Plasmonic nanofocusing of light in an integrated silicon photonics platform

Boris Desiatov, Ilya Goykhman and Uriel Levy*

Department of Applied Physics, The Benin School of Engineering and Computer Science, The Center for Nanoscience and Nanotechnology, The Hebrew University of Jerusalem, Jerusalem, 91904, Israel

*ulevy@cc.huji.ac.il

Abstract: The capability to focus electromagnetic energy at the nanoscale plays an important role in nanoscience and nanotechnology. It allows enhancing light matter interactions at the nanoscale with applications related to nonlinear optics, light emission and light detection. It may also be used for enhancing resolution in microscopy, lithography and optical storage systems. Hereby we propose and experimentally demonstrate the nanoscale focusing of surface plasmons by constructing an integrated plasmonic/photonic on chip nanofocusing device in silicon platform. The device was tested directly by measuring the optical intensity along it using a near-field microscope. We found an order of magnitude enhancement of the intensity at the tip’s apex. The spot size is estimated to be 50 nm. The demonstrated device may be used as a building block for “lab on a chip” systems and for enhancing light matter interactions at the apex of the tip.

©2011 Optical Society of America

OCIS codes: (250.5403) Plasmonics; (240.6680) Surface plasmons.

References and links

1. Introduction

Localization of optical energy at the nanoscale by using surface plasmon polariton (SPP) modes has been proposed and investigated in various applications: nanosensing [1,2], microscopy [3,4] and quantum optics [5,6]. In the past ten years different geometries of SPP waveguide for light concentration were studied and demonstrated like thin films [7], channel and v-groove waveguides [8–10], metal-dielectric-metal (MDM) and dielectric-metal-dielectric (DMD) waveguides [11–13]. Further enhancement of electromagnetic energy density via nanoscale focusing of surface plasmon waves has been proposed and demonstrated by using different approaches such as metallic plasmonic lenses [14–16], tapered metallic probes [17–22], metallic coated dielectric tips [23,24] and other sub-wavelength structures [25–27]. The integration of surface plasmonic devices with the well-developed on-chip photonic platform require efficiency coupling between these two platforms. Very recently theoretical and experimental works [28–31] showed the ability of direct coupling between photonic waveguides and surface plasmonic devices. In this paper we present the realization (design, simulation, optimization, fabrication and measurement) of an on-chip integrated approach by coupling light from the silicon photonic platform directly into the plasmonic nanoscale focusing device.

The device consists of a dielectric tip surrounded by metallic cladding. The electromagnetic energy is first propagating in the dielectric waveguide, coupled into the MDM tip and finally is being concentrated at the apex of the tip. A schematic drawing of our device with the calculated electromagnetic intensity distribution is presented in Fig. 1a and Fig.1b.
2. **Numerical simulations of coupling between dielectric and MDM waveguide**

At first we investigate a coupling mechanism between the photonic waveguide and the plasmonic tip. To do so, we replace the MDM tip by a MDM waveguide. In order to couple light into nanoscale we use the “butt coupling” approach [30] where the MDM structure is positioned in-line after the silicon nanowaveguide. Figure 2a shows the geometry of the device. We use the Finite-Element-Method (FEM) to calculate the electric field distribution inside the dielectric and the MDM waveguide with different dimensions at a wavelength of 1550 nm. The height of the dielectric waveguide and MDM structure was chosen to be 250nm. Figure 2c shows a fundamental in-plane (transverse electric, TE) mode ($n_{\text{eff}} = 2.79$) of a 1-micron wide silicon waveguide (refractive index of 3.46), on top of a silicon dioxide substrate (refractive index of 1.46). Figure 2d and Fig. 2e show the same field component calculated for MDM structures of 950 and 450 nm width respectively, where the metal is assumed to be gold with relative permittivity of $\varepsilon = -131.95 + 12.65i$ at the wavelength of 1.55μm. For these parameters, the effective indexes are $n_{\text{eff}} = 3.17 + 0.00494i$ and $n_{\text{eff}} = 3.25 + 0.0049i$ respectively. Clearly, there is a large difference in the electric field profile between the dielectric waveguide mode (Fig. 2c) and the MDM structure mode (Fig. 2d) with the same dimensions. By calculating an overlap integral and taking into account a Fresnel reflection due to the different propagation constants of the modes we found the coupling efficiency between these two modes to be around 30%. On the other hand, we found the coupling efficiency between the 1 micron width dielectric waveguide and the 450 nm width MDM structure to be around 70%. However, it was shown that the overlap integral does not necessarily provide accurate results because of additional plasmonic assisted coupling mechanism [32]. Therefore, we also verify these results by using three-dimensional (3D) Finite-Element-Time-Domain (FDTD) [33] simulations to calculate the power flow from the dielectric waveguide into the MDM structure. The Au permittivity is assumed to follow the Drude model, including damping [34]. The simulated structure is shown in Fig. 2a. To calculate the coupling between the dielectric waveguide and the MDM waveguide, we launch the fundamental TE-like waveguide mode into the dielectric waveguide and we measure the power flux along the simulated structure in the dielectric and the MDM waveguides. These power fluxes were normalized with respect to infinity long dielectric and the MDM waveguide respectively. The coupling efficiency was defined as the ratio between the power flux in dielectric waveguide before the dielectric-MDM interface and the power flux in MDM waveguide after the interface. Figure 2b shows the snapshot of the electric field (Ey component) distribution taken at the center height of the simulated structure. In general, the results calculated by the 3D FDTD simulations were very similar to the results found by the direct calculation of the coupling efficiency by the mode overlapping technique. The difference between the two approaches was smaller than 5%.
To find the optimal parameters we calculate the coupling efficiency between the photonic waveguide and the MDM structure as a function of the waveguide width and the MDM width. The results of these calculations are shown in Fig. 3.

