Three-dimensional nanoplasmonic surfaces with strong out-of-plane electric field enhancement

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Abstract: Conventional 2D plasmonic structures, with surface coverage ~50%, provide field enhancement in the plane. The proposed 3D nanoplasmonic surfaces, with unity coverage, achieve 7.2-fold stronger out-of-plane enhancement compared to the 2D counterparts.

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Two-dimensional (2D) plasmonic nanostructures implemented on a planar surface commonly posses a surface coverage significantly less than 100%. Also, the resulting field localization occurs in the vicinity of sharp corners and between small gaps of their nanopatterns on the flat surface. When a periodic layout is used as the repeating pattern (although periodicity is not a requirement), the plasmonic array inherently yields a duty cycle considerably less than unity (usually close to 0.5) [1,2]. As a result, the surface coverage of the nanopatterned plasmonic structures on a planar surface has intrinsically been limited and the field enhancement across their layout has been possible mostly in the plane (and slightly above it). In this work, we proposed and demonstrated three-dimensional (3D) nanoplasmonic structures designed and fabricated on a non-planar surface that enables strong field enhancement in the out-of-plane direction, while allowing for the surface coverage of the substrate close to unity in plan view. Also the process flow developed specifically for these 3D nanoplasmonic surfaces requires fewer fabrication steps than the 2D structure, reducing the complexity and cost of their nanofabrication.

Figures 1(a) and 1(b) show scanning electron microscopy (SEM) images of the 3D and 2D structures, respectively, with the corresponding illustrative unit cell sketches. These nanostructures were fabricated using electron beam lithography (EBL) on thin chromium layer coated fused quartz wafers. The interplanar spacing layers in the 3D structure consist of bilayer PMMA, which was also used as the EBL resist. Numerical simulations and experiments were compared by observing the far-field absorption of these 3D and 2D structures, presented in Figures 1(c) and 1(d). The two-fold rotational symmetry of these plasmonic structures led to polarization independent behavior, unlike the common 1D gratings having strong polarization dependence [3].

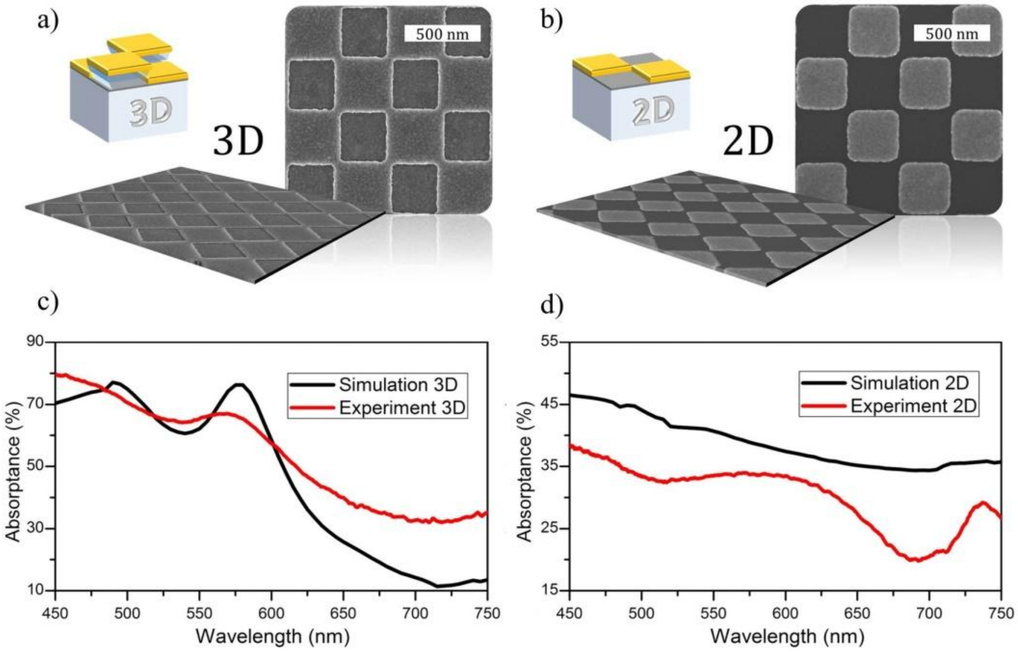

Fig. 1. Perspective and top view SEM images of the 3D (a) and 2D (b) plasmonic structures. Simulation and experimental far-field absorptance of these 3D (c) and 2D (d) structures [4].

