REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 05-12-2022	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 1-Jan-2019 - 30-Jun-2022

4. TITLE AND SUBTITLE Final Report: Spatially regular single photon emitters coupled via multifunctional collective Mie resonance of all dielectric metastructures: A new paradigm for on-chip integrated scalable quantum optical circuits	5a. CONTRACT NUMBER W911NF-19-1-0025
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611102
6. AUTHORS	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Southern California Contracts & Grants 3720 S. Flower St. Los Angeles, CA 90089 -0701	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 73214-SM.4

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Anupam Madhukar
UU	UU	UU	UU		19b. TELEPHONE NUMBER +12-137-4043

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 05-Dec-2022

Agency Code: 21XD

Proposal Number: 73214SM **Agreement Number: W911NF-19-1-0025**

INVESTIGATOR(S):

Name: Anupam Madhukar
Email: madhukar@usc.edu
Phone Number: +12137404323
Principal: Y

Organization: **University of Southern California**
Address: Contracts & Grants, Los Angeles, CA 900890701
Country: USA
DUNS Number: 072933393 EIN: 951642394
Report Date: 30-Sep-2022 Date Received: 05-Dec-2022
Final Report for Period Beginning 01-Jan-2019 and Ending 30-Jun-2022
Title: Spatially regular single photon emitters coupled via multifunctional collective Mie resonance of all dielectric metastructures: A new paradigm for on-chip integrated scalable quantum optical circuits
Begin Performance Period: 01-Jan-2019 **End Performance Period:** 30-Jun-2022
Report Term: 0-Other
Submitted By: Anupam Madhukar Email: madhukar@usc.edu
Phone: (+12) 137-404323

Distribution Statement:

STEM Degrees: 1 **STEM Participants:** 4

Major Goals: This Final Report summarizes the salient accomplishments under the grant W911NF-19-1-0025 aimed at examining:

(1) a new class of on-chip scalable spatially-ordered and spectrally-uniform single photon sources (SPSs) based upon mesa top single quantum dots (MTSQDs) and,

(2) their on-chip integration with a novel class of co-designed in-plane photon manipulating functional units based upon utilizing a new paradigm -- introduced under the preceding ARO Grant W911NF-16-1-0298-- that exploits the collective Mie resonance of all-dielectric subwavelength sized building blocks (DBBs) based metastructures.

We note that the Mie resonance approach to implementing the emitted light manipulating units (LMUs) is based on fundamentally different physics than underlies the commonly employed 2D photonic crystal-based approach which invokes discrete individual functional elements such as a resonant cavity, waveguide, etc. and is thus challenged by serious limitations of impedance matching in coupling these discrete elements into a functional LMU. By contrast, in our approach, the collective Mie resonance employed is a mode of the entire metastructure (i.e. the interconnected LMUs containing the ordered multiple quantum emitters) and, depending upon the spatial location of the emitted (into the collective Mie mode) photon wavepacket in the metastructure (the optical circuit), provides the required functions of cavity, waveguiding, beam-splitting, etc.—thus bypassing any issue of impedance matching.

Accomplishments: The grant has led to two major accomplishments that pave a path to a long-sought scalable on-chip scalable quantum photonic information processing platform:

1. Demonstration, for the first time, of the long-sought scalable platform of on-demand solid-state quantum emitters residing in spatially-regular arrays and exhibiting single photon figures-of-merit such as brightness, purity, and Hong-Ou-Mandel (HOM) indistinguishability that exceed those required for moving to implementing functional networks of interconnected quantum emitters-- quantum optical circuits;

2. Theoretical analysis and appropriate computational simulations of the design of dielectric metastructures having co-designed Mie resonance suitable for providing all of the required on-chip light manipulating functions for the photon emitted, on-chip, into the collective Mie mode—Purcell enhancement of the emission rate, uni-directional

emission into the waveguide, state-preserving propagation, beam-splitting, and beam combining.

Details see attached PDF document.

Training Opportunities: Nothing to Report

Results Dissemination: Nothing to Report

Honors and Awards: Invited Talk, IEEE-RAPID 2022, Sept.12-14,, 2022; J. Zhang,
Invited Talk, IEEE-RAPID 2021, Aug. 2-4, 2021; A. Madhukar and J. Zhang,
Invited Talk, MRS Spring/Fall Meeting, Nov. 29 - Dec.4, 2020; A. Madhukar and J. Zhang,
Invited Talk, ACPC, Oct 2020, J. Zhang,
Invited Talk, International Conference on Materials for Advanced Technology, Singapore, June, 2019; A. Madhukar, J. Zhang, S. Chattaraj
Invited Talk, China Quantum Information Science and Technology Symposium, Ji'nan, China, May 2019; Jiefei Zhang
Invited Talk, South Bay Interdisciplinary Science Center & IOP CAS Young Scientists Symposium, Dongguan, China, May 2019; Jiefei Zhang

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Jiefei Zhang
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Swarnabha Chattaraj
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Lucas Jordao
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Qi Huang
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Faculty
Participant: Jiefei Zhang
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: IEEE Journal of Quantum Electronics
Publication Identifier Type: DOI Publication Identifier: 10.1109/JQE.2019.2952387
Volume: 56 Issue: 1 First Page #: 1
Date Submitted: 12/7/19 12:00AM Date Published: 2/1/20 4:00PM
Publication Location:
Article Title: On-Chip Integrated Single Photon Source-Optically Resonant Metastructure Based Scalable Quantum Optical Circuits
Authors: Swarnabha Chattaraj, Jiefei Zhang, Siyuan Lu, Anupam Madhukar
Keywords: Photonics, Mie Resonance, Quantum Optical Circuit, Quantum Dot Single Photon Source
Abstract: We present an approach to realizing on-chip optical quantum information processing (QIP) systems comprising (1) single photon source (SPS) arrays, here based on a new class of ordered single quantum dots of controlled size and shape named Mesa-top Single Quantum Dots (MTSQDs) that are naturally integrable in scalable architectures with (2) on-chip light manipulating units (LMUs) based upon either the conventional 2D photonic crystal platform or metastructures made of subwavelength size dielectric building blocks (DBBs) whose collective Mie-like optical resonances provide, simultaneously, all the needed light manipulating functions. The MTSQDs can provide high spectral uniformity with as-grown pairs emitting within 300ueV—thus calling for exploration of pathways for implementing on-chip SPS-SPS coupling for quantum entanglement. ...
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

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I certify that the information in the report is complete and accurate:
Signature: Anupam Madhukar
Signature Date: 12/5/22 11:25AM

Final Report (01/01/2019 to 06/30/2022)

Spatially regular single photon emitters coupled via multifunctional collective Mie resonance of all dielectric metastructures: A new paradigm for on-chip integrated scalable quantum optical circuits

(Grant Number: W911NF-19-1-0025**)**

Program Manager
Dr. Evan Runnerstrom,
Army Research Office, RTP, NC 277709-2211

Submitted by:
Anupam Madhukar,
University of Southern California, Los Angeles, CA
madhukar@usc.edu, (213) 740-4323
nanostructure.usc.edu

Table of Content

I. Abstract

This Final Report summarizes the salient accomplishments under the grant W911NF-19-1-0025 aimed at examining:

(1) a new class of on-chip scalable spatially-ordered and spectrally-uniform single photon sources (SPSs) based upon mesa top single quantum dots (MTSQDs) and,

(2) their on-chip integration with a novel class of co-designed in-plane photon manipulating functional units based upon utilizing a new paradigm -- introduced under the preceding ARO Grant W911NF-16-1-0298-- that exploits the collective Mie resonance of all-dielectric subwavelength sized building blocks (DBBs) based metastructures.