![Figure 3](image)

Fig. 3. Coupling efficiency between dielectric photonic waveguide and MDM structure as function of waveguide and MDM widths.

We found the maximal coupling efficiency to be 75% for a dielectric waveguide width of 950 nm and an MDM width of 450 nm. The result was verified by the 3D FDTD simulations.

3. Numerical simulation of focusing devise

Next, we performed a fullwave electromagnetic simulation to study the focusing properties of the proposed device. The simulated structure is presented in Fig. 4. We performed a 3D FDTD simulation in order to calculate the time average electric field distribution in our structure. The simulated device consists of a 900 nm width and 250 nm height silicon...
waveguide core on top of the silicon dioxide. The silicon waveguide is butt coupled to the silicon tip with a 450 nm base width, 250nm height, 2 micron length and 10nm diameter rounded apex. We launched the fundamental in-plane transverse electric (TE) mode into the silicon waveguide at wavelength of 1550nm. Figure 4a shows a cross section of the time average electric field intensity distribution along the horizontal plane at the top of the silicon waveguide. At the apex of the tip the electric field intensity is enhanced by factor of 50 compared to the average electric field intensity in the silicon waveguide. Figure 4b shows a vertical cross section of the simulation result. Ones can clearly see that electromagnetic field is concentrated in the apex of the tip.

![Fig. 4. Calculated electric field intensity distribution of silicon tip surrounding by metal along the a) horizontal direction. b) vertical direction.](image)

The simulated waveguide supports the fundamental and the second (anti-symmetric) TE waveguide modes. We repeat the FDTD simulation by launching the anit-symmetric TE waveguide mode and we didn’t observe any focusing at the apex of the tip. Therefore, in experimental characterization, the excitation of anti-symmetric TE waveguide mode should not affect the field distribution at the apex of the device. It may only affect the efficiency, but this limitation can be mostly overcome by the use of symmetric coupling conditions, allowing to launch the fundamental mode into the silicon waveguide.

4. Fabrication

After validating the focusing properties of the proposed structure numerically, we turn into experimentally demonstrating the confinement of electromagnetic energy at the apex of the tip. We fabricate the device using a silicon-on-insulator (SOI) wafer with an upper silicon layer of 250 nm on top of a 2 micron buried oxide (BOX) substrate. The silicon waveguide and the tip were defined by electron-beam (ebeam) lithography (Raith e_line 150) followed by inductively coupled plasma (ICP) reactive ion etching (RIE) (Oxford Plasmalab 100). Next, the metallic pattern was defined in the ebeam resist by an additional ebeam lithography step with high alignment accuracy. Finally, 200nm thick gold layer was deposited on the structure, followed by a lift-off process. The metal thickness in the fabricated device was different than that of the designed structure. To accommodate this difference, we simulated the exact structure with the real geometry and found that difference in metal and silicon heights decrease the coupling efficiency and the field enhancement at the apex of the tip by ~5-10%.

The fabrication of this device involved three major challenges. The first was to fabricate the silicon tip with the smallest possible apex diameter. To mitigate this goal we used a different expose doses in the ebeam lithography for different parts of the structure to overcome the proximity effect. Using this approach we were able to fabricate silicon tips with 20nm diameter apex as shown in inset on Fig. 5b. The second challenge was to achieve accurate alignment between the first and the second mask used in the lithography process. The third challenge was to fabricate the metallization layer with the minimal possible gap between the silicon tip and the metal side cladding. In order to overcome these last two challenges we
used an overlapping mask design allowing compensating for the ebeam proximity effect and the misalignment errors. In Fig. 5a and Fig. 5b we show a Scanning Electron Microscope (SEM) micrograph of the fabricated device. Our simulations show that air gaps and misalignment of a few tens of nanometers between the metallic and dielectric structure could dramatically decrease the coupling efficiency and the field enhancement at the nanotip primarily because the modified structure supports additional modes due to the presence of the air gaps.

