

NBIT Phase II Final Report

Project Title: Integrated Nano Optoplasmonics

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Integrated electronic circuits have revolutionized how we generate and process information, but large-scale information transmission is performed primarily using photons. Photonic circuits can be faster and have larger bandwidth compared to their electronic counterparts, but many scientific and technical challenges remain for these circuits to become reality. First, the miniaturization of photonic circuit to the true nanometer scale is difficult due to the optical diffraction limit. Second, nonlinear interactions between photons (e.g. blockade and switching), an essential requirement for information processing, cannot be implemented without realizing strong light-matter interactions. The goal of the proposed research effort (Joint PI: Professor Moon-Ho Jo at POSTEC) was to realize integrated nanoscale optoplasmonic devices by leveraging the expertise of Korean and US PIs. Toward this end, we worked on two distinct, yet related, research fronts: (1) fabrication of active photonic/plasmonic devices that are made of nanoscale photonic/plasmonic cavities coupled to quantum emitters, and (2) fabrication of electrically driven photon/plasmonic sources and detectors on chip. During the grant period, we made solid progresses toward these goals, producing five publications in leading journals (one in *Phys. Rev. Lett.*,¹ one in *IEEE J. Sel. Topics Quantum Electron.*,² and three publications in *Nano Lett.*^{3,4,5}) and one additional publication on the unexpected side project on quantum-emitter based temperature sensing (published in *Nature*⁶). In addition, we are preparing two more manuscripts for submission based on our NBIT Phase II efforts.^{7,8} The progresses that we made during the grant period are summarized below.

Nanoscale Photonic/Plasmonic Cavities: Techniques for controlling light-matter interactions in engineered electromagnetic environments are essential for the realization of photonic/plasmonic devices. In atomic physics/quantum optics and solid-state photonics, two approaches are commonly employed to enhance the coupling between optical emitters and confined electromagnetic modes. One strategy is to increase the lifetime of the confined optical excitation in high-quality factor (Q) dielectric resonators, such as whispering gallery structures, micropillars, and photonic crystals (PCs). Another strategy is to reduce the effective cavity mode volume (V_{eff}) well below the diffraction limit, as is currently being explored with nanoscale plasmonic structures.

During the grant period, we experimentally demonstrated a new method to realize a plasmon resonator with an exceptionally small mode volume that can drastically modify the interaction between a quantum emitter and propagating surface plasmon polaritons (SPPs).^{1,2} Our approach makes use of a plasmon resonator composed of defect-free, highly crystalline silver nanowires surrounded by patterned dielectric distributed Bragg reflectors (Fig. 1). These resonators have an effective mode volume (V_{eff}) two orders of magnitude below the diffraction limit and quality factor (Q)

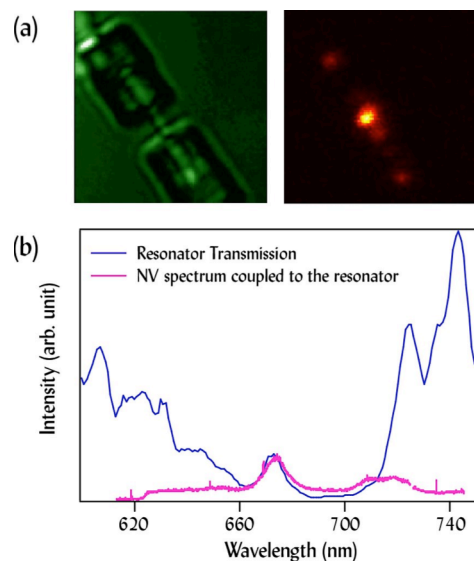


Fig. 1. (a) Scanning confocal microscope images of the device. The left panel shows an image of the reflected green laser light. The right panel shows fluorescence image in the red when the laser is focused onto the NV in the cavity. (b) The fluorescence spectrum of the NV collected from the end of the NW (red) shows significant modification, which corresponds to the transmission spectrum of the device (black).

