Electronic Supplementary Information

Direct Visualization of the Modulated Field Distribution along Single Gold Nanowires by Differential Interference Contrast Microscopy

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This document contains experimental methods and additional supplementary figures (Fig. S1 to S5).

Experimental Methods

1. Differential Interference Contrast Microscopy

Differential interference contrast (DIC) microscopy was preformed with an upright Nikon Eclipse 80i microscope in this study. The DIC mode used a pair of Nomarski prisms, two polarizers, a quarter-wave plate, a Plan Apo oil-immersion objective (100×, N.A. = 1.40), and an oil-immersion condenser (N.A. = 1.40). Band-pass filters (550 nm, 640 nm, 740 nm, 800 nm) with a full width at half-maximum (FWHM) of 10 nm were obtained from Thorlab (Newton, NJ, USA) and inserted into the light path in the microscope. A Hamamatsu CMOS camera (ORCA-Flash 2.8) was employed to record highly detailed DIC images of Au nanowires and to record dynamics of Au nanowires rotating on synthetic membranes.

2. The Working Principle of DIC Microscopy

In DIC microscopy the incident beam is split into two orthogonally polarized beams in the two bright (blue-line) and dark (red-line) polarization directions by the first Nomarski prism as shown in Fig. S1. When two beams pass through the specimen, they generate image contrasts for optical path length gradients in the specimen. Therefore, each of the two orthogonally polarized beams generates an independent intermediate image. One such image is shifted laterally by ∼100 nm and then overlapped with the other to generate the final interference image. For anisotropic shape of Au nanowires, the two intermediate images are different because the two illumination beams are phase-delayed to different extents, depending on the orientation of the Au nanowire relative to the two polarization directions. Therefore, the DIC images of Au nanowires have disproportionate bright and dark parts and they show different bright and dark intensities depending on the Au nanowire orientation.

3. Sample Preparation

Au nanowires were purchased from Nanopartz (Loveland, CO, USA). The Au nanowire colloid solution was first sonicated for 15 min at room temperature. A sample was prepared by spin casting the solution on the pre-cleaned glass slide. Then, a 22 mm × 22 mm No. 1.5 coverslip (Corning, NY) was covered on the glass slide. In this study, the concentration of Au nanowires on the glass surface was controlled to facilitate single particle characterization.

4. DIC Imaging of Au Nanowires

The sample glass slide was placed onto the microscope stage. For DIC imaging, single AuNWs were alighted parallel to bright axis (one of two polarization directions in DIC microscopy), which results in a totally bright image of the nanowire. To excite the Au nanowire with different SPR wavelengths, band-pass filters (550 nm, 640 nm, 740 nm, 800 nm) were inserted into the light path in the microscope. DIC images were taken with the Hamamatsu CMOS camera. The collected images and movies were analyzed with MATLAB and NIH ImageJ.

5. Dark-field Imaging of Au Nanowires

We further tested if the regularly spaced bright spots (Fig. 3) could be resolved under scattering-based dark-field (DF) microscopy using randomly polarized illumination. We placed a transmission grating beam splitter with 70 lines/mm in front of the CCD camera. This transmission grating allowed one portion of the incoming scattering light to form the zero-order image and dispersed another portion of the light to form the wavelength-resolved first-order image. Both the zero-order and first-order images can be captured by the camera. It can be seen that the zero-order image from an individual Au nanowire is a focused spot and the first-order image is a long streak. If the number density of Au nanowire spots on the substrate is not very high, there will be no overlap between zero-order and first-order images of different Au nanowires and they can be readily separated.

Fig. S5A shows the zero-order and the first-order images of a 3-μm Au nanowire. Figs S5B and S5C show the DF scattering intensity crosscuts at the positions of 550 (green-square) nm and 740 nm (red-square). Two bandpass filters of 550 nm and 740 nm were used to find the positions in the first-order image. As shown in Fig. S5, we found that the spaced bright spots were not observed under randomly-polarized DF microscopy when compared to DIC microscopy a linearly polarized light.

