Strain-Tunable Two-Dimensional Plasmonic Crystals

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Abstract: Resonance tuning characteristics of a plasmonic photonic crystal nanostructure under uniaxial compressive and tensile strains were investigated. The plasmonic device consists of a periodic array of metal-coated polymer nanoposts fabricated using a replica molding process. Applied strains regulate the period of the array, leading to flexible and repeatable resonance tuning of localized plasmons.

1. Introduction

The ability to tune optical properties of plasmonic nanostructures has great impact on the next generation plasmonic base devices. Plasmonic resonances can be tuned by changing material properties or geometry of plasmonic devices via optical, electronical, and thermal means [1-4]. Here, we report on a strain-tunable plasmonic crystal capable of precisely tuning its optical resonance by applying an external strain. The device is fabricated by the inexpensive nanoreplica molding process. It consists of a metal-coated array of nanoposts on a stretchable polydimethylsiloxane (PDMS) substrate. When a uniaxial strain is applied to the substrate, the period of the nanopost array changes, thus shifting the resonant wavelength of the structure. The plasmonic mode tuned here is highly confined around the metal nanodisks residing on top of the nanoposts. The applied strains only change the distance between nearby nanoposts, while without mechanically affecting the shape of the metal nanodisks that otherwise would degrade structural survivability and thus tuning reproducibility. Therefore, this unique design feature allows for a continuous and reproducible resonance tuning of the device.

Fig. 1(a) shows a schematic diagram of the tunable plasmonic crystal structure. The device fabrication was based on soft lithography and replica molding process that to generate a PDMS nanopost array with the help of a silicon stamp [5], followed by depositing a 50-nm-thick gold film on both top and bottom of the nanoposts by e-beam evaporation. This resulted in a square array of nanoposts with the lattice period of 600 nm, the post diameter of 195 nm, and the post height of 250 nm (Fig. 1(b)).

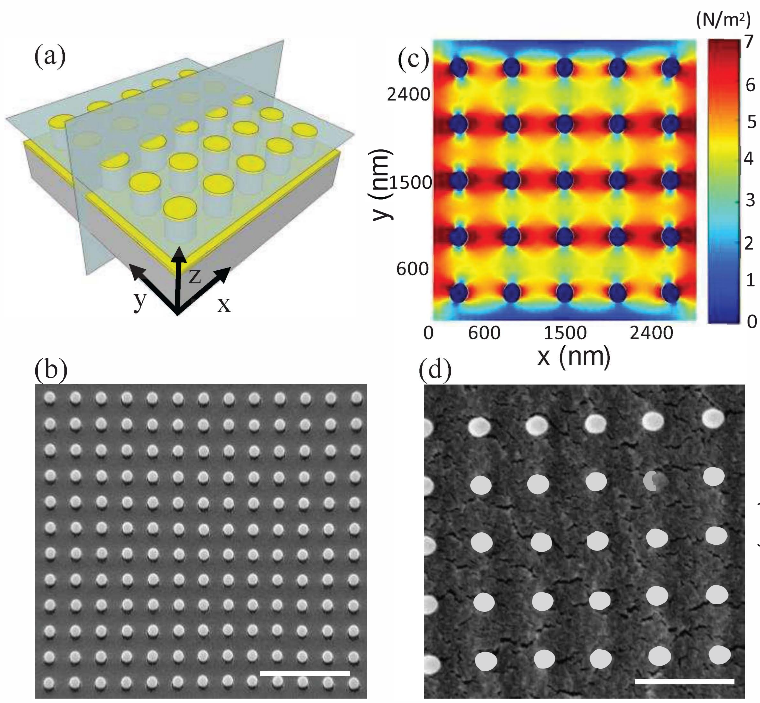

Figure 1. (a) Schematic illustration of the tunable plasmonic crystal. (b) Top-view SEM image of the device (scale bar: 2 µm). (c) Calculated stress distribution when a tensile strength of 0.7 MPa was applied. (Scale bar: 1 µm). (d) SEM image of tunable plasmonic crystal under a compressive strain.

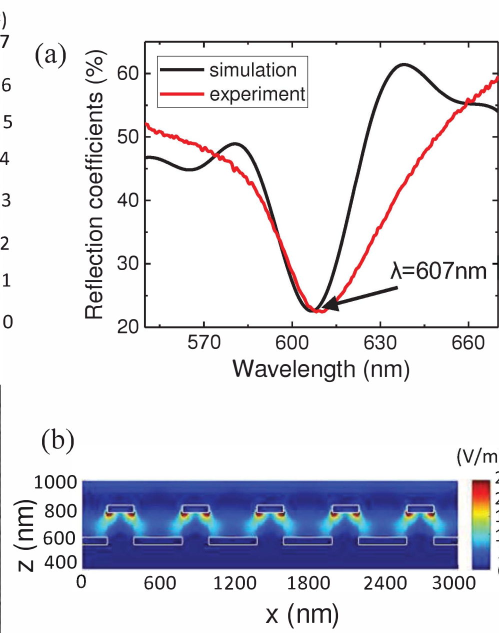

Figure 2. (a) Measured and simulated reflection spectra for the tunable plasmonic crystal device. (b) Simulated electric field intensity distribution for the resonance mode at $\lambda = 607$ nm for five periods. The gold film define the boundary with white box.

