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Mechanisms for photon sorting based on slit–groove arrays

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Abstract

Mechanisms for one-dimensional photon sorting are theoretically studied in the framework of a coupled-mode method. The considered system is a nanopatterned structure composed of two different pixels drilled on the surface of a thin gold layer. Each pixel consists of a slit–groove array designed to squeeze a large fraction of the incident light into the central slit. The Double-Pixel is optimized to resolve two different frequencies in the near infrared. This system shows high transmission efficiencies and a small crosstalk. It is found that the response of the system strongly depends on the effective area shared by overlapping pixels. According to such degree of overlap, photon sorting can be achieved within three different regimes, which are discussed in detail. Optimal photon-sorting efficiencies are obtained for a moderate number of grooves that overlap with grooves of the neighbor pixel. These results could be applied to both optical and infrared detectors.

Keywords: Photon sensing; Photon sorting; Nanostructured metals; Plasmonics

1. Introduction

Coupling between electromagnetic fields and surface modes in patterned metallic nanolayers offers the possibility for new mechanisms to guide, trap and localize light [1]. The optical response of nanostructured metallic layers is characterized by narrow spectral bands with resonant wavelengths mainly determined by the periodicity of the structure. Therefore, these systems can be used as filters by just tuning the periodicity [2]. A full analysis of the dependence of such resonances on other geometrical parameters is also available in the literature for systems like hole arrays [3] and apertures surrounded by corrugations [4–14].

In technological applications, like digital cameras or displays, color discrimination is performed through arrays of pixels, where each pixel acts as a separate entity sensitive to a single color [15]. Multispectral sensitivity have also been demonstrated in systems like waveguide resonators [16–18] and light harvesting structures; for instance, in triple bull's eye structures and triangular lattices of slit–groove arrays (SGAs) [19], or in a mosaic of free-standing arrays of slits used as band pass filter[20]. Such arrangements of nanostructured metallic pixels with multiple spectral resonances behave as wavelength-selective devices with promising advantages in spatial resolution.

In addition to their capability for selecting frequencies, these devices are also able to guide photons with

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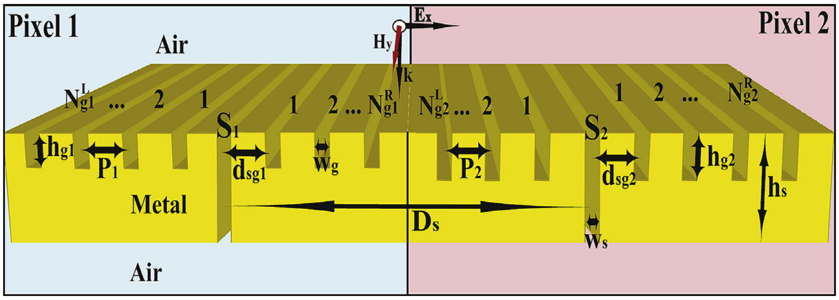

Fig. 1. Schematic representation of the Double-Pixel. Both pixels are sculptured on a uniform gold layer with thickness h_s. Pixel 1 has a central slit S_1 of width w_{s_1} surrounded by grooves of periodicity P_1, depth h_{g_1} and width w_{g_1}. The distance between the slit and the nearest groove is d_{sg_1}. Similar parameters are defined for pixel 2. The distance between slits is D_s.

different wavelengths through different channels, i.e. they can be considered as photon sorters; see, for instance, the overlapping light-collection structures reported in Ref. [19], where each pixel is devoted to harvest light of a single color and squeeze it through the central aperture even from the region where it overlaps with other collectors. Authors of Ref. [19] claim that, if photodetectors would be placed underneath the apertures, such devices could act as a miniature spectrometer that detects different wavelengths in the same area. It can be used to generate an image of the object, fulfilling in this way the requirements of the spectral imaging methodology [21].

Laux et al. [19] have proposed both 2D (a triple bull's eye structures) and 1D (SGAs) versions of such photon sorters. Notice that SGAs with different orientations were also arranged in a 2D triangular lattice making them sensible to both polarization and wavelength. These authors have found that the transmission peak intensity of the sorting device relative to that of the isolated pixel drops far more slowly than the percentage spatial overlap between the pixels. That is a signature of the low cross talk between individual pixels. However, one should expect that the interaction between pixels cannot be neglected under general conditions. To the best of our knowledge, the role played by the pixel interaction in photon-sorting devices has not been previously studied. In fact, we show in this paper that the process of photon sorting strongly depends on the pixel overlap and also that it varies in a non-monotonous way.

We choose the simplest version of the 1D photon sorter: two interacting pixels. We study, first, the main physical mechanisms appearing in the process of photon sorting and, second, how to optimize such photon sorters for having an enhanced response.

The building block of the system is a SGA that consists of a thin gold layer (optically opaque) perforated with a subwavelength slit, which is surrounded by an array of periodic grooves sculpted on the illuminated surface, see Fig. 1. Geometrical parameters of the SGA are adjusted in order to make the system resonant at a given wavelength. Optimal geometries for a single SGA can be obtained following simple rules recently reported [7,11,22].

We first design two isolated SGAs with optimal response at targeted wavelengths λ_1 and λ_2 and then the two SGAs are arranged in the Double-Pixel shown in Fig. 1 that resolves both wavelengths with a small cross-talk between the pixels. As we are interested in efficient mechanisms to collect the light impinging on a given pixel and redirect it to the other, i.e. to design and implement a photon sorter, we study the change in the optical response of the Double-Pixel as a function of the overlap between the SGAs. The system can be integrated with a standard photodetector [23–27], sensitive to the narrow band of the resonant wavelength.

We focus our attention on the near-infrared part of the spectrum. Integrating light harvesting structures on IR detectors has been recently proposed as an efficient way to increase the absorption of light in a given volume [28]. In this way it is possible to reduce the noise and raise the output signal. Results obtained here can be easily extended to other parts of the IR spectrum as well as to optical frequencies.

The paper is organized as follows. Next section describes the theoretical framework. Our results are discussed in Sec. 3. Section 3.1 first studies the spectral response of non-overlapping pixels. In Section 3.2 we evaluate the influence of the overlap between pixels, paying attention to physical mechanisms for photon sorting. The influence of the number of grooves in the optical response of overlapping pixels is analyzed in Section 3.3. Our main conclusions are presented at the end of the paper.

2. Theoretical framework

A schematic representation of the Double-Pixel is given in Fig. 1. Both pixels are sculptured in a uniform