Supplementary Figures

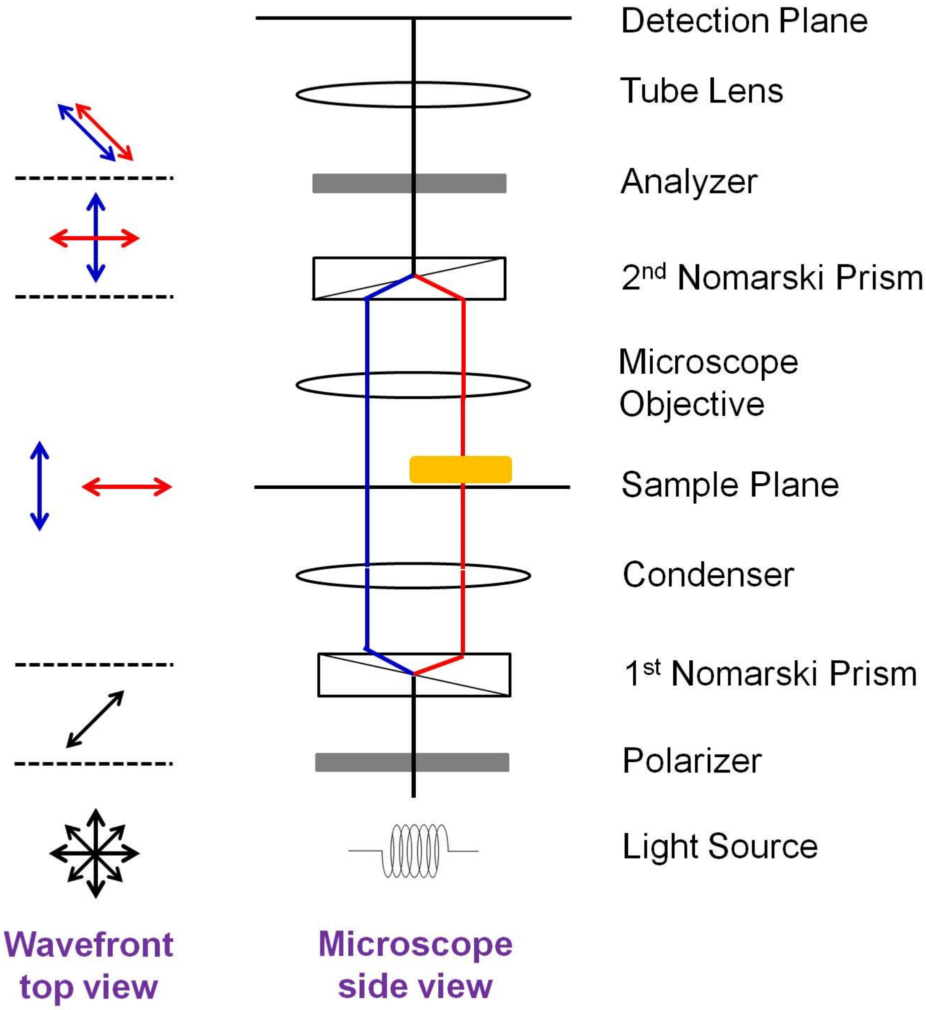

Fig. S1. The optical path and wavefront in the DIC microscope. The blue- and red- lines represent the optical path of two orthogonal beams split by the first Nomarski prism.

