Metamaterials for efficient and broadband transition from wave beams to evanescent packages

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Abstract

We suggested and theoretically studied a planar plasmonic nanostructure which can be excited by a dielectric ridge waveguide and creates in a broad band a subwavelength spatial region where the field is locally enhanced. This spatial region is V-shaped and repeats the contour of the tapered structure. The frequency region where the effect holds covers nearly one half of the visible range. Over one quarter of the visible range a hot spot is formed in front of the structure apex. The structure can also transform evanescent waves exciting the apex into wave beams.

1. Introduction

In most of works where the subwavelength concentration of the light energy initially transported by waves beams is studied the objective is to achieve either a very high resolution or a very large local field enhancement at a certain frequency. Most subwavelength light concentrators (such as a solid metal tip with nanometer scale curvature of the apex or a nanoantenna) operate in the regime when they are laterally illuminated. Our goal is to transform the conventional wave beam into an evanescent package concentrated within a subwavelength spatial region so that the surrounding space is not illuminated. Moreover, our goal is to obtain this transformation in a broad frequency range so that at all frequencies within this range the field would be distributed inside the same nanometer-scale region. The structure which performs this field transformation should operate also in the backward regime, namely transform the evanescent wave packages into wave beams. This effect should also hold within a broad range of frequencies. The problem formulation is actual for schemes of field-enhanced nanosensing through fluorescence of bio-cells and molecules [1], field-enhanced Raman spectroscopy [2] and field-enhanced microscopy [3]. Beside these known applications, a nanostructure which would realize such a regime could be used for interconnections between conventional optical information systems and prospective nanooptical devices. Nanodevices which need to be connected with usual optical waveguides are plasmonic nanowaveguides [4, 5], optical nanocircuits [6], optical memory cells, all-optical nanoswitches, nanolasers etc. [7].

2. Theory

The proposed structure is a planar array of parallel nanobars of noble metal separated with dielectric spacers. Each metal nanobar experiences two plasmon resonances corresponding to two mutually orthogonal polarizations. The length of the nanobars is gradually varied and

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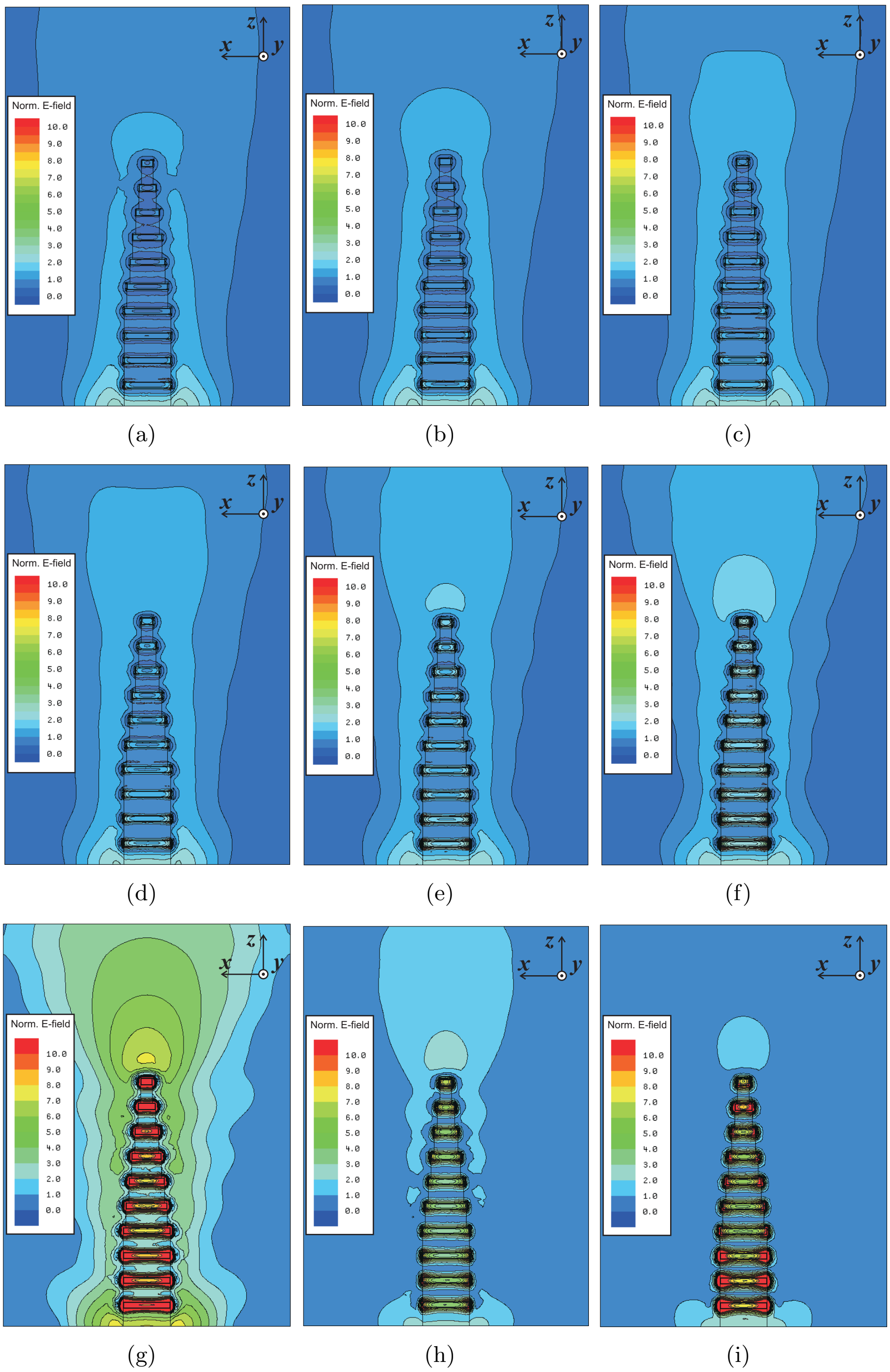

