Beam shaping using a chain of photonic nanojet induced plasmonics

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***Abstract*—Photonic nanojet arises from a microcavity leading to high electric field. On the other hand, metal nanoparticles (NPs) lead to high field due to localization in small volumes. In this work, PNJ from an array of cavity induced plasmon resonances has been studied. The sharp profile of the PNJ has been observed by the inclusion of NPs.**

***Index Terms*—Photonic nanojet, localized surface plasmon resonance (LSPR), PNJ induced LSPR, hybrid microcavity, SERS**

I. Introduction

Semi-transparent microcavities with symmetric structures form an intense and narrow beam from their shadow sides (Fig. 1). The emerging beam is known as photonic nanojet (PNJ) and is formed due to the lensing action of the microcavity. Such a beam can propagate distances longer than the incident wavelength. PNJ is characterized by electric field enhancement, length, width and working distance. The PNJ widths smaller than the classical diffraction limit ($\sim \lambda/2$) have been demonstrated. PNJ has been found to be useful in applications such as Raman spectroscopy [1], nonlinear optics [2], optical waveguides [3], single nanoparticle detection and manipulation [4] and nanopatterning [5].

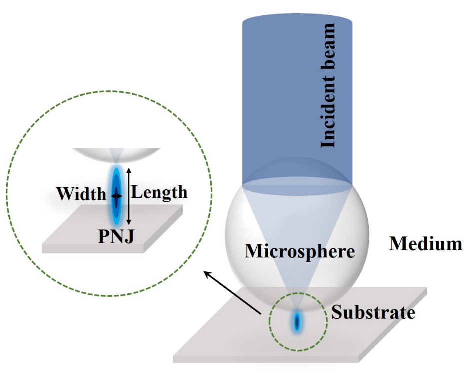

Fig. 1. Schematic of PNJ generation from a microsphere.

Metal nanoparticles (NPs) give rise to plasmon resonances when excited with wavelength larger than their size. Such resonances are known as localized surface plasmon resonances (LSPRs). LSPRs arise due to the coherent oscillations of the free electrons present on the surface of the NP with the incident oscillating field. Due to localization of field in small volumes, the electric field density in the vicinity of NPs are extremely high. LSPRs find applications in sensing, nonlinear optics, surface enhanced Raman spectroscopy (SERS), photocatalysis and photodynamic therapy [6].

PNJ when combined with LSPR result in field enhancement over a range of wavelength [7]. LSPRs strongly depend on the shape of the NP manipulating the LSPR properties. In this work, we have simulated the electric field due to PNJ induced LSPR. An array of microcavities have been formed to generate multiple PNJ. Gold (Au) NPs have been used as single and coupled (dimer) NPs to take advantage of field localization.

II. Numerical modelling

Two dimensional (2D) finite element method (FEM) using COMSOL multiphysics 5.2 is employed to simulate the scattered electric field from a microcavity and a gold nanoparticle (AuNP). Wave optics module is used to specify and obtain the input and output results in the form of electromagnetic fields. A Gaussian beam of the beam spot $20\mu m$ and wavelength $488nm$ is considered as the excitation beam. The beam propagates in the negative y-direction (top to bottom) and is x-polarized. The diameter of the microsphere is kept to be $8\mu m$ with refractive index of 1.45. An array of the microspheres is formed in which the microspheres are in contact with each other. A parameter sweep over a range of wavelength is performed due to the wavelength dependent LSPR of AuNP. The optical properties of AuNP are taken from the work of Johnson and Christy [8].

III. Results and discussions

A. PNJ of an array of cavities

Initially a single microsphere was simulated to observe the PNJ at 488 nm. The PNJ was found to vary with the beam size, and the size and the refractive index of the microsphere. After that, an array of microspheres was simulated to observed three separate PNJs (Fig. 2(A)) at 488 nm. The width profile of the PNJ (Fig. 2(B)) shows the PNJ corresponding to each cavity having width nearly equal to the incident wavelength. The field strength of the central PNJ is highest as compared

