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Chip-Scale Linear Non-Reciprocal Optomechanical Systems

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Final Report

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Time-reversal symmetry is a fundamental property of linear time-invariant media, and causes optical, electromagnetic, and acoustic systems to produce symmetric outputs between any input/output ports. However, it is necessary to break time-reversal symmetry to produce nonreciprocal behavior and to enable important devices like isolators and circulators. In the optical context, non-reciprocal behavior has been almost exclusively accomplished using magneto-optical effects. Unfortunately, this traditional approach has not been possible to implement on chip (e.g. in photonics foundries) due to the need for specialized materials and the high optical losses occurring with existing material options. Through this AFOSR Young Investigator Award we were able to study a new Brillouin scattering induced optical interference mechanism that can be efficiently used to achieve linear non-reciprocal behavior.

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Final Report

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Abstract

Time-reversal symmetry is a fundamental property of linear time-invariant media, and causes optical, electromagnetic, and acoustic systems to produce symmetric outputs between any input/output ports. However, it is necessary to break time-reversal symmetry to produce nonreciprocal behavior and to enable important devices like isolators and circulators. In the optical context, non-reciprocal behavior has been almost exclusively accomplished using magneto-optical effects. Unfortunately, this traditional approach has not been possible to implement on chip (e.g. in photonics foundries) due to the need for specialized materials and the high optical losses occurring with existing material options. Through this AFOSR Young Investigator Award we were able to study a new Brillouin scattering induced optical interference mechanism that can be efficiently used to achieve linear non-reciprocal behavior. The technique can, in principle, be used with nearly any dielectric material at any wavelength of choice and therefore is a potentially transformative technique for the goal of producing integrated nonreciprocal devices. Our effort focused on developing high-bandwidth nonreciprocal devices through a new electro-mechanically driven approach. We achieved this goal through systematic experimental studies in fiber-optics as well as integrated photonic devices.

Research products

Archival publications

1. S. Kim, J.M. Taylor, G. Bahl, "Dynamic suppression of Rayleigh light scattering in dielectric resonators," (in review) preprint available at arXiv:1803.02366
https://arxiv.org/abs/1803.02366

2. D.B. Sohn, S. Kim, G. Bahl, "Time-reversal symmetry breaking with acoustic pumping of nanophotonic circuits," **Nature Photonics**, 12, pp.91-97, doi:10.1038/s41566-017-0075-2, 2018.
https://www.nature.com/articles/s41566-017-0075-2

3. D.B. Sohn, S. Kim, G. Bahl, "Breaking optical symmetry with sound," **Optics and Photonics News**, vol.29, p.43, Dec 2018.
(Research summary for Optics in 2018 special issue)
https://www.osa-opn.org/home/articles/volume_29/december_2018/extras/breaking_optical_symmetry_with_sound/

4. S. Kim, X. Xu, J.M. Taylor, G. Bahl, "Dynamically induced robust phonon transport and chiral cooling in an optomechanical system," **Nature Communications** 8, 205, doi:10.1038/s41467-017-00247-7, 2017.
https://www.nature.com/articles/s41467-017-00247-7

5. J. Suh, K. Han, C.W. Peterson, G. Bahl, "Real-time sensing of flowing nanoparticles with electro-opto-mechanics," **APL Photonics** 2, 010801, doi:10.1063/1.4972299, 2017.
http://aip.scitation.org/doi/full/10.1063/1.4972299

6. J. Kim*, S. Kim*, G. Bahl [* = equal contribution], "Complete linear optical isolation at the microscale with ultralow loss," **Scientific Reports**, 7:1647, 2017.
http://www.nature.com/articles/s41598-017-01494-w

Patents filed

1. "System and method for linear non-reciprocal communication and isolation" Provisional patent # 62/104,391. Filed patent # 14/995,768 (USPTO).

2. "System and method for breaking time-reversal symmetry with acoustic pumping of nanophotonic circuits". Filed patent # 16/259,775 (USPTO)

Conference presentations

1. D.B. Sohn, S. Kim, G. Bahl, "GHz-Bandwidth Optical Isolation Through Acoustic Pumping of a Nanophotonic Circuit," at IEEE Photonics Conference, Reston, VA, Oct 2018.

2. S. Kim, J. M. Taylor, G. Bahl, "Suppression of Rayleigh Backscattering in Resonators," at IEEE Photonics Conference, Reston, VA, Oct 2018.

