Tunable caustic phenomena in electron wavefields

A. H. Tavabi[1], V. Migunov[1], C. Dwyer[1], G. Pozzi[2] and R. E. Dunin-Borkowski[1]

1. Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons and Peter Grünberg Institute, Forschungszentrum Jülich, Jülich, Germany
2. Department of Physics and Astronomy, University of Bologna, Viale B. Pichat 6/2, 40127 Bologna, Italy

E-mail: r.dunin-borkowski@fz-juelich.de

The coherence of a modern field emission transmission electron microscope (TEM) allows fascinating caustic phenomena to be observed, such as the hyperbolic umbilic catastrophe produced by a coma aberration function [1] and cusped fan-like structures in defocused images of electrically biased nanotube bundles [2] and metal needles [3].

Here, we study bright-field TEM images of two approximately collinear oppositely-biased metallic tips, which show rich caustic phenomena that are strongly reminiscent of the elliptic umbilic diffraction catastrophe that occurs when visible light is refracted by a water droplet with a triangular perimeter [4]. The observed patterns depend sensitively on defocus, on the applied voltage between the tips and on their separation and lateral offset.

An FEI Titan 60-300 field emission gun TEM was used to study two metallic tips that had been thinned electrochemically and mounted in a specimen holder equipped with piezo-electric drives and electrical contacts. The tips were placed in front of each other at a separation of ~1 µm and a potential difference of up to 130 V was applied between them. The positively charged wire was found to act like a terminating convergent electron biprism, producing an overlapping region of intensity containing two-beam fringes, whereas the negatively charged wire acted like a terminating divergent biprism. The combined effect of the fields resulted in highly complex interference patterns, examples of which are shown in Figs. 1 and 2. We interpreted the key features in our experimental images using a relatively simple electrostatic model based on line charges, in which equipotential surfaces were used to mimic the nearly ellipsoidal shapes of the tips. The qualitative agreement between the experimental and simulated images shown in Fig. 1 is very good. Although it has not yet been possible to obtain fully quantitative agreement between the experimental and theoretical results, owing in large part to uncertainties in several experimental parameters (e.g., the defocus and illumination conditions), as well as the inability to model the electrode shapes precisely, the good qualitative agreement confirms the soundness of the model.

Our experimental setup offers, in a single experiment, the ability to transform simple caustics into more complex ones. Such transformations have been difficult to achieve in previous studies using light, which have employed a single lens, e.g., a water droplet, to produce only a specific caustic. Work is in progress to relate the underlying phase shifts to the catastrophe interpretation of caustic patterns.

[1] T. C. Petersen, M. Weyland, D. M. Paganin, T. P. Simula, S. A. Eastwood and M. J. Morgan, “Electron vortex production and control using aberration induced diffraction catastrophes”, Phys. Rev. Lett. 110 (2013) 033901
[2] M. Beleggia, T. Kasama, R. E. Dunin-Borkowski, S. Hofmann and G. Pozzi, “Direct measurement of the charge distribution along a biased carbon nanotube bundle using electron holography”, Appl. Phys. Lett. 98 (2011) 243101
[3] M. V. Berry, J. F. Nye and F. J. Wright, “The elliptic umbilic diffraction catastrophe”, Phil. Trans. Roy. Soc. London A 291 (1979) 453-484
[4] G. Matteucci, G. F. Missiroli, M. Muccini and G. Pozzi, “Electron holography in the study of the electrostatic fields: the case of charged microtips”, Ultramicroscopy 45 (1992), 77-83

Acknowledgements
We are grateful to Prof. M. Farle and his colleagues in the Fakultät für Physik and Center of Nanointegration (CeNIDE), Universität Duisburg-Essen for technical support, to the Deutsche Forschungsgemeinschaft for a Deutsch-Israelische Projektkooperation (DIP) Grant, to the European Commission for an Advanced Grant and to the European Union Seventh Framework Programme for funding under Grant Agreement 312483-ESTEEM2 (Integrated Infrastructure Initiative-I3).

