Energy-efficient active integrated photonic isolators using electrically driven
acoustic waves

Nathan Dostart1,* Yossef Ehrlichman1, Cale Gentry1, and Miloš Popović2

1Department of Electrical, Computer, and Energy Engineering, University of Colorado, Boulder, CO, 80309, USA
2Department of Electrical and Computer Engineering, Boston University, Boston, MA, 02215, USA
*Corresponding author: nathan.dostart@colorado.edu

Compiled November 6, 2018

Abstract

We propose and investigate the performance of integrated photonic isolators based on a triply-guided waveguide system on chip comprising two optical modes and an electrically-driven acoustic mode. One optical mode carries a signal of interest; the second is ancillary and takes away optical power rejected by the isolator. The acoustic wave induces linear optical non-reciprocity with no additional optical loss, without magnetic-optic materials, and with low power consumption. These properties suggest the potential for straightforward integration with the drive circuitry, possibly in monolithic CMOS technology, enabling a fully contained ‘black box’ optical isolator with two optical ports and DC electrical power. The approach is theoretically evaluated using realistic parameters; our example implementation includes a novel optical-mechanical multiplexer design. Expected performance is a predicted 20 dB of isolation and 3.5 dB of insertion loss with 380 GHz optical bandwidth and a 1 cm device length. The isolator utilizes 1 mW of electrical drive power, or 10 fJ/bit at the 100 Gbps equivalent data rate supported by the isolator, an improvement of 1–3 orders of magnitude over the state-of-the-art. Such isolators could be valuable in integrated photonic communication and sensing circuits, especially those using coherent detection.

Integrated photonics is rapidly advancing and will become an integral part of future computing and communication technologies, including through co-integration of state-of-the-art electronics and silicon photonics [1]. Many integrated photonics applications call for co-integration with on-chip lasers, which require optical isolators. Even for architectures that use off-chip lasers, on-chip isolators or circulators could enable simultaneous bi-directional communication links and other capabilities. Conventional isolators use the magneto-optic (Faraday) effect to induce non-reciprocity, but magneto-optic materials have substantial loss and have been challenging to integrate in photonic platforms [2, 3, 4, 5]. To our knowledge, no silicon photonics foundry currently has an optical isolator in its component library. In contrast, monolithic co-integration of electronics and photonics has been demonstrated in advanced process nodes (28 – 45 nm) [6, 1]. Hence, non-magnetic approaches to integrated photonic isolation, preferably CMOS-compatible, are desirable and would be rapidly adopted.

Aside from the magneto-optic effect, two other avenues exist to produce a non-reciprocal system: nonlinearity and time variance [7]. Signal-nonlinear approaches cannot be used for many applications, but some nonlinear approaches based on stimulated Brillouin scattering (SBS) are signal-linear [8, 9]. However, these approaches require two optical pumps, which combined with typical laser wall plug efficiencies of ~ 10% and high required pump power cause this to be a power hungry and expensive prospective approach. Time-varying systems, mostly based on optoelectronic interactions, are the basis for a wide array of proposed isolator designs using effects such as frequency conversion, traveling wave phase shifters, and optical interband transitions [10, 11, 12, 13]. The main drawback of current silicon photonic approaches is free carrier loss inherent to plasma-dispersion modulators [14] and their typically low isolation ratios of < 15 dB [11, 13, 10].

In this Letter we investigate integrated photonic isolators that utilize an optical guided wave ‘interband transition’ i.e. mode conversion [12] facilitated by non-reciprocal coupling induced by an electronically excited traveling guided acoustic wave. We refer to them as electro-mechanical photonic (EMP) isolators. This approach avoids the requirement of two optical pumps [8, 9], achieves lower insertion losses and higher isolation than carrier plasma approaches [13, 11, 10], and may use potentially co-integrated electronics to generate the acoustic wave to result in a self-contained device. A recent paper demonstrates a similar isolation approach in an optical resonator with an unconfined, standing acoustic wave [15]. Our design uses a co-propagating, guided acoustic wave in a velocity-matched optical/acoustic waveguide to achieve broader bandwidth and higher energy efficiency.

