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Leaky domino-modes in regular arrays of substantially thick metal nanostrips☆

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Abstract

In previous works, an efficient light trapping performed by arrays of metal nanoantennas whose building block was a slightly tapered (trapezoidal) substantially thick nanostrip was revealed. This light trapping implied a broad spectrum of solar light concentrated in a subwavelength depth of the semiconductor substrate. This is a very advantageous feature allowing our structure to enhance thin-film solar cells. However, the physics of the broadband resonant absorption in the substrate was not investigated. In the present paper, we show that our arrays support so-called *leaky domino-modes*, responsible for such the light trapping. These modes are multipole oscillations of the array of substantially thick nanostrips. In this work we have thoroughly studied these leaky modes relating them to resonances of high-order multipole moments and to broadband light-trapping effect.

Keywords: Light-trapping structures; Nanoantennas; Leaky modes; Multipole resonances

1. Introduction

In thin-film solar cells with strongly submicron photovoltaic layers, the so-called light-trapping structures (LTSs) replace conventional anti-reflecting coatings (ARCs) because ARCs cannot prevent the solar light transmission through so thin layers. This transmission results in the energy loss and harmful heating of the photovoltaic layer from the bottom electrode [1]. Many suggestions of LTSs are based on so-called plasmonic nanoantennas (NAs) – regular arrays of specially shaped nanoelements of gold or silver (see e.g. in [2]). The term NAs is adequate for unit cells of such LTSs because a receiving antenna is by definition a passive device, efficiently transforming the electromagnetic field of incoming waves into near fields. In optics, the near fields are manifested by so-called hot spots – subwavelength packages of evanescent waves. The absorption of such a concentrated electromagnetic energy in a lossy material is much higher than the absorption of a plane wave. Therefore, NAs forming an LTS convert the incident solar light into a set of hot spots, located in the photovoltaic medium, increasing the useful absorption and preventing the parasitic transmission.

For this mechanism of light-trapping the key point is where these hot spots are located [3]. If they are even partially located within the NAs, the harmful dissipation

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☆ The article belongs to the special section Metamaterials.

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of the solar energy occurs in NAs, which is not better than the harmful transmission. Unfortunately, the partial location of the hot spot inside a nanoparticle with dipole-type plasmonic response is an inherent feature of the plasmon resonance. This drawback makes usual plasmonic absorbers not very efficient for the enhancement of solar cells. Practically, they rarely stand a comparison with anti-reflecting coatings. Researchers have put significant efforts into creation of NAs, which create the hot spots beyond their own volume. Such NAs are not dipole scatterers (see e.g. in [4–6]). Another key point of plasmonic light-trapping is the bandwidth. Since the solar light has a very broad frequency spectrum, in order to be efficient for thin-film solar cells, the NAs have to be multi-resonant [4–6]. One of the best known theoretical results for such LTSs were reported in works [7,8]. In these works multi-resonant NAs were performed of tapered silver nanostrips forming cross-like structures. It was claimed in [7,8] that these NAs exploit collective modes of the NA array called *leaky domino-modes*. However, this claim was not proven because these modes in planar arrays of NAs were never studied. The present paper fills in this lacuna and explains the excellent light trapping achieved in [7,8].

2. Previous studies of optical domino-modes

Domino modes were first revealed in paper [9]. They were defined as the guided modes in a one-dimensional array (chain) of metal elements shaped as finite-length parallel strips or bars of rectangular cross section called domino elements. The bars in [9] were staying on their edges in parallel to one another. The length a of the strips was comparable with the wavelength in free space, and the thickness Δ significantly exceeded the skin-depth δ. The peculiarity of the guided mode was very weak penetration of the electric field inside themetal. The electric field was concentrated in the gaps between the adjacent metal elements. Therefore, the electric losses in the domino elements are very low, and the propagation length of the mode is large, much larger than that in most of the discrete optical guides. Since the guided mode is an essentially collective propagating oscillation, domino-modes refer to the class of so-called spoof plasmons [10]. The dispersion is nearly the same as that of a surface plasmon-polariton and modifies slightly when the chain period d increases up to a certain threshold. When d exceeds this threshold, the electromagnetic interaction between adjacent elements becomes insufficient and the mode vanishes.

Work [9] considered such a spoof plasmon in the chain of silver, gold or copper strips operating in the THz and mid IR ranges. In work [11], similar waveguide modes were founded in the chain of parallel nanostrips operating at near infrared frequencies. The geometry of the chain was modified keeping the same ratios as in [9] length/width, width/thickness and thickness/skin-depth higher than 2. Since it would be quite challenging to fabricate a submicron domino-element staying on its edge, nanostrips were lying, as it is shown in Fig. 1a. Fortunately, the guided domino-mode survived in this geometry. The conditions of the spoof plasmon kept the same as those formulated for the staying domino elements. Period of a chain should be smaller than $1.1a-1.2a$, where a is the strip length, thickness Δ of the domino element should be substantial (at least twofold skin-depth δ), and geometry of the element should be proper (thickness of the strip should be several times smaller than the width). The key argument in favor of keeping the same terminology (domino modes, domino elements) is the main peculiarity of the domino-mode – almost complete concentration of **E** in the gaps between adjacent metal elements and, therefore, surprisingly low attenuation of the guided mode in the chain [9,11].

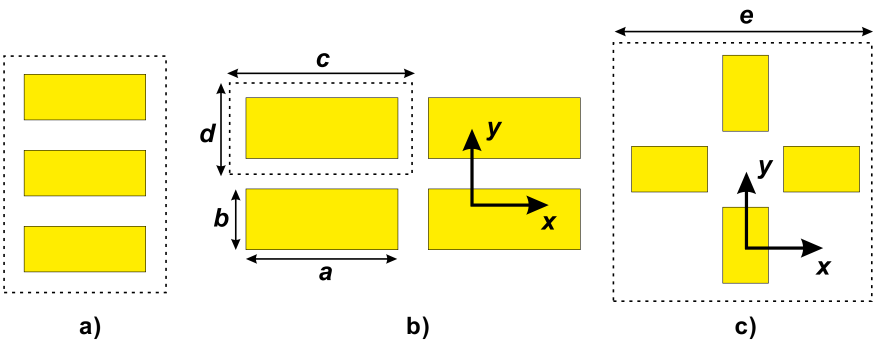

Fig. 1. Geometries of some arrays supporting optical domino modes (top view). (a) Chain of nanostrips from work [11]. (b), (c) Two structures supporting leaky domino modes studied in the present work.