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**Nonreciprocal Photonics for Suppression of Disorder Induced Scattering**

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Nonreciprocal Photonics for Suppression of Disorder Induced Scattering

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## Executive summary

Isolators and circulators are frequently used in photonic systems to introduce directionality and to block the back-propagation of light. However, these non-reciprocal devices are only a “fix” for backscattering and do not perform any “preventative” function. Such fixes do nothing to address the problem of scattering from defects, which results in signal decoherence, loss of power, localized resonances, and spurious scattering. In this project we sought to demonstrate waveguides and chip-scale photonic components in which such back-scattering never occurs even in the presence of disorder or defects. Our proposed approach to counteract such backscattering was to break time-reversal symmetry in the medium so that modes for opposite, i.e. time-reversed, propagation are simply not symmetric in energy-momentum space. With support from this grant we were able to demonstrate record setting on-chip optical isolators and new approaches to produce non-reciprocity. Most importantly, we were able to experimentally demonstrate the suppression of Rayleigh backscattering in resonators with broken T-symmetry, in both on-chip and off-chip scenarios, using a variety of pumping approaches.

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## Accomplishments

### **1. Optical isolators in thin film lithium niobate integrated photonics**

One of our biggest accomplishments in this project was the demonstration of lithographically defined chip-scale optical isolators that are electrically/acoustically pumped, do not use any magneto-optic materials, and are wavelength agnostic.

In recent years, a lot of progress has been made towards producing chip-scale photonic integrated circuits for sensing and communications. Optical isolators are a crucial piece of this puzzle as they can protect laser sources and can additionally ensure robust operation of these photonic systems. Isolators are conventionally produced using materials that exhibit a strong magneto-optic effect. Unfortunately, current magneto-optic isolator architectures cannot be scaled and translated into common integrated platforms due to multiple technical constraints. A generalized non-reciprocal photonic component technology that avoids these constraints, and that can be produced in nearly any material platform, will be a transformative development.

With support from this project we were able to develop a new isolator technology that uses non-reciprocal inter-band scattering of light from phonons (acoustic waves). The isolator device we demonstrated can be nearly lossless for light propagating in one direction and strongly absorbing in the opposite direction, i.e. it can exhibit complete linear optical isolation. Moreover, the demonstrated devices do not require any magneto-optic materials and could enable production of optical isolators over a variety of optical wavelengths. We were successful in developing this new optical isolator using a lithium niobate PIC platform that can be easily ported to foundries. Instead of magneto-optic materials, this isolator uses an electrical stimulus to piezoelectrically launch acoustic waves through the PIC and produce a non-reciprocal effect. As the main result from this effort, we demonstrated optical isolators with  $< 1$  dB forward loss and  $> 39$  dB directional contrast. The isolators were shown to operate at both 780 nm and 1550 nm using the same starting substrate, which demonstrates the flexibility of this platform.

Citation: D. Sohn, O.E. Orsel, G. Bahl, "Electrically driven optical isolation through phonon-mediated photonic Autler-Townes splitting," Nature Photonics 15, 822-827, 2021.

Link: <https://www.nature.com/articles/s41566-021-00884-x>

The Optica Publishing Group also featured our achievement in a summary article recognizing it as one of the top developments in optics of 2022.

Citation: D. Sohn, O.E. Orsel, G. Bahl, "Lithium niobate isolators that outperform magneto-optics," Optics and Photonics News, 33(12), p.33, Dec 2022

Link: [https://www.optica-opn.org/home/articles/volume\\_33/december\\_2022/extras/lithium\\_niobate\\_isolators\\_outperform\\_magneto-optic/](https://www.optica-opn.org/home/articles/volume_33/december_2022/extras/lithium_niobate_isolators_outperform_magneto-optic/)

## **2. Electrically driven non-reciprocal polarization rotation in integrated photonics**

Polarization is an important degree of freedom for light and is widely leveraged in free space and fiber optics. Notably, non-reciprocal polarization rotation, enabled via the magneto-optic Faraday effect (MOFE), has been an unbeatable feature that is used for broadband isolators and circulators. For integrated photonics foundries, however, there is still no good path to producing low-loss magneto-optic components, which has prompted a search for alternatives that do not use polarization rotation. Moreover, magneto-optic materials tend to be highly lossy, and while large (10–100 rad/cm) polarization rotation can be achieved, the key figure of merit (rotation-per-loss) is typically  $<1$  rad/dB.

