Performance of multi-segment nanolens for a near-field transport in the visible domain

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Abstract

We analyze capabilities and functionalities of a multi-segment superlens recently suggested by S. Kawata *et al.* [Nature Photonics **2**, 438 (2008)] for long-distance transport of color images with subwavelength resolution. We study the performance of three-segment nanolens structures by analyzing numerically both transmission and reflection coefficients and by employing the full-wave simulations for a particular source arrangement. We observe that such a stacked structure offers *limited subwavelength imaging performance* due to operation with coherent sources only within narrow frequency band, typically 3-5% wide.

1. Introduction

Subwavelength imaging is a subject of a special interest in the study of metamaterials, and it attracted a lot of attention in recent times due to its potential applications in various areas. Such imaging results from the restoration of the evanescent field components that goes beyond the capability of a conventional dielectric lens which can handle only the far-field of a source and operates only with propagating waves. Therefore, the image formation is prohibited at the far-field region by a conventional lens. To overcome this problem several solutions such as perfect lens [1], silver superlens [2] and hyperlens [3] have been put forward by various groups. Another type of superlens that employs array of silver nanorod was suggested for imaging in the visible range [4]. Such a lens functions through the excitation of surface plasmon polaritons (SPPs) on the individual rods. The improved multi-segment superlens [5] has been claimed to have the color imaging capability, and it can be employed to achieve magnification with a divergent arrangement of the nanorod assembly. Another salient feature of stacked superlens is that it can be employed to transport an image for a longer distance as compared to solid nanorods. The SPP excited in the first segment by a near-field source couples with the second segment which then excites next segment and so on. This so-called domino effect in the plasmon excitation can bring eventually the source information to the other side of the device where a field-distribution similar to the source-field can be obtained. The above mentioned devices pave the way for the development of a new class of optical microscope capable of scanning the whole area of interest and thus can save considerable amount of time. This would eventually replace the incumbent ones which make the microscopy process very slow (10 microns per second) as it employs a single probe.

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2. Numerical simulations of three-segment stacked nanolens

First, we consider a three-segment nanolens composed of three arrays of silver nanorods with the same parameters as in Ref. [5]. The lens was numerically modeled using full-wave electromagnetic simulator CST^{TM} Microwave Studio. Although it was suggested in [5] that the device with a rod length of 50 nm diameter 20 nm and gap 10 nm operates at a frequency of 622 THz, we were unable to find any discernible image at this frequency. This result contradicts to the conclusions of [5] where dramatic imaging performance was predicted for the device under consideration. This inconsistency results from the fact that our result was obtained by full-wave simulation of finite-sized nanorod array, whereas in [5] the image was obtained under assumption that the linear arrays of nanorods composing the nanolens does not interact with each other. It is clear that in the considered case the interaction between the rows of nanorods is dramatic and this results in destruction of desired imaging capability. It is not possible to neglect interaction between different rows of nanorods.

A detailed step-by-step procedure of how to calculate the parameters of a single-segment nanolens for proper functioning in a particular band is given in Ref. [6] following an investigation that the lens exhibits problems in proper operation [4] for arbitrary coherent sources. The idea of this paper is to apply similar procedure in order to determine the right parameters of the stacked lens that can improve the operation of the device. Therefore, for proper imaging one needs to modify the parameters of the array (length of the rods and/or gap between them) and hence alter the pattern of the transmission and reflection coefficients. Another way could be to find another frequency band of operation different from the one suggested in Ref. [5] with the existing parameters that would support the imaging operation of the device.

