Monolithically Integrated Unidirectional Circulators Utilizing non-Hermiticity and Nonlinearity on InP

Parinaz Aleahmad*, Mercedeh Khajavikhan, Patrick L. LiKamWa, and Demetrios Christodoulides
CREOL/The College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816, USA
**parinaz.aleahmad@creol.ucf.edu*

Abstract: We demonstrate unidirectional monolithically integrated 4×4 optical circulators operating at 1.55 μm on InP. By exploiting the interplay between non-Hermiticity and nonlinearity, an isolation exceeding 20dB is experimentally observed with pulsed inputs.

OCIS codes: (230.4320) Nonlinear optical devices; (230.3240) Isolators; (130.0130) Integrated optics

The need to integrate critical optical components on a single chip has been an ongoing quest in both optoelectronics and optical communication systems. Among the possible devices, elements supporting non-reciprocal transmission are of great interest for applications where signal routing and isolation is required. In this respect, breaking reciprocity is typically accomplished via Faraday rotation through appropriate magneto-optical arrangements. Unfortunately, standard light emitting optoelectronic materials like for example III-V semiconductors, lack magneto-optical properties and hence cannot be directly used in this capacity. To address these issues, a number of different tactics have been attempted in the last few years. These range from directly bonding garnets on chip, to parametric structures and unidirectional nonlinear arrangements involving ring resonators, to mention a few [1-4]. Clearly, of importance will be to realize families of non-reciprocal devises that not only can be miniaturized and readily integrated on chip but they also rely on physical processes that are indigenous to the semiconductor wafer itself. Quite recently we have theoretically shown that such unidirectional systems can be implemented, provided one simultaneously exploits the presence of gain/loss processes and optical nonlinearities. In principle, these all-dielectric structures can be broadband, polarization insensitive, color-preserving, and can display appreciable isolation ratios provided they are used under pulsed conditions. In this study, we experimentally demonstrate a compact, monolithically integrated unidirectional 4×4 optical circulator, based on non-reciprocal optical transmission through successive amplification/attenuation stages and elements with very large resonance nonlinearities associated with InGaAsP quantum wells. Our results indicate that isolation ratios over 20dB can be experimentally achieved in pulse-mode operation. Our design can be effortlessly extended to other existing optoelectronic device systems beyond InP.

Figure 1(a) shows a schematic view of an all-dielectric 4×4 circulator design on InP meant for 1550 nm. Red segments in this figure depict regions with optical gain while blue sections represent regions with loss and high defocusing nonlinearities. A pulse entering port 1 (red channel) in Fig. 1(a), eventually passes through a non-symmetric, non-Hermitian, coupled waveguide structure. The pulse is first amplified in a semiconductor optical amplifiers (SOA) segment and therefore remains in the same channel of the heavily lossy nonlinear coupler. This is achieved through a substantial detuning in the propagation constants of the two adjacent waveguides involved in the coupling section (indicated by blue).

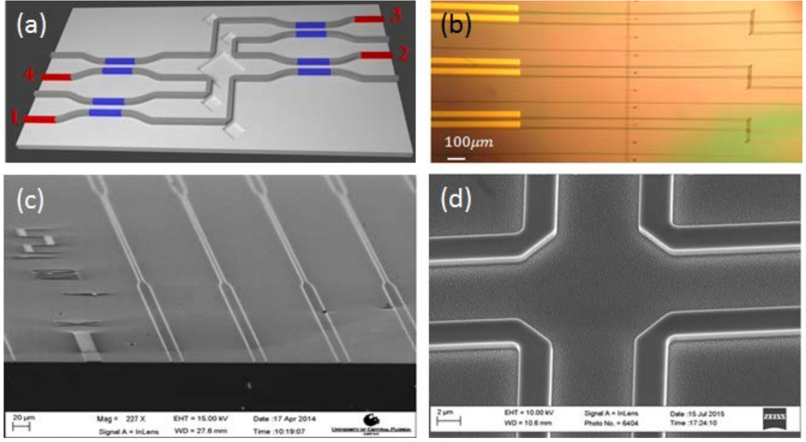

Fig. 1. a) Schematic view of a 4-port circulator device. b) Microscopic view of a fully integrated active InP circulator. c) and d) SEM pictures of the fabricated system. The footprint of this device is $4\ mm \times 120\ \mu m$.

The optical pulse is then subjected to two successive total internal reflections in order to reach a second non-Hermitian nonlinear directional coupler - identical to that previously encountered. In this second lossy segment, where the pulse is already weak, no change in the refractive index is induced. Therefore the wave will cross-over and hence exit from port 2, after being amplified (red section of port 2) so as to compensate for all the losses suffered during propagation in this unidirectional circulator structure. Similarly, a pulse from port 2 will reach port 3, and so on. The various fabricated sections of this device are shown in Figs. 1(b-d). In all cases, we assume a 10dB amplification stage at the exit ports so as compensate for the incurred losses. Figures 2(a) and (b) depict beam propagation simulations for low and high optical intensities, respectively, akin to those encountered in the actual device. The nonlinear switching needed to make this circulator function is clearly evident in Figs. 2(a,b).

