grating couplers. The measured transmissions spectrum of the MZI is shown in figure 3. 25 dB isolation is achieved experimentally. A spectral shift of 1.1nm is measured which corresponds to a NRPS of 0.987 rad/mm. This is in agreement with a BCB thickness of around 100-120nm. The insertion loss of the bonded MZI is about 8 dB. This includes loss at interface between the BCB covered SOI and garnet covered SOI (simulation is shown in figure 2b) and propagation loss in the Ce:YIG/SOI waveguide, which was characterized to be 14.5dB/cm.



**Figure 3: Normalized transmission spectrum of MZI**

## Conclusion

In this paper we present the experimental realization of an optical isolator on an SOI platform using BCB adhesive bonding. The performance of the device still can be optimized but this approach paves the way for the co-integration of an optical isolator with a heterogeneously integrated laser diode.

## References

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