The key components of the EMP isolator are a triply-guiding (bi-optical, uni-acoustic) waveguide cross-section with strong optomechanical coupling and tailored dispersion, and a novel ‘acoustic injector’ which multiplexes the optical modes with a transduced acoustic mode. We assume a piezoelectric transducer for maximum transduction efficiency since low-loss
Piezoelectrics have been co-integrated with CMOS photonics [16]. However, use of non-piezoelectric CMOS transducers, previously demonstrated [17], could enable entirely monolithic (and ‘zero-change’ [1]) CMOS photonic isolators.

The operating principle and a schematic of one embodiment are shown in Fig. 1. We use a non-reciprocal ‘interband’ (mode-to-mode) transition [12], where conversion from one optical spatial mode to another occurs in one direction but not in the other due to direction-dependent phase-matching. We then spatially separate these two modes using an adiabatic mode multiplexer. The converted power is discarded for an isolator (or retained for a circulator).

The non-reciprocal interband transition is provided by a linear optomechanical interaction. As shown in Fig. 1, a traveling acoustic wave is launched by a transducer into an ‘active’ optomechanical waveguide via an ‘acoustic injector’, which unidirectionally injects the acoustic wave into the optomechanical waveguide without affecting the optical modes. The optomechanical waveguide co-confines both light and sound such that the acoustic mode couples the incident optical mode and a second optical mode via Brillouin scattering [18]. The active section converts all power in one optical mode to the other due to direction-dependent phase-matching. We then spatially separate these two modes using an adiabatic mode multiplexer. The converted power is discarded for an isolator (or retained for a circulator).

The non-reciprocal interband transition is provided by a linear optomechanical interaction. As shown in Fig. 1, a traveling acoustic wave is launched by a transducer into an ‘active’ optomechanical waveguide via an ‘acoustic injector’, which unidirectionally injects the acoustic wave into the optomechanical waveguide without affecting the optical modes. The optomechanical waveguide co-confines both light and sound such that the acoustic mode couples the incident optical mode and a second optical mode via Brillouin scattering [18]. The active section converts all power in one optical mode to the other due to direction-dependent phase-matching. We then spatially separate these two modes using an adiabatic mode multiplexer. The converted power is discarded for an isolator (or retained for a circulator).

The operating principle and a schematic of one embodiment are shown in Fig. 1. We use a non-reciprocal ‘interband’ (mode-to-mode) transition [12], where conversion from one optical spatial mode to another occurs in one direction but not in the other due to direction-dependent phase-matching. We then spatially separate these two modes using an adiabatic mode multiplexer. The converted power is discarded for an isolator (or retained for a circulator).

The non-reciprocal interband transition is provided by a linear optomechanical interaction. As shown in Fig. 1, a traveling acoustic wave is launched by a transducer into an ‘active’ optomechanical waveguide via an ‘acoustic injector’, which unidirectionally injects the acoustic wave into the optomechanical waveguide without affecting the optical modes. The optomechanical waveguide co-confines both light and sound such that the acoustic mode couples the incident optical mode and a second optical mode via Brillouin scattering [18]. The active section converts all power in one optical mode to the other due to direction-dependent phase-matching. We then spatially separate these two modes using an adiabatic mode multiplexer. The converted power is discarded for an isolator (or retained for a circulator).