3. S. Kim., X. Xu, J.M. Taylor, and G. Bahl, “Optomechanical cooling without added damping,” Frontiers in Optics 2017, Washington DC, Sept 2017.

4. D. Sohn, S. Kim, and G. Bahl, "Piezo-optomechanical nonreciprocal modulator," at Workshop on Optomechanics and Brillouin Scattering: Fundamentals, Applications and Technology (WOMBAT), Besancon, France, July 2017.

5. D. Sohn, J. Kim, S. Kim, and G. Bahl, "Non-reciprocal Optomechanical Modulator," at Conference on Lasers and Electro-Optics (CLEO), San Jose, CA, May 2017.

6. J. Suh, K. Han, C.W. Peterson, G. Bahl, "High-throughput real-time sensing with microfluidic electro-opto-mechanical resonators," at SPIE Photonics West, San Francisco, Feb 2017.

7. S. Kim, X. Xu, J.M.Taylor, G. Bahl, "Dynamically induced chiral phonon transport in an optomechanical system," at Nanometa 2017, Seefeld, Austria, Jan 2017.

8. J. Kim, S. Kim, G. Bahl, "Ultralow loss optical isolation in silica microresonators," at Nanometa 2017, Seefeld, Austria, Jan 2017.

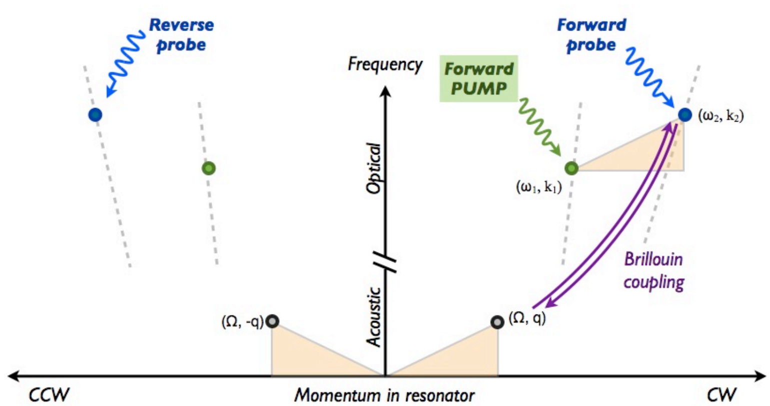
9. D. Sohn, J. Kim, G. Bahl, “Ultrahigh-Q Silica-AlN Hybrid Disk Optomechanical Modulator,” IEEE MEMS 2017, Las Vegas, Jan 2017.

Summary of research results

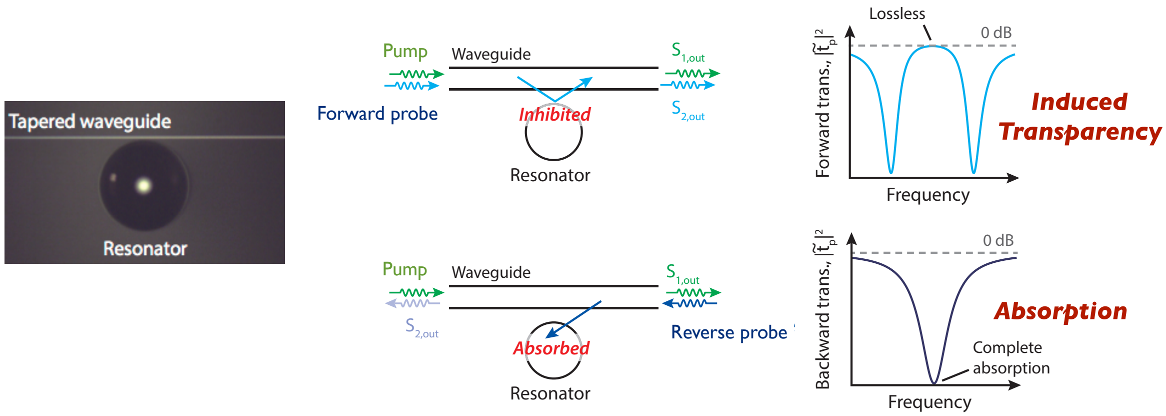
Introduction

Reciprocity is a fundamental property of wave propagation in electromagnetic and optical media, that arises from time-reversal symmetry of Maxwell's equations. Stimuli that can break time-reversal symmetry, such as magnetic fields and spatiotemporal modulation, can be employed for producing non-reciprocal devices. Common examples of such devices are isolators and circulators which are widely employed for signal protection and routing in photonic and microwave systems.

