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Report Date: 10-Apr-2017 Date Received: 22-Nov-2018
Final Report for Period Beginning 11-Jan-2012 and Ending 10-Jan-2017

Title: A Single-Nanoparticle Transducer and Its Applications

Begin Performance Period: 11-Jan-2012 **End Performance Period:** 10-Jan-2017
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STEM Degrees: 0 **STEM Participants:** 8

Major Goals: A portable, real-time, in-situ detection system with nanometer resolution lays the groundwork to investigate the properties and kinetic behaviours of materials and structures as well as phenomena at nano-scale. It will enable a new class of ultra-sensitive and low-power sensors for bio/chemical warfare defense, environmental monitoring, clinical diagnostics, and pharmaceutical studies. This project will utilize ultra-high-quality whispering-gallery-mode optical resonators to form an ultra-sensitive, real-time, in-situ sensing platform. Various sensing mechanisms will be explored in these optical structures. For example, mode-splitting, a phenomenon resulting from significantly enhanced interactions of nanoparticles and light in an ultra-high-quality optical micro-resonator, can be utilized to construct an on-chip nanoparticle sensor. Position-independent detection and accurate sizing of a single nanoparticle down to several nanometers can be achieved in an on-chip device for the first time. In such a system, the nanoparticle can also be employed as an ultra-sensitive nano-scale sensing element to detect trace amount of chemical species or changes in the environment, and the ultra-high-quality resonators will work as the transducer to process the valuable information obtained by the nanoparticle. Other technologies, such as Raman spectroscopy, can be integrated to further enhance the functionalities of the resonator based sensing technologies to study dynamic behaviors of materials and structures at nano-scale. Knowledge learned from new physical phenomena can also be exploited to develop new strategies to develop a new class of sensing platform with performance superior to existing optical sensors. The interdisciplinary nature of this work encourages collaborative research to discover new physical mechanisms and explore novel photonic devices with unprecedented performances for a broad range of applications, including sensing, imaging, spectroscopy, and technologies for communication and information processing.

Accomplishments: The research discoveries from this ARO funded work has led to more than 35 papers in peer-reviewed journals, including Nature, Science, Nature Physics, Nature Photonics, Nature Communication and Proceedings of the National Academy of Sciences.

• Label-free nanoscale sensing and measurement: Nanoparticles are now used extensively in consumer products, biomedical diagnostics, pharmaceuticals and other applications. Meanwhile, nanoparticles as end/by-products of industrial processes have been shown to pose risks to the environment and public health, causing tissue damage, asthma or respiratory allergies and other negative impacts. Thus there is an urgent need to develop better means of assessing the benefits and risks of nanoparticles. Current technologies/equipment for accurate size measurement of single nanoparticles, such as scanning electron microscopes and atomic force microscopes, are bulky and expensive and need to be operated under well-controlled conditions, so cannot be used for in-situ measurements in biological, environmental and other complex media. The PI successfully demonstrated the first real-time, in-situ and label-free detection and size measurement of nanoscale structures by using on-chip micro-resonators. Specifically, she exploited two self-referencing optical modes triggered by light scattering from nanoscale structures in high-quality on-chip whispering-gallery-mode (WGM) resonators as signals for high-precision measurement. The unique feature of built-in self-reference in her technology provides superior noise suppression in sensing tests and enables quantitative size measurement of single nanoparticles smaller than 50 nm. By adding optical gain in the resonator to decrease loss in the sensor, she improved the detection limit to ~10 nm. Recently, her group demonstrated that the detection limit and sensitivity of the WGM sensors could be further improved by operating them at exceptional points, a special state of the resonator occurring as a spectral singularity at which the eigenstates of the devices coalesce. Her technology lays the groundwork for multifunctional platforms for label-free detection, characterization and measurement of nano-objects.

• A versatile sensing optical sensing platform: Among various optical microresonators, ultrahigh-Q WGM resonators have become the frontrunners for sensing applications. Leveraging on their superior capability to strongly enhance light-matter interactions, PI's group has demonstrated various sensing applications including gas sensing, electric/magnetic field sensing, IR sensing, ultrasound sensing, and dynamic measurements of chemical reactions. For example, ultra-sensitive magnetometers are indispensable for many applications such as magnetic resonance imaging and geological surveying. They demonstrated a magnetometer using polymer encapsulated WGM microcavity actuated by a micro-magnet. This magnetometer works in the frequency range of hertz-to-kilohertz range and achieves a sensitivity of several hundred pT/Hz^1/2 in a micro-scale sensor volume. They also demonstrated an on-chip microtoroid IR sensor that can achieve a noise equivalent power around several nanowatt. A WGM ultrasound sensor with sensitivity more than two orders of magnitude better than a commercial hydrophone was also demonstrated. The PI has received two seed funding from the Leadership in Entrepreneurial Acceleration Program (LEAP) at Washington University to advance the WGM sensing technology.

