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Brillouin Scattering Induced Transparency for Microscale Rotation Sensing

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Abstract

The main objective for this project was to explore the physics of Brillouin opto-acoustic scattering in microresonators – with the goals of manipulating optical responses and for developing novel physical sensors. Specifically, we aimed to study the measurement of rotation using optical response of Brillouin optomechanical systems through Brillouin Scattering Induced Transparency (BSIT) measurements. The AFOSR support that we received through this grant, enabled significant progress on both experimental and theoretical aspects of the above goals. We demonstrated that Brillouin optomechanical coupling within microresonators can be enhanced by orders-of-magnitude by surface interactions between light and sound. We also demonstrated the first optomechanical system that achieves complete optical isolation. We advanced the understanding of Brillouin cooling, in both linear and resonant systems. We demonstrated the dynamic suppression of disorder-induced phonon scattering by breaking time-reversal symmetry using Brillouin scattering. The stage is now set for tremendous advances in Brillouin-scattering based microsensors.

Research products

Archival journal publications

1. 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

2. S. Kim, G. Bahl, "Role of Optical Density of States in Two-Mode Optomechanical Cooling," **Optics Express** 25(2), pp.776-784, 2017.
   https://www.osapublishing.org/oe/abstract.cfm?uri=oe-25-2-776

3. 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

4. Y-C. Chen, S. Kim, G. Bahl, "Brillouin Cooling in a Linear Waveguide," **New Journal of Physics**, 18, 115004, doi:10.1088/1367-2630/18/11/115004, 2016.
   http://iopscience.iop.org/article/10.1088/1367-2630/18/11/115004

5. N. Dostart, S. Kim, G. Bahl, "Giant Gain Enhancement in Surface-Confined Resonant Stimulated Brillouin Scattering," **Laser and Photonics Reviews**, doi:10.1002/lpor.201500141, Oct 2015.
   http://onlinelibrary.wiley.com/doi/10.1002/lpor.201500141/abstract

6. J. Kim, M. Kuzyk, K. Han, H. Wang, G. Bahl, "Non-reciprocal Brillouin scattering induced transparency," **Nature Physics** 11, pp.275-280, doi:10.1038/nphys3236, 2015.
   http://www.nature.com/nphys/journal/vaop/ncurrent/full/nphys3236.html

Patents filed / granted

1. "System and method for Brillouin Scattering Induced Transparency"
   Patent granted 9,592,267 (USPTO).

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

Conference presentations

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

2. 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.

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

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

5. Y.-C. Chen, G. Bahl, "Raman cooling in silicon photonic crystals," at SPIE Photonics West (Optical and Electronic Cooling of Solids), San Francisco CA, Feb 2016.

6. J. Kim, M. Kuzyk, K. Han, H. Wang, G. Bahl, “Magnet-Free Linear Nonreciprocity in Brillouin Systems,” at 8th International Conference on Materials for Advanced Technologies (ICMAT), Materials Research Society of Singapore (MRS-S), Symposium F: Emerging Infrared Technologies and Applications, June 2015.

7. J. Kim, M. Kuzyk, K. Han, H. Wang, G. Bahl, "Observation of optical non-reciprocity in a Brillouin optomechanical system," at SPIE Photonics West (Laser Resonators, Microresonators, and Beam Control XVII), San Francisco CA, Feb 2015.