We note that the Mie resonance approach to implementing the emitted *light manipulating units* (LMUs) is based on fundamentally different physics than underlies the commonly employed 2D photonic crystal-based approach which invokes discrete individual functional elements such as a resonant cavity, waveguide, etc. and is thus challenged by serious limitations of impedance matching in coupling these discrete elements into a functional LMU. By contrast, in our approach, the collective Mie resonance employed is a mode of the entire *metastructure* (i.e. the interconnected LMUs containing the ordered multiple quantum emitters) and, depending upon the spatial location of the emitted (into the collective Mie mode) photon wavepacket in the metastructure (the optical circuit), provides the required functions of cavity, waveguiding, beam-splitting, etc.—thus bypassing any issue of impedance matching.

The grant has led to two **major accomplishments** that pave a path to a long-sought scalable on-chip scalable quantum photonic information processing platform:

1. Demonstration, for the first time, of the long-sought **scalable platform of on-demand solid-state quantum emitters residing in spatially-regular arrays** *and* **exhibiting** single photon figures-of-merit such as **brightness, purity,** and Hong-Ou-Mandel (HOM) **indistinguishability** *that exceed those required for moving to implementing functional networks of interconnected quantum emitters-- quantum optical circuits;*

2. Theoretical analysis and appropriate computational simulations of the **design of dielectric metastructures** having co-designed Mie resonance suitable for providing all of the required on-chip light manipulating functions for the photon emitted, on-chip, into the collective Mie mode—*Purcell enhancement of the emission rate, unidirectional emission into the waveguide, state-preserving propagation, beam-splitting, and beam combining.*

Furthermore, as networks are based upon interconnections between quantum emitters, we also analyzed **superradiant emission** between two quantum emitters coupled in a waveguide. As a two-photon state is inherently beyond the scope of classical electromagnetic theory, we formulated a field-theoretic analysis of (a) TPI evolution to analyze the HOM measurements and (b) the evolution of super-radiance between two SQDs communicating through the Mie resonance of a DBB waveguide.

II. Submissions or Publications under ARO sponsorship

(a) Papers published in peer-reviewed journals

1. Jiefei Zhang, Swarnabha Chattaraj, Siyuan Lu and Anupam Madhukar, "Highly pure single photon emission from spectrally uniform surface-curvature directed mesa top single quantum dot ordered array", **Appl. Phys. Lett. 114**, 071102, **(2019)**
2. S. Chattaraj, J. Zhang, S. Lu, and A. Madhukar, "On-Chip Integrated Single Photon Source Optically Resonant Metastructure Based Scalable Quantum Optical Circuits", **IEEE Jour. Quantum Electronics**, **56**, 1, 9300109 **(2020)**.
3. J. Zhang, Q. Huang, S. Chattaraj, L. Jordao, S. Lu, and A. Madhukar, "Buried spatially-regular arrays of spectrally uniform single quantum dots as on-chip scalable single photon sources for quantum optical circuits", **APL Photonics**, **5, 116106 (2020)**
4. J. Zhang, Q. Huang, S. Chattaraj, L. Jordao, S. Lu, and A. Madhukar, **Science Advances**, **8, eabn2 (2022)**

(b) Papers published in non-peer-reviewed journals

None

(c) Presentations

i. Presentations at meetings, but not published in Conference Proceedings

2022

1. **(Invited Talk)** Jiefei Zhang, Q. Huang, S. Chattaraj, L. Jordao, S. Lu and A. Madhukar, "A New platform of single photon source arrays for on-chip quantum photonic", **IEEE Research and Applications of Photonics in Defense Conference, Sept. 2022**

2021

2**. (Invited Talk)** Anupam Madhukar, Jiefei Zhang, Qi Huang, Swarnabha Chattaraj, Lucas Jordao, and Siyuan Lu, "Single Photon Emitter Arrays for On-chip Quantum Photonics", Invited talk in Session "Semiconductor Materials and Quantum Nanoscience", WB2.1, **IEEE Research and Applications of Photonics in Defense Conference, Aug 2021.**

3. J. Zhang, Qi Huang, Lucas Jordao, Swarnabha Chattaraj, Siyuan Lu, Anupam Madhukar, "A New Paradigm for On-chip Quantum Photonics: Highly Uniform Single Photon Source Arrays", TuA2.3, Oral Presentation in Session "Nonlinear Effects and Quantum New Devices", **IEEE Photonics Conference, Oct 2021.**

4. Swarnabha Chattaraj, Jiefei Zhang, Siyuan Lu, and Anupam Madhukar, "Mie Resonance Based Quantum Optical Circuits Integrated with on-chip Single Photon Source Array for Quantum Information Processing", *Oral Presentation* in Session "Integrated Quantum Photonics", TuA4.3, **IEEE Research and Applications of Photonics in Defense Conference, Aug 2021.**

5. Jiefei Zhang, Qi Huang, Lucas Jordao, Swarnabha Chattaraj, Siyuan Lu, Anupam Madhukar, “Planarized Ordered Uniform Mesa-top Single Quantum Dot Single Photon Source Arrays: A Platform for Scalable Quantum Optical Networks”, *Oral Presentation* in Session “Hybrid Photonic Systems”, B31.13, **APS March Meeting, March 2021**.

6. Swarnabha Chattaraj, Jiefei Zhang, Siyuan Lu, Anupam Madhukar, “Entanglement in optical circuits based on Mie resonant metastructures integrated with on-chip array of single photon sources”, *Oral Presentation* in Session “Hybrid Photonic Systems”, B31.11, **APS March Meeting, March 2021.**

2020

7. S. Chattaraj, J. Zhang, S. Lu and A. Madhukar, “Mie Resonant Dielectric Metastructure based Quantum Optical Circuits Integrated with Single Photon Source: A new paradigm for Quantum Information Processing”, **G65.00013,** Oral Presentation, **APS March Meeting, Denver, Colorado. Mar. 2020.**
8. J. Zhang, S. Chattaraj, S. Lu and A. Madhukar, “On-chip Integrable Highly Spectrally Uniform Ordered Semiconductor Quantum Dot Single Photon Source Arrays for Scalable Quantum Optical Networks”, **J65.00002**, Oral Presentation, **APS March Meeting, Denver, Colorado. Mar. 2020.**
9. **(Invited)** A. Madhukar, J. Zhang, S. Chattaraj, and S. Lu, “A New Paradigm for Scalable Quantum Optical Circuits: On-Chip Single Photon Source Arrays Integrated with Optically Resonant Metastructure Based Light Manipulating Units”, **MRS Spring Meeting Phoenix, Arizona, April. 2020**.
10. **(Invited Talk)** J. Zhang, S. Chattaraj, Q. Huang, L. Jordao, S. Lu and A. Madhukar, “Mesa-Top Single Quantum Dot Arrays as Single Photon Sources: A new paradigm for On-chip Quantum Photonics”, **Asia Communications and Photonics Conference (ACPC) 2020**, China (October, 2020)
11. **(Invited Talk)** Anupam Madhukar, Jiefei Zhang, Swarnabha Chattaraj, and Siyuan Lu, “A New Paradigm for Scalable Quantum Optical Circuits—On-Chip Single Photon Source Arrays Integrated with Optically Resonant Metastructure Based Light Manipulating Units”, Invited Talk in Session “Single Photon Emitters”, S.EL06.05.02, **MRS Spring/Fall Meeting, Nov 29-Dec 4, 2020.**
12. Swarnabha Chattaraj, Jiefei Zhang, Siyuan Lu, Anupam Madhukar, “Mie Resonant Dielectric Metastructure based Optical Circuits Integrated with Quantum Dot Single Photon Source for on-chip Scalable Quantum Information Processing”, *Oral Presentation* in Symposium “Photonic Materials for information Processing and Computing**” MRS Spring/Fall Meeting, Nov 29-Dec 4, 2020.**

