Plasmonic-Photonic Hybrid Nanodevice: A New Route Toward 3D Light Harnessing

Ali Belarouci, Taiping Zhang, Than Phong Vo, Ségolène Callard, Pedro Rojo-Romeo, Xavier Letartre, Pierre Viktorovitch
Institut des Nanotechnologies de Lyon (INL), UMR 5270 CNRS-ECL-INSA-UCBL
Ecole Centrale de LYON, 36, Avenue Guy de Collongue, F - 69134 Ecully Cedex
Fax: (33) (0)478433593 - Tel: (33) 0472186066 - E-mail: ali.belarouci@ec-lyon.fr

ABSTRACT
We propose and demonstrate a hybrid cavity system in which an optical nano-antenna (NA) is evanescently coupled to a dielectric photonic crystal (PC) cavity. While the plasmonic component leads to strongly localized fields, photon storage mechanism is provided by the surrounding photonic crystal structure. The combined effect of plasmonic field enhancement and high quality factor opens new routes for the control of light-matter interaction at the nanoscale.

1. INTRODUCTION

In recent years, we have witnessed a flurry of activity in the fundamental research and development of surface plasmon based structures and devices [1]. Their unique properties enable a wide range of practical applications, including optical devices [2], optical energy transport [3], near field scanning optical microscopy [4], surface-enhanced spectroscopies [5], and chemical and biological sensors [6]. The present surge in plasmon based research is happening at a time where crucial technological areas such as optical lithography, optical data storage, and high density electronics manufacturing are approaching fundamental physical limits. Surface plasmons are collective charge oscillations that occur at the interface between conductors and dielectrics. They exist in two forms, propagating and localized. On a flat smooth film, the surface plasmon polaritons (SPPs) are propagating at the metal-dielectric interface. Localized surface plasmon resonances (LSPRs) are not propagating electromagnetic waves; rather they are localized electromagnetic fields near the surface of the isolated nanoparticles. Although it may seem that metallic nanoparticles (or optical antennas) are almost an off-the-self product, some issues need special attention and specific research. A key challenge is to address and collect light from those nano-scale systems. The tiny active area of the optical antenna is both an advantage for its miniaturization, and a real limit for the level of the collected signal. Therefore, one needs to reconsider how to drive efficiently such nano-antenna. We propose to tackle this important issue by designing and realizing a novel nano-optical device based on the use of a PC cavity to generate an efficient coupling between the external source and a nano-antenna. Nano-antennas are usually illuminated from the far field in a large, at best diffraction limited, focus. However, this procedure is not very efficient to address metallic micro-nano-structures or NAs. The reason lies in the difficulty to achieve a sufficient coupling rate between the incoming optical beam and the NA in order to compensate for the rather large optical losses (radiation to free space and metallic absorption). A new approach is proposed in the present work for the optimum addressing of NA with a free space optical beam via the use of an intermediate coupling resonator structure, which is aimed at providing the appropriate modal conversion of the incoming beam, in the time domain. Details of the PC-NA coupling analysis and its optimization were published elsewhere [7]. The efficiency of the coupling between the nano-antenna and a slow-Bloch mode depends both on the spectral tuning and the spatial overlap between the mode and the NA. To address the issue of optimal positioning of an emitter inside a cavity and to investigate its coupling with the SBM, it is crucial to know the actual field intensity profile on a much smaller scale than the wavelength, typically the length of the nano-antenna gap. For that purpose, near-field scanning optical microscopy (NSOM) has proved to be an invaluable tool because it allows access to spatial distributions that are not accessible with far-field techniques. In this work, we use an optical near-field microscopy to probe the coupling between a slow Bloch-mode (SBM) and a NA.

2. STRUCTURE DESIGN AND SIMULATION

The basic photonic design is 2D graphite PC lattice of cylindrical air holes (with a lattice parameter A = 730nm and a 245 nm hole diameter) patterned in a 240 nm thick InP membrane bonded on top of a SiO_2 substrate. The resonant structure is designed to exploit a low curvature band-edge mode located at the center of the first Brillouin zone, i.e., the Γ point. The band diagram is reported on Fig. 1 and calculated using the plane wave expansion method for an infinite structure. Among the different surface addressable band-edge modes located at the Γ point, we took advantage of the monopolar mode (M) corresponding to the lowest energy flat band and presenting a good overlap of the electromagnetic field intensity and the semiconductor material.