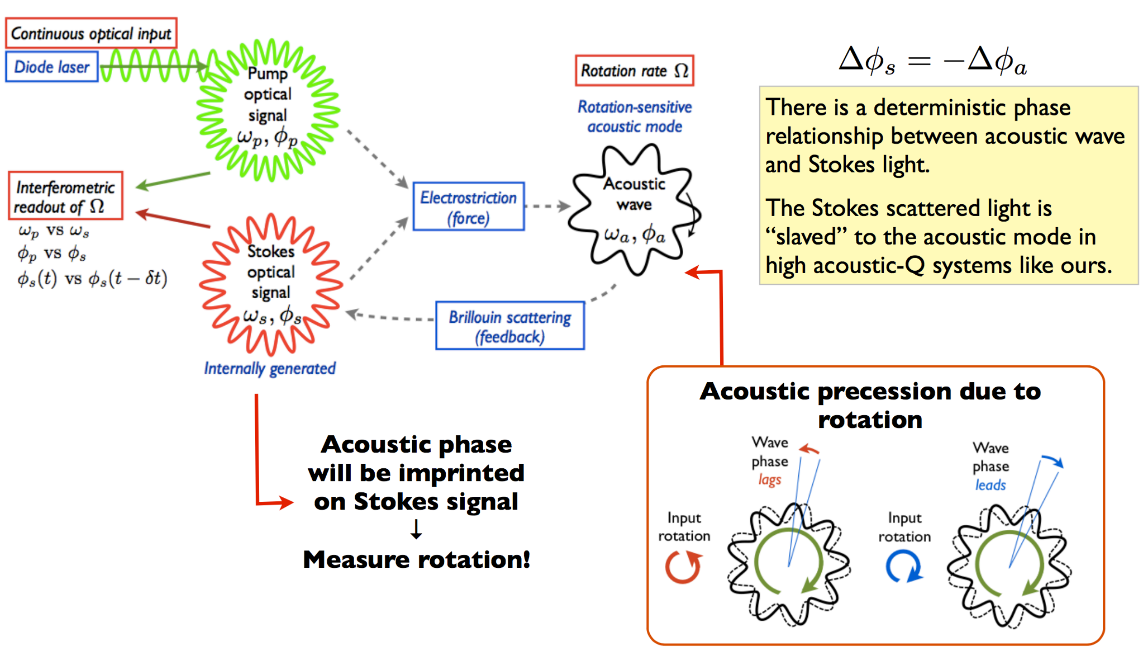
<u>**Summary of research results**</u>

Introduction

This project focused on the mechanism of stimulated Brillouin scattering (SBS) in microsphere whispering gallery resonators (WGRs). In the Brillouin interaction (Figure below), the optical and acoustic fields of the resonator are mutually coupled through photoelastic scattering and optical electrostriction. With an appropriate selection of optical and acoustic states that participate in this interaction, we have shown that both phonon creation and phonon annihilation can be selectively achieved. Specifically, the principle of rotation sensing involves a stimulated phonon creation (i.e. lasing or SBS) process in which the acoustic field is amplified into a coherent oscillation, and subsequently experiences Coriolis acceleration. The resulting precession of the acoustic field is directly transferred to the measured optical phase at the output as shown in the figure below.

The transformative impact of this project lies in the miniaturization of optical rotation sensors, which cannot be achieved if only relying on the optical Sagnac effect (which scales with the area of the device). A sub-millimeter Brillouin gyroscope would still have high optical sensitivity to rotation owing to the *acoustic* Coriolis effect.

Achieving the Brillouin interaction in a WGR requires a careful phase matching condition, which is not easy to achieve. Through this work, we aimed to more broadly develop an understanding of the Brillouin interaction physics within microresonators, how to develop greater control on the process, with a special focus on sensor applications.



Publication –

J. Kim, M. Kuzyk, K. Han, H. Wang, G. Bahl, "Non-reciprocal Brillouin scattering induced transparency," **Nature Physics** 11, pp.275-280, doi:10.1038/nphys3236, 2015.

1. **Giant enhancement of Brillouin opto-acoustic coupling within whispering gallery resonators.**

Through this grant, we completed a detailed theoretical study on modeling the Brillouin opto-acoustic coupling within whispering gallery resonators. This work was published in Laser and Photonics Reviews. We established the first complete model of optical bulk forces and optical boundary forces that participate in Brillouin scattering within a WGR environment. We revealed that there is a surface mechanism that generates a particularly strong acousto-optic response. Specifically, our work showed a surprising result that a “giant-enhancement” of Brillouin gain takes place routinely in whispering gallery resonators, when the optical and acoustic fields are confined at a free surface. This enhancement can be 10^4 times greater than the predictions of traditional scalar theory that is based only on material properties. With optical resonant amplification included, extreme gains on the order of 10^{12} $m^{-1}W^{-1}$ may be realized, which is 10^8 times greater than the highest predicted gains in linear waveguide systems. These giant opto-acoustic gains can directly influence our ability to measure rotation in the Brillouin / BSIT system, and such high gains also influence several applications of Brillouin lasers.

Publication –

N. Dostart, S. Kim, G. Bahl, "Giant Gain Enhancement in Surface-Confined Resonant Stimulated Brillouin Scattering," **Laser and Photonics Reviews**, doi:10.1002/lpor.201500141, Oct 2015.