2019

13. Swarnabha Chattaraj, Jiefei Zhang, Siyuan Lu and Anupam Madhukar, “Integrated Quantum Networks of Mie-resonance based All-Dielectric Optical Circuits with Single Photon Sources for Quantum Entanglement”,

P29.7, Oral Presentation in the Symposium on "Semiconductor QD Architectures and Quantum Photonics" in the **APS March Meeting Boston, Massachusetts. Mar. 2019.**

14. Jiefei Zhang, Swarnabha Chattaraj, Siyuan Lu and Anupam Madhukar, "On-chip Integrable Spectrally Uniform Ordered Quantum Dot Single Photon Source Array with High Emission Purity (>98.99%) for Scalable Quantum Optical Networks", **P29.5**, Oral Presentation in the Symposium on "Semiconductor QD Architectures and Quantum Photonics" in the **APS March Meeting Boston, Massachusetts. Mar. 2019.**
15. **(Invited)** Jiefei Zhang, Siyuan Lu, Swarnabha Chattaraj and Anupam Madhukar, "On-Chip Integrated Scalable Single Photon Source-All-Dielectric Metastructure Based Nanophotonic Quantum Optical Circuits", Oral Presentation in the Session "Quantum Device" in the **2019 China Quantum Information Science and Technology Symposium, Ji'nan, China, May 2019**.
16. **(Invited)** Jiefei Zhang, Siyuan Lu, Swarnabha Chattaraj and Anupam Madhukar, "On-Chip Integrated Scalable Single Photon Source-All Dielectric Metastructure Based Nanophotonic Quantum Optical Circuits towards Quantum Information Science", Oral Presentation, **South Bay Interdisciplinary Science Center & IOP CAS Young Scientists Symposium, Dongguan, China, May 2019.**
17. **(Invited)** Anupam Madhukar, Jiefei Zhang, Swarnabha Chattaraj, Siyuan Lu, "On-Chip Integrated Scalable Single Photon Source-Optically Resonant Metastructure Based Quantum Optical Circuits: A new paradigm for quantum information processing", **C2-07**, Oral Presentation in Symposium C: Semiconductor Photonics, **International Conference on Materials for Advanced Technology, Singapore, June, 2019.**
18. Swarnabha Chattaraj, Jiefei Zhang, Siyuan Lu, Anupam Madhukar, "On-chip Scalable Integrated Quantum Photonic Networks based on Quantum Dot Single Photon Source Array Integrated with Dielectric Light Manipulating Circuits", **WF1.4**, Oral Presentation in Symposium on "Valleytronics and Single and Entangled Photons" in **IEEE Summer Topical Meeting, Fort Lauderdale, Florida, July, 2019.**

ii. Non-Peer-Reviewed Conference Proceeding publications (other than abstracts)

None

iii. Peer-Reviewed Conference Proceeding publications (other than abstracts)

None

(d) Manuscripts

2022

J. Zhang, Q. Huang, S. Chattaraj, L. Jordao, S. Lu, and A. Madhukar, **Science Advances**, **8, eabn2 (2022)**

2021

1. J. Zhang, S. Chattaraj, Q. Huang, L. Jordao, S. Lu and A. Madhukar, "Indistinguishable single photons from spatially-ordered array of highly efficient and pure mesa-top single quantum dots: A step closer to on-chip quantum optical circuits", **arXiv: 2108.01428v2** (2021)

2020

1. J. Zhang, S. Chattaraj, Q. Huang, L. Jordao, S. Lu and A. Madhukar, "Buried spatially-regular arrays of spectrally uniform single quantum dots as on-chip scalable single photon sources for quantum optical circuits", **APL Photonics**, 5, 116106 (2020)

2019

1. S. Chattaraj, J. Zhang, S. Lu, A. Madhukar, "On-Chip Integrated Scalable Single Photon Source-Optically Resonant Metastructure based Quantum Optical Circuits", **IEEE Jour. Quant. Elec.** 56, 1 (2019).
2. Jiefei Zhang, Swarnabha Chattaraj, Siyuan Lu and Anupam Madhukar, "Highly pure single photon emission from spectrally uniform surface-curvature directed mesa top single quantum dot ordered array", **Appl. Phys. Lett. 114**, 071102, (2019)

1 Books

None

2 Honor and Awards

Invited Talk, IEEE-RAPID 2022, Sept.12-14,, 2022; J. Zhang,
Invited Talk, IEEE-RAPID 2021, Aug. 2-4, 2021; A. Madhukar and J. Zhang,
Invited Talk, MRS Spring/Fall Meeting, Nov. 29 - Dec.4, 2020; A. Madhukar and J. Zhang,
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Invited Talk, International Conference on Materials for Advanced Technology, Singapore, June, 2019; A. Madhukar, J. Zhang, S. Chattaraj
Invited Talk, China Quantum Information Science and Technology Symposium, Ji'nan, China, May 2019; Jiefei Zhang
Invited Talk, South Bay Interdisciplinary Science Center & IOP CAS Young Scientists Symposium, Dongguan, China, May 2019; Jiefei Zhang

3 Title of Patents Disclosed during the reporting period

None

4 Patents Awarded during the reporting period

None

III. Student/Supported Personnel Metrics

(a) Number of Undergraduate STEM Students
One.
Emily Kretschmer

(b) Number of Graduate STEM Students
Three
Swarnabha Chattaraj, Qi Huang and Lucas Jordao

(c) Number of Students that received a STEM degree
One.
Swarnabha Chattaraj [PhD in EE]

(d) Other Research staff
Postdoctoral Fellow: Dr. Jiefei Zhang 2018-2020
Research Asst. Professor: Dr. Jiefei Zhang 2020-2021

IV. Technology transfer

None

V. Scientific Accomplishments:

This Final Report covers accomplishments during the grant period **(01/01/2019 to 06/30/2022)** of the ARO Grant # W911NF-19-1-0025. The project was aimed at the ultimate realization of the long-sought goal of scalable quantum optical circuits (QOCs) that require spatially regular arrays of on-demand single photon sources (SPSs) of requisite spectral emission characteristics integrated on-chip with co-designed light manipulating units (LMUs) to enable controlled interference and entanglement between photons from known distinct on-chip sources.

This vision is symbolically captured in Fig.1(a) and (b) below. Both implementations are enabled by the realization of *spatially-ordered* and scalable on-demand *single photon emitters* (red regions) around which are placed co-designed emitted single photon manipulating units that provide the required functions of enhancing the photon emission rate (Purcell enhancement), uni-directional emission into a waveguiding mode, state-preserving photon transport, photon combining, and splitting functions. The light manipulating units (LMUs) maybe implemented using the well-developed photonic 2D crystal-based approach to creating resonant cavity, waveguide, and beam-splitting and combining (Fig.1a) or, as we proposed and developed (analyzed and simulated) under this program, based upon the above-noted *functions* being *provide by a designed collective Mie-mode of all-dielectric metastructures* surrounding each quantum emitter of the array (Fig.1b).