We were able to demonstrate that broadband non-reciprocal polarization rotation can be produced using electro-optics in nanophotonic devices. Our demonstration leverages electro-optic inter-polarization scattering around 780 nm in lithium niobate, in which the reciprocity is broken with the help of a radiofrequency stimulus that carries synthetic momentum. While the demonstrated electro-optic polarization rotation rate is  $\approx 1$  rad/cm, the exceptionally low loss of lithium niobate enables non-reciprocal polarization rotators with figures of merit that are 1-2 orders of magnitude better than what is possible with magneto-optics. This approach can be replicated on III–V platforms, paving the way for high-performance lasers with co-integrated monolithic non-reciprocal devices.

Citation: O.E. Orsel, G. Bahl, " Electro-optic non-reciprocal polarization rotation in lithium niobate," APL Photonics 8, 096107, 2023.

Link: <https://doi.org/10.1063/5.0146238>

## **3. Suppression of disorder-induced light scattering in on-chip and off-chip photonics**

Undesirable light scattering is a fundamental cause for photon loss in nanophotonics. Rayleigh backscattering can be particularly difficult to avoid in wave-guiding systems and arises from both material defects and geometric defects at the subwavelength scale, and can even be dynamically induced.

The most common manifestation of such subwavelength disorder is Rayleigh light scattering, which is observed in nearly all waveguiding technologies today and can lead to both irreversible radiative losses as well as undesirable intermodal coupling. While it has been shown that backscattering from disorder can be suppressed by breaking the time-reversal symmetry in magneto-optic and topological insulator materials, common optical dielectrics possess neither of these properties.

Around the beginning of this project, we showed that systems exhibiting chiral dispersion due to broken time-reversal symmetry (TRS) can naturally mitigate Rayleigh backscattering, yet this has never been explored in integrated photonics. In silica microspheres we achieved this by locally breaking the time-reversal symmetry through a Brillouin phonon-photon scattering interaction. Near-complete suppression of Rayleigh backscattering was experimentally confirmed through two independent measurements — the elimination of a commonly seen normal-mode splitting or “doublet” effect and by measurement of the reduction in intrinsic optical loss. Additionally, a reduction of the back-reflections caused by disorder was also observed.

Citation: S. Kim, J.M. Taylor, G. Bahl, "Dynamic suppression of Rayleigh light scattering in dielectric resonators," *Optica* 6(8), pp. 1016-1022, 2019.

Link: <https://www.osapublishing.org/optica/abstract.cfm?uri=optica-6-8-1016>

Most recently, we were able to leverage our experimental results from optical isolators to demonstrate the dynamic suppression of disorder-induced Rayleigh backscattering in lithium niobate integrated photonic devices. Our experimental devices broke time-reversal symmetry through an electrically driven acousto-optic interaction. We experimentally observed near-complete suppression of Rayleigh backscattering within the resonator by measuring the optical states and through direct measurements of the back-scattered light. We additionally provided a new and intuitive generalization argument that explains this suppression of backscattering as a form of topological protection in synthetic space.

Citation: O.E. Orsel, G. Bahl, " Electrically-controlled suppression of Rayleigh backscattering in an integrated photonic circuit," *Nanophotonics* 13(2), pp.173-181, 2024.

Link: <https://www.degruyter.com/document/doi/10.1515/nanoph-2023-0431/html>

#### **4. Non-reciprocity through a synthetic Hall effect for electromagnetic excitations**

Thanks to this project we were also able to study nonreciprocity in spatiotemporally modulated 1D resonator chains from the perspective of equivalent 2D resonator arrays with a synthetic dimension and transverse synthetic electric and magnetic fields. These synthetic fields are related to temporal and spatial modulation of the resonator chain, respectively, and we learned that their combination can break transmission reciprocity without additional elements being needed. Around the beginning of this project, we had recently demonstrated this effect in a microwave circuit platform and measured over 58 dB of isolation contrast (see Peterson et al, *Physical Review Letters*, 123, 063901, 2019). Since the approach is agnostic to the technology platform in use. We leveraged this idea to explore optical nonreciprocity in photonic ring resonator chains. We fabricated an on-chip acousto-optic system that employs mechanical modulation of photonic resonators to produce a non-reciprocal transmission effect. While we were only able to

demonstrate 3 dB of contrast, we have been actively working on an improved version of this experiment using lithium niobate integrated photonics.