2. **Exploration of Brillouin cooling physics within whispering-gallery resonators**

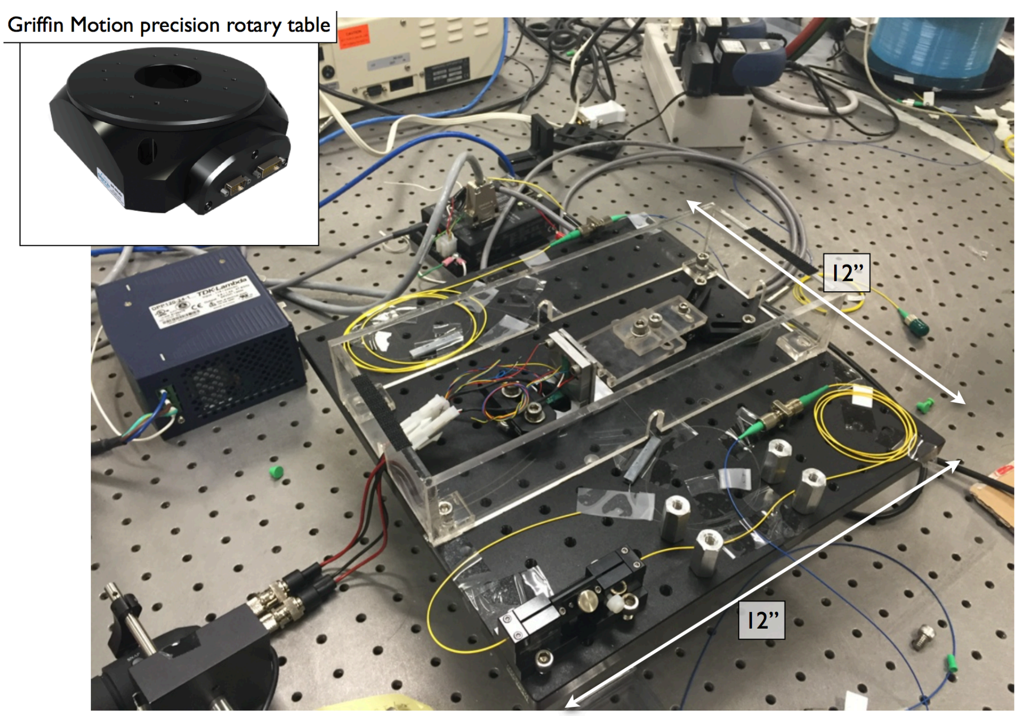
As discussed above, Brillouin scattering is an interaction involving two optical modes and one acoustic mode. In resonators, this phase-matching is tricky to achieve. Thus, multiple detuning parameters are involved that represent how close each optical and acoustic signal are located to their respective modes. The effect of these individual detunings had not been previously explored in any Brillouin or two-mode optomechanical system. In our paper published in Optics Express, we showed that systems with two optical modes have the potential to reach significantly higher cooling rate through resonant enhancement of both pump and scattered light. We experimentally investigated the role of these dual optical resonances on optomechanical/Brillouin cooling, and the deviation from theory that can be caused by thermal locking to the pump laser. We used these resonance characteristics to demonstrate a room temperature Brillouin system operating very close to the strong coupling regime, where saturation of cooling is anticipated. These results directly help us understand the influence of the individual fields in our rotation measurement experiments.