2. Results and discussion

Fig. 1(c) illustrates the simulated stress distribution in the horizontal cross section of the structure (the x-y plane specified in Fig. 1(a)) under a tensile strength of 0.7 MPa. Fig. 1(d) shows the scanning electron microscopy (SEM) image of the structure under a compressive strain of 5% along the x direction. The SEM analysis demonstrates that the mechanical stretch and compression on the substrate has little influence on the morphology of the metal nanodisks.

Fig. 2(a) shows the experimental and simulated reflection spectra of the device. Finite-difference time-domain simulations were used to calculate the reflection spectra and the electromagnetic field distributions in the vertical cross section of the device (the x-z plane shown in Fig. 2(a)). The calculated near-field intensity pattern at the resonant wavelength of 607 nm in Fig. 2(d) confirms that the plasmonic resonance mode is highly confined near the nanodisks. The tuning of plasmonic resonance is expected to be reproducible because the plasmonic mode only slightly overlaps the bottom of the nanoposts and the top nanodisks remain intact, despite the fact that the bottom gold film may crack after repeated stretching and compressing of the substrate.

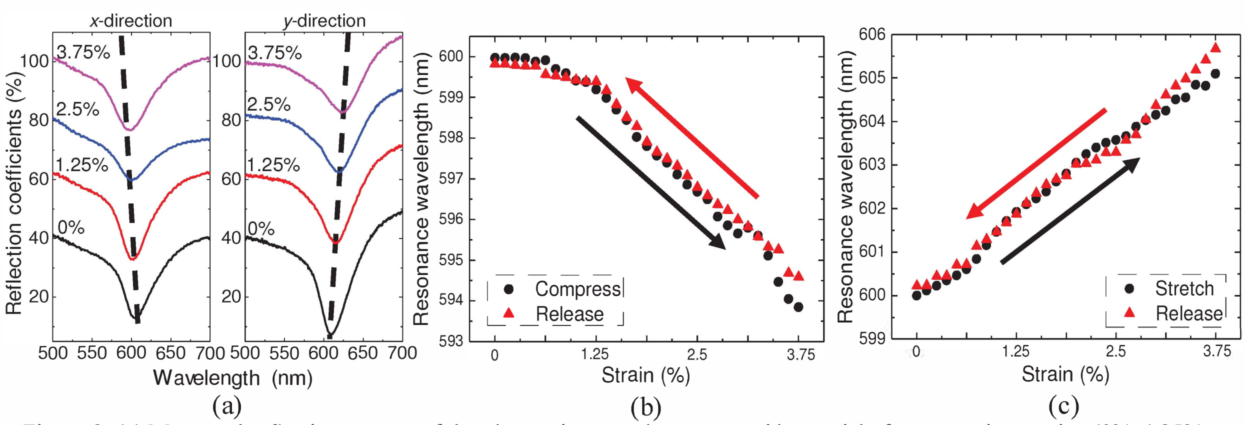

Figure 3. (a) Measured reflection spectra of the plasmonic crystal structure with a serial of compressive strains (0%, 1.25%, 2.5%, 3.75%) for the incidence light polarized in the x-direction (left panel) and the y-direction (right panel). (b) Continuous tuning of the plasmonic resonance when the compressive stain was applied and removed. Light was polarized along the x-direction. (c) Continuous tuning of the plasmonic resonance as a function of tensile strain.

To characterize the tuning capability of the device, different uniaxial strains were applied along the x direction by a motorized puller. The device was illuminated by a collimated, linearly polarized white light in its normal direction. The zero-order reflection characteristics of the device were studied in the wavelength range of 500 - 700 nm. When the light was polarized along the x direction (defined in Fig. 1(a)), the compressive strains blue shift the resonance wavelength of the device. Under the same strain but with the polarization rotated to the y direction, the resonance is found to shift to a longer wavelength. This polarization-dependent tuning characteristic is due to the break of lattice symmetry by unidirectional stretching or compression. Fig. 3(a) shows the reflectance spectra measured with different compressive strains for the incidence light polarized along x-direction and y-direction, respectively. The resonant wavelength shifts 6 nm at 3.75% strain.

Fig.3 (b) and (c) demonstrate the continuous tuning of the plasmonic resonance under compressive and tensile strains. The resonant wavelength versus compressive strain is plotted in Fig. 3(b), in which the black dots represent the compression phase and red triangles were measured when the strain was gradually removed. Fig. 3(c) shows the effect of tensile strain to the same device. Our later experiments showed that the device could be tuned for at least 100 compression/stretch cycles without a significant degradation of the resonance spectrum.

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