Optical computing of spatial differentiation without Fourier optics

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Abstract: We propose optical analog computing of spatial differentiation with two new effects: the surface plasmon excitation and the spin Hall effect of light. Also we experimentally demonstrate their applications on edge-enhanced imaging.

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1. Introduction

Traditionally, edge contrast enhancement is applied to phase contrast microscopy by shifting the phase of the zero-order Fourier component of the object wave [1]. Later the Nomarski prism method and the spiral phase filter method based on Fourier optics were developed to strongly amplify the image intensity at edges, where the output field is related to the differentiation or the gradient of incident field. Recently, significant efforts have been taken to shrink the thickness of such computing elements down to a single-wavelength or even sub-wavelength scale. In particular, Silva *et al.* theoretically proposed a complex array of meta-atoms to realize desired mathematical operations [2].

Here, without complex Nomarski prisms and filter-based Fourier optics, we propose optical analog computing of spatial differentiation with two new effects: the surface plasmon excitation and the spin Hall effect of light. Within the sub-wavelength scale, we experimentally demonstrated that a 50nm-thick silver layer can realize spatial differentiation by exciting surface plasmon polariton [3, 4]. Moreover, the spin-optical scheme offers a simple but powerful mechanism to process vectorial field with even thin and common structure, a single planar interface [5].

2. Results

2.1. *Surface-plasmon-based scheme for spatial differentiation*

In order to achieve spatial differentiation, we consider the Kretschmann prism configuration as schematically shown in Fig. 1(a). In the special case where the incident angle θ_0 satisfies the phase-matching condition, that is where the plane wave has a wavevector component parallel to the interface that matches with the wavevector of a propagating surface plasmon polariton (SPP) at the metal-air interface, the incident plane wave then strongly excites the SPP. By using the spatial coupled-mode theory formalism, when the critical coupling condition is satisfied, we show that the spatial spectral transfer function has linear dependence on the spatial frequency; thus in the spatial domain, the reflected field profile corresponds to spatial differentiation of the incident field. We demonstrated various aspects of our plasmonic differentiator that are important for high-throughput image processing. The device can be used to detect an edge either in the intensity or the phase distribution of the incident field. More details about the plasmonic differentiator have been discussed in Ref. [4].

2.2. *Spin-optical scheme for spatial differentiation*

Fig. 2 shows the schematic of spatial differentiation based on the spin Hall effect (SHE) of light. We experimentally demonstrated that during reflection or refraction at a single optical planar interface, the optical computing of spatial differentiation can be realized by analyzing specific orthogonal polarization states of light. We show that the spatial differentiation can occur at any planar interface, regardless of material composition or incident angles. The proposed spin-optical method takes advantages of a simple and common structure to enable vectorial-field

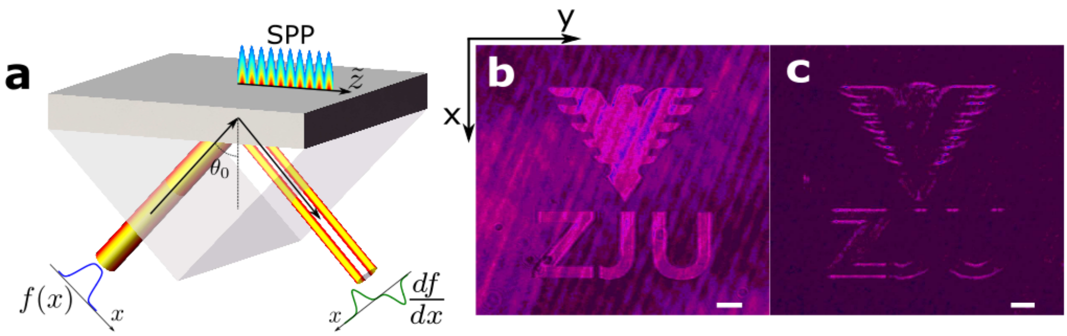

Fig. 1. (a) Schematic of the plasmonic spatial differentiator with the Kretschmann configuration to excite the surface plasmon polariton (SPP). The dark grey layer and the light grey area correspond to the 50nm thick silver film and the glass, respectively. (b) Incident field intensity generated by an adjustable slit. (c) Measured reflected intensity image corresponding to the incident field of (b).

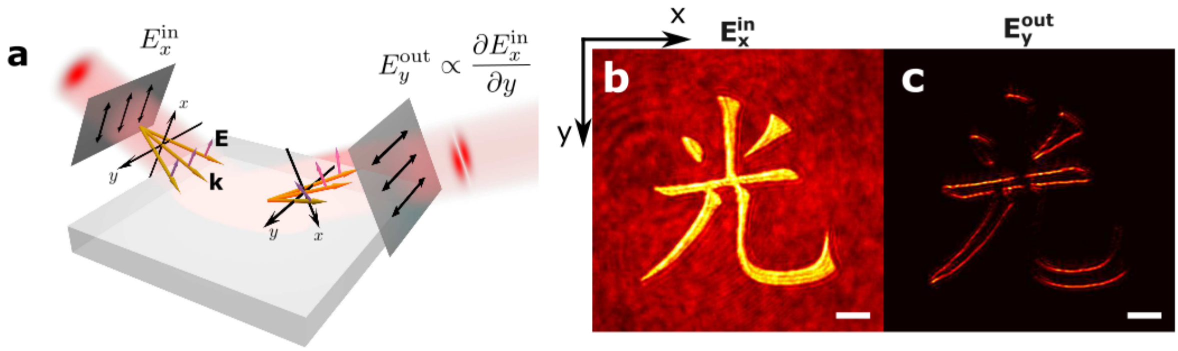

Fig. 2. (a) Schematic of spatial differentiation from the SHE of light on an optical planar interface between two isotropic materials, e.g. an air-glass interface. The two polarizers (dark grey) are with the polarizations indicated with double-head arrows, for example, preparing along x and analyzing along y. Edge detections for different images stored in E_x^{in} and E_y^{in}, respectively, with either amplitude or phase modulation. (b) Incident image consisting of a Chinese character of Light with amplitude modulation on E_x^{in}. (c) Reflected intensity image corresponding to (b) by measuring E_y^{out}.

computation and perform edge detection in ultra-fast image processing. Ref. [5] can be referred to for more details about the spin-optical differentiator.

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References

1. F. Zernike, "Phase contrast, a new method for the microscopic observation of transparent objects part ii," Physica **9**, 974–986 (1942).
2. A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alù, and N. Engheta, "Performing mathematical operations with metamaterials," Science **343**, 160–163 (2014).
3. Z. Ruan, "Spatial mode control of surface plasmon polariton excitation with gain medium: from spatial differentiator to integrator," Optics Letters **40**, 601–604 (2015).
4. T. Zhu, Y. Zhou, Y. Lou, H. Ye, M. Qiu, Z. Ruan, and S. Fan, "Plasmonic computing of spatial differentiation," Nature Communications **8**, 15391 (2017).
5. T. Zhu, Y. Lou, Y. Zhou, J. Zhang, J. Huang, Y. Li, H. Luo, S. Wen, S. Zhu, Q. Gong, M. Qiu, and Z. Ruan, "Generalized spatial differentiation from spin hall effect of light," arXiv:1804.06965 (2018).