We use the coupled mode theory treatment of optomechanical interactions in [18]. The optical and acoustic fields are represented in their respective modal bases, $\tilde{E} = A_1(z)\tilde{E}_1(x,y) + A_2(z)\tilde{E}_2(x,y)$, and $\tilde{U} = B(z)\tilde{U}(x,y)$, where $\tilde{E}_1$ and $\tilde{E}_2$ are the optical field shapes; $\tilde{U}$ is the acoustic displacement field; $A_1$ and $A_2$ are the mode amplitudes; and $\omega_1$, $\omega_2$, $\beta_1$, and $\beta_2$ are the optical and acoustic frequencies, respectively. Here $\tilde{A}_1$ and $\tilde{A}_2$ are the total electric field and acoustic displacement field, respectively. The coupled mode equations that describe interactions between these modes are [18]

$$\frac{\partial A_1}{\partial z} = j\omega_1\kappa_1 B e^{j\Delta Kz} A_2 - \alpha_{opt} A_1$$

$$\frac{\partial A_2}{\partial z} = j\omega_2\kappa_2 B e^{-j\Delta Kz} A_1 - \alpha_{opt} A_2$$

$$B = B_0 e^{-\alpha_{acst} z}$$

where $\kappa_{ij}$ denotes the optomechanical coupling between mode $i$ and mode $j$ induced by the presence of the acoustic wave, $\Delta K = K - (\beta_1 - \beta_2)$ is the wave-vector mismatch of the interaction, $\alpha_{opt}$ is the optical propagation loss rate, and $\alpha_{acst}$ is the optical propagation loss rate.
The example active region, interacting modes, and phase-matching considerations are shown in Fig. 2. For the active design point, acoustic propagation loss rate. The optomechanical coupling $\kappa_{ij}$ between the two optical modes is principally induced by the photothermal effect and the moving boundary effect. Through field symmetries $\kappa \equiv \kappa_{ij} = \kappa_{ij}^{*}$. We neglect terms which involve optical pumping of the acoustic wave because we assume that the acoustic wave is an ‘undepleted pump’. Brillouin scattering requires one phonon per converted photon, hence to convert $P_{\text{opt}} = 1 \text{nW}$ of optical power between two optical modes with a 10 GHz acoustic wave, only $(\Omega/\omega)P_{\text{opt}} = 5 \text{nW}$ of acoustic power is required. Thus, for acoustic guided power of $\geq 1 \mu W$, this assumption is justified.

For simplicity, we define an effective optical coupling $\bar{\kappa} \equiv |\kappa||B_{0}|\sqrt{\omega_{1}\omega_{2}}$, analogous to the coupling coefficient used in standard optical waveguide coupled mode theory [19]. We then find the lossless coupling length (at which all power is mode-converted in the absence of acoustic loss and with perfect phase-matching) as $l_{c} = \pi/(2\bar{\kappa})$. Strong mechanical coupling between the two optical modes (\kappa) and efficient excitation of the acoustic wave (|B_{0}|) are therefore essential for a short device length. We can tune the strength and phase of the effective optical coupling in situ via the acoustic power and phase. In the presence of high acoustic propagation loss, the optical coupling decays with the acoustic wave, which can be compensated by re-injecting acoustic power periodically along the waveguide.

The phase-matching condition for forward Brillouin scattering determines the needed acoustic wave-vector $K = \beta_{1} - \beta_{2}$ and acoustic frequency $\Omega = \omega_{1} - \omega_{2}$. The second optical mode starts out unexcited at the entrance to the structure and is automatically built up along the waveguide at the energy-matched frequency in steady-state operation. Correct phase-matching in the block direction provides mode conversion, and lack of phase-matching in the pass direction suppresses it, providing the non-reciprocity. The effect of phase-mismatch can be evaluated by solving Eqs. (1–2) (without loss) for the output amplitudes, with the primary effect being a shorter coupling length $l'_{c} = (\pi/2)\bar{\kappa}^{2} + \Delta K^{2}/4)^{1/2}$.