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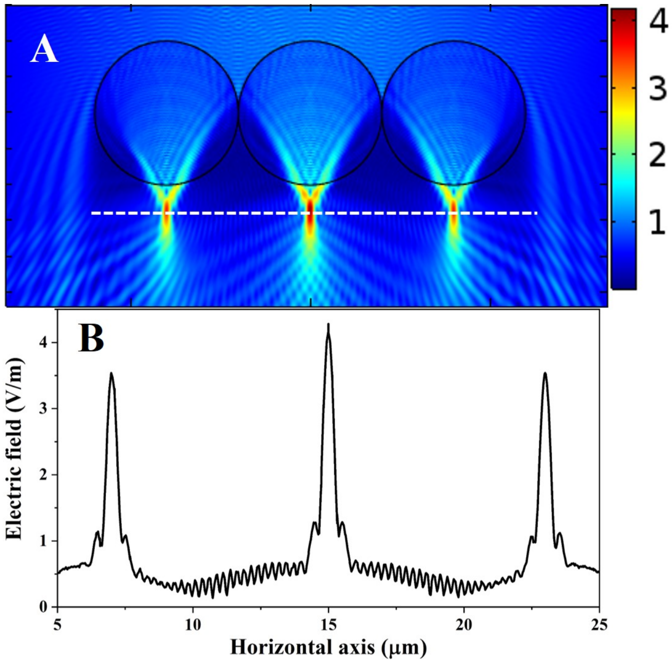

Fig. 2. Scattered field distribution (A) and width profile (B) due to an array of microspheres of diameter $8\mu m$ and refractive index 1.45. Color bar denotes the field strength.

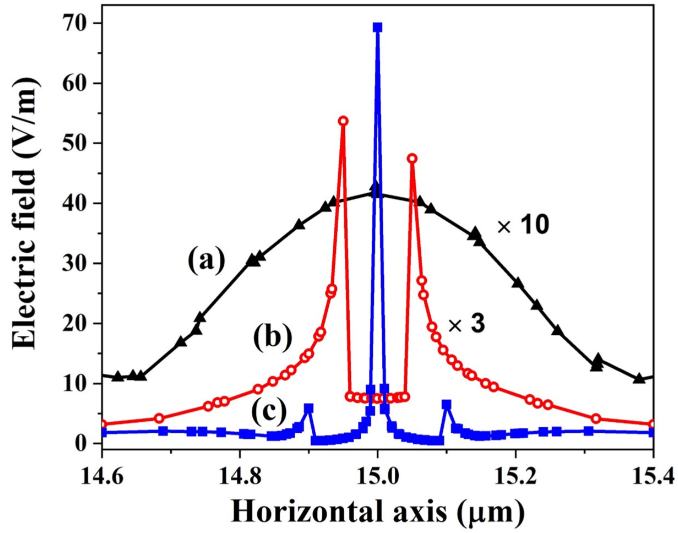

Fig. 3. Width profiles of central PNJ of an array of microspheres without (a), with single NP (b) and NP dimer (c).

to the accompanying PNJs due to the maximum coupling of the input beam.

B. PNJ induced LSPR

A single elliptical AuNP of aspect ratio 2 is placed at the focus of the PNJ and the maximum field is found at 560 nm. As seen in Fig. 3, the electric field is observed to be increased as compared to that without AuNP (curve (a)). In addition, the PNJ profile has a structure similar to a quantum potential well (curve (b)). This is due to the fact that field cannot penetrate the metal surface but has the maximum strength on the surface.

When a dimer is coupled with microsphere to form hybrid system, it leads to strong LSPR-LSPR coupling besides the PNJ-LSPR coupling. In addition, the maximum field is shifted at 700 nm. The PNJ profile in this case has a structure similar to double potential wells (curve (c)). Also, the change in the field ratio of potential well has been found to be higher for the case of NP dimer as compared to that of single NP.

IV. Conclusions

In summary, the PNJs formed by an array of dielectric microspheres have been investigated. The intensity of the central PNJ has been found to be maximum due to the maximum coupling of the incident beam. On inserting a single elliptical AuNP in the focus of the PNJ, the field enhances as well as the PNJ splits into two narrow beams. This is due to the localization of the electric field near AuNP. This field further enhances for the case of a dimer of AuNP. In addition, the strong LSPR-LSPR coupling between the dimer NPs, the field has been found to be maximum at the coupling point. The PNJ obtained due to microcavity-NP hybrid system has found to be ultra-narrow as compared to that from the microcavity alone. This works can be used to manipulate the PNJ parameters and utilize them for applications such as nanopatterning and superresolution.

Acknowledgment

We thank Dr. Soumyodeep Dey for fruitful discussions during initial part of this work. We acknowledge financial support from Science and Engineering Research Board (SERB), New Delhi (Sanction no. CRG/2021/000136).

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