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Nanophotonic Architectures for Quantum Control of Light Emission

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Active hybrid nanophotonic structures are the key building block components for future nanophotonic networks, and can enable dynamical control of light emission. In this theory-guided experimental effort, we created novel tunable antenna-emitter hybrid structures to manipulate all of the key constitutive properties, including the intensity, propagation direction, and polarization of emitted photons. Active emission control was achieved by incorporating either materials with tunable refractive index (ITO, VO2, etc.) into the nanophotonic structures in the vicinity of photon emitters. In 2019, we proposed and experimentally demonstrated the design of tunable nanophotonic structures, including electrically-tunable III-V multiple-quantum-well-based metasurfaces and VO2 based metasurfaces and their ability to achieve dynamic control of light (amplitude, phase, deflected angle, etc.). This past year, we designed and realized a multifunctional metasurface that enables active switching of optical functionality. An ITO-based active metasurface operating at the epsilon-near-zero condition was also developed to dynamically control the polarization state of reflected light in near-infrared. The polarization converter can realize three polarization states (linear, circular and elliptical) under a fixed incident polarization condition. We also reported results on quantum emitters, including experimental characterization of exfoliated hexagonal boron nitride (hBN)
flakes, relating structure and quantum light emission properties. We identified single emitters at the surface of a hBN flake, and performed a clean g(2) measurement that shows a correlation dip at short delays. Additionally, high index dielectric TiO2 based metasurface were designed to support strong Mie resonances at the wavelengths for photon emission from hBN emitters, enabling the control of photon emission via antenna-emitter interaction. In May 2021, our studies of tunable nanophotonic configurations were published in several top journals like Nano Letters, Nature Communications, and ACS Nano. The tunable polarization converter has also been granted for US patent. In 2019, Dr Wu visited Dr Atwater's group at Caltech several times for closer interaction. In May-December 2021, we experimentally characterized the photoluminescence (PL) signal from supporting substrate of high index nanoantenna
to avoid its influence upon single photon emission. We also performed temperature-dependent PL measurement to investigate how the heat control/change the defects on the hBN flake surface. Manipulation of photon emission control was performed by incorporating electrostatic gating into our tunable nanophotonic platform with hBN defects. Dr. Atwater's research group at Caltech has extensive experience in quantum plasmonics and 2D material growth and analysis. They also have diverse experience in device integration of nano-antennas and 2D materials, especially for gate-tunable devices. Dr. Wu's research team has extensive experience with nano-antenna
design for realizing specific optical functions, such as phase compensation for achromatic metasurface components and optical amplitude modulation for beam deflection. This collaborative AFOSR MOST project indeed accelerated the research and major milestones in the field of control of quantum light emission using nanophotonic architecture.

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Nanophotonic Architectures for Quantum Control of Light Emission

[US] [TW]

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California Institute of Technology **National Cheng Kung University**

Research Objectives:

Active hybrid nanophotonic structures are the key building block components for future nanophotonic networks and can enable dynamical control of light emission. In this theory-guided experimental effort, our objectives were to create novel tunable antenna-emitter hybrid structures to manipulate all the key constitutive properties, including the intensity, propagation direction, and polarization of emitted photons. Active emission control was achieved by incorporating either material with tunable refractive index (ITO, VO_2, *etc.*) into the nanophotonic structures in the vicinity of photon emitters.

Accomplishments:

In 2019, we proposed and experimentally demonstrated the design of tunable nanophotonic structures, including electrically-tunable III-V multiple-quantum-well-based metasurfaces and VO_2 based metasurfaces and their ability to achieve dynamic control of light (amplitude, phase, deflected angle, *etc.*). This past year, we designed and realized a multifunctional metasurface that enables active switching of optical functionality. An ITO-based active metasurface operating at the epsilon-near-zero condition was also developed to dynamically control the polarization state of reflected light in near-infrared. The polarization converter can realize three polarization states (linear, circular and elliptical) under a fixed incident polarization condition. We also reported results on quantum emitters, including experimental characterization of exfoliated hexagonal boron nitride (hBN) flakes, relating structure and quantum light emission properties. We identified single emitters at the surface of a hBN flake, and performed a clean $g^{(2)}(0)$ measurement that shows a correlation dip at short delays. Additionally, high index dielectric TiO_2 based metasurface were designed to support strong Mie resonances at the wavelengths for photon emission from hBN emitters, enabling the control of photon emission via antenna-emitter interaction.

