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# Observation of optical domino modes in arrays of non-resonant plasmonic nanoantennas

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## ABSTRACT

Domino modes are highly-confined collective modes that were first predicted for a periodic arrangement of metallic parallelepipeds in far-infrared region. The main feature of domino modes is the advantageous distribution of the local electric field, which is concentrated between metallic elements (hot spots), while its penetration depth in metal is much smaller than the skin-depth. Therefore, arrays of non-resonant plasmonic nanoantennas exhibiting domino modes can be employed as broadband light trapping coatings for thin-film solar cells. However, until now in the excitation of such modes was demonstrated only in numerical simulations. Here, we for the first time demonstrate experimentally the excitation of optical domino modes in arrays of non-resonant plasmonic nanoantennas. We characterize the nanoantenna arrays produced by means of electron beam lithography both experimentally using an aperture-type near-field scanning optical microscope and numerically. The proof of domino modes concept for plasmonic arrays of nanoantennas in the visible spectral region opens new pathways for development of low-absorptive structures for effective focusing of light at the nanoscale.

**Keywords:** Domino modes, plasmonic nanoantennas, light trapping, scanning near-field optical microscopy

## 1. INTRODUCTION

The main advantage of thin-film solar cells (TFSC) as compared to conventional bulk solar elements is a very small amount of purified semiconductor per unit area, which reduces its cost and the amount of toxic waste produced during the fabrication process.<sup>1,2</sup>

To fabricate efficient solar cells with a very small thickness, however, a conventional anti-reflecting coating (ARC) should be replaced by a light-trapping structure, since ARC cannot prevent the transmission of light through a very thin photovoltaic (PV) layer. This transmission results in energy loss and in substrate heating, which leads to an additional reduction of the solar cell efficiency.<sup>1,2</sup> On the contrary, a light-trapping structure (LTS) is capable to reduce both the reflection from a solar cell and transmission through its PV layer. Therefore, we believe that the future of TFSC in solar cell industry depends on the development of the novel types of LTS that provide effective suppressing of the light transmission through the PV layer.

A number of solutions for the realization of light trapping in TFSC are based on the use of plasmonic absorbers,<sup>3,4</sup> which are amorphous planar arrays of silver or gold nanoparticles with plasmon resonances within the operation band of solar cells. However, the high level of parasitic losses, including losses in metal nanoparticles and scattering losses, make these types of LTS hardly promising. Though they successfully prevent the transmission through an optically thin PV layer, none of them, to the best of our knowledge, stands the comparison with a conventional ARC.

The efficient conversion of the incident waves into evanescent wave packages (hot spots) whose electric field is concentrated mainly inside the semiconductor can be achieved in regular grids of rather large (50 nm or more) silver or gold nanoparticles.<sup>5,6</sup> We can call such regular nanoparticles nanoantennas (NA) because they effectively transform far-field electromagnetic radiation into near fields and vice versa. If the array of NA is

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properly designed, the energy of solar light received by NA is then transformed into a set of hot spots located mainly beyond NA so that the parasitic dissipation is avoided. If these hot spots are at least partially located inside the PV layer the incident energy is converted into electricity. This is the useful PV absorption that reduces both reflection from the structure and transmission through the PV layer.

