Advancing Ultrafast Transmission Electron Microscopy with Dielectric Metalenses

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Background incl. aims

In 2005, Ahmed H. Zewail merged ultrafast femtosecond laser with femtosecond precision with TEM's sub-nanometer spatial resolution developing Ultrafast Transmission Electron Microscopy (UTEM). This technique combines the sub-nm spatial resolution of TEMs with the fs temporal resolution of ultrafast lasers and is paving the way to the study of ultrafast fundamental processes at the nanoscale. In the last years, a new paradigm for the arbitrary modulation of the probing-electron wave function phase through quantized photon-electron interaction was put forward and has the potential for enhanced microscopic sensitivities to material properties [1]. The quality and the extent of the electron beam shaping strongly depend on matching the transverse coherence of the electron beam (~ 1 µm) with the spot size of the laser beam, which generally exceeds the former by more than one order of magnitude. This mismatch prevents the modulation of the electron wave function phase, which is crucial for the ability to probe specific materials degree of freedom (such as chirality of materials when adopting a vortex electron beam). In order to address this issue, we propose the integration of a crystallin silicon metalens in the platform that enables electron-light interaction.

Methods

The electron beam shaping inside the UTEM is facilitated by a Photonic free-ELectron Modulator (PELM). An external Spatial Light Modulator (SLM) imprints an arbitrary amplitude and phase pattern on an ultrafast optical field. The light is then projected on a flat electron-transparent metallic thin film on the PELM platform, where it interacts with the electron beam. The integration of a dielectric metalens into the PELM enables the focusing of incident light down to a few micrometers before its interaction with the electron beam. We fabricated a metalens on a free-standing silicon membrane kept in place by a silicon window. Then, we integrated the silicon windows to the PELM platelet positioned at 45° with respect to the metallic film. The focal distance of the metalens is on the order of several hundreds of µm's. This geometry allows the focusing of the light arriving horizontally from the side of the microscope on the metallic film, where the electron-photon interaction will occur. A metalens is composed of properly arranged nano antennas (also called meta-atoms) [2]. We designed the meta-atoms geometric parameters by performing extensive finite element method (FEM) simulations through the wave optics module of the COMSOL Multiphysics® software. The position and orientation of the meta-atoms on the metalens surface are then arranged to obtain the geometric phase spatial variation needed to focalize the incident light beam.

Results

From the Comsol simulations we obtained the meta-atoms dimension that optimizes the transmission and the phase difference condition, as well as mechanical constraints. The obtained theoretical transmission is equal to 44%. The metalens-integrated PELM geometry requires a focal length of 0.7 mm to let the electron beam interact with the focused laser spot and then proceed along the microscope. For that focal length and a 500 µm metalens diameter, the wave propagation simulations provide the focusing of the incident laser down to 2.5 µm.

We have also computationally characterized the performance of the designed dielectric metalens by simulating the propagation of a gaussian plane. Moreover, we explored the metalens robustness to non-idealities by applying a random noise on the phase and we verified that a transversely-patterned light beam, such as a Hermite-Gaussian profile, is correctly focused without distortions.

Conclusions

This setup is a compact solution that can be inserted in the UTEM to allow matching the laser spot size with the transverse coherence length of the electron beam, providing access to a wide range of excitation schemes and pump-probe geometries. Currently, we are working on the optical characterization of the metalens, in order to experimentally confirm its performances. The next step will be to mount the metalens windows in the PELM and characterize its performance inside the UTEM.

Funding

This work is part of the SMART-electron Project that has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 964591.

Graphic:

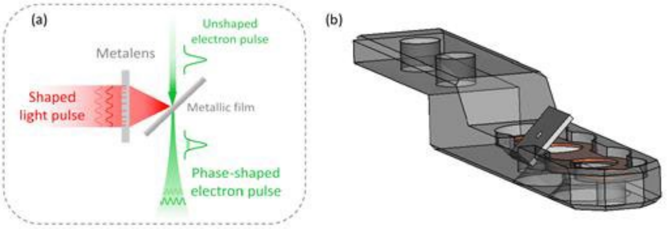

Figure 1| Electron beam shaping setup. (a) schematics of electron-photon interaction using a dielectric metalens. (b) Metalens-integrated Photonic free-ELectron Modulator (PELM). A silicon window is angled at 45° relative to the metallic mirror on the PELM platform.

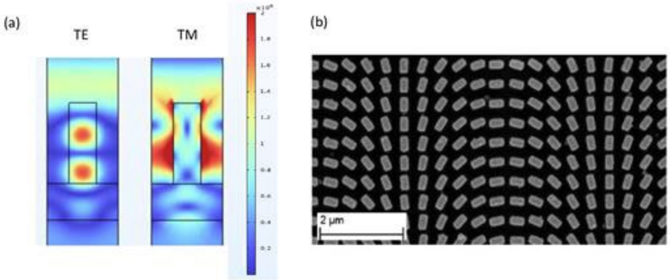

Figure 2| Metalens design. (a) Electric field [V/m] maps of TE and TM mode in a meta-atom from wave optics module of COMSOL Multiphysics® simulations (xy view). (b) SEM image of meta-atoms orientation in the metalens surface.

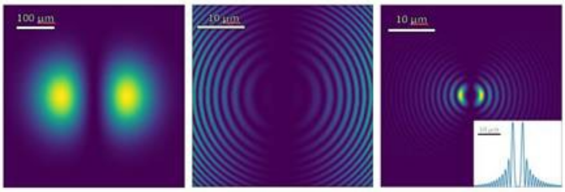

Figure 3| Wave propagation simulation of a Hermite-Gaussian beam through a 12-level discretized focalizing phase profile. (Left) Initial beam wavefront. (Middle) Wavefront after the interaction with the focalizing phase profile. (Right) Beam spot in the focal plane and normalized intensity.

Keywords:

Metalens, electron-photon interaction, Ultrafast TEM

Reference:

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