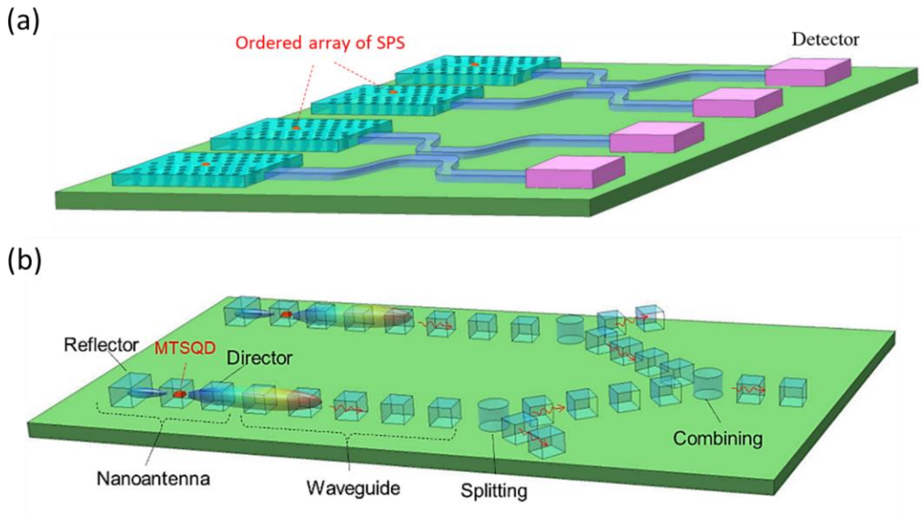

Fig.1 Schematic drawing of on-chip quantum optical circuits created via integration of ordered array of single photon emitter and on-chip codesigned light manipulating elements created using (a) conventional 2D PhC approach and (b) using Mie resonances in dielectric building blocks.

Our approach to realizing this vision is thus based upon realizing the two major elements:

(1) Developing on-chip scalable spatially-regular single quantum dots (SQDs) that we invented dubbed mesa-top single quantum dots (MTSQDs) [1-3] and demonstrated to be highly spectrally-uniform single photon sources (SPSs), and established their single photon emission characteristics (brightness, purity and indistinguishability) to be above the required thresholds for applications in LOQC, quantum communication, metrology, and imaging.

(2) A novel approach to implementing on-chip light manipulating units that exploits a collective Mie resonance of co-designed integrated metastructures of subwavelength scale dielectric building blocks (DBBs) [4,5].

Accomplishments in each of these two areas are briefly summarized below. The details are in the corresponding publications listed.

I. Spatially-Ordered MTSQD Arrays as On-Demand Scalable Single Photon Emitters:

Three accomplishments under this category are highlighted below—the realization of the arrays of ordered single quantum dots as high-quality single photon emitters, their measured HOM two-photon indistinguishability, and a three-level model based theoretical analysis and simulation of the time evolution of the HOM indistinguishability to explain and understand the nature of the quantum emitters

I.1 The basic structure of mesatop single quantum dots (MTSQDs) in spatially-ordered arrays that we established earlier and which has served the objectives of this grant is captured in Fig. 2 (a) and (b). It is a 5×8 arrray of planarized GaAs/InGaAs/GaAs MTSQDs placed on a substrate bearing an AlGaAs/GaAs DBR (distributed Bragg reflector). The DBR enhances the emitted photon collection efficiency from ~1% to ~12%, as shown in Fig.2(c) by the finite element method based simulation of collection efficiency at the first objective lens- indicating 10× enhancement by the DBR. The ~10K emission from these MTSQD arrays around 910nm with a remarkably low nonuniformity of ~3nm is nearly 100% efficient and shows >99.5% single photon purity [ref.3]. The measured HOM based two-photon indistinguishbility and dephasing time are briefly captured next.

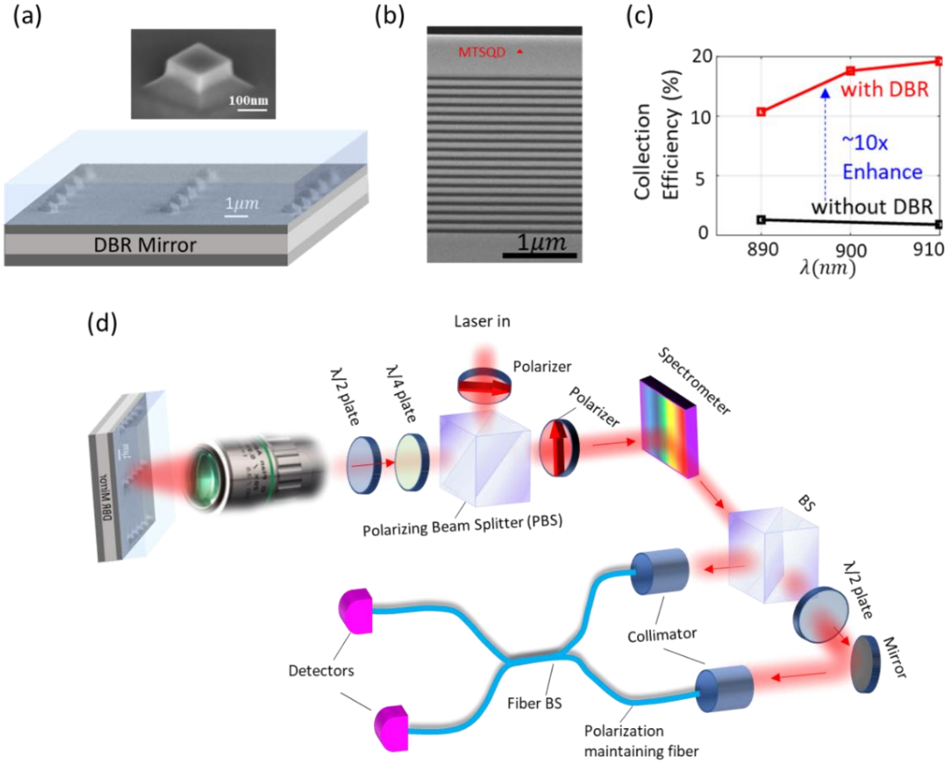

Figure 2. (a) SEM images of the mesa-shape and grown planarized (schematic) In$_{0.5}$Ga$_{0.5}$As MTSQD array on DBR with MTSQD sitting at the apex of the of pedestal as-etched pedestal mesa (SEM in the top panel) (b) Cross-sectional SEM image of the as-grown DBR with planarized MTSQD (shown artificially as the red dot) sitting on 17 pairs GaAs/AlAs DBR. (c) finite element method based simulation of collection efficiency at the first objective lens- indicating 10× enhancement by the DBR. (d) Schematic of the measurement instrumentation including the Hong-Ou-Mandel interferometry *for resonant excitation* where the scattered excitation laser light is filtered out with *a cross-polarization configuration*.

I.2. HOM Indistinguishability (Visibility) under Resonant Excitation

Two Photon Interference (TPI): Indistingushability of emitted photons is the essential characteristic of a quantum emitter for it to be of value to quantum informaiton processing. Traditionally this indistinguishability has been exracted from the HOM configuration to measure two photon interference. We thus carried out TPI using HOM interferometer (Fig. 2(d)).

