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Efficient Coupling to Plasmonic Nanoresonators using On-chip Silicon Nitride Integrated Photonic Structures

Maysamreza Chamanzar, Siva Yegnanarayanan, Ehsan Shah Hosseini, Ali Adibi
School of Electrical and Computer Engineering, Georgia Institute of Technology,
Atlanta, GA, USA 30332

ABSTRACT

We demonstrate a hybrid integrated photonic-plasmonic platform in which photonic guided modes are used to efficiently excite localized surface plasmon resonance (LSPR) modes of plasmonic nanoresonators. Efficient coupling of light to the LSPR modes of plasmonic nanoresonators is demonstrated by tight integration of plasmonic nanoresonators on silicon nitride (SiN) microresonators. It is shown that by integrating gold nanoparticles with SiN microresonators, we can achieve high coupling efficiencies (>35%), resulting in large field enhancements. We will discuss the design, fabrication, and characterization of the hybrid platform which consists of gold nanoparticles integrated with SiN microring resonators.

Keywords: Plasmonics, Integrated optics, Microresonators

1. INTRODUCTION

Plasmonic nanoresonators show localized surface plasmon resonance (LSPR) modes. These resonances have very small mode volumes and can localize light beyond diffraction limit and they provide ultrahigh field enhancements that can be used in a variety of applications ranging from surface enhanced Raman spectroscopy (SERS) [1] to nonlinear optics [2]. Plasmonic nanoresonators are made in different shapes such as nanodisks [3], nanorods[4] , bowties [5], and nanoshells [6] and from different materials such as gold and silver. By changing the size and shape of the plasmonic nanoparticles LSPR modes can be tuned from visible to infrared range of the spectrum and different levels of field enhancements can be achieved. Plasmonic nanoparticles are either fabricated using top down fabrication techniques or they are chemically synthesized [7]. The LSPR modes of these plasmonic nanoparticles are usually excited using free space optics by focusing light using a lens on the nanoparticles either dispersed in a solution or immobilized on a substrate. In practice, many of these nanoparticles are interrogated to obtain an appreciable level of signal to be detected. The ability to efficiently couple light to individual plasmonic nanoresonators is necessary to realize practical devices. Also, it makes the study of resonance behavior of plasmonic nanoresonators possible without the interference effect of a collection of these nanoresonators. There have been some efforts to characterize the resonance behavior of single plasmonic nanoresonators [8, 9]. The coupling of light to the LSPR mode of single nanoresonators is not usually efficient and only a small portion of the incident power is coupled to the LSPR modes. For example a gold nanorod with an aspect ratio of 3.9 and an effective radius of r_{eff} = 21.86 nm has an extinction cross section of 3.04×10^{-14} m^2 [10]. This means that if this nanorod is excited using a light source polarized along the long axis of the nanorod and focused with a lens onto a focal spot of 5μm, only 0.17% of the incident power is coupled to the LSPR mode of this nanorod. It should be noted that part of this light which is coupled to the LSPR mode of the nanoparticle is absorbed and part of it is scattered by the nanoparticle depending on the ratio of the absorption cross section to the scattering cross section of the plasmonic nanoparticle. In this paper we propose and demonstrate a hybrid plasmonic-photonic resonator structure in which light is efficiently coupled to the plasmonic resonance mode of plasmonic nanoresonators integrated with photonic microresonators. The design, fabrication, and experimental characterization of this hybrid resonator structure are discussed in this paper.

2. Theory and Design

The proposed hybrid resonator structure is illustrated in Fig. 1. It consists of a photonic integrated microring resonator made in a silicon nitride (SiN) platform on silicon dioxide (SiO_2) substrate integrated with a plasmonic nanoparticle on

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top. Throughout this paper we assume that the plasmonic nanoparticle is a gold nanorod; however, the architecture can be realized with different types of plasmonic nanoresonators. In this structure light is coupled to the bus waveguide which carries the light to the vicinity of the hybrid resonator. Light is then coupled to the SiN microring resonator mode and travels around the ring resonator and is gradually coupled to the plasmonic nanoresonator mode through the evanescent tail of the microring resonator mode.