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 16 DEC 2013		2. REPORT TYPE Final		3. DATES COVERED 30-06-2010 to 29-06-2013	
4. TITLE AND SUBTITLE Integrated Nano Optoplasmonics (NBIT Phase II)			5a. CONTRACT NUMBER FA23861014064		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Hongkun Park			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Harvard University,12 Oxford Street,Cambridge 02138,United States,MA,02138			8. PERFORMING ORGANIZATION REPORT NUMBER N/A		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AOARD, UNIT 45002, APO, AP, 96338-5002			10. SPONSOR/MONITOR'S ACRONYM(S) AOARD		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) AOARD-104064		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The goal of the proposed research effort (Joint PI: Professor Moon-Ho Jo at POSTEC) was to realize integrated nanoscale optoplasmonic devices by leveraging the expertise of Korean and US PIs. Toward this end, we worked on two distinct, yet related, research fronts: (1) fabrication of active photonic/plasmonic devices that are made of nanoscale photonic/plasmonic cavities coupled to quantum emitters, and (2) fabrication of electrically driven photon/plasmonic sources and detectors on chip. During the grant period, we made solid progresses toward these goals, producing five publications in leading journals.					
15. SUBJECT TERMS nano materials, nano science and technology, nano technology, Nanobiotechnology					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 4	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

approaching 100, enabling enhancement of spontaneous emission rates by a factor exceeding 75 at the cavity resonance. As shown in Fig. 1, the fluorescence of a quantum emitter (the nitrogen vacancy (NV) center in diamond) changes drastically upon fabrication of the plasmon cavity. Before resonator fabrication, the plasmon-coupled NV fluorescence exhibits a broad spectrum spanning a range of 630-740 nm. After resonator fabrication, the plasmon-coupled NV spectrum exhibits a peak on resonance with the cavity mode and suppressed fluorescence within the stopband (Fig. 1(b)). These resonators can thus be used to convert a broadband quantum emitter to a narrowband single-photon source with color-selective emission enhancement.

We also reported a three-dimensional fabrication technique for constructing a variety of diamond nanophotonic structures using anisotropic plasma etching.^{3,4} Despite the fact that the NV centers has attracted a significant attention for a variety of solid-state photonic applications, such as a stable source of single photons at room temperature and as an optically addressable solid-state spin qubit, lack of scalable nanofabrication techniques capable of realizing complex three-dimensional nanostructures in diamond has been the major limiting factor to more widespread application of diamond in nanoscale science and technology. In order to overcome this problem, we developed an angled etching technology that can be used to fabricate free-standing nanoscale components in bulk single-crystal diamond and fabricated nanobeam mechanical resonators, optical waveguides, and PC and microdisk cavities.

In addition, we demonstrated a new approach for realizing a flexible PC cavity that enables wide-range tuning of its resonance frequency.⁵ Our PC cavity consists of a regular array of silicon nanowires (NWs) embedded in a polydimethylsiloxane (PDMS) matrix, forming a mechanically compliant composite structure (Fig. 2). Because the dielectric contrast of our PC is essentially the inverse of that found in a traditional PC cavity defined on a high-index semiconductor substrate, our PC cavity supports transverse magnetic modes (the electric field of the cavity mode is polarized along the NW length and perpendicular to the PC plane). We used both finite-element and finite-difference time-domain simulations to design and optimize the NW dimensions and spacing. These NW-polymer PC cavity can support several well-defined resonant modes with theoretical quality (Q) factors exceeding 4,000, and exhibits a cavity resonance in the telecommunication band that can be reversibly tuned over 60 nm via mechanical stretching – a record for two-dimensional (2D) PC structures. This study demonstrates that a combination of high-index dielectrics and stretchable polymeric materials can be used to construct flexible PC cavities with broadband, controllable, and reversible frequency tuning. In coming years, we plan to construct flexible photonic crystal cavities using diamond nanowire arrays, where the cavity resonance can be tuned to the zero-phonon line of nitrogen-vacancy centers for quantum electrodynamics experiments.

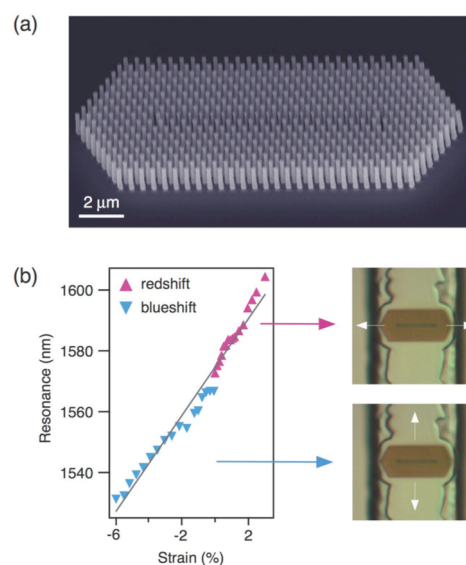


Fig. 2. (a) Scanning electron microscope image of a PC cavity tilted at 45°. Design dimensions: regular NW diameter is 200 nm; defect NW diameter is 140 nm; NW length is 1.2 μm . (b) Resonance (e1) shift as a function of strain along the cavity. The black line is a linear fit. Strain is defined as the percentage change of the cavity length. Two stretching directions were explored (as shown in the optical images): along or orthogonal to the line defect.