In this project we proposed a new non-reciprocal mechanism based on an EIT-like resonant interference between two optical modes of a resonator, mediated through Brillouin scattering. This Brillouin Scattering Induced Transparency (BSIT) is intrinsically non-reciprocal due to the stringent momentum conservation requirements as shown in the figure below. In preliminary work we demonstrated this optically pumped non-reciprocity for signal transmission amplitude and phase. We then predicted that the effect can also be acoustically (i.e. electromechanically) controlled, and results in a wider-bandwidth linear non-reciprocity that can be implemented with many common optical dielectrics. Isolators and circulators could then be engineered with nearly any optoelectronic material in foundries, at any wavelength of choice. Our main research goal was therefore to experimentally validate our hypothesis that acoustic pumping of the triply resonant interaction can generate practical linear non-reciprocity. We focused on achieving this goal through experimental and analytical studies targeting a better understanding of triply-resonant acousto-optic scattering and on how an acoustic drive can influence this isolation effect. The figures below summarize the phase-matching diagram for the BSIT process as well as the expected behavior, i.e. unidirectional transparency for light propagation. In the sections that follow, we discuss our achievements using this process.



Example phase matching diagram for Brillouin Scattering Induced Transparency (BSIT) in a micro-resonator. A cw pump laser couples a higher (anti-Stokes) optical mode (ω_2, k_2) with a MHz-GHz frequency acoustic mode (Ω, q) of the same resonator via Brillouin scattering. The directionality of the process is dictated by the pump, which sets this coupling unidirectionally.



An interference visible as a Brillouin Scattering Induced Transparency (BSIT) is produced for cw (or forward) optical probing in a waveguide-resonator system. High transparency can be simultaneously accompanied by strong absorption in the opposite direction if critical coupling is arranged between the waveguide and the resonator.

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1. Nonreciprocal photonics and complete optical isolation with Brillouin scattering

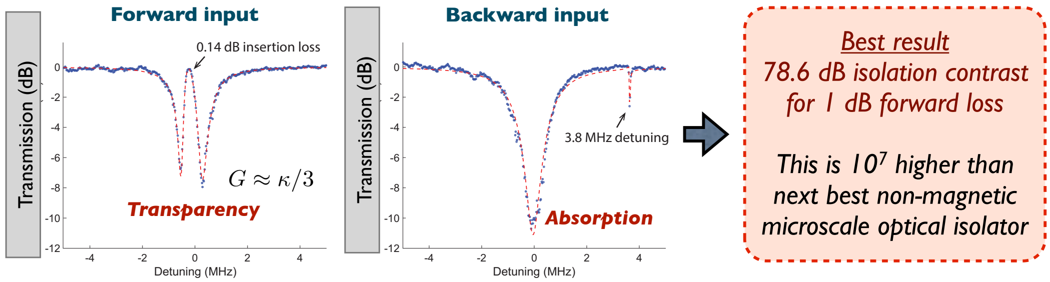
This component of our research effort was jointly supported by the AFOSR grant FA9550-14-1-0217.

The BSIT mechanism produces a strong nonreciprocal effect and is extremely useful for compact optical isolation without the use of special materials. With this concept, we showed for the first time that complete linear optical isolation can be obtained within a dielectric waveguide, using only a whispering-gallery microresonator pumped by a single-frequency laser. Complete optical isolation implies ultra-low forward insertion loss with extremely large backward suppression i.e. high contrast. We experimentally demonstrated that BSIT in a silica resonator device is capable of generating an enormous 78.6 dB of isolation contrast per 1 dB of forward insertion loss, which is comparable to commercial optical isolators. The data shown in the figure below reveals that this comes with a significant sacrifice of bandwidth (only a few 100 kHz). We also demonstrated optical control and dynamic reconfigurability for the process. A microscale optical isolator with this level of performance, based on new physics, with this degree of simplicity, has never been reported and thus represents a high-impact advance beyond the state of the art. Our discovery showed that material-agnostic and wavelength-agnostic perfect optical isolation is far more accessible for chip-scale photonics than previously thought.

Publication –

J. Kim, S. Kim, G. Bahl, "Complete linear optical isolation at the microscale with ultralow loss," **Scientific Reports**, 7:1647, 2017.