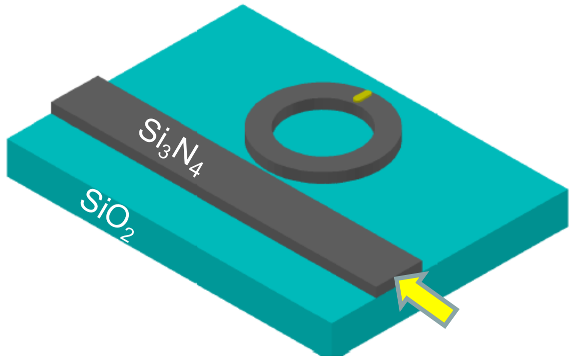

Fig. 1 Schematic illustration of the hybrid resonator structure. Light is coupled to the bus waveguide and is carried to the vicinity of the hybrid resonator and is then coupled to the hybrid resonator and travels around the SiN ring resonator, which gradually couples light to the nanorod LSPR mode.

In order to analyze and design the structure we use scattering matrix analysis method to relate the lightwave at the input of the waveguide to the modes of the plasmonic and photonic resonators. We define the coupling efficiency as the ratio of the input power which is coupled to the LSPR mode of the plasmonic nanoresonator mode. In order to design the structure, we first assume that the microring has a radius of 20 μm and dimensions of (700×200nm). It should be noted that if the width and the thickness of the microring are large, then the extension of the mode outside the core of the microring becomes small and the LSPR mode cannot be efficiently excited. On the other hand if the width and the thickness of the microring are very small the microring mode can be cut off. Therefore, the dimensions of the ring resonator should be chosen in such a way that the coupling of microring resonator mode and the plasmonic nanoresonator mode is strong and at the same time the propagation loss is minimum and the quality factor is large. The plasmonic nanoresonator is assumed to be a gold nanorod with dimensions of 100nm×56nm×30nm which has a resonance at a wavelength of λ_0=764.68nm.

We first assume the weak coupling regime, in which the gap between the waveguide and the microring is large. This way only the interaction between the microring and the plasmonic nanoresonator is investigated. The transmission and the reflection of the bus waveguide coupled to the hybrid resonator structure are plotted in Fig. 2a and Fig. 2b, respectively for the weak coupling regime in which the coupling Q is much larger than the intrinsic Q of the SiN microring, i.e. ($Q_c = 1x10^6$, $Q_0 = 1.5x10^4$). It can be seen that the effect of the plasmonic nanorod is a broadening of the resonance lineshape in the transmission spectrum. Without the nanorod, there is no reflection, which means that the input light is not coupled to the counter propagating mode in the microring resonator. However, with the gold nanorod both clockwise and counterclockwise modes are excited in the microring resonator and part of the input light is reflected.

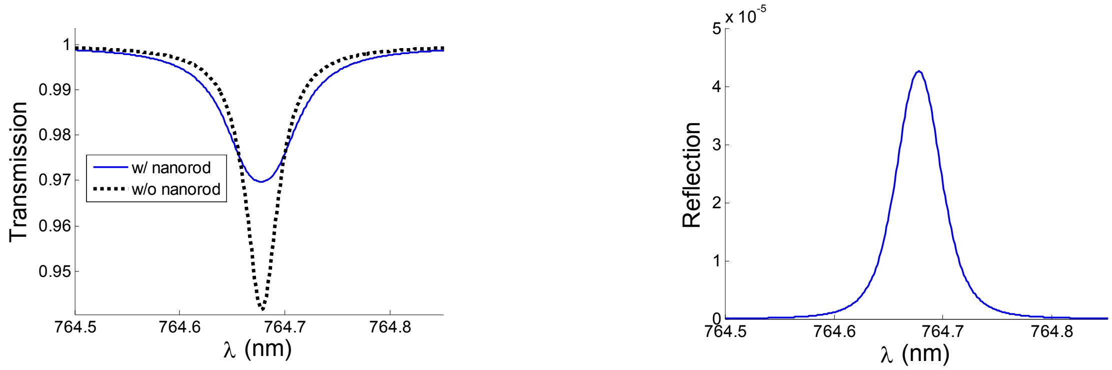

Fig. 2 (a) Transmission of the bus waveguide coupled to a 20 μm microring resonator with dimensions of 700×200nm without nanorod (dashed line) and with nanorod of dimensions 100×56×30nm (solid line). (b) Reflection spectrum.