The MTSQDs are resonantly excited with pulses of 3ps width and at Δt=2ns time interval. Figure 3 (a) shows the measured coincidence counts between the two output ports of HOM interferometer as a function of time difference (τ) between consecutive detection events in the co-polarized (parallel, upper panel). The data have been corrected for the leakage of pulsed excitiation laser under the measurement condition. The two photon interference is manifested in the strong reduction of the coincidence counts at τ=0 in the case of co-polarized configuration as compared to the data taken in the cross-polarized configuration.

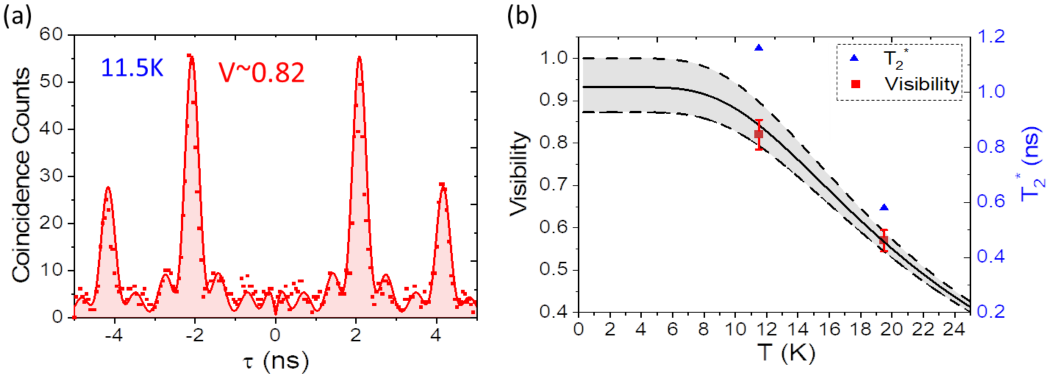

Figure 3. (a) Histogram of coincidence counts of TPI using HOM interferometry with data collected under parallel (upper panel, red triangles) configuration with laser leak corrected. The MTSQD at 10.5K is excited by Ti:Sa laser at 780nm with two pulses separated by 2ns and a repetition rate 78MHz with $\pi/2$ pulse. The red and green curves are the fits to the data using Eq. 1 and 2 (see text), respectively, derived from our three-level model. The HOM coincidence data shows beating patterns ~0.6ns away from main peaks at τ=0, ±2ns and ±4ns. (c) Calculated temperature dependent photon visibility using phonon dephasing time and spectral diffusion time reported for the InGaAs/GaAs material system. The red square shows the measured corrected (see text) visibility of 0.57 at 19.5K, 0.82 at 10.5K.

The TPI visibility can be extracted from the fomula $V = (C_\perp - C_\parallel)/C_\perp$ with $C_\perp (C_\parallel)$ being the total counts in the central peak at τ=0 with orthogonal (parallel) polarization. Using the total counts at the central peak (covering a range of -1ns to 1ns) for $C_\parallel$ and $C_\perp$, we calculate the TPI visibility V ~ 0.55±0.025 at 19.5K. After correcting for the non-zero probability of double excitation of the QDs ($g^{(2)}(0)$ ~ 0.015), we find the TPI visibility to be V_c~0.57±0.025 (red dot figure 3(b)). A total of three MTSQDs picked randomly were measured at ~21K and an average TPI visibility V_c of ~ 0.54±0.04 is found.

The TPI visibility is comparable to the best reported values on QDs in samples without the Purcell enhancement effect *and* at the elevated temperature of ~20K (limited by our cryogen-free cryostat).

With the resonant excitation cutting down on the spectral diffusion induced dephasing, the TPI visibility is largely limited by the phonon induced dephasing. Taking account of the typical known temperature dependence of the exciton dephasing time in InGaAs/GaAs material system, the TPI visibility at 4K is expected to be near unity. As a check on the predicted temperature dependence (Fig. 3(b)), we revived a liquid helium continuous flow cryostat and measured the photon indistinguishability at 11.5K (the base temperature of the cryostat). The measured HOM coincidence counts histogram under parallel configuration is shown in Fig. 3(a). The data indicate an as-measured TPI visibility of 0.80±0.03 and TPI visibility of 0.82±0.03 corrected for multiphoton events.

It can thus be concluded that the MTSQDs in arrays provide spectrally uniform single photon sources that *can generate single photons with near unity purity* and with near-unity photon indistinguishability when integrated in a cavity for a modest Purcell enhancement of ~5 (see below) and operating at 4K.

Dephasing Time. The HOM coincidence count data (Fig. 3), besides providing a value for the TPI visibility, also allow extracting a value for the dephasing time (T_2*) of the photons. In Fig. 3, note the beating pattern accuring at ±0.6ns from the main peaks at τ=0, ±2ns and ±4ns in the measured HOM coincidence data. It shows that the emitted photon wavepacket is in a coherent superposition of the two states separated by 6.4μeV. This is independently confirmed by time-resolved PL data (not shown). The observed beat signal originates from single-photon self-interference, not two-photon interference. At τ=0, note the clear dip with barely any detected coincidence counts. This indicates that the *two-photon* interference at τ=0 at the second beam splitter of the interferometer generates *energy-entangled photon pairs*. The probablity of a two-energy entangled photon pair generation decreases as one moves away from τ=0 as indicated by the observed rise of coincidence counts within τ~200ps.

To understand the intrisic physics, we used a three-level model to calculate the evolution of states. The HOM coincidence counts $g_{||}^{(2)}(\tau)$ and $g_{\perp}^{(2)}(\tau)$ can be respresented as,

$$g_{||}^{(2)}(\tau) = \int_0^\infty dt\, e^{-\frac{2t}{T_1}} \sin^2\left(\frac{\Delta}{2}t\right) \sin^2\left(\frac{\Delta}{2}(t+|\tau|)\right) \left[1 - e^{-\frac{2|\tau|}{T_2^*}}\right] e^{-\frac{|\tau|}{T_1}} \tag{1}$$

$$g_{\perp}^{(2)}(\tau) = \int_0^\infty dt\, e^{-\frac{2t}{T_1}} \sin^2\left(\frac{\Delta}{2}t\right) \sin^2\left(\frac{\Delta}{2}(t+|\tau|)\right)\ e^{-\frac{|\tau|}{T_1}} \tag{2}$$

We used Eq. 1 and 2 to analyze the measured data with the known decay lifetime T_1 and Δ obtained from the time-resolved PL data using Maximum Likelihood method to estimate the dephasing time T_2^*. The instrument response function was folded into the fitting as well. The fitting (red curve shown in upper panel of Fig. 3) leads to T_2^*~0.58ns. Such a long dephasing time is also clearly seen in the *time-resolved* HOM coincidence counts plot shown in Fig. 4 where the coincidence counts ($\propto g^{(2)}(t_1, t_1+\tau)$) corresponding to photon detection at time t_1 and $t_1+\tau$ at the two detectors are plotted as a funciton of t_1 and τ. The break at τ=0 and the rise of coindience counts with a scale of 200ps is clearly revealed in the measured data shown in Fig 4 (a) (see the right expanded plot).