Fig. 1: The normalized amplitude of the electric field over the horizontal plane (top view on the structure) at (a) 450 THz, (b) 470 THz, (c) 490 THz, (d) 510 THz, (e) 530 THz, (f) 550 THz, (g) 570 THz, (h) 590 THz, and (i) 610 THz.

their number is large so that there were many overlapping resonances. The excitation of every nanobar in the structure fed from its base becomes possible due to newly revealed plasmonic waveguide modes (edge modes).

We numerically studied the dispersion properties of planar periodic plasmonic waveguides with different width (length of the nanobar) and saw that the edge modes in these different waveguides matches well with one another. They are broadband modes and their slow-wave factor is sufficient for their localization.

Then we simulated the performance of the structure in HFSS. A structure comprised 10 coplanar silver nanobars having thickness $y-$dim. = 70 nm, along the waveguide axis the size is $z-$dim. = 35 nm, and the length across the waveguide (x-dim.) reduces from 256 nm to 64 nm. The length of last 6 nanobars decreases with step 32 nm. The structure was excited with a wave port located at the input. The dielectric spacers had z-dimension 100 nm and same x-dim. and y-dim. In Figs. 1(a)–(i) we show the distribution of the absolute value of the electric field amplitude normalized to that calculated in absence of the plasmonic structure. The relative field distribution is depicted for the lower horizontal plane of the metamaterial.

In all these figures the typical field distribution of the edge wave is clearly seen in the narrow part of the tapered waveguide. The field distributions corresponds to the smooth transition between edge modes corresponding to different lengthes of the nanobar. The field is locally enhanced along the contour of the structure until the distances of $30-70$ nm away from this contour. The amplitude enhancement factor is equal $1.5\ldots7.5$ (depending on the frequency). Within the frequency range $450-530$ THz the field decreases fast at larger distances from the contour. Within the frequency region $530-590$ THz the field is enhanced not only along the contour. The constructive interference of two edge waves observes at these frequencies and leads to a hot spot located near the apex. At $590-610$ THz the field enhancement along the contour disappears but the hot spot at the apex keeps.

3. Conclusion

The main conclusion from Figs. 1 is that the regime which offers the local field enhancement in front of the end of the structure whereas practically no wave is transmitted forward refers to the frequency region which covers 46 percent of the visible range. In this work we do not consider the matching of our nanostructure with a conventional optical waveguide. This problem will be addressed in our next paper.

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