The coupling efficiency spectrum for this structure is calculated and plotted in Fig. 3 for different values of coupling Q (Q_c), where it can be seen that for a coupling Q of Q_c=10400, the coupling efficiency has a maximum of 0.38. This means that 38% of the input power is coupled to the LSPR mode of the plasmonic nanoresonator.

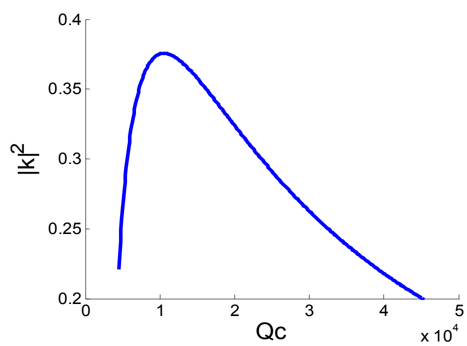

Fig. 3 Coupling efficiency to the LSPR mode of the plasmonic nanorod versus the coupling Q (Q_c) from the bus waveguide to the hybrid resonator structure.

Under optimum conditions obtained from Fig. 3, we have calculated the coupling efficiency spectrum which is shown in Fig. 4. It can be seen that the envelope of this coupling efficiency spectrum follows the lineshape of the nanoresonator LSPR mode and is sampled by the sharp resonances of the dielectric resonator. It can be seen from the inset of Fig. 4 that a large coupling efficiency is achieved over several modes of the hybrid resonator separated by the free spectral range (FSR).

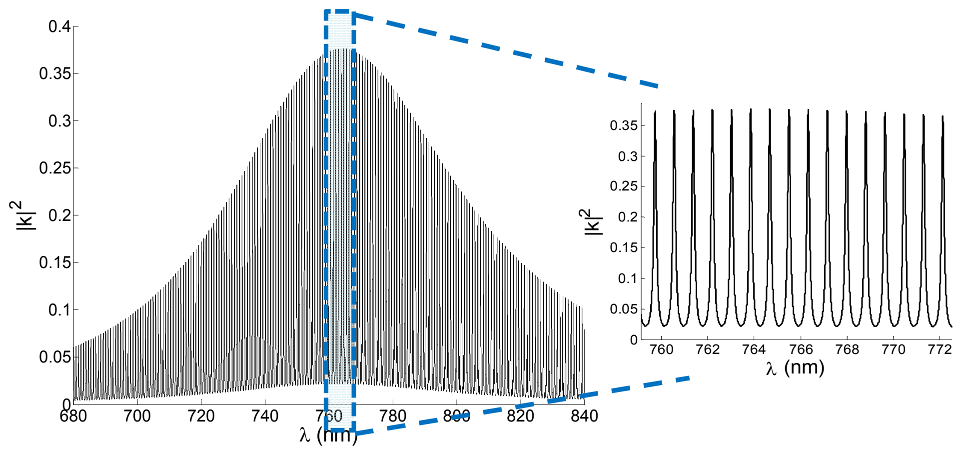

Fig. 4 Coupling efficiency spectrum to the LSPR mode of the plasmonic nanorod (100×56×30nm) over a broad range of wavelengths. The envelope of the coupling efficiency spectrum follows the plasmonic resonance lineshape. The inset shows the portion of the coupling efficiency spectrum near the resonance peak where it can be seen that a large coupling efficiency of about 38% is possible over several of the hybrid resonator modes.

3. FABRICATION

The hybrid structure is fabricated using a two-step electron beam lithography. In the first step ZEP 520A is used as the electron beam resist. The photonic structure is defined using electron beam lithography. In the next step, inductive coupled plasma (ICP) etching is used to realize the waveguide and the microring resonator in SiN. In the next step, Polymethyl methacrylate (PMMA) is spin coated on the sample and the plasmonic nanoresonator structure is defined using electron beam lithography. Then gold is deposited using electron beam evaporation and finally a lift-off process is carried out. Different steps of the fabrication process are shown in Fig. 5.