I.3 Simulation of the *Time Evolution* of HOM Indistinguishability

To further understand the HOM indistinguishability measurements shown under Achievement 1 above, we undertook studies of time evolution of the coincidence count in the HOM measuremenst. To this end, a fully quantum picture of the interference of two photon-wavepackets is employed. Each single photon wavepacket emitted from the SQD is modelled as a photon emitted from a 3-level system as we reported in [6], as $|\Psi_{Photon}(t)\rangle = \int_0^t f(t) a^\dagger(t)\, dt$ where $f(t) \propto \left(e^{-i\Delta\, t}\, e^{-\frac{t}{2T_1^{(a)}}} - e^{-\frac{t}{2T_1^{(b)}}}\right)$, Δ is the fine structure splitting between the two exciton states, and $T_1^{(a)/(b)}$ are the corresponding radiative decay life times. The time resolved HOM coincidence counts ($\propto g^{(2)}(t_1, t_1+\tau)$) corresponding to photon detection at time t_1 and $t_1+\tau$ at the two detectors is estimated as [6],

$$\begin{aligned} g^{(2)}(t_1, t_1+\tau) &\\ = |f(t_1-\Delta T)f(t_1+\tau-2\Delta T)|^2 &+ |f(t_1+\tau-\Delta T)f(t_1-2\Delta T)|^2 \\ + |f(t_1)f(t_1+\tau-2\Delta T)|^2 &+ |f(t_1+\tau)f(t_1-2\Delta T)|^2 \\ + |f(t_1)f(t_1+\tau-\Delta T)|^2 &+ |f(t_1+\tau)f(t_1-\Delta T)|^2 \\ + 2|f(t_1-\Delta T)f(t_1+\tau-\Delta T)|^2 &\left[1-e^{-\frac{2|\tau|}{T_2^*}}\right] \end{aligned} \tag{3}$$

The calculated response $g^{(2)}(t_1, t_1+\tau)$ using our three-level model and dephasing time T_2^* of 0.58ns is shown in Fig 4 (b). The calculation matches the measured data (Fig. 4(a)) and thus supports the validity of the three level model of the MTSQD exciton and the dephasing time of $T_2^* \sim 0.58ns$. *Such a long dephasing time has, to the best of our knowledge, not been reported for SAQDs and appears to be unique to MTSQDs.*

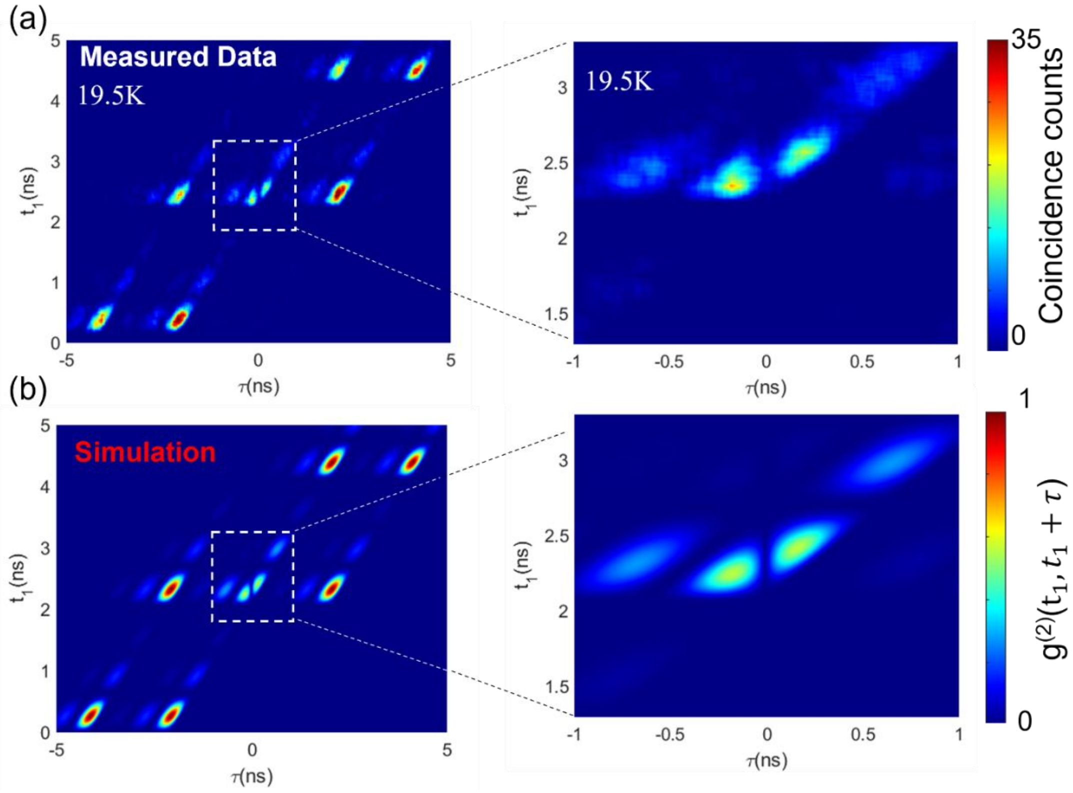

Figure 4. (a) Measured result of time-resolved HOM coincidence counts. The coincidence counts are plotted as a function of detector 1 detection time (t_1) and the time difference between detection event of the two detectors (τ). (b) Simulation results from the three-level model based on the known emission dynamics parameters.

In summary, we demonstrated the first realization of on-chip spatially-ordered (to within a few nm) solid-state quantum emitters that pave the way to fabrication and study of a variety of quantum photonic information processing networks. This is enabled by the substrate-encoded size-reducing epitaxy (SESRE) based shape and size controlled mesa-top single quantum dots (MTSQDs) in ordered arrays that provide a (so far, the only) highly promising scalable approach to realizing the needed single photon source platform that potentially can satisfy all of the on-chip system level and individual device level requirements (Fig. 5 (a) and (b) below) for enabling monolithic and hybrid (Fig.5(c) below) quantum photonic networks / circuits based on the following required attributes: quantum emitters located at designed positions; amenable to horizontal photon emission and manipulation utilizing the mature 2D photonic crystal (PhC) technology; on-demand emission into appropriately matched PhC waveguide mode with near unity efficiency; having adequate spectral uniformity (nonuniformity within the range of demonstrated on-chip local tuning technologies); and possessing individual device-level requirements of simultaneously near unity internal quantum efficiency, near unity purity per generation pulse, near unity indistinguishability (visibility) for near unity photon detection probability per pulse. The demonstrated characteristics of the MTSQDs make a compelling case for further exploration and rigorous assessment of a potentially viable platform for taking on-chip quantum photonics to the long-awaited next level—creation of well-designed functional quantum optical circuits (schematically shown in Fig. 5 (c)).

