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Electron-photon quantum interaction enables novel ultrafast electron imaging approaches

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Background incl. aims

Coherently controlling the electronic and structural properties of new generation materials and devices down to the sub-nm level with femtosecond precision is one of the ultimate challenges in quantum technology, and has the potential to engineer novel states of matter with exceptional macroscopic functionalities. Here, we respond to such pressing need by introducing a new paradigm where the interaction between light and free-electrons can be exploited for coherently manipulating electron beams [1,2], enabling dynamical investigation of materials with enhanced sensitivities to specific materials degrees of freedom, unattainable using conventional schemes. We develop innovative ultrafast electron microscopy (UEM) methods based on light-induced electron modulation aiming to observe, understand, and control the non-equilibrium behavior of low-dimensional systems at such ultrasmall and ultrafast scales, which would be otherwise hidden in standard UEM observations.

Methods

The playground for these experiments is a modified Ultrafast Transmission Electron Microscope (UTEM) with multiple optical accesses for: i) electron pulse generation, ii) electron wavefunction modulation, and iii) sample excitation. Arbitrary longitudinal and transverse modulation of a free-electron wave function is obtained using light fields properly modulated in space and time. In particular, a femtosecond electron pulse interacts with the chosen configuration of the optical distribution as generated via a spatial light modulator (SLM) (see schematics in the left panel of the figure), and the energy-momentum quantum exchanges between electron and photons resulting from such coupling are mapped in the electron multidimensional phase space. [3]

Results

In this contribution, we will first demonstrate how to coherently modulate the spatial, momentum, energy, and temporal distributions of the electron wave function with high versatility on different modulation basis. This derives from the technological development of a new device: a photonic-based modulator for dynamic multidimensional control of electrons. Then, we will show how our approach for versatile transverse and longitudinal electron modulation at the fs-timescale is crucial for the first time implementation of new imaging techniques (see schematics in the right panel of the figure), such as Ramsey-like holography [4] – for phase- and time-resolved imaging of hybridized low-energy modes in strongly-correlated systems – and Single Pixel Imaging [5] – that has been only recently proposed for optical detection and now is possible also in electron microscopy permitting lower electron doses, faster acquisition rates for individual nanoscale objects in their natural environment.

Conclusion

In conclusion, we report on the realization of an all-optical rapidly-programmable phase mask for electrons, which allows us to implement new electron imaging approaches with enhanced sensitivities and performance, thus radically changing how matter is investigated in electron microscopy. This is based on a specific sensitivity to materials' inner coherence when light-modulated structured electron waves are adopted. Our results pave the way for achieving unprecedented insights into new generation materials and their dynamic behavior, impacting also future photonics and electronics applications. More generally, unlocking this potential will play a decisive role in our ability to address the grand challenges that the world is facing nowadays, especially regarding 'energy', 'information' and 'health'.

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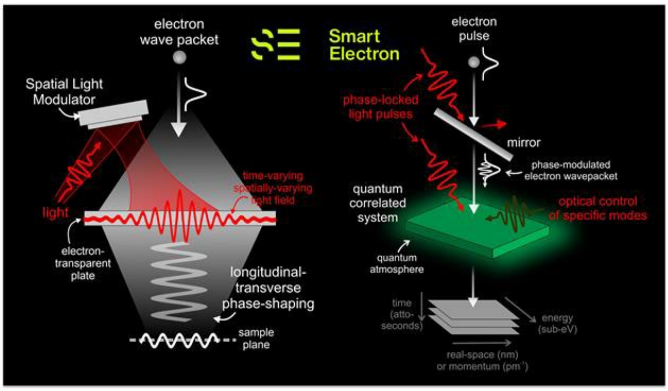
Graphic:



Keywords:

UTEM; electron-wavefunction modulation; low-dimensional materials.

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