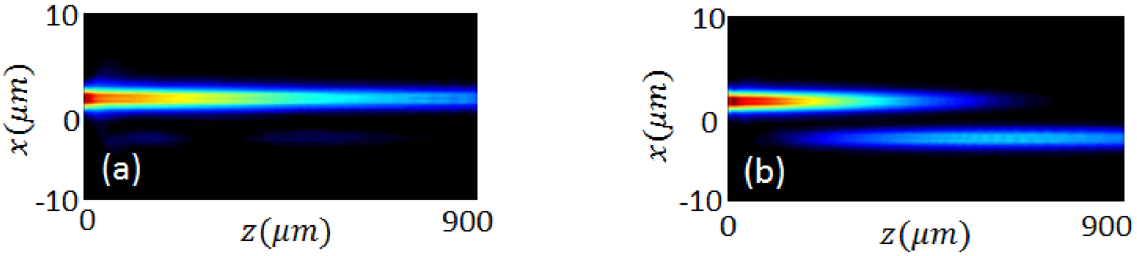

Fig. 2. Intensity switching as obtained from beam-propagation simulations for (a) a high intensity pulsed beam (after amplification) in the first leg of the circulator and b) a low intensity beam in the absence of gain, as needed for the second segment before port 2.

In our system, p-type contact metals consisting of Ti, Zn and Au were deposited on top of the waveguides so as to operate as semiconductor optical amplifiers (SOAs), thus providing the necessary gain in the red sections of Fig. 1(a). The fully integrated devices were then tested by supplying the SOA with a current of 140mA. The modal gain coefficient at this current level was measured to be $20cm^{-1}$. The input power at each port was then adjusted to reach 1mW after the coupling losses. The SOA length was prudently designed for a 10dB gain for each input pulse. In addition, the band filling nonlinear coefficient was measured using a free space Mach-Zehnder interferometer and was found to be $1.5 \times 10^{-12}\ m^2/W$. The input pulses (10 ps) were generated through a tunable mode-locked Erbium-doped fiber laser operating at 1550nm. The waveguide losses in this arrangement were engineered by utilizing bandgap intermixing techniques. This was necessary in order to avoid excessive losses in the intervening guiding channels. Through this intermixing processes, the bandgap structure of the coupler section remained high as intended (with losses up to $23cm^{-1}$), while the remaining regions have been shifted down to $8cm^{-1}$. The output light from port 2 (amplified back to 1 mW), was finally imaged on an infrared camera and a fast p-i-n photodiode using a X20 microscope objective lens. An adjustable slit on a translation stage was placed in front of the photodiode so as to measure the output power from either port independently. Our results indicate that an isolation of 20dB can be obtained in this pulsed circulator in a broadband way around 1550 nm. This is consistent with all the possible transitions (from and to all ports) that *unidirectionally take place in a counter-clockwise fashion* in this configuration. In all cases, we found that ASE (which can be filtered-out) did not have any noticeable effects on the functionality of our device. In principle, by further optimizing the pertaining sections involved, even higher isolation ratios can be achieved.

In summary, we demonstrated unidirectional monolithically integrated 4×4 optical circulators operating at 1.55 μm on InP. Isolation ratios exceeding 20dB were experimentally observed with pulsed inputs.

This work was partially supported by NSF (Grant No. ECCS-1128520) and AFOSR (Grant No. FA9550-14-1-0037).

[1] Lei Bi, Juejun Hu, Peng Jiang, Dong Hun Kim, Gerald F. Dionne, Lionel C. Kimerling, and C. A. Ross, "On-chip optical isolation in monolithically integrated non-reciprocal optical resonators," Nature Photonics **5**, 758–762 (2011).
[2] Yuya Shoji, Tetsuya Mizumoto, Hideki Yokoi, I-Wei Hsieh, and Richard M. Osgood, Jr., "Magneto-optical isolator with silicon waveguides fabricated by direct bonding," Appl. Phys. Lett. **92**, 071117 (2008).
[3] Hugo Lira, Zongfu Yu, Shanhui Fan, and Michal Lipson, "Electrically Driven Nonreciprocity Induced by Interband Photonic Transition on a Silicon Chip", Phys. Rev. Lett. **109**, 033901 (2012).
[4] Li Fan, Jian Wang, Leo T. Varghese, Hao Shen, Ben Niu, Yi Xuan, Andrew M. Weiner, and Minghao Qi, "An All-Silicon Passive Optical Diode," Science **335**, 447 (2012).