In May 2021, our studies of tunable nanophotonic configurations were published in several top journals like *Nano Letters*, *Nature Communications*, and *ACS Nano*. The tunable polarization converter has also been granted a US patent.

In 2019, Dr Wu visited Dr Atwater's group at Caltech several times for closer interaction, but visits were not possible after 2020 owing to the COVID pandemic.

In May-December 2021, we experimentally characterized the photoluminescence (PL) signal from supporting substrate of high index nano-antenna to avoid its influence upon single photon emission. We also performed temperature-dependent PL measurement to investigate how the heat control/change the defects on the hBN flake surface. Manipulation of photon emission control was performed by incorporating electrostatic gating into our tunable nanophotonic platform with hBN defects.

Publications:

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Impacts

Development of the principal discipline(s) of the project

This collaborative AFOSR MOST project indeed accelerated the research and major milestones in the field of control of quantum light emission using nanophotonic architecture. Dr. Atwater's research group at Caltech has extensive experience in quantum plasmonics and 2D material growth and analysis, and in device integration of nano-antennas and 2D materials, especially for gate-tunable devices. Dr. Wu's research team has extensive experience with nano-antenna design for realizing specific optical functions, such as phase compensation for achromatic metasurface components and optical amplitude modulation for beam deflection. The collaboration work resulted in new designs for active metasurfaces for tunable polarization conversion, active metasurfaces for beam steering, and control of quantum light emission from hexagonal boron nitride, and designs for antenna-coupled quantum emitters.

Other disciplines:

The observation of homogeneously broadened light emission from color center quantum emitters in hexagonal boron nitride has opened a new and promising direction for coherent single photon emission with potentially significant impacts for quantum science and engineering, such as the potential for future generation of optical qubits in a solid-state host by quantum entanglement of hBN emitters located within a subwavelength distance from one another.

Describe the impact in this reporting period on the development of human resources

This grant supported research by two Applied Physics graduate students, Hamid Akbari and Melissa Li. Neither has graduated to date, but the AFOSR-MOST project provided principal support for the PhD thesis for Akbari, which is anticipated in 2023.

Describe the impact on teaching and educational experiences

For example, has the project: Developed and disseminated new educational materials; led to ideas for new approaches to course design or pedagogical methods; or developed online resources that will be useful for teachers and students and other school staff?

Describe the impact in this reporting period on physical, institutional, and information resources that form infrastructure.

We were able to capital and commission new instruments, including a tunable dye laser system and and AttoCube low temperature confocal microscope capable of achieving cryogenic operation at 4K with state-of-the-art confocal image resolution. These enabled new and enabling measurement capability not anticipated at the time the AFOSR-MOST proposal was written.

Impact on society beyond science and technology:

This international collaboration project provided for stimulating cultural exchanges between the PIs and students from the US and from Taiwan.

Changes

Changes in approach

None.

Problems or delays

The only challenges faced by the team were those imposed by the worldwide COVID pandemic which inhibited travel exchanges. The PIs compensated for this by organizing periodic Zoom meetings to exchange scientific information.

Expenditure Impacts

We were able to leverage support from private foundations to purchase an AttoCube low temperature confocal microscope capable of achieving cryogenic operation at 4K with state of the art confocal image resolution.

Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards

Not applicable.

Changes to the primary place of performance from that originally proposed

None.

Technical Updates

In work begun under the AFOSR MOST project but performed after completion of the grant, we made a significant step forward by observing homogeneously broadened light emission from color center quantum emitters in hexagonal boron nitride. This finding has opened a new and promising direction for coherent single photon emission with potentially significant impacts for quantum science and engineering, such as the potential for future generation of optical qubits in a solid-state host.