Enhanced Carrier-Envelope Phase Detection with Photoelectron Emission in Plasmonic Nanoantenna Arrays

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The carrier-envelope phase (CEP) is the phase delay between the optical frequency carrier wave and the intensity envelope of an ultrafast optical pulse. Detection of the CEP is essential for determining the optical pulse waveform in attosecond science and strong field physics, as well as stabilizing optical frequency combs. Conventionally, CEP detection requires a complex vacuum apparatus or interferometric methods. Recent work has demonstrated CEP detection via optical-field induced photoelectron emission on a chip[1,2]. Here we show on-chip detection of CEP by measuring the photoelectron emission current in electrically-connected bow-tie plasmonic nanoantenna arrays (Figure 1). The photocurrent arises from the difference of electron emission from one half of the bow-tie to the other half and vice versa, which is driven by the optical fields in opposite directions and hence depends on the CEP. We used parallelized nanoantenna arrays with a nanoscale cathode-anode separation, leading to improved photoelectron collection, higher photoemission current and stronger signal compared to previous work[1,2].

Gold plasmonic nanoantenna arrays were fabricated on a transparent glass (BK7) substrate via electron beam lithography and metal lift-off. The fabricated bow-tie antenna gap size varied from the nominal size due to process variations. If the two triangles of a bow-tie were connected, they would electrically short the cathode and anode, making the whole array unresponsive for CEP detection. Electromigration was used to remove these shorted devices by breaking their contact wires (Figure 2).

We illuminated the plasmonic nanoantenna array with an average gap size of ~20 nm by an ultrafast optical pulse train with a center wavelength of 1177 nm, near the resonance wavelength of the plasmonic antennas. The average pulse duration was ~10 fs (~2.5 optical cycles), the maximum pulse energy was ~190 pJ, and the repetition rate was 78 MHz. The carrier-envelope offset frequency of the pulse train was stabilized to 100 Hz. We measured up to 5 pA CEP-sensitive current when illuminating ~12 bow-tie antennas with a 2.25 μm × 4.1 μm beam spot size. (Figure 3).

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[1] T. Rybka et al., Nature Photonics 10(10), 667 (2016).

[2] W. P. Putnam et al., Nature Physics 13(4), 335 (2017).

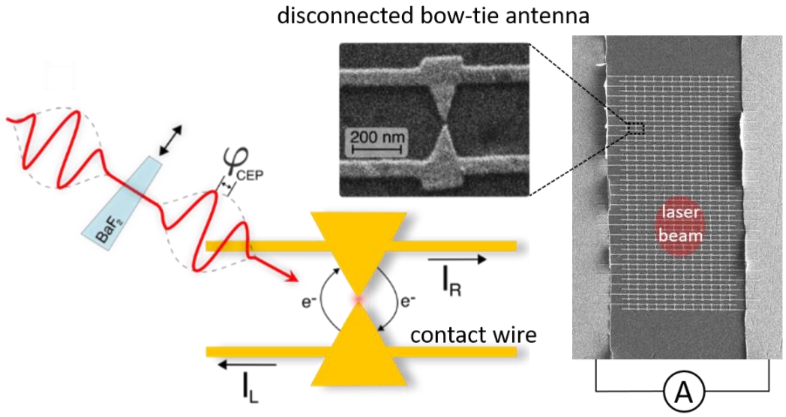

Figure 1. CEP detection with photoelectron emission in a plasmonic bow-tie antenna array. When illuminated with a short optical pulse, the photoemission current from one half of the bow-tie to the other half can be different from the photoemission current in the opposite direction, depending on the CEP. Hence, the net photoemission current is CEP-sensitive. SEM images show a disconnected bow-tie antenna from the array shown on the right.

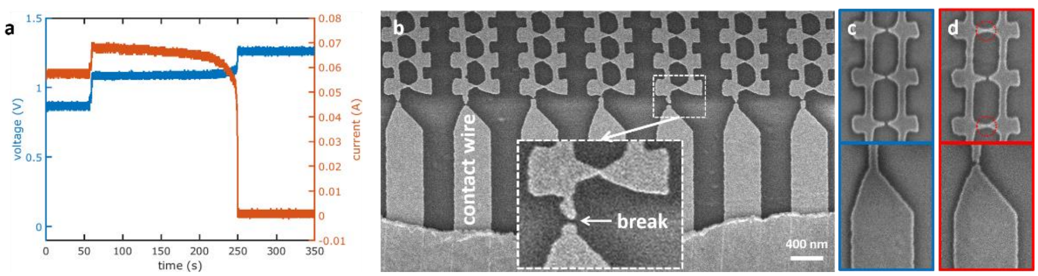

Figure 2. Electromigration of the plasmonic nanoantenna array. **a**, Applied voltage and current across a plasmonic nanoantenna array during the electromigration process. Electromigration transformed a shorted array into an open array. **b**, SEM image of a connected plasmonic nanoantenna array after electromigration. The electrical contact wires were broken and disconnected during electromigration. Inset: zoomed-in image of the connected bow-tie antenna and the broken contact wire. **c,** For an unbroken wire, the bow-tie nanoantennas along the wire are all disconnected. **d,** For a broken wire, there is usually a short circuit caused by connected bow-tie nanoantennas (red dashed circles).

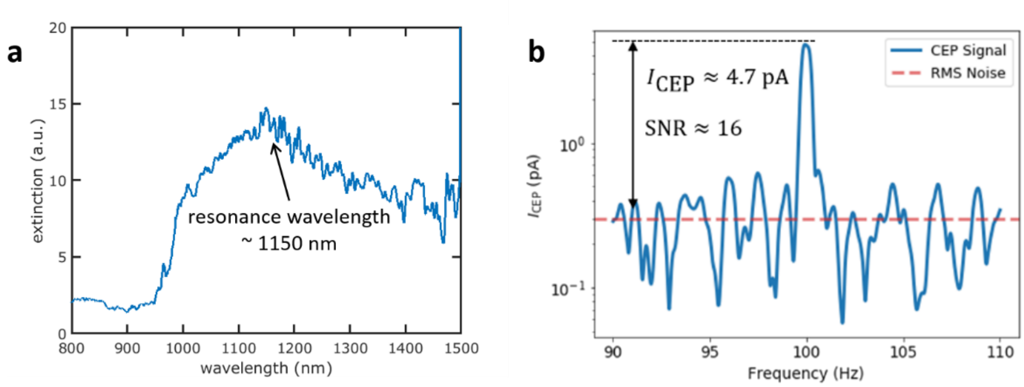

Figure 3. Optical response of the nanoantenna array. **a,** Measured extinction spectrum of a nanoantenna array. The plasmonic resonance wavelength is around 1150 nm. **b,** Measured spectrum of photoemission current while the CEP is oscillating. The peak at 100 Hz corresponds to the CEP-sensitive current, with an amplitude of 4.7 pA from 12 illuminated bow-tie antennas. This result represents a ~5× increase in signal relative to previous work.