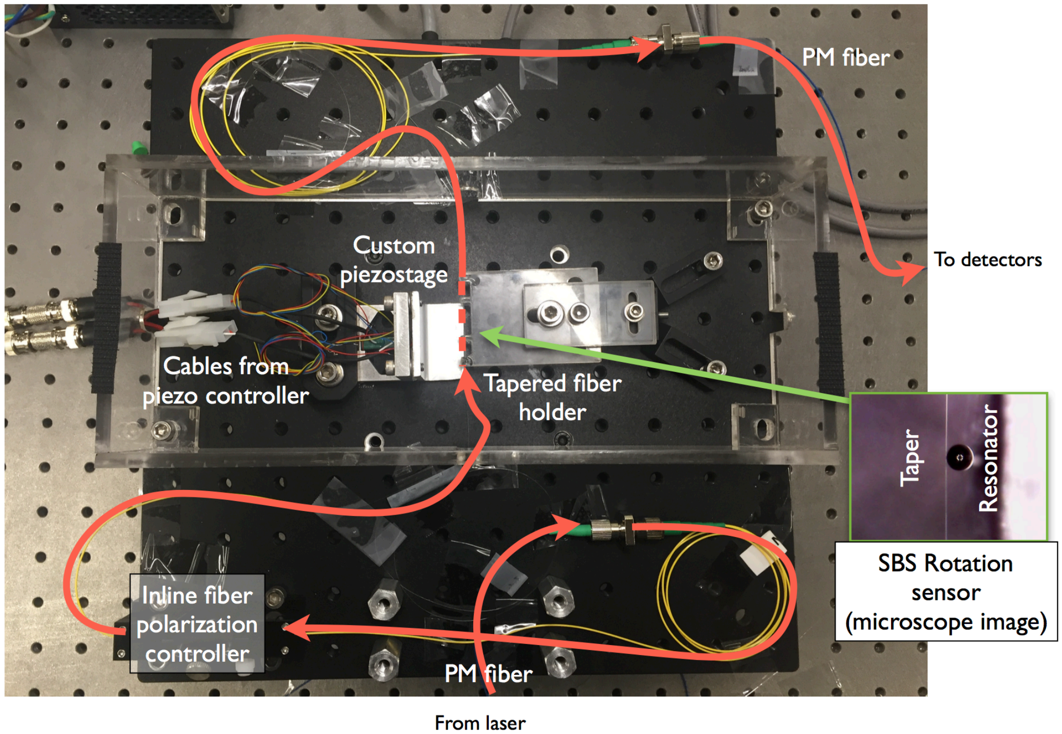
Publication –

S. Kim, G. Bahl, "Role of Optical Density of States in Two-Mode Optomechanical Cooling," **Optics Express** 25(2), pp.776-784, 2017.

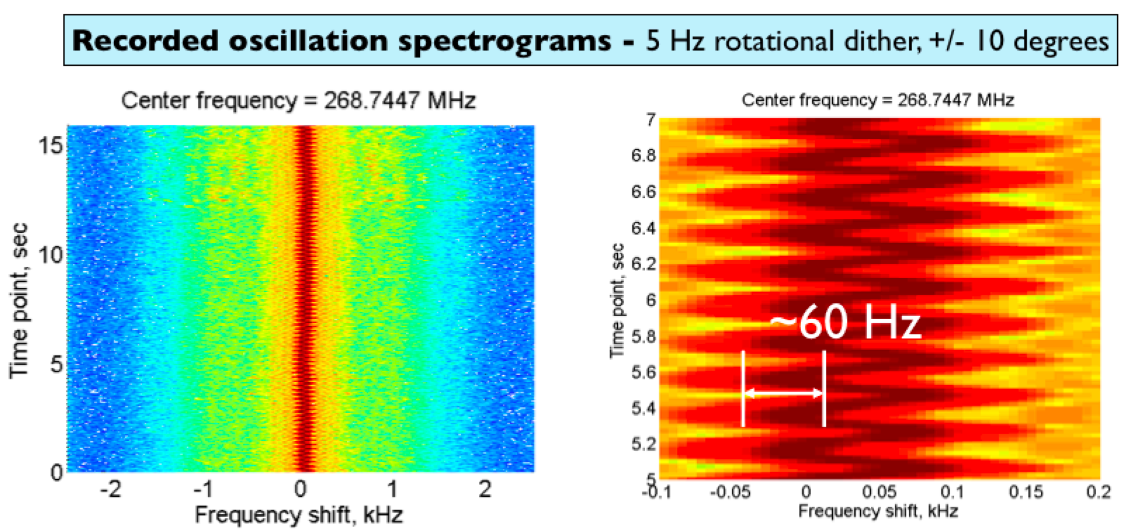
3. Rotation sensing with Brillouin scattering in WGRs

This grant also permitted us to develop an experimental setup for measuring rotation using a microresonator SBS system (images follow). The setup incorporates a Griffin Motion precision rotary table, on which we built a small 12" x 12" optical table supporting the silica microresonator and supporting fiber optics. A custom manufactured nanopositioner was used to place the resonator and the optical waveguide in close proximity for performing the rotation measurement. A telecom laser and appropriate photodetectors were placed outside the platform.





Using this setup we were able to perform the first ever experiments on microresonator SBS during dithered (periodic) rotation. However, the experiment proved exceedingly difficult to control. Our experimental data (below) provides the first evidence of the sensitivity of the Brillouin oscillation to dithered applied rotation. Unfortunately, we were unable to discriminate the effect of the Coriolis acceleration alone relative to other translational motions of the system. The sensitivity to rotation appears far higher than predicted by theory. Since this result is extremely promising, continued progress on this research track is advised (but will require more time and funding).



