Optical Metasurfaces Based on Gap Plasmon Resonators

Sergey I. Bozhevolnyi
Department of Technology and Innovation
University of Southern Denmark
DK-5230 Odense M, Denmark
seib@iti.sdu.dk

Abstract— **Plasmonic metasurfaces, i.e., nm-thin surface metal nanostructures with subwavelength-sized lattice units, that are composed of gap plasmon resonators and used for controlling reflected light are overviewed, emphasizing the unique possibility to simultaneously and independently control the reflection direction of orthogonal linear polarizations as well as to realize efficient unidirectional polarization-controlled surface plasmon-polariton excitation.**

I. Introduction

Plasmonic metasurfaces, i.e., nm-thin surface metal nanostructures with subwavelength-sized lattice units, have recently attracted considerable attention due to their abilities to efficiently control both phase and amplitude of transmitted and reflected radiation. Following the detuned electrical dipoles concept [1], we have demonstrated both theoretically and experimentally, that nanometer-thin quarter-wave plates can be realized using anisotropic detuned electric resonant scattering with orthogonally oriented electric dipoles whose resonances detuned (with opposite signs of detuning) from the operation wavelength [2]. It should be noted that these metasurfaces are not related to the optically active extrinsic chiral metamaterials as they only display an electric response (no magnetic response), eliminating the possibility of extrinsic chirality. Later on, the same principle was extended to the realization of wave plates utilizing gap surface plasmons (GSPs) supported by metal-insulator-metal (MIM) configurations [3]. We have shown that MIM nanostructures, in which the top layer consists of a periodic array of nanobricks, thus supporting GSP resonances, offer improved control of the phase of the reflected light. At the same time, by choosing a subwavelength periodicity and weak coupling between the nanobricks and the metal underlay one can strongly suppress the strong absorption typically related to GSP resonances (that can also be advantageously used for efficient and broadband suppression of light reflection [4]), thereby allowing one to design efficient, compact (i.e., subwavelength thick) and background-free (i.e., no diffraction and no scattering into other polarizations) wave plates in reflection. Encouraged by the simulation results obtained for GSP-based quarter-wave plates operating in reflection with ~ 90% efficiency [5], we have designed, fabricated and characterized GSP-based half-wave plates operating in the near infrared and featuring broadband (> 100 nm) operation and relatively high (> 50%) efficiency despite fabrication-induced defects and dispersion in the structural parameters [6].

In this talk, starting with the underlying physics of GSP resonant elements, the concept of GSP-based metasurfaces is introduced, including the design of efficient, compact (i.e., subwavelength thick) and background-free (i.e., no diffraction and no scattering into other polarizations) wave plates in reflection and flat focusing mirrors - the latter functionality is obtained by gradient (i.e., inhomogeneous) metasurfaces that facilitate the independent control of reflection phases of orthogonal light polarizations. Finally, GSP-based gradient birefringent metasurfaces are shown to enable the design of efficient unidirectional polarization-controlled surface plasmon polaritons couplers.

II. Main Results

The understanding of light reflection by arrays of GSP resonators led us to further developments, including the design of highly efficient and background-free (i.e., no diffraction and no scattering into other polarizations) plasmonic metasurfaces providing strong phase gradients in the reflected optical fields at the same polarization as that of the incident one. This work opened exciting avenues for very efficient (up to 90%) and broadband manipulation of reflected optical fields in a manner similar to what has recently been shown with V-shaped optical antennas, which however influence only the orthogonal polarization with a limited (less than ~10%) efficiency [7].

Our first work on GSP-based gradient metasurfaces demonstrated possibility of realization of efficient and broadband flat mirrors strongly focusing incident radiation in reflection [8]. Developing further our understanding of the main physical mechanisms responsible for operation of GSP-based gradient metasurfaces comprising a periodic arrangement of metal nanobricks, we realized that two degrees of freedom in the nanobrick geometry allow one to independently control the reflection phases of orthogonal light polarizations [9]. Thereafter we have demonstrated, both theoretically and experimentally, how orthogonal linear polarizations of light at wavelengths close to 800 nm can be manipulated independently, efficiently and in a broad wavelength range by realizing polarization beam splitters and polarization-independent beam steering, showing at the same time the robustness of metasurface designs towards fabrication tolerances [9]. The developed approach established thereby a new class of compact optical components, viz., plasmonic metasurfaces with controlled gradient birefringence, with no dielectric counterparts. It became also clear that our approach can

978-1-4799-3682-3/14/$31.00 ©2014 IEEE

straightforwardly be adapted to realize new optical components with hitherto inaccessible functionalities as well as extended to other wavelength ranges.