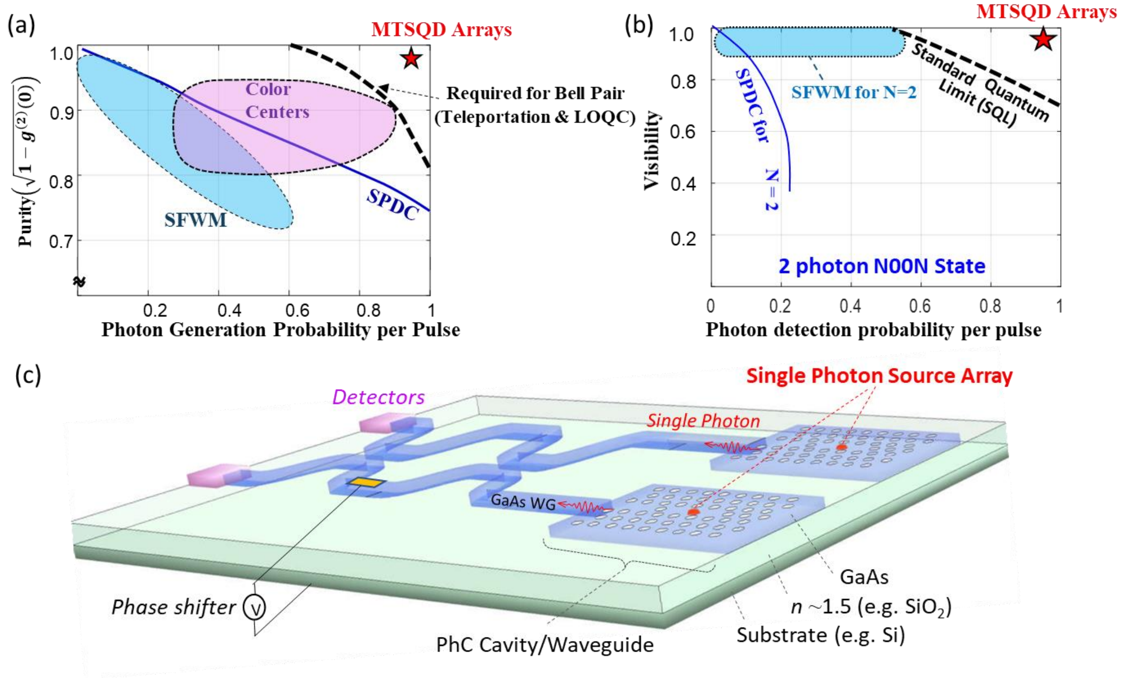

Figure 5. Potential of MTSQD Arrays for Quantum Optical Circuits. The requirements for (a) photon purity vs photon generation probability per pulse for single photon generation for creating linear optical quantum circuits and (b) the visibility vs photon detection probability per pulse of single photon sources for generation of 2 photon N00N states for quantum sensing at the standard quantum limit. Panel (c) is an illustration of an ordered MTSQD enabled on-chip Mach-Zehnder interferometer - the basic functional building block for on-chip quantum optical networks / circuits. Taken from Ref. 6.

II. Collective Mie-Resonance-based Co-Designed On-Chip Integrated Light Manipulating Units: Towards Quantum Optical Circuits

The above recorded demonstration of buried high-quality ordered arrays of single photon emitters has enabled, for the first time, a path to creating scalable on-chip quantum photonic circuits aimed at applications ranging from linear optical quantum computing (LOQC), to secure quantum communication, to metrology and sensing at the Heisenberg quantum limit. The basic building unit for such circuits, however, is the next hierarchical (beyond single quantum emitter) structure comprising the single quantum emitter (here the MTSQD) placed locally in a structure that ensures (i) controlled enhancement of the single (and for some applications, paired) photon emission rate and (ii) unidirectional emission into a guiding mode. Conventionally such light manipulating elements as resonant cavity and waveguides have been fabricated (around selected island QDs or other solid-state quantum emitters from a random distribution) using the well-established photonic 2D crystal approach that exploits creating localized photonic modes by designed introduction of localized defects in an otherwise perfect 2D photonic crystal. Scaling such an approach has been thwarted by the issues of lack of spatially-ordered quantum emitters and of mode /impedance matching between the three states: the quantum emitter (photon), the cavity, and the waveguide. Consequently, under a preceding ARO grant (W911NF-15-1-0298) we proposed bypassing such issues by exploiting a single collective Mie resonance of high refractive index interacting dielectric building blocks (DBBs) of subwavelength size metastructures fabricated around each quantum emitter, the metastructure being, in principle, the interconnected network of the quantum emitters. Under this grant we analyzed and simulated the use of a single collective Mie-like mode of these co-designed metastructures to provide-- in different spatial regions of the metastructure-- the required five functions for creating optical networks: enhancing the SPS emission rate, directing the emission, guiding the photons, beam splitting, and beam combining [1,5]. This eases the difficulty of mode-matching between different regions ("functional components") of the optical network. For the $In_{0.5}Ga_{0.5}As$ alloy MTSQDs emitting ~920nm we demonstrated and reported finite element method (FEM) based simulations of the optical response of circuits involving all five above noted functions in a comprehensive paper [5]. Below we briefly summarize the major accomplishments.

Accomplishment 1: Analysis of a Mie-Resonance based Yagi-Uda Nanoantenna

In the Mie resonance paradigm, the basic *functional photon unit* is implemented using the nanoscale version of the well-known (from radio transmission) Yagi-Uda nanoantenna represented by the first three blocks from the left (two blue and one with the red pyramid indicating the MTSQD in the middle) depicted in Fig.6(a). The remainder of the bule blocks to the right represent the region of "waveguiding" the emitted photon. The interference of the collective magnetic and electric dipole-based Mie resonance provides and controls the directional emission of the photons into the Mie mode. The simulated results, based upon FEM (finite element method), are for MTSQD emitting at 980nm. Shown as inset in Fig.6(a) is the Poynting vector as a function of position in the metastructure. Panel (b) shows total E-field distribution of the collective Mie mode excited by the 980nm emitted photon plotted on the XY plane passing through the center of the DBBs. Panel (c) shows the Purcell enhancement as a function of wavelength. An enhancement of ~7 is readily obtained. We note this magnitude of Purcell enhancement is quite adequate for the reduction of the MTSQD spontaneous emission time from ~580ps to significantly less than the ~120ps dephasing time of the MTSQDs.

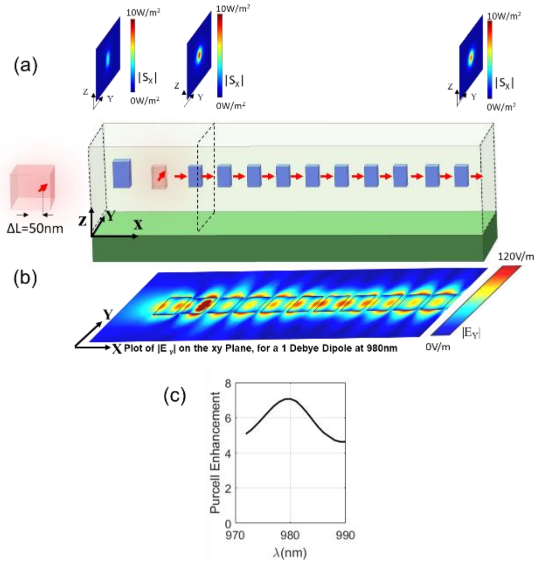

Figure 6. (a) The MTSQD SPS integrated with the nanoantenna-waveguide unit based on rectangular shaped DBBs. As shown in the left inset, the transition dipole representing the MTSQD is placed at ΔL =50nm from the center of the DBB. The DBB containing the MTSQD as well as the DBBs in the waveguide are of size 220nmx220nmx220nm, with a pitch of 275nm. The Reflector DBB of the nanoantenna is of size 220nm×250nm×220nm. The top insets show the cross-sectional distribution of the Poynting vector calculated for 1Debye transition dipole at three different positions along the axis of the nanoantenna-waveguide. (b) Total E-field distribution of the collective Mie mode excited by the source dipole emitting at 980nm plotted on the XY plane passing through the center of the DBBs. c) The Purcell enhancement as a function of wavelength.

Accomplishment 2: Design of Mie-resonance based on-chip functional circuits

The basic MTSQD in a nanoantenna functional unit shown above, when interconnected as shown in panel (a) of Fig.7 below, creates the co-designed metastructure that represents the optical network. The essential added functions, provided by the same collective Mie mode of the enlarged metastructure, are those of beam-splitting and beam-combining as seen in panel (a). Panels (b) and (c) of Fig.7 show the electric field distribution around the two single photon sources (MTSQDs) labeled SPS1 and SPS2 when only one (panel b) and both (panel c) quantum emitters are excited. Note the recombination of the photons in the common branch. This demonstration has opened the pathway for designing and implementing interconnected networks aimed at providing the desired quantum information processing function.