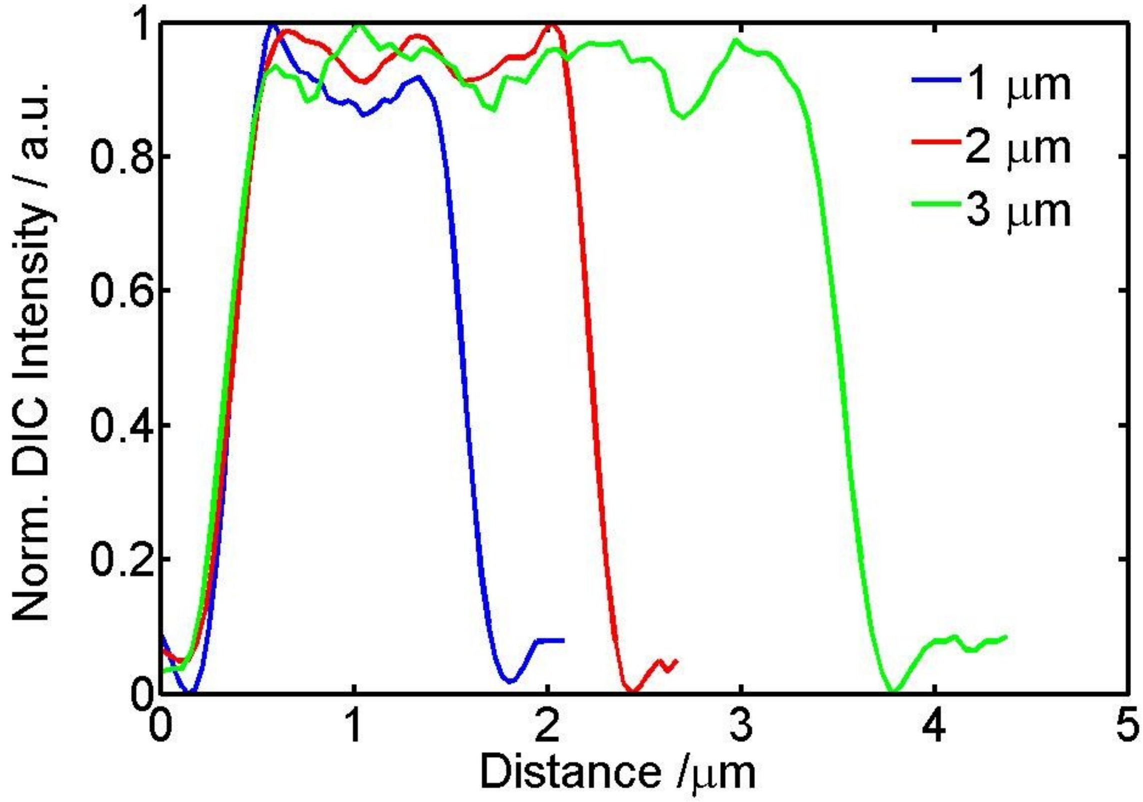

Fig. S2. The normalized DIC intensity crosscuts for single gold nanowires with different lengths from 1 μm to 3 μm in Fig. 2.