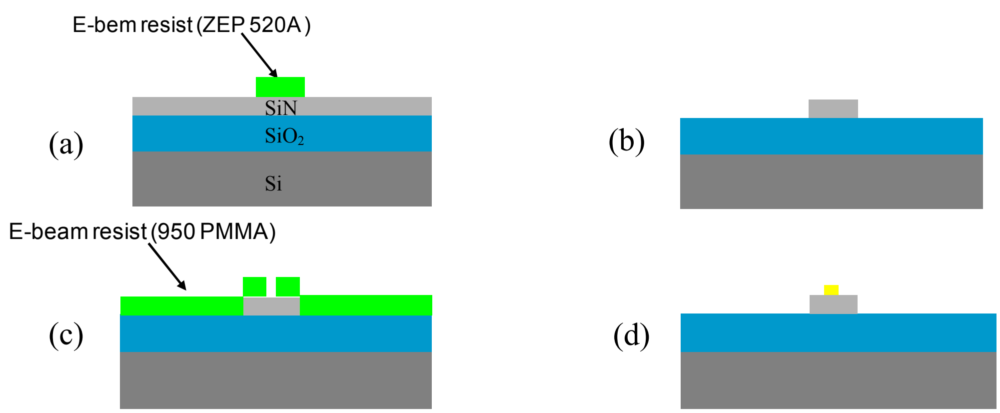

Fig. 5 (a) First step of electron beam lithography using ZEP 520A as the e-beam resist to define the photonic structure. (b) Inductive coupled plasma etching to realize the photonic structure. (c) Second step of lithography to define the plasmonic nanoresonator using PMMA as the electron beam resist. (d) Lift-off process to realize the plasmonic structure.

It should be noted that the alignment between the two steps of lithography is important. Fig. 6 shows the scanning electron micrograph (SEM) of a hybrid resonator structure in which the microring has a radius of 20μm and dimensions of 880×200nm. The gold nanorod has dimensions of 100.3×56×30nm.

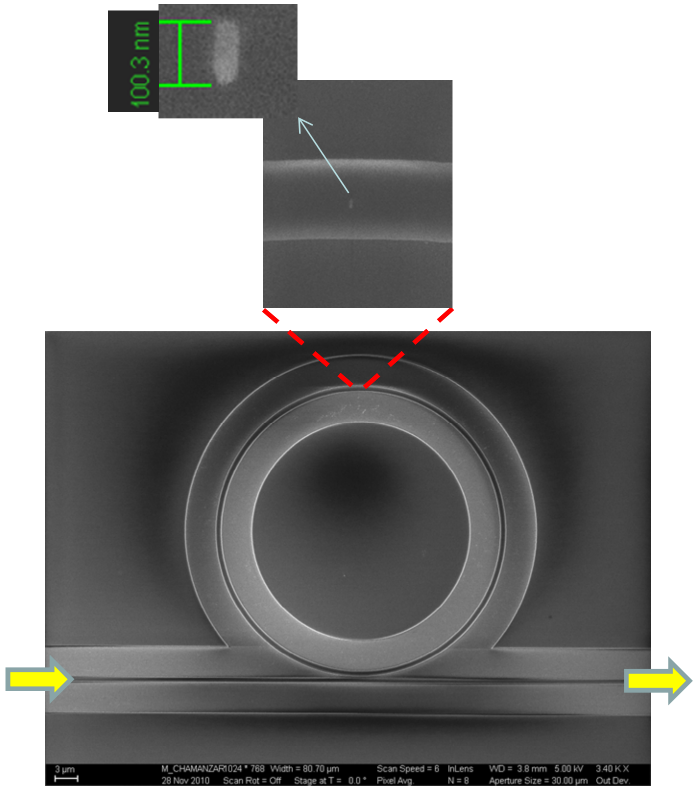

Fig. 6 Scanning electron micrograph (SEM) of a 20μm ring with dimensions of 880×200nm integrated with a gold nanorod (100.3×56×30nm).