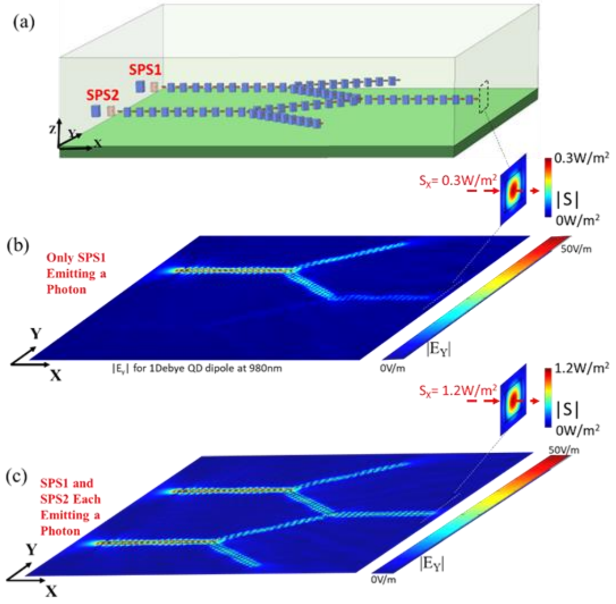

Figure 7. Panel (a) shows two quantum emitters (red blocks) in a DBB (blue blocks) based metastructure coupled to each other through a common Mie resonance mode of the entire metastructure. Panels (b) and (c) show the finite element method based calculated Poynting vector magnitude distribution in the metastructure. Panel (b) depicts excitation of one quantum emitter whereas panel (c) shows the behavior for *simultaneous* excitation of both the quantum emitters.

Accomplishment 3 : Quantum field theoretic analysis of SQD-SQD interaction mediated by a common Mie resonance of a DBB based waveguide.

Under this grant we also undertook the important step of understanding coupling of two distant MTSQD single photon sources mediated by the DBB based Mie resonant metastructures. To this end, quantum field theoretic analysis was carried out for a metastructure comprising two coupled SQDs in a back-to-back nanoantenna-waveguide substructures as shown in Fig. 8(a). Owing to the lossless nature of the collective Mie mode, such a structure allows long range super-radiance effect wherein the collective emission of a single photon from the two SQDs is ~1.7 times faster compared to the situation with only one SQD [5]- as shown in Fig. 8(b).

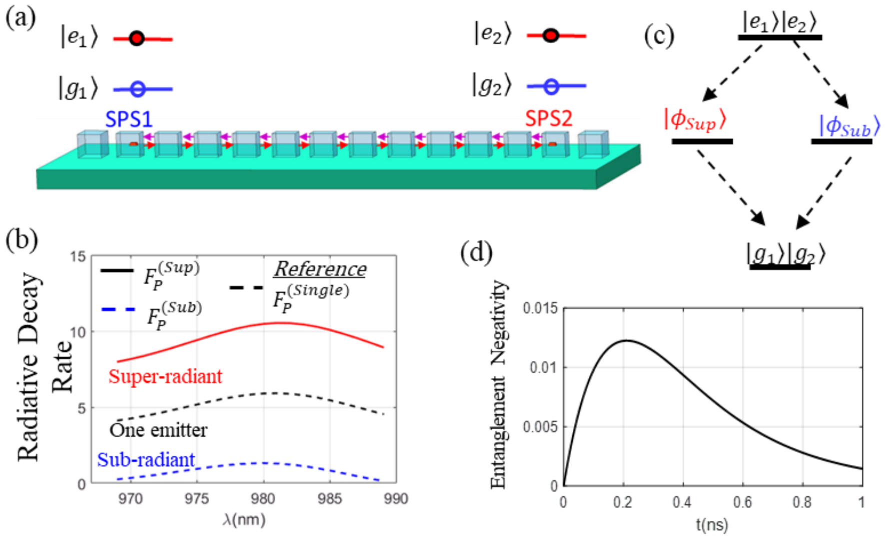

Figure 8. (a) Back-to-back nanoantenna waveguide structure where two distant SPSs are coupled via the same collective magnetic dipole mode of the DBB metastructure. (b) Super-radiant decay rate enhancement the coupled SPSs in (a) analyzed using the classical EM Green function. (c) Level transition diagram for decay in the two-excitation Hilbert space. $|\phi_{Sup}\rangle$ and $|\phi_{Sub}\rangle$ represent the superrradiant and subradiant states respectively. (d) Degree of entanglement (black line) as a function of time showing emergence of entanglement of the coupled SPS system.

To account for the two-photon processes, we employed a fully quantum Von-Neumann Lindblad approach [7] that accounts for both coherent and incoherent decay processes in the generic two-exciton Hilbert space, indicated in level transition diagram in Fig. 8(c). We demonstrated that, starting from a pure product state ($|e_1\rangle|e_2\rangle$), the Mie resonance mediated photon emission results in emergence of entanglement between the distant SQDs, as shown in Fig. 8(d). The approach and the result for the simple structure of Fig. 8 provides the framework to analyze larger and more complex SQD-DBB quantum optical networks towards various applications of quantum information processing.

References / Publications:

1. J. Zhang, S. Chattaraj, S. Lu and A. Madhukar, "Mesa-top quantum dot single photon emitter arrays: Growth, optical characteristics, and the simulated optical response of integrated dielectric nanoantenna-waveguide systems," J. Appl. Phys. **120**, 243103 (2016).
2. J. Zhang, S. Chattaraj, S. Lu and A. Madhukar, "Highly pure single photon emission from spectrally uniform surface-curvature directed mesa top single quantum dot ordered array", Appl. Phys. Lett. 114, 071102 (2019)
3. J. Zhang, S. Chattaraj, Q. Huang, L. Jordao, S. Lu and A. Madhukar, "Buried spatially-regular arrays of spectrally uniform single quantum dots as on-chip scalable single photon sources for quantum optical circuits", APL photonics, **5,** 116106 (2020).
4. S. Chattaraj and A. Madhukar, "Multifunctional all-dielectric nano-optical systems using collective multipole Mie resonances: toward on-chip integrated nanophotonics", Jour. Opt. Soc. America B **33**(12), 2414-2555 (2016).

5. S. Chattaraj, J. Zhang, S. Lu, A. Madhukar,” On-Chip Integrated Scalable Single Photon Source-Optically Resonant Metastructure based Quantum Optical Circuits”, IEEE Jour. Quant. Elec. **56**, 1, 9300109 (2020).
6. J. Zhang, S. Chattaraj, Q. Huang, L. Jordao, S. Lu and A. Madhukar, “On-chip scalable highly pure and indistinguishable single-photon sources in ordered arrays: Path to quantum optical circuits”, Sci. Adv. 8, eabn9252 (2022).
7. S. Chattaraj, “Studies on All-Dielectric Mie Resonant Metastructures for On-Chip Optical Circuits in Classical and Quantum Regimes”, Ph. D Dissertation, University of Southern California (2021); S. Chattaraj, “Quantum Theory of the Emergence of Emitter-Emitter Entanglement in Dielectric Mie Resonance-Mediated On-Chip Light Manipulating 2D Optical Metastructures”, (To be published).

VI. Copies of technical reports

None