For the proposed device, the achievable wave-vector mismatch in the pass direction (given a requirement of phase-matching in the block direction) sets the minimum device length. To design a short device we need to maximize the coupling coefficient $\bar{\kappa}$ for a given $\Delta K$. Power conversion occurs with a shorter cycle period (length) in the presence of phase-mismatch [19]. We can use this to achieve full isolation by choosing the device length $L$ to correspond to a null of the sinusoidal conversion in the phase-mismatched direction $(L = 2l'_{c})$ and a peak of the conversion in the phase-matched direction $(L = l''_{c})$. Assuming the bandwidth-maximizing scenario of identical optical group indices for the two optical modes (described later), the phase-mismatch is a function only of the acoustic frequency and optical group index, $\Delta K = 2\Omega n_{g}/c$. Using this relation we see that the device length required for full isolation is fully determined by these two parameters:

$$L = \frac{\pi\sqrt{3}}{2} \frac{1}{\Omega n_{g}} c.$$

A shorter device requires increasing the acoustic frequency or decreasing the optical group velocity (e.g. slow light).

Next we evaluate the device’s performance for an example implementation, by numerically solving Eqs. (1–3). We choose a standard silicon thickness of 220 nm and assume some device parameters necessary to calculate the isolator performance based on previously fabricated device literature. We assume a piezoelectric transducer with efficiency of $-14 \text{dB}$ [15], an acoustic loss rate of $\alpha_{\text{acst}} = 1 \text{mm}^{-1}$ (87 dB/cm) [20], and an optical loss rate of $\alpha_{\text{opt}} = 2.4 \text{dB/cm}$ [21]. For the optical mode multiplexer in 220 nm SOI we use $-30 \text{dB} \text{crosstalk}$ and $\sim 1 \text{dB}$ of insertion loss over a $\sim 2 \text{THz}$ bandwidth as demonstrated in adiabatic couplers [22].

The example active region, interacting modes, and phase-matching considerations are shown in Fig. 2. For the active section geometry we consider a suspended beam [Fig. 2(a)]. For the optomechanical interaction, a horizontal shear wave [Fig. 2(b)] is used to couple the first and second TE optical modes [Fig. 2(c)]. For this configuration the optimal beam width is 570 nm at which the two optical modes have identical group indices of $n_{g} = 4.11$ [Fig. 2(d)]. We match group velocities to
Table 1: Comparison to other published on-chip isolators (EM – electro-mechanical, OE – optoelectronic, MO – magneto-optic).

| Parameter       | Kittlaus [9] | Sohn [15] | Poulton [8] | Dong [11] | Lira [13] | Doerr [10] | Huang [4] | Huang [5] | This Work |
|-----------------|--------------|-----------|-------------|-----------|-----------|------------|-----------|-----------|-----------|
| Approach        | SBS          | EM        | SBS         | OE        | OE        | OE         | MO        | MO        | EM        |
| Broadband       | Yes          | No        | Yes         | Yes       | Yes       | No         | Yes       | Yes       | Yes       |
| Length (mm)     | > 10         | 0.17      | 100         | 50        | 1.5       | 9          | 0.07      | 1.5       | 10        |
| Power (mW)      | 50           | 100       | 5000        | 500       | 25        | 2000       | 9.6       | 260       | 1.14      |
| IL (dB)         | 20           | 7.7       | 10          | 5.5       | 70        | 4          | 2.3       | 8         | 3.5       |
| Isolation (dB)  | 25           | 15        | 20          | 12.5      | 3         | 3          | 32        | 29        | 20        |
| Bandwidth (THz) | 0.15         | 0.001     | 3.1         | 11.3      | 0.2       | 4.5        | 0.011     | 2.3       | 0.38      |

Energy/bit (fJ/bit): 13,000, 400,000, 6,500, 177, 500, 1780, 3490, 452, 12.0

The proposed EMP isolators offer a self-contained photonic component with equivalent function to a passive isolator, and no magneto-optic materials. This comes at the cost of non-zero electrical power consumption, but as shown this power is expected to be extremely low relative to other relevant components. For example, energy per bit is a key metric for links in intra- and inter-chip optical communication applications [24]. The example isolator is more than an order of magnitude
more efficient in terms of energy per bit than the next-best on-chip approach without external magnets, both resonant and non-resonant. Being in the 10 fJ/bit regime in energy cost, it adds a negligible footprint to the energy budget of integrated photonic communication links, where modulators and detectors average 10s to 100s of fJ/bit efficiencies, respectively [1]. Other on-chip (no external magnet) isolation approaches add at least comparable amounts of power to the budget as current transceiver circuitry, which may scale further down to fJ/bit levels [21], and in the majority of cases dominate the power budget.

