Real- and momentum-space imaging of plasmonic waveguide arrays

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Application Note

Introduction

The coupled mode theory, which describes the light propagation in evanescently coupled arrays of single mode waveguides, can be cast in the same mathematical form as the equation of motion that governs the quantum mechanical evolution of electrons in the framework of the tight-binding model. Using this analogy, properly designed photonic waveguide structures can be employed to simulate the quantum mechanical evolution of electrons in crystals. Hereby, the spatial light intensity distribution in the waveguides is mapped onto the time-dependent probability distribution of the electronic wave packet and the propagation distance z along the waveguides plays the role of time. Based on this approach, discrete diffraction, Bloch oscillations, Zener tunneling, and Anderson localization have been observed in dielectric waveguide arrays.

We have recently demonstrated that these ideas can be extended to the field of plasmonics [1]. In our experiments, we use arrays of evanescently coupled dielectric-loaded surface plasmon polariton waveguides (DLSPPWs) [see Fig. 1] that are fabricated by placing Poly(methyl methacrylate) (PMMA) ridges on top of a 60 nm thin gold film. DLSPPWs offer a number of features, which make them very attractive for our experiments. They can be easily, quickly and reliably fabricated by negative-tone gray-scale electron beam lithography. The typical exposure time for a single array is in the order of several minutes. Furthermore, this method allows us to control both, the effective refractive index of the individual waveguides as well as their mutual couplings in a wide range, by simple variations of the sample geometry.

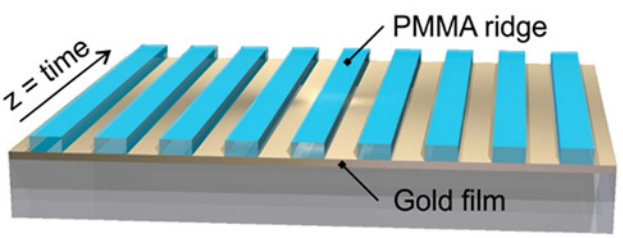

Fig. 1 Scheme of an array of evanescently coupled DLSPPWs.

Leakage radiation microscopy

A distinct advantage of DLSPPWs is that one can easily monitor the SPP propagation in the waveguides by leakage radiation microscopy [see Fig. 2]. Our optical setup uses of a 980 nm diode laser, which is TM-polarized with respect to the SPP propagation direction. This laser wavelength has been chosen to ensure relatively low losses in the gold film. SPPs are launched in the array by focusing the laser beam with a microscope objective (× 20 magnification, numerical aperture NA = 0.4) on a grating coupler. A fraction of the excited SPP leaks through the thin gold film and couples to propagating modes in the glass substrate. This so-called leakage radiation (as well as the directly transmitted laser beam) is collected with an oil immersion objective (× 100 magnification, NA = 1.49). Leakage radiation microscopy allows us to characterize the SPP evolution in a given array both in real and momentum space. By imaging the sample plane onto the camera (Zyla-5.5-USB3 from Andor Technology), we can directly record the real space SPP distribution. The corresponding momentum-space intensity distribution is obtained by imaging the back-focal plane of the oil immersion objective onto the camera.

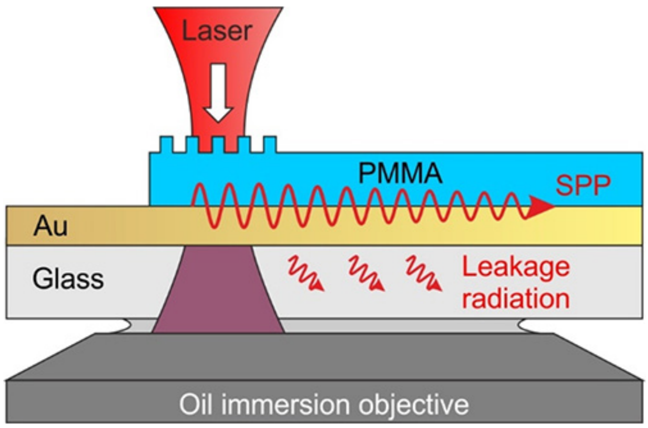

Fig. 2 Excitation and detection of SPPs by leakage radiation microscopy.

The Zyla camera combines serval advantages, making it a great choice for our experiments. It has a high resolution 5.5 megapixel sCMOS sensor with a large dynamic range that allows to record the SPP distribution in the whole array in one single shot. Moreover, TE cooling to 0 °C guarantees low dark currents. Together with the low read-out noise of the camera, we obtain images with an excellent signal to noise ratio.

Arrays of identical waveguides

As an example, we consider in the following the SPP-propagation in an array of identical DLSPPWs arranged in a periodic lattice with a lattice constant of 1000 nm. In order to excite a single DLSPPW in the middle of the array, the laser beam is focused on