Electrically Driven Photon/Plasmon Sources and Detectors on Chip: SPPs can be confined and guided on a variety of smooth interfaces, including those between metal nanowires and air or dielectric nanowires and metals. SPPs can confine light far below the free-space diffraction limit, resulting in strong electric fields that enhance light-matter interactions and optical nonlinearities. However, these highly

confined SPP modes have a large momentum mismatch with far-field light, making optical coupling into and out of SPP modes a significant challenge, particularly as the SPP becomes more confined.

Near-field interfaces have recently been shown to be an efficient way for generating and collecting SPPs. Several studies have demonstrated that near-field coupled photoluminescence from single-photon emitters, such as quantum dots and NV centers in diamond, can be efficiently converted into SPPs propagating on waveguides. In the NBIT Phase I research, we also demonstrated on-chip electrical detectors for propagating SPPs (*Nature Phys.* 2009), suggesting that an efficient and seamless integration of small-footprint electronics and plasmonics may be possible. To date, however, all of these studies relied upon far-field optical coupling for either SPP generation or detection.

During the NBIT Phase II grant period, we demonstrated the first prototypical near-field-coupled plasmonic circuits wherein SPPs are both generated and detected electrically on chip. In our circuit design, an Ag nanowire lies across two parallel GaAs nanowires (Fig. 3).⁷ The SPP source is based on inelastic electron tunneling across one of the Ag/GaAs junctions, which results in electroluminescence (EL) that couples both to the far field and to SPPs propagating along the Ag nanowire. The electrical SPP detector relies upon near-field excitation of photocurrent in another GaAs nanowire. We measured the coupling efficiencies between the SPP waveguide and the near-field source and detector to be 30% and 6%, respectively, higher than or comparable to the corresponding far-field coupling efficiency for these SPP waveguides. Finite-difference time-domain simulations indicate that these efficiencies can be further improved with proper geometry optimization and with smaller nanowires, suggesting a path forward for efficient electrical SPP circuits with very small footprints.

In addition, we also demonstrated an electrically driven single SPP source, where a single quantum emitter (colloidal quantum dot) is excited near-field by a built-on-chip light emitting diode (Fig. 4).⁸ In this device, the coupling between the quantum emitter and nearby plasmonic nanostructure subsequently creates single SPPs. The device studied here represents the first demonstration of on-chip electrical/electro-optical generation of single SPPs. The wide spectral range covered by various types of colloidal quantum dots means that the operation frequency of the device can be easily tuned from visible to near infrared. This proof-of-principle realization demonstrates the potential of integrated plasmonic devices in quantum information processing and cryptography.

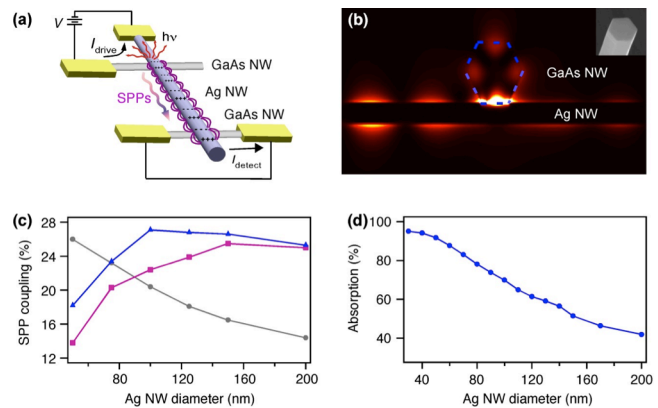


Fig. 3. (a) An illustration of a nanowire-based plasmonic circuit in which SPPs are generated and detected in the near field. (b) The mode profile in both the GaAs and Ag nanowires using FDTD simulation. The Ag nanowire diameter is 100 nm and the GaAs nanowire edge-to-edge diameter is 277 nm. The inset shows the hexagonal cross section of a GaAs nanowire. (c) Coupling efficiency from dipole in GaAs nanowire to SPP modes, as a function of Ag nanowire diameter with varying dipole distances of (•) 15, (▲) 30 and (■) 45 nm. (d) At $\lambda = 700$ nm, the percentage of dipole energy absorbed by the GaAs detector as a function of Ag nanowire diameter.

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