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# Inelastic Holography and Interaction-Free Measurements with Interferometric STEM

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Here we report the use of scanning electron interferometry to probe the coherence and symmetry of nano-optical excitations as well as demonstrating interaction-free measurements. We have used two specialized holographic apertures in a conventional STEM instrument to create a scanning electron Mach-Zehnder interferometer [1]. Material phase gratings provide a way to efficiently diffract electrons with desired properties in transmission electron microscopes [2,3]. In the interferometer setup, a STEM probe is coherently dividing into two or more probes by a grating in the condenser system. These probes are then overlapped and recombined at a second grating placed post-specimen, such that the separate paths interfere to form discrete output beams diffracted by the second grating (see Fig. 1).

In one set of experiments, we apply this 2-grating electron Mach-Zehnder interferometer to probe coherence and inelastic scattering of optical transitions such as plasmons. For instance, two STEM probes – each described by superpositions of single electrons – incident on the same nanoplasmonic structure can excite the same optical transition, albeit from different positions. These two paths still interfere, despite the inelastic scattering interaction with the specimen. We observe that the excitation of a plasmon introduces a relative π phase shift between the two probes and show that this is predicted from a dipole optical transition. More details are described in [4].

In another set of experiments, we use the same set up to demonstrate interaction-free measurements, a type of quantum measurement protocol. Interaction-free measurements involve a single particle traversing two paths in an interferometer and self-interfering destructively at an output. Blocking or scattering one of the paths disrupts this interference and results in an increase in events at the output. We implement this
interferometric technique in a STEM the 2-grating electron interferometer, demonstrating that inserting a completely opaque object into one path results in an *increase* in electron interferometer output at the camera. We and others are exploring the use of this interaction-free measurement technique to reduce the electron dose required to image objects in the TEM [4].

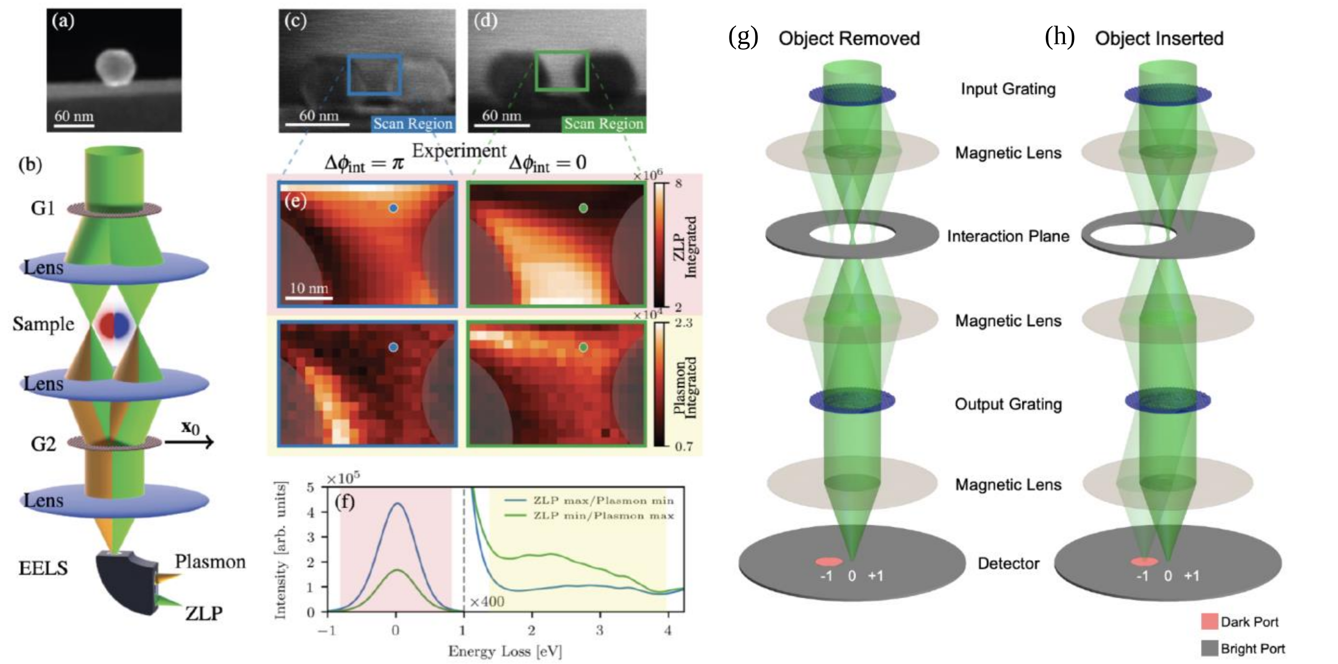


**Figure 1.** (a-f) Borrowed from [4]. (a) Dark field STEM image of a 60 nm gold nanoparticle (NP) isolated on the edge of a carbon substrate. (b) Sketch of the two-grating electron Mach Zehnder interferometer consisting of a STEM with two gratings used as beamsplitters. The first grating (G1) prepares electrons in a superposition of two separate paths, each of them interacting with the NP sample, with some probability of losing energy to a plasmon resonance (orange). (c,d) The electron paths are then recombined using the second grating (G2), which can be positioned for (c) destructive (blue borders) and (d) constructive (green borders) interference, conversely modifying the elastic and inelastic signals. Two NPs are observed in the image because of the two-spot beam configuration, with the central frame selecting the interference region (i.e., each beam passing by one side of the NP). (e,f) For both alignment schemes, we integrate over the plasmon (yellow-shaded) and ZLP (red-shaded) regions of the energy loss spectra (f) at every scan location to create the spectral images shown in (e). The raw spectra in (f) correspond to the dotted positions in (e). (g) and (h), borrowed from [5], illustrate the interaction free measurement.

References:

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