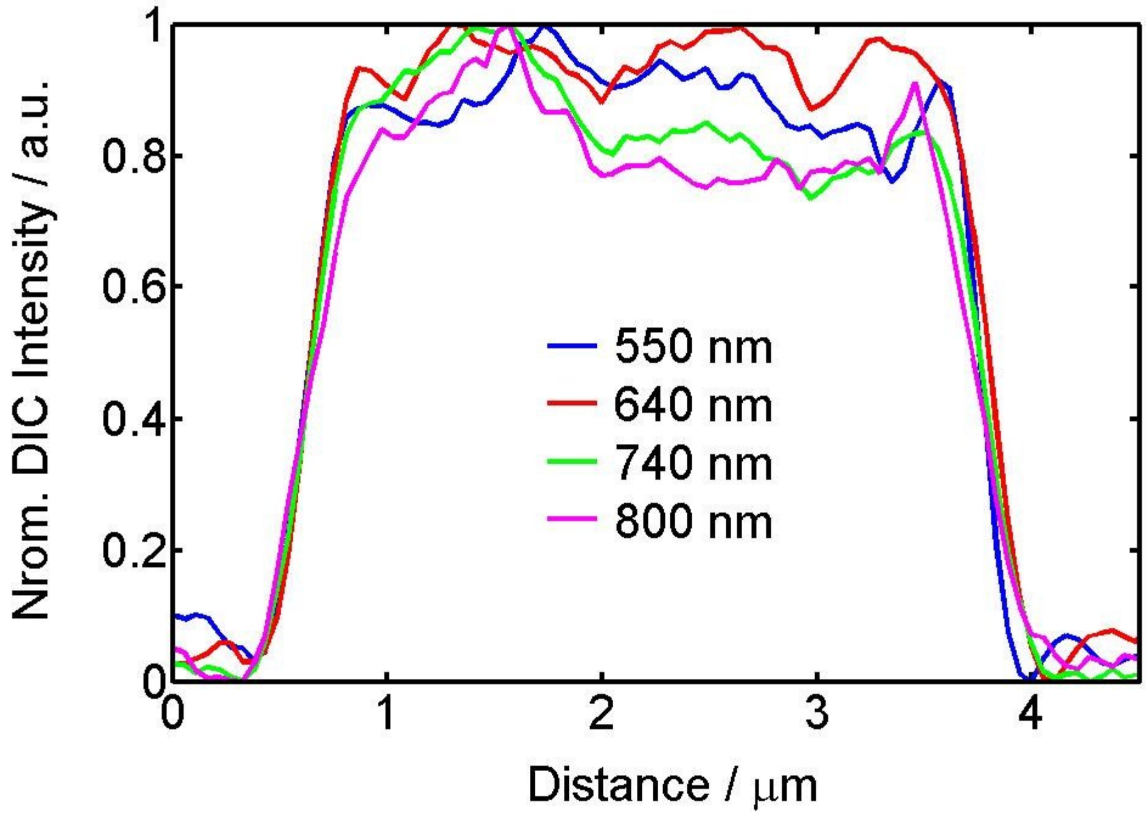

Fig. S3. The corresponding normalized DIC intensity crosscuts along the nanowire axes for the gold nanowire measured at different incident wavelengths of 550 nm, 640 nm, 740 nm and 800 nm in Fig. 3.

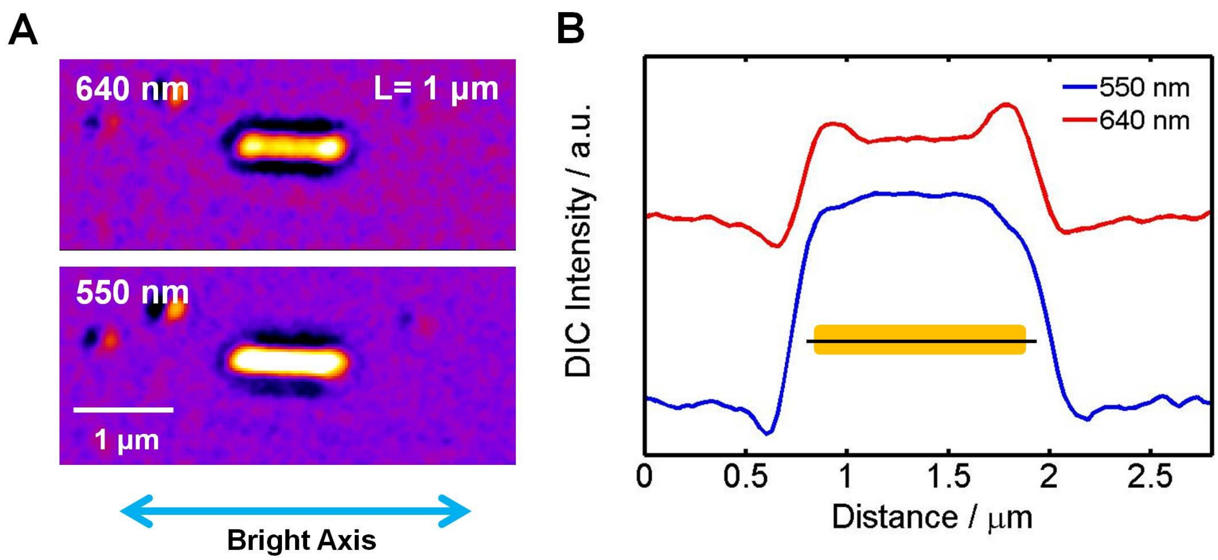

Fig. S4. (A) DIC images of a gold nanowire (Length: 1 μm) at the different wavelengths of 640 nm (top) and 550 nm (bottom). (B) The corresponding DIC intensity crosscuts along the nanowire axes.