• Parity-time-symmetric photonic systems: Most physical laws hold true whether time is moving forward or backward – that is, they are time symmetric. However, violation of time-reversal symmetry underlies many of today' s most important devices – from nanoscale diodes of integrated electronics to the macroscale isolators and circulators of fiber optical networks. To enable next-generation applications like integrated photonic circuits, it is crucial to manipulate time-reversal symmetry in optics. Starting as an abstract concept with remarkable mathematical properties in the context of quantum theory, recently parity-time symmetry (PT-symmetry) has been recognized as a significant scheme for technological breakthroughs in the "real" world. By merging PT-symmetry in high-quality on-chip optical WGM resonators for the first time, the PI's group demonstrated nonreciprocal light transport on chip, i.e., an all-optical analog of an electronic diode that allows current flow in one direction. Her study lays the groundwork for exploiting PT-symmetric phenomena to develop a new generation of synthetic optical systems enabling unconventional and advanced functionalities for on-chip manipulation and control of light flow. This opens new opportunities in communication, information science, physics, material science, nanotechnology and more.

• Non-Hermitian physics and its exceptional points: Exceptional points (EPs) are non-Hermitian degeneracies that feature the coalescence of the eigenvalues and the corresponding eigenstates when the parameters of a dissipative system are tuned appropriately. EPs universally occur in all open physical systems and dramatically affect their behavior, leading to counterintuitive phenomena such as loss-induced lasing, unidirectional invisibility and enhanced sensors. The PI used WGM resonators as a platform to demonstrate a significant effect of EPs that will provide a new route to control lasing direction. By directly establishing the essential link between the non-Hermitian scattering properties of the WGM resonator and a strong asymmetric backscattering in the vicinity of EPs, she managed to dynamically control the chirality of resonator modes. Consequently, the direction of the WGM microlaser can be tuned from a bidirectional emission to a unidirectional emission in the preferred direction. Moreover, exploiting the EPs concept, recently her group demonstrated the realization of a counter-intuitive aspect of a lasing system; when the system is operated close to an EP, lasing turns out to be inducible solely by adding loss to a resonator – a surprising effect that upends the conventional knowledge of lasers. In her system, the hallmarks of this curious phenomenon are manifested as the loss-induced suppression and revival of lasing. Below a critical value, adding loss to the system annihilates an existing lasing signal. Beyond this critical threshold, however, the lasing recovers despite the increasing loss, in stark contrast to what one would expect from conventional laser theory. Her work paves the way for new strategies to control lasers and provides insight in utilizing loss engineering to operate physical systems.

• Recently protein-based devices have been of great interests due to their flexibility, biodegradability, biocompatibility and molecular level structural tenability that cannot be achieved by rigid inorganic materials. However, current photonic devices fabricated using proteinaceous materials have only exhibited limited light-matter interactions. WGM resonators, on the other hand, have the ability to manipulate and control the light flow and light–matter interactions, and they have created significant interest in biosensing, cavity quantum electrodynamics, low-threshold nonlinear optics and optomechanics. The PI’s team demonstrated optical properties of protein structures via enhanced light-matter interactions for the first time using WGM resonators. Raman gain from protein structures is obtained at milliwatt power thresholds. The broader impact of this research is the design of functional photonic devices using sequence-structure-property relationships of proteins. By genetic modifications of protein sequences, novel materials with photonic non-linear responses could be designed and manufactured for flexible photonics applications.

Training Opportunities: The PI has actively provided various opportunities for students at different levels to work on projects in her nano/micro photonics lab. She has been passionate about training young students and nurturing their interests in science and technologies. During the reporting period, she mentored and advised five undergraduate students, two from the department of electrical and systems engineering, two from the department of biomedical engineering and one from the department of physics, to get research experiences in her group. She also mentored a high-school student to do research in her lab. The students learned the fabrication process to pull a fiber taper that can be used to couple light in and out of nano/micro-photonic devices. They also had hands-on experiences in fabricating high-quality photonic whispering-gallery-mode microresonators in different forms, such as chip-scale resonators or fiber-based resonators. From the fundamental understanding of the physics associated with fiber-taper waveguides and high-quality photonic resonators, the undergraduate students learned to design resonators in various forms and investigate their applications for public health, environmental monitoring, and communication. The research experiences in the lab greatly improve thestudents' problem solving skills and enhance the undergraduate students' interests in science andengineering.