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Figures 2(a)-2(d) show the cross-sectional near-field electric field intensity distribution maps of the 3D and 2D structures as well as those of the upper plane and the lower plane components, together making up the full 3D structure, with respect to the incoming source intensity in the logarithmic scale. Here the upper plane contains the partial structure remaining after removal of the gold plane between z=5 and z=45 nm; and, in a complementary fashion, the lower plane consists of the partial structure remaining after the gold layer between z=85 nm and z=125 nm is removed (Figure 2(e)). These simulations are performed using commercially available FDTD solver, called FDTD Solutions, from Lumerical Inc. using 3D simulation environment under impinging plane wave from the air side. From Figure 2(f), it is evident that the resonance of the 3D structure results from the coupling between the upper and lower plane structures since the plasmonic resonance of the upper plane structure blue-shifts and develops a stronger resonance. Figure 2(a) shows that the 3D structure is superior to the other structures, with its volumetric field enhancement reaching a maximum field enhancement factor 7.2 times larger than that of the 2D structure.

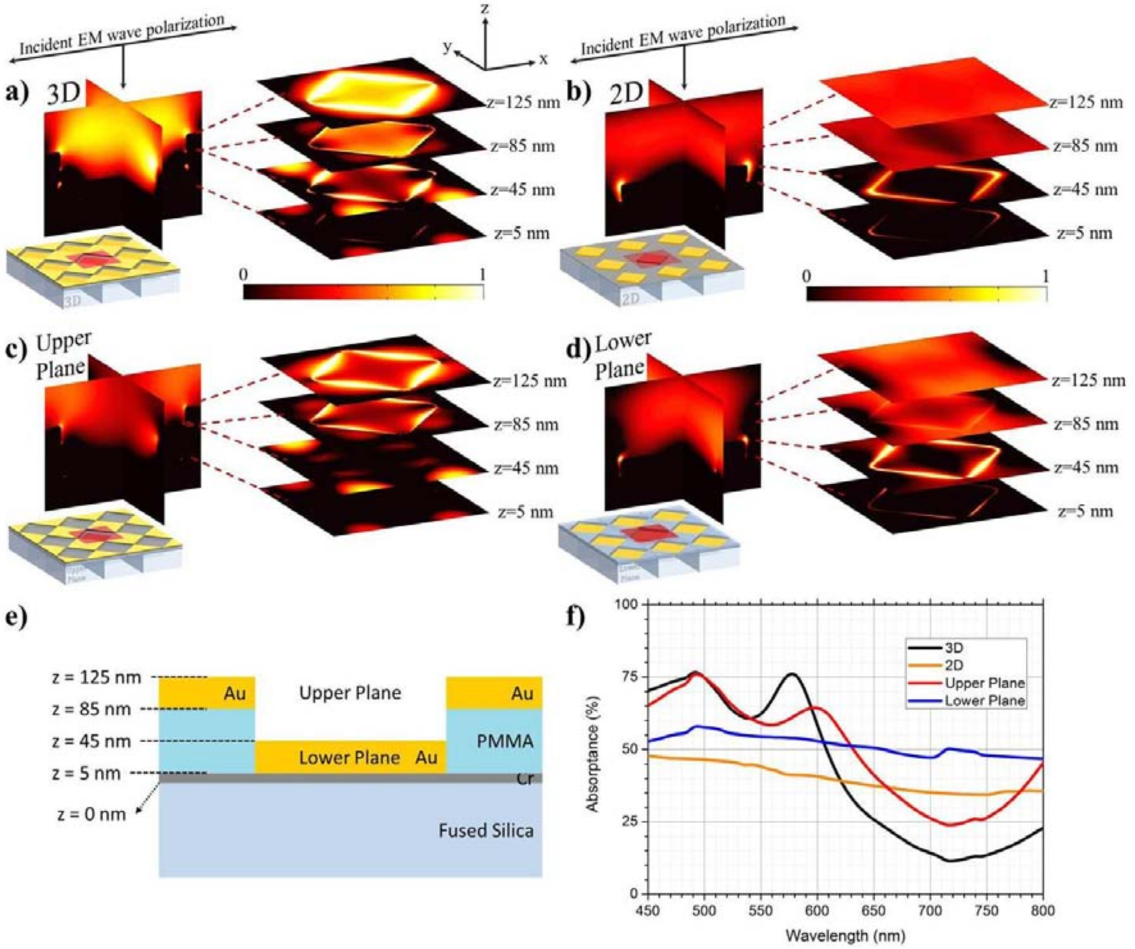

Fig. 2. Simulation results showing electric field intensity distributions for the 3D (a), the 2D (b), the upper plane (c) and the lower plane (d) structures. Important positions along z-direction and the components of the upper and lower plane structures are illustrated (e). Percent absorptance of the given structures showing coupling between the upper and lower planes in the 3D structure (f) [4].

In conclusion, the 3D nanoplasmonic surfaces provide volumetric electric field intensity enhancement, significantly stronger than the 2D planar counterparts, as verified by the numerical simulations agreeing well with the experimental far-field measurements. In addition to the out-of-plane field enhancement observed in the 3D structure, the maximum enhancement factor is found to be 7.2 times larger than that in the 2D structure. This showcases the strength and potential of the 3D nanoplasmonic surfaces.

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