Complete optical isolation (figure of merit record) with BSIT



We experimentally observed BSIT resulting from optical interference with a propagating mechanical mode of the resonator. The process is experimentally confirmed to be nonreciprocal due to intrinsic phase-matching rules. This system holds the figure of merit record in microscale optical isolation, compared against any non-magnetic approach to date.

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2. Suppression of disorder induced phonon scattering, and sideband cooling without damping

This component of our research effort was jointly supported by the AFOSR grant FA9550-14-1-0217.

We investigated how induced optical chirality within a resonator can modify phonon propagation. Chirality implies the breaking of parity symmetry in a medium (often the same as time-reversal symmetry) and leads to specialized physical phenomena, including the quantum Hall effect and non-reciprocal wave propagation. In our work, we experimentally produced optically-induced chirality for phonons using unidirectional sideband Brillouin cooling in a silica whispering gallery resonator. While one set of phonons of the resonator were cooled, the degenerate phonons in the opposite direction were not, implying a chirality in the medium. This chiral effect was observed to produce robust phonon propagation even in the presence of material disorder. Specifically, we observed that the phonon backscattering was reduced significantly when the chiral effect was activated, resulting in a striking improvement of phonon coherence properties.

Sideband cooling has been to date the only mechanism available for suppressing the thermal motion of mechanical resonators using light — but is necessarily accompanied by linewidth broadening (damping). In this work, we also confirmed a fundamentally different mechanism for cooling mechanical oscillators, that occurs through sideband cooling of the bath modes. No previous experiment in optomechanics has provided either direct or indirect evidence of such bath cooling. This effect was observed as a reduction in the heat load of the mechanics as the chirality of the resonator increased. In the context of sensing, this approach enables the simultaneous reduction of thermal load (temperature) while increasing the mechanical quality factor of a resonant mode – an effect we directly observe which has not been seen before. This fundamentally alters the noise calculus for sensor design, with far-reaching consequences.

Publication –

S. Kim, X. Xu, J.M. Taylor, G. Bahl, "Dynamically induced robust phonon transport and chiral cooling in an optomechanical system," **Nature Communications** 8, 205, doi:10.1038/s41467-017-00247-7, 2017.

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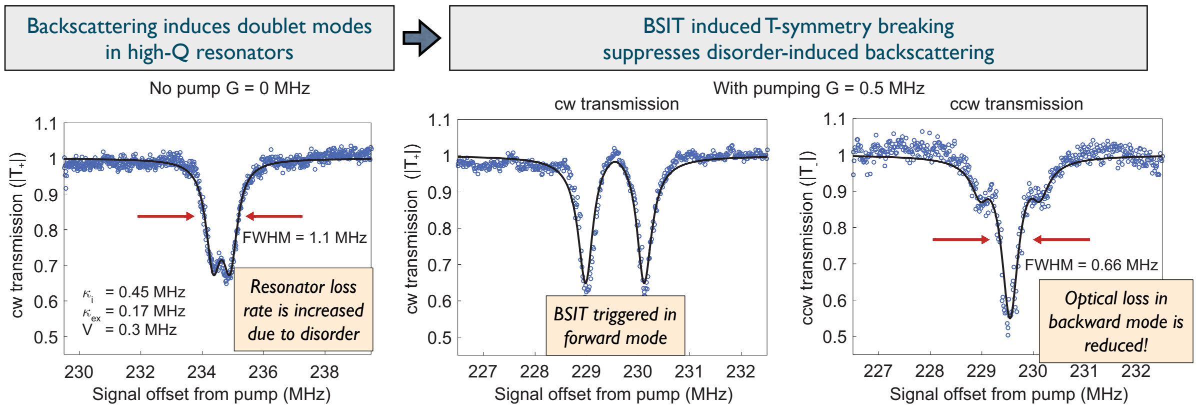
3. Dynamic suppression of Rayleigh light scattering in dielectric resonators

The limits of performance for any optical system are set by sub-wavelength material defects. These material fluctuations can be frozen-in e.g. during material synthesis, or dynamically induced e.g. through thermal energy. The most common result of such disorder is Rayleigh light scattering, which is observed in almost all photonics technologies and can lead to irreversible radiative losses as well as undesirable intermodal coupling. In the past it has been shown that backscattering from such defects can be suppressed by breaking time-reversal symmetry in magneto-optic and topological insulator materials. However, common optical dielectrics possess neither of these properties.