Citation: S. Kim, D.B. Sohn, C.W. Peterson, G. Bahl, "On-chip optical non-reciprocity through a synthetic Hall effect for photons," APL Photonics 6, 011301, 2021.  
Link: <https://aip.scitation.org/doi/10.1063/5.0034291>

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### **Workforce development**

This grant benefitted workforce development by providing training opportunities for several graduate students in our group, including – Ogulcan Emre Orsel (now at Analog Photonics), Donggyu Benjamin Sohn (now at PsiQuantum), Josephine Melia (now at Advanced Materials).

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### **Research products**

#### **Journal publications**

1. O.E. Orsel, G. Bahl, "Electrically-controlled suppression of Rayleigh backscattering in an integrated photonic circuit," Nanophotonics 13(2), pp.173-181, 2024.
2. O.E. Orsel, G. Bahl, " Electro-optic non-reciprocal polarization rotation in lithium niobate," APL Photonics 8, 096107, 2023.
3. D. Sohn, O.E. Orsel, G. Bahl, "Lithium niobate isolators that outperform magneto-optics," Optics and Photonics News, 33(12), p.33, Dec 2022
4. D. Sohn, O.E. Orsel, G. Bahl, "Electrically driven optical isolation through phonon-mediated photonic Autler-Townes splitting," Nature Photonics 15, 822-827, 2021.
5. S. Kim, D.B. Sohn, C.W. Peterson, G. Bahl, "On-chip optical non-reciprocity through a synthetic Hall effect for photons," APL Photonics 6, 011301, 2021.
6. S. Kim, J.M. Taylor, G. Bahl, "Dynamic suppression of Rayleigh light scattering in dielectric resonators," Optica 6(8), pp. 1016-1022, 2019.

#### **Conference presentations**

1. Orsel, J. Noh, G. Bahl, "Giant on-chip non-reciprocity and gyration through synthetic fields in modulated LiNbO3 ring resonators," at Frontiers in Optics, FW5E.3, Oct 2023.
2. Orsel, J. Noh, G. Bahl, "Suppression of Intrinsic Backscattering in Integrated Optical Resonators via Acoustic Pumping," at Conference on Lasers and Electro Optics (CLEO), SF2K.6, May 2023.

3. Orsel, G. Bahl, "Piezoelectric enhancement of SBS in LiNbO<sub>3</sub> thin films," at Workshop on Optomechanics and Brillouin Scattering (WOMBAT), 2022
4. Orsel, G. Bahl, "Electrically-driven nonreciprocal polarization rotation at 780 nm in thin-film lithium niobate," at Conference on Lasers and Electro-Optics (CLEO), SW50.7, 2022.
5. Orsel, D.B. Sohn, G. Bahl, "On-chip lithium niobate isolators at 780 nm with nm-scale tuning bandwidth," at Conference on Lasers and Electro-Optics (CLEO), SW50.6, 2022.
6. D.B. Sohn\*, O. Orsel\*, G. Bahl [\* equal contribution], "Low loss wavelength-agnostic optical isolators through acoustic pumping in a lithium niobate platform," at Frontiers in Optics, FW1D.4, 2021.
7. D.B. Sohn\*, O. Orsel\*, G. Bahl [\* equal contribution], "Ultralow-loss wavelength-agnostic linear optical isolators through acoustic pumping in a lithium niobate platform," at Workshop on Optomechanics and Brillouin Scattering (WOMBAT), 2022.
8. D.B. Sohn, O. Orsel, G. Bahl, "Electrically-driven linear optical isolation in a lithium niobate nanophotonic platform," at Conference on Lasers and Electro-Optics (CLEO), JTu3A.84, 2021.
9. D.B. Sohn, J. Melia, S. Kim, O. Orsel, G. Bahl, "On-chip electrically driven 780 nm frequency-shifting optical isolation," at Conference on Lasers and Electro-Optics (CLEO), STh4B.5, 2021
10. S. Kim, D.B. Sohn, C.W. Peterson, G. Bahl, "A synthetic Hall effect for photons," at Conference on Lasers and Electro-Optics (CLEO), STu3J.3, San Jose, CA, May 2020.
11. D.B. Sohn, S. Kim, G. Bahl, "Unreleased on-chip frequency-shifting optical isolator," at Conference on Lasers and Electro-Optics (CLEO), STh4J.5, San Jose, CA, May 2020.