Results Dissemination: The research results have been disseminated through papers published in peer-reviewed journals, presentations given in conferences and invited seminars in other universities.

Papers:

- “A phonon laser operating at an exceptional point,” J. Zhang, B. Peng, Sahin. K. Özdemir, K. Pichler, D. O. Krimer, G. Zhao, F. Nori, Y. Liu, S. Rotter, and L. Yang, Nature Photonics, 12, 479-484 (2018).
- "Exceptional points enhanced sensing in an optical microcavity," W. Chen, Sahin. K. Özdemir, G. Zhao, J. Wiersig, and L. Yang, Nature, 548, 192-196 (2017).
- “Parity-time-symmetric whispering-gallery mode nanoparticle sensor,” W Chen, J Zhang, B Peng, SK Özdemir, X Fan, L Yang, Photonics Research 6 (5), A23-A30 (2018) (Invited).
- “Scatterer assisted whispering gallery mode microprobe,” F Shu, X Jiang, G Zhao, L Yang, Nanophotonics, 7 (8), 1455-1460 (2018)
- “Optomechanically Induced Transparency at Exceptional Points,” H Lü, C Wang, L Yang, H Jing, Physical Review Applied 10 (1), 014006 (2018)
- “Polymer encapsulated microcavity optomechanical magnetometer,” J Zhu, G Zhao, I Savukov, L Yang, Scientific Reports 7 (1), 8896 (2017)
- “Controllable oscillatory lateral coupling in a waveguide-microdisk-resonator system,” F Bo, SK Özdemir, F Monifi, J Zhang, G Zhang, J Xu, L Yang, Scientific Reports 7 (1), 8045 (2017)
- "Structural Protein-Based Whispering Gallery Mode Resonators," H Yilmaz, A Pena-Francesch, R Shreiner, H Jung, Z Belay, MC Demirel, S. K. Ozdemir, L. Yang, ACS Photonics 4 (9), 2179-2186 (2017)
- "Raman lasing and Fano lineshapes in a packaged fiber-coupled whispering-gallery-mode microresonator", G. Zhao, S. K. Ozdemir, T. Wang, L. Xu, G.-L. Long, L. Yang, Science Bulletin, 62 (12), 875-878 (2017)

Selected talks:

- “Whispering-gallery-mode resonators for functional devices,” SPIE Photonics West, San Francisco, CA, Jan 28-Feb 2, 2017.
- “Whispering-gallery-mode resonators and their applications for nanoscale sensing and measurement,” SPIE Photonics West, San Francisco, CA, Jan 28-Feb 2, 2017.
- “Whispering-gallery-mode resonators and their applications: from nanoscale measurement to directional lasing,” The 6th International Multidisciplinary Conference on Optofluidics, Beijing, China, July 24-27, 2016, (Keynote talk)
- "Whispering-gallery-mode microresonators and microlasers for nanoscale sensing and beyond," Washington University School of Medicine in St. Louis, September 2016
- "Whispering-gallery-mode microresonators for nanoscale sensing and beyond," Molecular Engineering Seminar, University of Washington, October 2016
- "Recent explorations in whispering-gallery-mode microresonators for functional devices: from nanoscale measurement to non-Hermitian physics", Wesleyan University, November 2016

Honors and Awards: The PI was elected a fellow of the optical society (OSA).

Protocol Activity Status:

Technology Transfer: Since the start the of this funding period, two patents relevant to technologies developed from the research sponsored by this grant were granted. One is on the method and system for parity-time symmetric optics and nonreciprocal transmission (US20150295379) and the other one is about a Resonance enhanced Raman spectroscopy (US9733125).

PARTICIPANTS:

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Participant: Lan Yang
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N

Other Collaborators:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:

National Academy Member: N
Other Collaborators:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Participant: Zaneta Belay
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Victor Chiang
Person Months Worked: 3.00 **Funding Support:**
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Other Collaborators:

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Nothing to report in the uploaded pdf (see accomplishments).