Further work is needed to experimentally validate this concept, as well as to investigate improved designs that achieve higher isolation, wider optical bandwidths above 1 THz, pure CMOS acoustic wave excitation, and shorter device lengths.

The EMP isolator can be extended to a 4-port circulator by adding a second mode multiplexer (resulting in one at either end of the non-reciprocal section). The circulator bandwidth is slightly degraded from picking up the multiplexer crosstalk twice, and would have 20 dB isolation and directivity over a 220 GHz bandwidth with 4.5 dB insertion loss.

**Funding Information**
National Science Foundation Graduate Research Fellowship Grant (1144083); Packard Fellowship for Science and Engineering (2012-38222).

**Acknowledgments**
We thank Kelvin Wagner for discussions.

**References**

[1] C. Sun, M. T. Wade, Y. Lee, J. S. Orcutt, L. Altoatti, M. S. Georgas, A. S. Waterman, J. M. Shainline, R. R. Avizienis, S. Lin, B. R. Moss, R. Kumar, F. Pavanello, A. H. Atabaki, H. M. Cook, A. J. Ou, J. C. Leu, Y.-H. Chen, K. Asanovic, R. J. Ram, M. A. Popovic, and V. M. Stojanovic, “Single-chip microprocessor that communicates directly using light,” *Nature*, vol. 528, no. 7583, pp. 534–538, 2015.

[2] S. Ghosh, S. Keyvavinia, W. Van Roy, T. Mizumoto, G. Roelkens, and R. Baets, “Ce:YIG/silicon-on-insulator waveguide optical isolator realized by adhesive bonding,” *Optics Express*, vol. 20, no. 2, pp. 1839–1848, 2012.

[3] B. J. Stadler and T. Mizumoto, “Integrated magneto-optical materials and isolators: a review,” *IEEE Photonics Journal*, vol. 6, no. 1, pp. 1–15, 2014.

[4] D. Huang, P. Pintus, C. Zhang, Y. Shoji, T. Mizumoto, and J. E. Bowers, “Electrically driven and thermally tunable integrated optical isolators for silicon photonics,” *IEEE J. Sel. Top. Quantum Electron.*, vol. 22, no. 6, p. 4403408, 2016.

[5] D. Huang, P. Pintus, Y. Shoji, P. Morton, T. Mizumoto, and J. E. Bowers, “Integrated broadband Ce:YIG/Si Mach–Zehnder optical isolators with over 100 nm tuning range,” *Optics Letters*, vol. 42, no. 23, pp. 4901–4904, 2017.

[6] Y. Chen, M. Kibune, A. Toda, A. Hayakawa, T. Akiyama, S. Sekiguchi, H. Ebe, N. Imaizumi, T. Akahoshi, S. Akiyama, et al., “A 25Gb/s hybrid integrated silicon photonic transceiver in 28nm CMOS and SOI,” in *IEEE International Solid-State Circuits Conference*, p. 402, 2015.

[7] D. Jalas, A. Petrov, M. Eich, W. Freude, S. Fan, Z. Yu, R. Baets, M. Popovic, A. Melloni, J. D. Joannopoulos, M. Vanwolleghem, C. R. Doerr, and H. Renner, “What is–and what is not–an optical isolator,” *Nature Photonics*, vol. 7, no. 8, p. 579, 2013.

[8] C. G. Poulton, R. Paut, A. Byrnes, S. Fan, M. Steel, and B. J. Eggleton, “Design for broadband on-chip isolator using stimulated Brillouin scattering in dispersion-engineered chalcogenide waveguides,” *Optics Express*, vol. 20, no. 19, pp. 21235–21246, 2012.