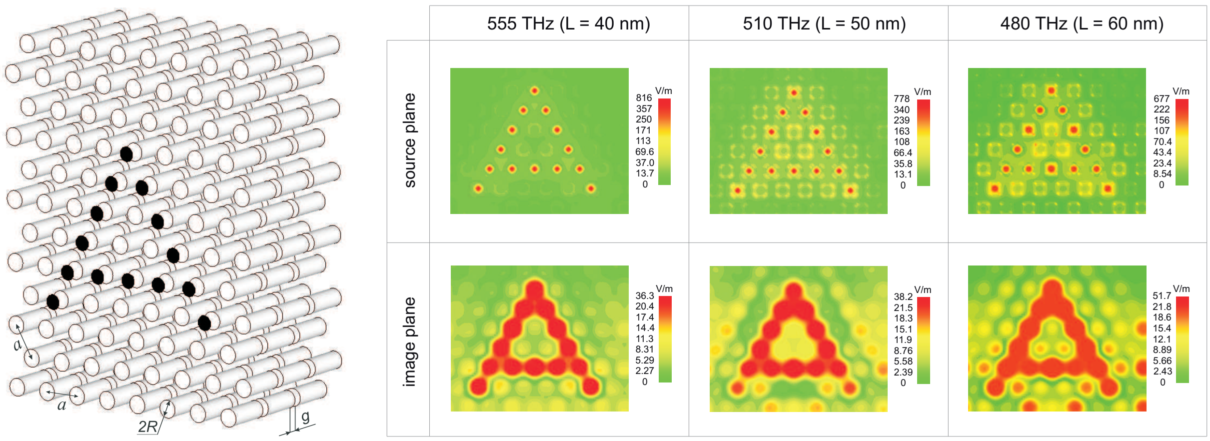

Fig. 1: Electric field distributions at the source and the image planes obtained for various lengths of the rod with a constant gap of 10 nm.

We opted for the latter in order to find the imaging capability of the device. We found that for a rod-length of 50 nm and gap 10 nm the device operates at 510 THz in contrast to 622 THz as suggested in [5]. The result of numerical simulation is presented in Fig. 1. The letter ‘A’ is clearly seen in the image plane. Also, we have observed that the decrease of the rod length leads to the increase of the operating frequency: The nanolens with 40 nm long nanorods operates at 555 THz (see Fig. 1). The increase of the rod length leads to the decrease of the operating frequency: The nanolens with 60 nm long nanorods operates at 480 THz. However, as it can be seen from Fig. 1, the image appears slightly distorted by ripples due to excitation of surface waves. The further increase of the rod length leads to complete degradation of the image. Interestingly, the decrease of the gap between the nanorods from 10 nm to 5 nm significantly improves quality of imaging provided by the device and leads to decrease of operating frequency. The images obtained for device with 5 nm gap are shown in Fig. 2. The image quality and sharpness is better as compared to results presented in Fig. 1 for nanolens with 10 nm gap. It

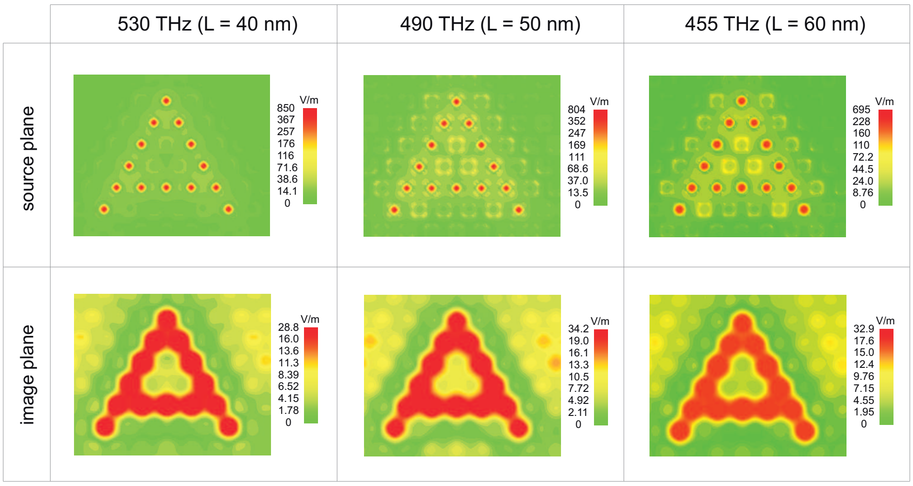

Fig. 2: Electric field distributions at the source and the image planes obtained for various lengths of the nanorod with inter-segment gap of 5 nm.

should be noted that with the decreased gap between segments, the operating regime exhibits a red-shift which can be attributed to the increased capacitance between the rods resulting from the reduced gap.

3. Conclusion

We have analyzed the imaging capabilities of the stacked nanolens formed by a lattice of nanorods. Such a multi-segment nanolens was suggested earlier for transporting color images for long distances by virtue of the so-called domino plasmon effect. We have investigated a three-segment structures in order to reveal advantages and limitations of their operation. For a stacked nanolens, we have two parameters, the gap between consecutive segments and the length of the nanorod which can be exploited in order to manipulate the transmission characteristics. We have shown that decreasing of the gap significantly improves the imaging performance of the device: it increases the bandwidth and diminishes resonant excitation of surface waves. The adjustments of the nanorod length allows to tune the nanolens to operate at a particular frequency. Despite all the positive traits for the performance of such an stacked nanolens, the color imaging characteristics still remains elusive.

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