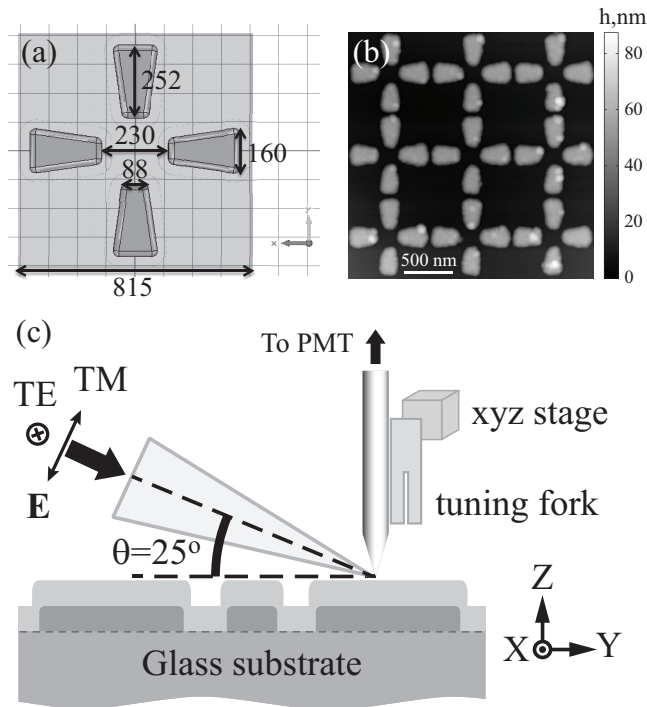


Figure 1. (a) Design of nanoantenna array unit cell. (b) AFM image of an array of nanoantennas fabricated by electron beam lithography and covered with 45 nm silica passivation layer. (c) Schematic view of the NSOM configuration used in the experiments.

NA coating which meets these requirements was proposed by Simovski et al.<sup>7</sup> The design of a single unit cell of this coating is similar to the one presented in Fig. 1a. In the same paper it was shown numerically that such a structure with minor design tweaks can substantially increase the efficiency of thin film solar cell with either amorphous silica or copper indium gallium selenide(CIGS) active layer in broad spectral range.

The operation principle of this structure is based on the excitation of the specific collective oscillations, termed *domino-modes*, in the array of NAs.<sup>7</sup>

Such modes possess the following important qualities:<sup>7</sup>

1. The electromagnetic field is mainly concentrated in the spacings between the array elements and beneath them;
2. The internal electric field in metal is very small: the field penetrates the metallic elements to the distances much smaller than the skin-depth;
3. They are excited far from the dipole plasmonic resonance of the metallic elements.

These qualities grant several advantages, namely, low absorption and scattering losses, and effective light trapping. Moreover, the specific design of the elements of NA array can ensure broadband polarization-independent operation of the coating.<sup>7</sup> These aspects make domino-modes an extremely promising phenomena to be exploited in the light-trapping structures.

To the best of our knowledge, however, up to now such light-trapping structure has not been realized experimentally, and, in particular, no experimental demonstration of the excitation of the optical domino modes

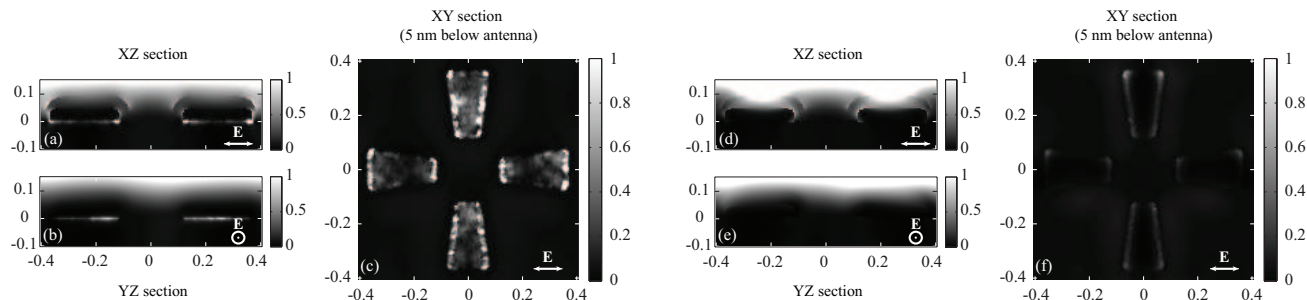


Figure 2. Sections of  $|\mathbf{E}|^2$  within the unit cell of the array of plasmonic nanoantennas at  $\lambda = 633$  nm (a-c) and 532 nm (d-f) on silicon substrate. The XZ and YZ sections are taken through the centre of the nanoantenna, while the XY section is taken at 5 nm below the substrate surface. The polarization of the TE-polarized incident light is along the X axis, the tangential component of the wavevector of incident wave is parallel to the Y axis (see Fig. 1). The field intensity is normalized to the intensity of the electric field in the incident wave. All units are in  $\mu\text{m}$ .

was carried out. Therefore, the aim of this work is to verify the existence of such unique collective modes in the arrays of non-resonant plasmonic antennas.