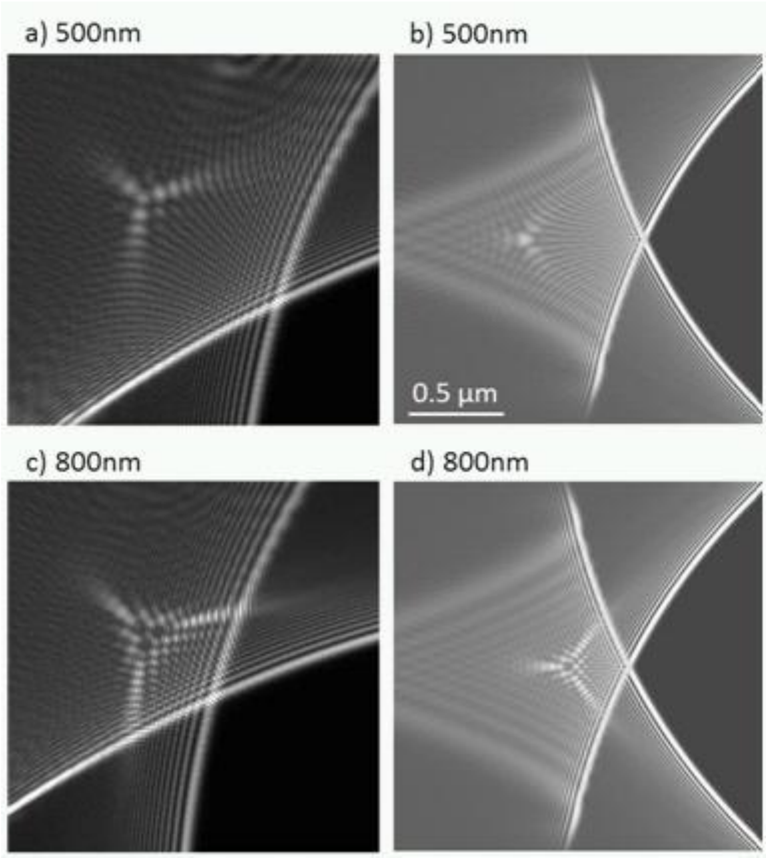

Fig. 1. a, c) Experimental defocused bright-field TEM images of two metallic tips that had been thinned electrochemically and mounted in a specimen holder equipped with piezo-electric drives and electrical contacts. The tips were placed in front of each other at a separation of ~1 µm. The images were recorded at a nominal defocus of -9 mm and a potential difference of -80 V for tip separations of a) 500 and c) 800 nm. b) and d) show simulated images for the experimental conditions in a) and c).

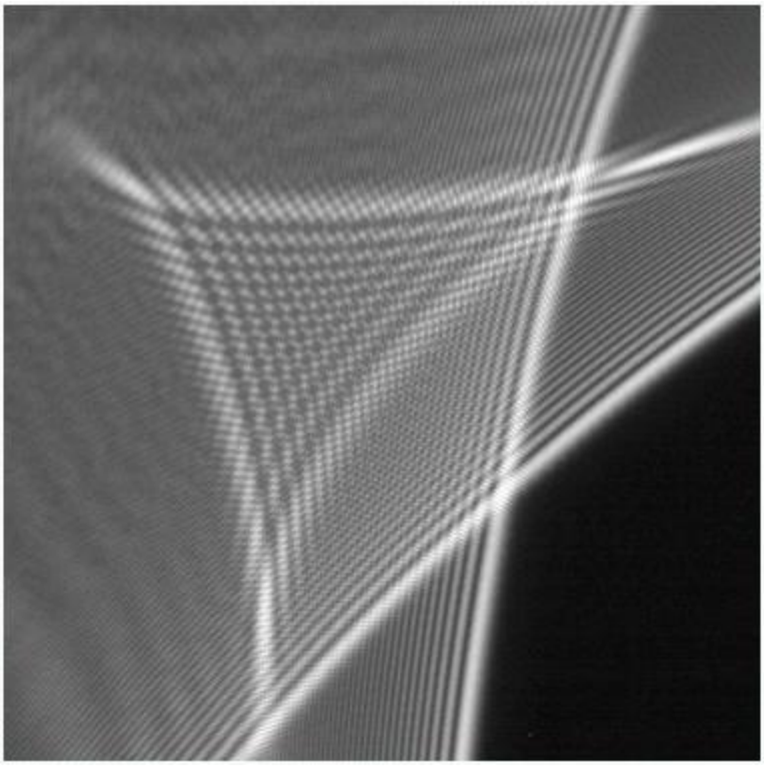

Fig. 2. High magnification defocused bright-field TEM image for a potential difference between the tips of 130 V and a defocus of -8 mm.