Through this grant, we were able to explore how the BSIT non-reciprocity technique could be used to dynamically suppress Rayleigh backscattering within dielectric resonators. We achieved this by breaking time-reversal symmetry in a silica resonator through the Brillouin scattering non-reciprocal interaction. This allowed us to demonstrate near-complete suppression of Rayleigh backscattering. The result was confirmed using two independent experimental measurements – the elimination of a commonly seen normal-mode splitting or 'doublet' effect (see figure below), and by measurement of the reduction in intrinsic optical loss. In addition, a reduction of the back-reflections caused by disorder was also observed. Our results provide new evidence that it is possible to dynamically suppress Rayleigh backscattering within any optical dielectric. The approach allows us to achieving robust light propagation even in the presence of scatterers or defects. The principle we demonstrated here can readily be translated to other techniques that break T-symmetry, for example, nonlinear optics, chiral atoms, parity-time symmetry breaking, and spatiotemporal modulation. Applications of this principle certainly extend to fiber networks and integrated waveguides, where broadband nonreciprocal phenomena have already been demonstrated but suppression of disorder-induced backscattering is yet to be shown.

Publication –

S. Kim, J.M. Taylor, G. Bahl, "Dynamic suppression of Rayleigh light scattering in dielectric resonators," (in review) preprint available at arXiv:1803.02366



Experimental suppression of Rayleigh backscattering in a silica microresonator through BSIT induced T-symmetry breaking. When there is no Brillouin coupling applied, the optical modes in cw and ccw directions each exhibit a doublet shape due to the Rayleigh backscattering-induced hybridization of the cw and ccw modes. However, when BSIT is induced for the cw mode, the ccw mode exhibits a significantly reduced linewidth and the doublet disappears. This data shows that the effects of Rayleigh scattering have been almost completely mitigated for the ccw / backward propagating optical mode.

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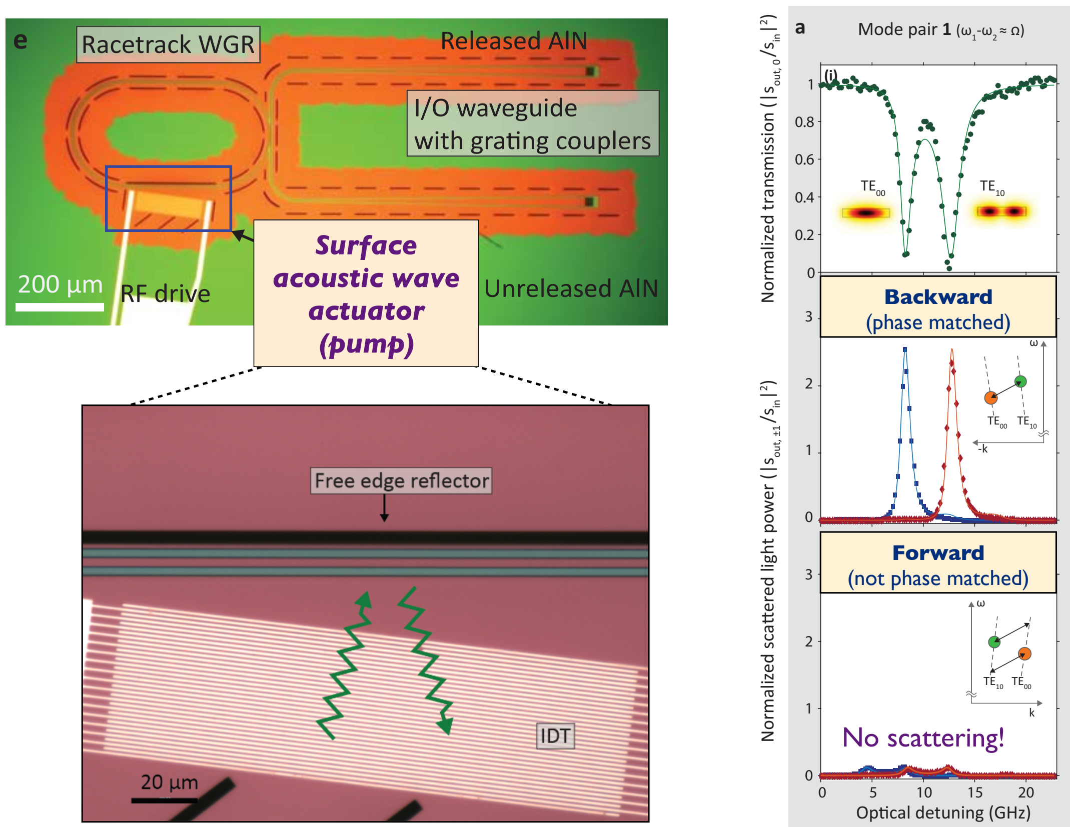
4. Time-reversal symmetry breaking with acousto-optics