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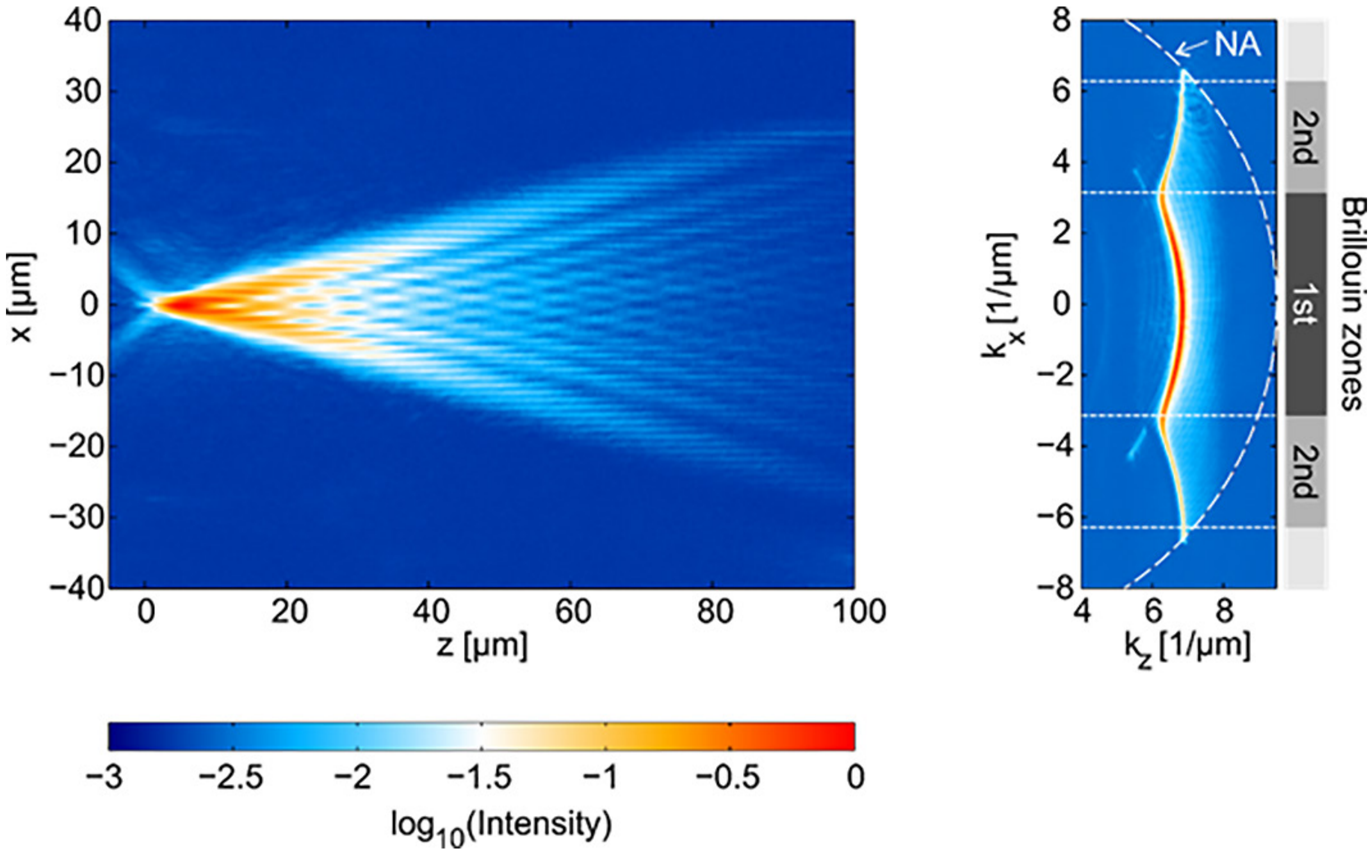

Fig. 3 (left) Real-space leakage radiation microscopy of SPPs propagating (in z-direction) in an array of identical DLSPPWS. (Right) Corresponding momentum space image. The numerical aperture (NA) of the objective lens restricts the maximum value of the momentum.

a grating coupler, placed on top of the central waveguide. As the SPP propagates along the waveguide, a part of the field is coherently transferred to the neighboring waveguides. From there, the SPP couples to their neighboring waveguides and so on and so forth. This results in a ballistic spreading of the SPP wave packet as well as a characteristic interference pattern (see Fig. 3, right hand-side). On account of the mathematical equivalence between the classical and quantum mechanical wave evolution, the observed SPP transport behavior is analogous to the temporal evolution of electronic wave packets tunneling along a chain of lattice sites with identical coupling strengths and hence shows the well-known form of a quantum random walk probability distribution.

In order to access the momentum distribution of SPPs in the waveguide array, we image the back-focal plane of the high NA objective lens onto the camera. In doing so, we take advantage of the fact that the spatial intensity distribution in the back-focal plane of an aplanatic objective lens is related to the angular distribution of the collected light by the sine-condition. For this reason, the SPP wave vector $k_{SPP}=(k_x,k_y)$ is directly mapped to a given position r in the back-focal plane, $r=f_{eff.} kS_{PP} / k_0$, where k_0 is the vacuum wavenumber and f_{eff} is the effective focal length. The left hand-side of Fig. 3 shows the measured SPP momentum distribution of the array of identical waveguides. It consists of a single cosine-like band. Based on the time-space mapping discussed above, we can interpret k_x (transverse direction) as the quasi momentum and the k_z distribution (SPP propagation direction) as the energy spectrum. From this point of view, the measured SPP momentum distribution directly visualizes the electronic band structure of one-dimensional crystal composed of identical sites.

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Summary
The example demonstrates that real- and momentum-space imaging of plasmonic waveguide arrays allows us to simulate the dynamics of electrons in crystals. By controlling the effective refractive index of the individual waveguides as well as their mutual couplings, a wide range of different condensed matter systems can be addressed. Further studies with plasmonic waveguide arrays performed in our group are related to Bloch oscillations [1] and topological insulators [2].

References

[1] A. Block, C. Etrich, T. Limboeck, F. Bleckmann, E. Soergel, C. Rockstuhl, S. Linden, Bloch oscillations in plasmonic waveguide arrays, Nat. Commun. 5:3843 doi: 10.1038/ncomms4843 (2014).
[2] F. Bleckmann, S. Linden, A. Alberti, Spectral imaging of topological edge states in plasmonic waveguide arrays, arXiv:1612.01850 [quant-ph]

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