Efficient excitation of surface plasmon polaritons (SPPs) remains one of the most challenging issues in areas of plasmonics related to information communication technologies. In particular, combining high SPP excitation efficiency and acceptance of any polarization of incident light appeared to be impossible to attain due to the polarized nature of SPPs. In our latest work, extending further our concept of GSP-based gradient metasurfaces, we have demonstrated efficient SPP couplers that represent arrays of GSP resonators producing upon reflection two orthogonal phase gradients in respective linear polarizations of incident radiation [10]. These couplers are thereby capable of efficiently converting incident radiation with arbitrary polarization into SPPs that propagate in orthogonal directions dictated by the phase gradients. Fabricated couplers operate at telecom wavelengths and feature the coupling efficiency of ~ 25% for either of two linear polarizations of incident radiation and directivity of SPP excitation exceeding 100. We further demonstrated that an individual wavelength-sized unit cell, representing a meta-scatterer, can also be used for efficient and polarization sensitive SPP excitation in compact plasmonics circuits.

III. Outlook

We believe that the efficient unidirectional polarization-controlled excitation of SPPs, using either individual metascatterers or their periodic arrays, opens a unique possibility to simultaneously achieve both high SPP excitation efficiency and acceptance of any polarization of incident light that can be exploited for the realization of polarization-independent plasmonic components, an important milestone in the development of integrated plasmonic circuits. The developed approach represents also a new way of encoding the polarization information in SPPs, suggesting the efficient method for inter-conversion of polarization-encoded photon qubits and SPPs, a process that is very important in the context of quantum plasmonic circuits. Another interesting development can be to realize complete on-chip characterization of polarization states of light by combining the polarization-controlled SPP coupler, which allows one to excite separate SPPs associated with orthogonal linear polarizations, with a suitable plasmonic interference circuitry to compare their phases and integrated SPP detectors to conduct quantitative analysis of amplitudes of the incident orthogonal linear polarizations as well as their phase difference. Overall, we foresee many exciting developments and applications of the demonstrated approach within plasmonics.

Acknowledgment

The author would like to acknowledge the financial support from the Danish Council for Independent Research (the FTP project ANAP, contract no. 09-072949, and the FNU project, contract no. 12-124690).

References

[1] S. I. Bozhevolnyi *et al.*, “Optical transparency by detuned electrical dipoles,” New J. Phys. **13**, 023034 (2011).

[2] A. Pors *et al.*, “Plasmonic metamaterial wave retarders in reflection by orthogonally oriented detuned electrical dipoles,” Opt. Lett. **36**, 1626-1628 (2011).

[3] M. G. Nielsen *et al.*, “Continuous layer gap plasmon resonators,” Opt. Express **19**, 19310-19322 (2011).

[4] M. G. Nielsen *et al.*, “Efficient absorption of visible radiation by gap plasmon resonators,” Opt. Express **20**, 13311-13319 (2012).

[5] A. Pors and S. I. Bozhevolnyi, “Efficient and broadband quarter-wave plates by gap-plasmon resonators,” Opt. Express **21**, 2942-2952 (2013).

[6] A. Pors, M. G. Nielsen, and S. I. Bozhevolnyi, “Broadband plasmonic half-wave plates in reflection,” Opt. Lett. **38**, 513-515 (2013).

[7] N. Yu *et al.*, “Light propagation with phase discontinuities: generalized laws of reflection and refraction,” Science **334**, 333-337 (2011).

[8] A. Pors *et al.*, “Broadband focusing flat mirrors based on plasmonic metasurfaces,” Nano Lett. **13**, 829-834 (2013).

[9] A. Pors, O. Albrektsen, I. P. Radko, and S. I. Bozhevolnyi, “Gap-plasmon based metasurfaces for total control of reflected light,” Scientific Reports **3**, 2155 (2013).

[10] A. Pors et al., “Efficient unidirectional polarization-controlled excitation of surface plasmon polaritons,” Light: Science & Applications, in press.