## 2. RESULTS AND DISCUSSION

The numerical simulations of the electromagnetic fields distribution in the vicinity of NA array were carried out in the CST Microwave Studio®. The numerical data obtained for two experimentally available wavelengths, 532 and 633 nm, are presented in Fig. 2. For  $\lambda = 633$  nm (Fig. 2(a-c)), one can immediately see the characteristic features indicating the excitation of domino-modes: low penetration depth of the electric field inside the metallic elements (Fig. 2(a,b)) and high localization of the field under the nanoantenna (Fig. 2(c)). On the contrary, the numerical data for 532 nm excitation (Fig. 2(d-f)) demonstrates both low field localization and high density of the electric field inside the NA, which correspond to the regime without the excitation of domino-modes.

To demonstrate the excitation of the collective modes in such NA coating experimentally, we fabricated by means of electron beam lithography an array of silver nanoantennas on a crystalline silicon substrate following the design presented in Fig. 1a. An atomic force microscopy (AFM) image of the fabricated nanoantenna array is presented in Fig. 1b. We then investigated the nanoantenna coating with an aperture-type near-field optical microscope (NSOM). Since the sample substrate is optically dense, we used the reflection configuration with the incident beam falling at  $25^\circ$  degrees to the sample surface (note that the same excitation geometry was used

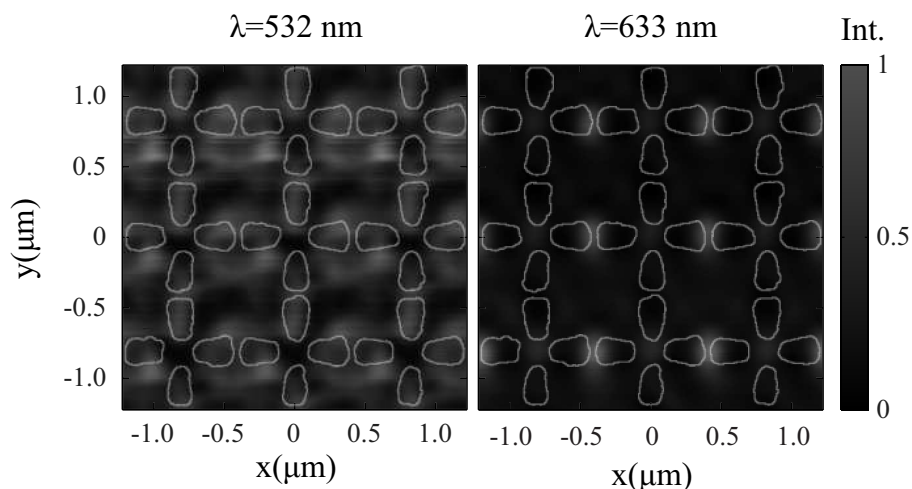


Figure 3. NSOM signal patterns obtained for 532 and 633 nm excitation in TE polarization. Nanoantenna contours are added for the reference.

in the calculations). The experiments were carried out for two excitation wavelengths (532 and 633 nm) and for two polarizations: TE and TM. Two experimental patterns obtained in TE polarization for both 532 and 633 nm excitation are presented in Fig. 3.

One can clearly see that NSOM pattern obtained at  $\lambda = 532$  nm (Fig. 3a) demonstrates complicated field distribution above NA array. The observed near-field pattern shows notable field localization above the antennas, which corresponds to non-domino-mode (plasmonic) regime. On the contrary, for the case of  $\lambda = 633$  nm (Fig. 3b) the field is concentrated in the spacings between the silver nanoantenna array elements, which is a characteristic attribute of domino-modes.

## CONCLUSIONS

In this work we performed numerical and experimental studies of an array of silver nanoantennas excited by an obliquely incident wave at two different wavelengths. Analysing the numerically obtained field distributions, we show that the array really supports very interesting collective oscillations called domino-modes possessing an advantageous distribution of electric field. By employing near-field optical microscopy we demonstrate experimentally the excitation of optical domino modes in arrays of non-resonant plasmonic nanoantennas. The proof of domino modes concept for plasmonic arrays of nanoantennas in the visible spectral region opens new pathways for development of low-absorptive structures for effective focusing of light at the nanoscale and opens the door to a new class of light trapping structures for the enhancement of thin-film solar cells.

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