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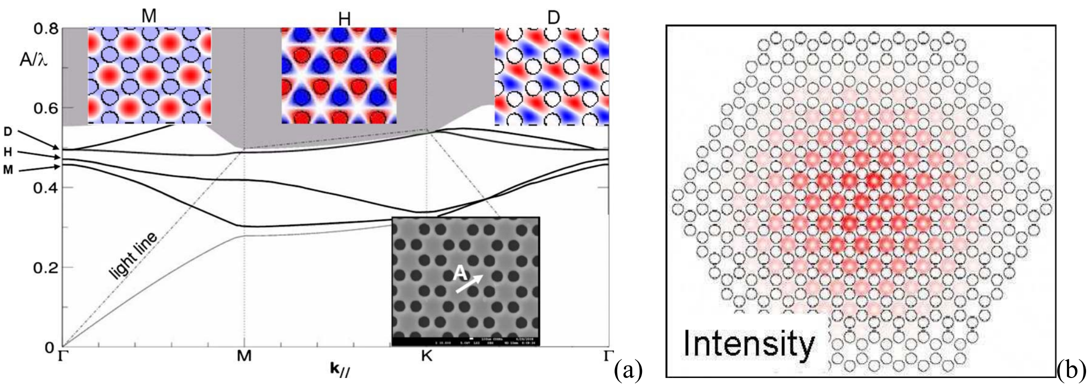

Figure 1: (a) Band diagram of the 2D PC structure. The frequency is expressed in units of A/λ, for transverse-electric (TE) modes, A being the lattice parameter of the graphite structure. The three bands indicated in bold correspond to the monopolar (M), hexapolar (H) and dipolar (D) modes of the PC structure. The corresponding maps of the electromagnetic field (Hz component) are indicated in the top insets. (b) Monopolar mode intensity pattern at the center of the slab by 3D-fdtd calculation.

We modelled optical bowtie antennas on InP/SiO_2 substrate using 3D-fdtd calculation. The plasmonic structure consists of two coupled gold triangles separated by a 30 nm gap. Geometrical parameters are optimized to tune the optical response to 1.5 µm (Fig. 2). The electric field enhancement in the gap normalized to the incident intensity can reach few hundreds.

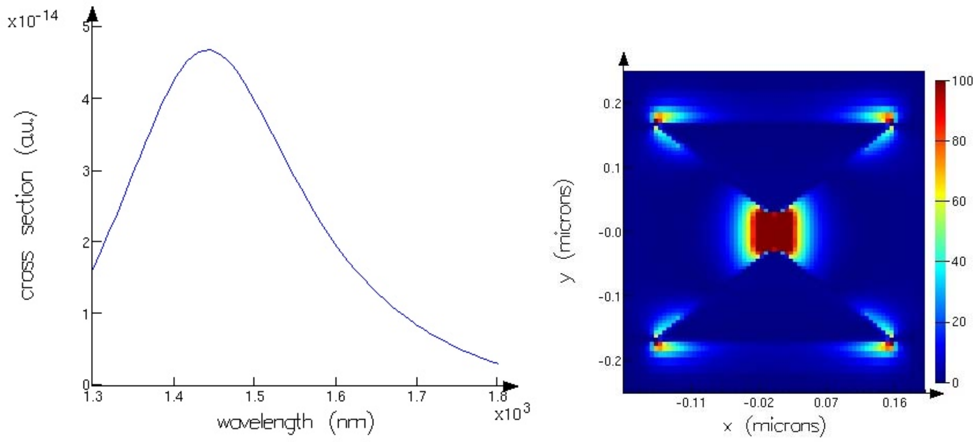

Figure 2. Numerical simulation of the NA optical response (extinction cross section on the left) and the total electric field intensity enhancement with respect to the incident intensity. The enhancement reaches values of few hundreds near the middle of the gap.

3. FABRICATION

As the dielectric building block of the hybrid device we use a graphite PC lattice of air holes formed in an active high refractive index InP-based membrane. The III-V heterostructures were grown by solid source molecular-beam epitaxy. A 300 nm-thick sacrificial/etch-stop layer of $In_{0.53}Ga_{0.47}As$ is grown on a 2-inch InP(001) wafer. Then, a 250 nm InP layer, including InAsP quantum wells as active material for light emission in the 1.5 µm range, is deposited. The structure is then transferred on a silica substrate using SiO_2–SiO_2 wafer bonding. The InP substrate and etch stop layer are eliminated by selective wet chemical etching. A 90nm-thick SiO_2 layer is then deposited on the top of the sample by plasma assisted sputtering as a mask layer for the etching process. Processing of the PC is done by electron beam lithography on a polymethylmethacrylate (PMMA). Reactive ion beam etching (RIBE) is used to open the holes in the SiO_2 layer with a CHF_3/N_2 mixture. The hard mask pattern is transferred to the semiconductor material by reactive ion etching (RIE) with a CH_4/H_2 mixture combined with O_2 plasma cycling. The lateral size of the fabricated structures is 30×30 µm^2. Individual metallic nano-antennas are then deterministically positioned on the backbone of the PC cavity by a second e-beam exposure followed by a lift-off process. A bilayer resist system has been investigated for positive tone lift-off and optical antennas with gap sizes down to 10 nm have been successfully produced (Fig. 3a). Overlay measurements showed that the deviation in the alignment error could be as small as 50 nm. The SEM picture of the final structure is reported on figure3b.