[9] E. A. Kittlaus, N. T. Otterstrom, P. Kharel, S. Gertler, and P. T. Rakich, “Nonreciprocal modulation via intermodal Brillouin scattering in a silicon waveguide,” in *CLEO: Science and Innovations*, pp. SM1I–8, Optical Society of America, 2018.

[10] C. Doerr, L. Chen, and D. Vermeulen, “Silicon photonics broadband modulation-based isolator,” *Optics Express*, vol. 22, no. 4, pp. 4493–4498, 2014.

[11] P. Dong, “Travelling-wave Mach-Zehnder modulators functioning as optical isolators,” *Optics Express*, vol. 23, no. 8, pp. 10498–10505, 2015.

[12] Z. Yu and S. Fan, “Complete optical isolation created by indirect interband photonic transitions,” *Nature Photonics*, vol. 3, no. 2, pp. 91–94, 2009.

[13] H. Lira, Z. Yu, S. Fan, and M. Lipson, “Electrically driven nonreciprocity induced by interband photonic transition on a silicon chip,” *Physical Review Letters*, vol. 109, no. 3, p. 033901, 2012.

[14] R. A. Soref and B. Bennett, “Electrooptical effects in silicon,” *IEEE Journal of Quantum Electronics*, vol. 23, no. 1, pp. 123–129, 1987.
[15] D. B. Sohn, S. Kim, and G. Bahl, “Time-reversal symmetry breaking with acoustic pumping of nanophotonic circuits,” Nature Photonics, p. 1, 2018.

[16] F. Eltes, D. Caimi, F. Fallegger, M. Sousa, E. O'Connor, M. D. Rossell, B. Offrein, J. Fompeyrine, and S. Abel, “Low-loss BaTiO3–Si waveguides for nonlinear integrated photonics,” ACS Photonics, vol. 3, no. 9, pp. 1698–1703, 2016.

[17] R. Marathe, B. Bahr, W. Wang, Z. Mahmood, L. Daniel, and D. Weinstein, “Resonant body transistors in IBM’s 32 nm SOI CMOS technology,” Journal of Microelectromechanical Systems, vol. 23, no. 3, pp. 636–650, 2014.

[18] C. Wolff, M. J. Steel, B. J. Eggleton, and C. G. Poulton, “Stimulated Brillouin Scattering in integrated photonic waveguides: forces, scattering mechanisms and coupled mode analysis,” Physical Review A, vol. 92, p. 013836, 2015.

[19] H. A. Haus, Waves and fields in optoelectronics. Prentice-Hall., 1984.

[20] H. Li, S. A. Tadesse, Q. Liu, and M. Li, “Nanophotonic cavity optomechanics with propagating acoustic waves at frequencies up to 12 GHz,” Optica, vol. 2, no. 9, pp. 826–831, 2015.

[21] W. Bogaerts, R. Baets, P. Dumon, V. Wiaux, S. Beckx, D. Taillaert, B. Luyssaert, J. Van Campenhout, P. Bienstman, and D. Van Thourhout, “Nanophotonic waveguides in silicon-on-insulator fabricated with CMOS technology,” Journal of Lightwave Technology, vol. 23, no. 1, pp. 401–412, 2005.

[22] C. Sun, Y. Yu, M. Ye, G. Chen, and X. Zhang, “An ultra-low crosstalk and broadband two-mode (de) multiplexer based on adiabatic couplers,” Scientific Reports, vol. 6, 2016.

[23] Y. Yang, C. Galland, Y. Liu, K. Tan, R. Ding, Q. Li, K. Bergman, T. Baehr-Jones, and M. Hochberg, “Experimental demonstration of broadband lorentz non-reciprocity in an integrable photonic architecture based on mach-zehnder modulators,” Optics Express, vol. 22, no. 14, pp. 17409–17422, 2014.

[24] D. A. Miller, “Attojoule optoelectronics for low-energy information processing and communications,” Journal of Lightwave Technology, vol. 35, no. 3, pp. 346–396, 2017.