5. Near-Field characterization

In order to experimentally characterize the functionality of our device we used a Near-Field Scanning Microscope (NSOM) technique (NANONICS MultiView 4000). We launched an in-plane (TE) polarized light at the wavelength of 1552 nm into the waveguide in a butt coupling configuration using a lensed fiber and performed NSOM scans using metallic coated tip with the 300nm aperture diameter. In Fig. 6a we present a 3-dimensional representation of the near-field intensity distribution as was collected by the NSOM tip. Figure 6b shows a collage between the obtained topography and the near-filed intensity pattern. From the Fig. one can clearly observe the high concentration of the electromagnetic energy in the region of the tip’s apex. We found the intensity of the electromagnetic field at the apex of the tip to be ~10 times larger than the average intensity in the silicon waveguide.

In order to evaluate the dimensions of the focusing spot we took longitudinal and transverse profiles of the NSOM scan as shown in Fig. 7. From the NSOM scans we found the full width half maximum (FWHM) of the spot to be 300 nm in the longitudinal direction.
and 460 nm in the transverse direction. Practically, these measurement results are limited by the aperture of the NSOM tip. In order to estimate the real FWHM we should deconvolve the NSOM signal with the 300 nm aperture of the metallic coated tip. However, the two-dimensional deconvolution of the NSOM signal is a non-trivial and unique solution is not guaranteed.

In order to take into account the fabrication errors and the effect of the signal broadening caused by interaction of light with the NSOM tip we performed a 3D FDTD simulation to calculate the field propagating in the actual fabricated geometry as revealed from the SEM micrograph. We assume the metal height to be 200 nm, the air gap between the silicon tip and the gold cladding to be 15 nm, and the diameter of the tip’s apex to be 20nm. Additionally we convolved the FDTD results with the 300nm diameter aperture of the NSOM tip. In Fig. 8a we present the 2d horizontal slice of the convolved intensity distribution. As expected the simulated intensity distribution is much wider than the “ideal” simulated result (Fig. 4).

Figure 8b and Fig. c show profiles of the calculation result (Fig. 8a) along the longitudinal and transverse directions respectively after being convolved with the NSOM probe aperture. We found the spot size of the convolved results to be very similar to the measured results. Based on this result, we estimate the size of our spot to be in order of 50 nm.

We believe that our results provide a clear evident for the field enhancement and the nanoscale focusing of our on chip integrated device. However, further research is needed in order to obtain optimum both in device performances and in its characterization. For example, to overcome the difficulty in directly measuring the spot size, one may consider using a...
higher resolution measurement approach, e.g. aperturless NSOM [35]. The resolution of this method is practically limited by the apex diameter of the NSOM to about 50 nm and thus may be applied for directly measure the spot size at the apex of the tip without the need for performing convolution which is subject to ambiguity. On the other hand, the aperturless NSOM may have stronger interaction with our metallic tip. This can result in artificial quenching or enhancement of the electric field at the apex of the tip. A combination of the two approaches (aperture and aperturless NSOM) may be the ideal solution. In addition, the device can be further optimized in its geometry and material selection to improve the coupling efficiency from the dielectric waveguide to the plasmonic nanotip. Finally, advanced fabrication processes may be used to obtain an even sharper tip apex and to completely remove the gaps between the dielectric and the metallic structures. Such improvements are expected to allow the obtaining of even higher field enchantment and smaller spot size at the apex of the nanotip.

The high concentration of electromagnetic energy that produced at the apex of the tip could be used for enhancing light-matter interaction. For example, the operation speed and the efficiency of an emitter or a detector that is located in the vicinity of the tip apex may be greatly enhanced. In addition, on-chip point-like light source can be created by removing the metal from the very apex of the tip. This structure is expected to behave like an on-chip aperture NSOM tip and thus may be used for the realization of local nanometric illumination sources. Another promising future direction is the on-chip integration arrays of such plasmonic focusing devices with a microfluidic/nanofluidic platform, giving rise to the construction of a new integrated plasmonic-photonic based “Lab-On-a-Chip” system for sensing and high resolution microscopy applications.

6. Conclusions

In conclusion, we designed, fabricated and empirically demonstrated the on-chip integration in silicon platform between a photonic waveguide and a plasmonic nanotip for the purposes of obtaining field enhancement and nanoscale spot size at the apex of the tip. Both the photonic waveguide and the plasmonic nanofocusing device are made of silicon, where the later is surrounded by a metallic cladding from its both sides. This configuration supports the propagation of a plasmonic mode with no cutoff, thus facilitating the nanoscale focusing at the apex of the tip. The device was tested directly by measuring the optical intensity along it using a near-field microscope. We found an order of magnitude enhancement of the intensity at the tip’s apex. The spot size is estimated to be about 50 nm. The demonstrated device may be used as a building block for “lab on a chip” systems and for enhancing light matter interactions at the apex of the tip.

Acknowledgments

The authors acknowledge fruitful discussions with Meir Orenstein and Joseph Shappir as well as technical support from David Shlosberg and Noa Mazursky. The research was supported in parts by the U.S-Israel binational science foundation, and the Israeli Science Foundation. Ilya Goykhman acknowledges the Eshkol fellowship from the Israeli Ministry of Science and Technology. The devices were fabricated at the Center for Nanoscience and Nanotechnology, The Hebrew University of Jerusalem.