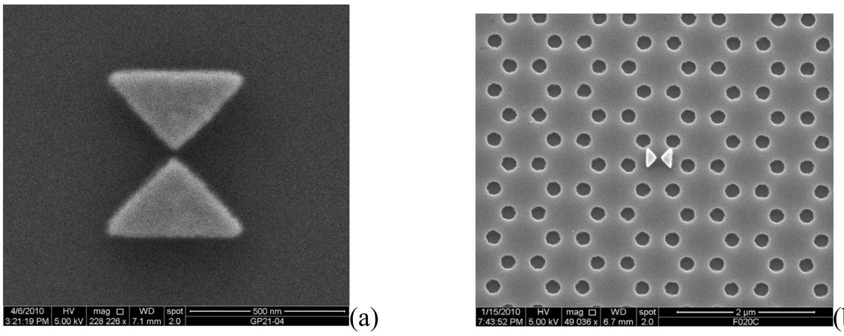

Figure 3: SEM image of an optical nano-antenna (a) and the plasmonic-photonic nano-device (b).

4. EXPERIMENTAL RESULTS

The NSOM experimental set up is presented in Fig. 4a. It uses a stand alone commercial head (NT-MDT SMENA), positioned at the top of an inverted microscope. The NSOM is working in collection mode: a polymer metalized tip collects the photoluminescence (PL) in near-field at the surface of the sample, the PL signal is sent to a monochromator (1 nm resolution) and a thermo-electrically cooled InGaAs photodetector. The PC structures are optically pumped at 780 nm with a pulsed laser diode (with a 10% duty cycle) and modulated at 2 kHz. In this set up the sample is pumped from the back side. The collimated laser beam is focused on the 2D-PC through the silica substrate with a corrected objective (NA = 0.75). The excitation spot focused on the surface has a Gaussian profile and a surface area less than 10 µm by 10 µm. In this configuration, topographic and photoluminescence images are recorded simultaneously.

The topographic and near-field images of the PC alone are shown in Fig. 4b. In each unit cell of the PC, small doughnuts are clearly visible underlining the monopolar nature of the mode. The metalized probe succeeds to reveal the fine structure of the slow Bloch mode with typical doughnut dimensions of 310 nm for the outer radius and 70 nm for the inner radius which is consistent with the theoretical predictions (see Fig. 1). Experiments are under progress to investigate the near field optical coupling of the NA and the PC resonator.

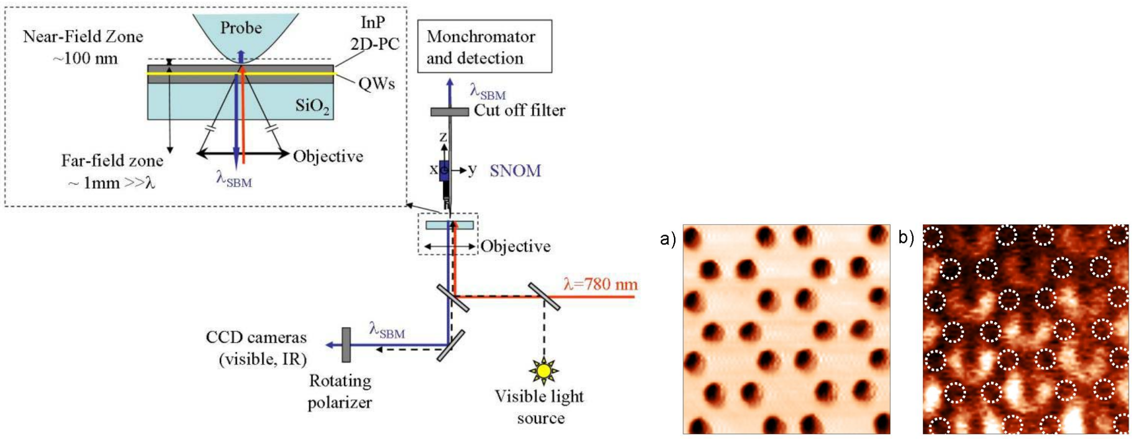

Figure 4: Experimental set-up for near-field and far-field analysis (a) and topographic- optical near-field images of the PC structure without antenna (b).

5. CONCLUSION

We designed and realized a novel nano-optical device based on the exploitation of a photonic crystal cavity to drive efficiently a single optical antenna. This type of hybrid structure can exhibit both high quality factors and pronounced hot spot of the electromagnetic field, potentially enhancing the interaction of the cavity mode with emitters or other types of active materials. This novel system may open the route to applications in integrated opto-plasmonic devices for quantum information processing, as efficient single photon sources or nanolasers, or as sensing elements for bio-chemical species.

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