4. Characterization

The hybrid resonator structure is characterized using an in-plane characterization setup in which light from a tunable laser source is coupled to the bus waveguide and is then coupled to the hybrid resonator structure. The output of the bus waveguide is coupled to a silicon detector. The scattering of the structure is imaged from top using an objective lens into a camera. The transmission of a bus waveguide coupled to a 20μm microring with dimensions of 880×200nm is plotted in Fig. 7 without a nanorod (blue curve) and with a nanorod of dimensions (100.3×56×30nm). It can be seen that the structure without nanorod has a loaded Q of $Q_L = 1.7\text{x}10^4$ and a coupling Q of $Q_c = 1\text{x}10^5$. The structure with nanorod has a loaded Q of $Q_L = 1.55\text{x}10^4$. By fitting the theoretical model to these measurements we can find out that the coupling efficiency is about 10% (i.e., $|k|^2=0.1$).

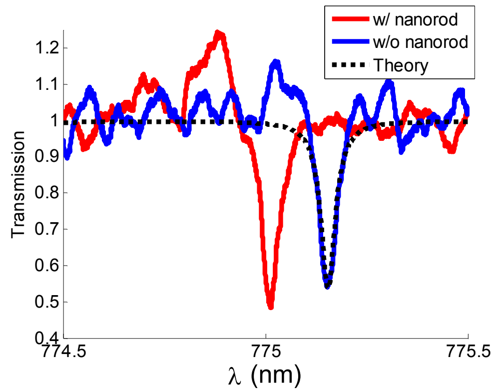

Fig. 7 Transmission spectrum of a bus waveguide coupled to a hybrid resonator consisting of a 20μm ring with dimensions of 880×200nm integrated with a gold nanorod with dimensions of 100.3×56×30nm (Red curve). The blue curve shows the transmission spectrum without the nanorod. The dashed curve shows the theory result.

The microscope image of the hybrid structure near the resonance of the hybrid resonator structure at λ=775.1 nm is shown in Fig. 8, where it can be seen that the scattering from the plasmonic nanorod is very strong which indicates efficient coupling of light to the LSPR mode of the nanorod.

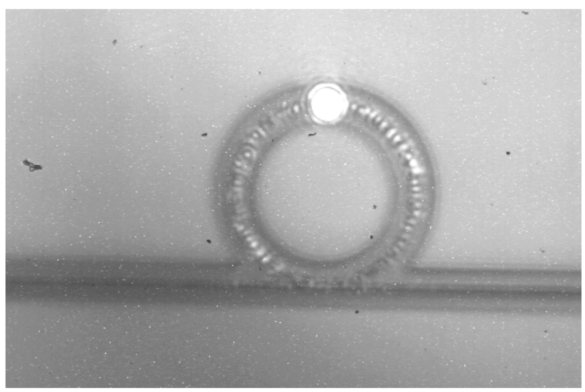

Fig. 8 Microscope image looking from top of a 20μm ring with dimensions of 880×200nm integrated with a gold nanorod with dimensions of 100.3×56×30nm. The structure is excited at a resonance wavelength of λ=775.1. The bright scattering from the gold nanorod indicates efficient coupling to the LSPR mode of the gold nanorod.

5. Conclusions

In this paper, a hybrid plasmonic-photonic integrated resonator structure is introduced. We have shown that by proper design of the coupling structure, more than 35% of the input power can be coupled to the LSPR mode of individual plasmonic nanoresonators. The proposed structure is realized in SiN platform and can be used in visible and near-infrared range of the spectrum. We have shown experimentally that about 10% coupling efficiency is possible. This can be further improved to reach the theoretical predictions by improving the fabrication and optimizing the structure. It should be noted that the proposed structure is realized on a chip in an integrated platform. Therefore, this structure can be used as a building block to make an integrated circuit by combining several of these hybrid resonators designed for different resonance wavelengths. Also, the advantage of this structure is that it is not alignment sensitive and once light is launched into the bus waveguide, the LSPR mode of the plasmonic nanoresonator is excited and there is no stringent requirement on the alignment. This hybrid structure can open up new potentials for different practical applications of plasmonic nanoresonators such as SERS, light generation, manipulation, and localized heating.

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