4. Nonreciprocal photonics with Brillouin scattering

Thanks to this grant, we were also able to exploit the physics of Brillouin interactions to pursue experiments on phonon and photon nonreciprocity. This component of our research effort is jointly supported by the AFOSR YIP grant FA9550-15-1-0234.

We explored a fundamentally new approach to pursue optical isolation, using a strong nonreciprocal effect achieved through Brillouin scattering induced transparency (BSIT). Using 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. We experimentally demonstrated a device capable of generating an enormous 78.6 dB of isolation contrast per 1 dB of forward insertion loss within the induced transparency bandwidth, with optical control and reconfigurability. 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 shows 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.

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

We also experimentally demonstrated the modification of phonon propagation within chiral / nonreciprocal systems that use Brillouin physics. Chirality is the breaking of parity symmetry, and leads to novel behavior in a variety of systems, including the quantum Hall effect and non-reciprocal wave propagation. Through our work, we experimentally demonstrated optically-induced chirality for phonons using sideband Brillouin cooling in a whispering gallery resonator. The chiral effect produces robust phonon propagation even in the presence of material disorder, 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 demonstrated the existence of 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 was observed as a reduction in the heat load of the mechanics. 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, to our knowledge, 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.

Conclusions and Impact

The research conducted under this grant has produced significant knowledge on Brillouin scattering physics within whispering-gallery microresonators. Our experiments have unveiled a deeper understanding of the phase matching conditions for Brillouin scattering, on the enhancement of Brillouin gain, on the control of Brillouin cooling, and how these effects can be exploited for rotation sensing and nonreciprocal photonic systems. Surprisingly, we have also been able to showcase a new optomechanical cooling mechanism that takes place without optical damping.

While this experimental work has broken new ground, there are at the same time many avenues opened for continued research as outlined in our papers and in this report. Continued effort on this system will enable scaling of optical gyros to sub-millimeter dimensions, which is currently not believed to be practical with traditional optical rotation sensing technologies. In particular, compact optical gyroscopes are indispensable in many DoD applications, including miniaturized unmanned aerial vehicles (UAVs) and for navigation in times of GPS denial.

In addition, we have demonstrated for the first time 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. To date such scattering immunity for phonons has only been demonstrated in topological insulators. Our results thus dramatically push forward the known physics for both laser cooling and for monolithic chiral systems.

This work also enabled the training of three graduate student researchers. The original scientific results from this effort were presented by the PI and graduate researchers through 6 journal papers and 7 conference presentations. This effort also generated 2 patent applications (1 issued, 1 pending).

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Gaurav Bahl

Program Officer
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Gernot Pomrenke

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Abstract

The main objective for this project was to explore the physics of Brillouin opto-acoustic scattering in microresonators – with the goals of manipulating optical responses and for developing novel physical sensors. Specifically, we aimed to study the measurement of rotation using optical response of Brillouin optomechanical systems through Brillouin Scattering Induced Transparency (BSIT) measurements. The AFOSR support that we received through this grant, enabled significant progress on both experimental and theoretical aspects of the above goals. We demonstrated that Brillouin optomechanical coupling within microresonators can be enhanced by orders-of-magnitude by surface interactions between light and sound. We also demonstrated the first optomechanical system that achieves complete optical isolation. We advanced the understanding of Brillouin cooling, in both linear and resonant systems. We demonstrated the dynamic suppression of disorder-induced phonon scattering by breaking time-reversal symmetry using Brillouin scattering. The stage is now set for tremendous advances in Brillouin- scattering based microsensors.

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Archival Publications (published) during reporting period:

1. 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

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http://www.nature.com/nphys/journal/vaop/ncurrent/full/nphys3236.html

New discoveries, inventions, or patent disclosures:
Do you have any discoveries, inventions, or patent disclosures to report for this period?

Yes

Please describe and include any notable dates

1. "System and method for Brillouin Scattering Induced Transparency"
Patent granted 9,592,267 (USPTO).

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

Do you plan to pursue a claim for personal or organizational intellectual property?

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Changes in research objectives (if any):

Change in AFOSR Program Officer, if any:

Former (2014-2015): Dr. Howard Schlossberg
Former (2015-2017): Dr. John Luginsland
Current (2017-): Dr. Gernot Pomrenke

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Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

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	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

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Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

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