A limiting characteristic of non-reciprocal optomechanical and Brillouin systems has been the relatively small kHz-MHz bandwidth over which the non-reciprocity is produced. This fundamental constraint arises since the interaction is primarily determined by the mechanical linewidth, and was observed in our earlier work on BSIT-based nonreciprocity and complete isolation. Here, we demonstrated a new approach that inverts the roles of light and vibration in optomechanics, employing acoustic pumping with propagating phonons instead of optical pumping. The practical implications of this strategy are transformative; we no longer need additional lasers to drive the non-reciprocity, and more importantly, the bandwidth of the effect is now defined by the optics (potentially THz with improvements). With this approach, for the first time, we have broken the GHz-bandwidth barrier in an acoustically pumped non-reciprocal nanophotonic device.

To demonstrate this concept, we fabricated a nanophotonic racetrack resonator in an aluminum nitride-on-air platform, with a piezoelectric actuator (interdigitated transducer) co-integrated over a segment of the racetrack to produce the acoustic pump. All nanofabricated components were written using e-beam lithography in the UIUC cleanrooms. The propagating RF-driven acoustic wave was designed at 4.8 GHz with a 2-dimensional characteristic that simultaneously satisfies the unidirectional phase-matching requirement and breaks the orthogonality between the two optical modes of the resonator. An image of our device and representative data are shown in the figure below. In our best result, we demonstrated optical isolation with non-reciprocal mode conversion asymmetry up to 15 dB and efficiency as high as 17% and exhibiting, for the first time, bandwidth exceeding 1 GHz. This result was highlighted as a top development in optics by the Optical Society in December 2018, and was featured on the cover of Nature Photonics in February 2018.



Microscope images of our nanofabricated aluminum nitride-on-air integrated nonreciprocal resonator. The surface acoustic wave breaks reciprocity within the racetrack. Data on the right presents acoustically pumped nonreciprocal mode conversion on-chip. We reached 15 dB optical contrast over 1.1 GHz bandwidth, with only 7 dB insertion loss. This result represents the first optomechanical non-reciprocal system that has broken the GHz-barrier.

Publications –

D.B. Sohn, S. Kim, G. Bahl, "Time-reversal symmetry breaking with acoustic pumping of nanophotonic circuits," **Nature Photonics**, 12, pp.91-97, doi:10.1038/s41566-017-0075-2, 2018.

D.B. Sohn, S. Kim, G. Bahl, "Breaking optical symmetry with sound," **Optics and Photonics News**, vol.29, p.43, Dec 2018.
(Research summary for Optics in 2018 special issue)

Conclusions and Impact

The research conducted under this grant broadly advanced knowledge on nonreciprocal systems and nonlinear optics. Our specific approach leveraged Brillouin scattering, which is the strongest known material-level optical nonlinearity, to produce nonreciprocal behavior in silica. This behavior was shown to be highly controllable and capable of producing high-contrast isolators and circulators. More importantly, since Brillouin scattering is almost universally available, the approach can readily be implemented in common dielectrics and without specialized fabrication techniques, and is also extensible to photonics foundries. We were able to demonstrate the first optomechanical device that breaks the GHz bandwidth barrier for nonreciprocal operation, and is extremely useful for optical isolators.

Through this work we have also uncovered a new use of time-reversal symmetry breaking in dielectrics. For the first time, we showed that not only can phonon chirality be induced optically, but also that it mitigates the influence of disorder on propagating phonons, a technique that potentially revolutionizes phonon-assisted measurements. We were also able to demonstrate the same technique for Rayleigh light scattering that occurs due to material-scale subwavelength disorder. To date such scattering immunity for phonons and photons has only been demonstrated in topological insulators. Our results thus dramatically push forward the known physics for both laser cooling and for chiral systems. The increased robustness to disorder can be transformative for optical communications and sensing systems.

This work enabled the training of four graduate student researchers (JunHwan Kim, Benjamin Sohn, Seunghwi Kim, Soonwook Kim). The original scientific results from this effort were presented by the PI and graduate researchers through 6 journal papers and 9 conference presentations. This effort also generated 2 patent applications.