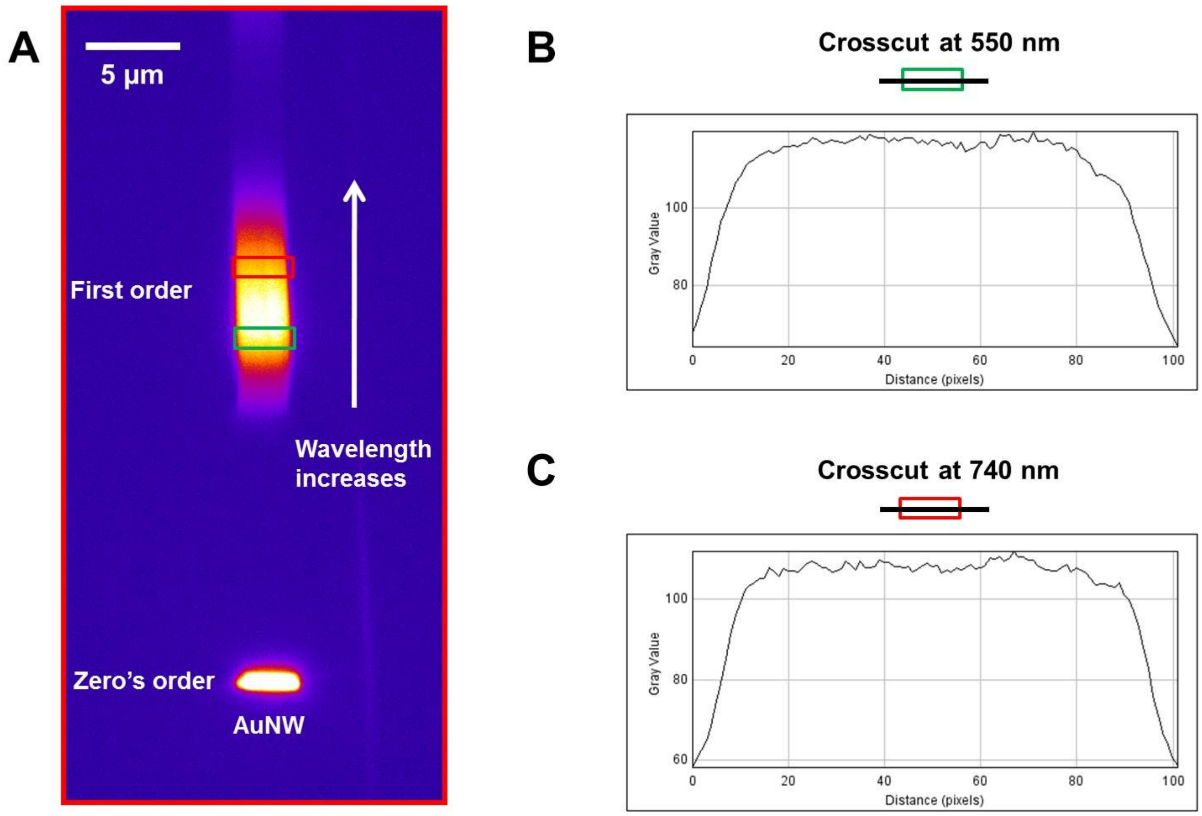

Fig. S5. (A) Zeroth- and first-order DF scattering image of single Au nanowire. The λ increases from bottom to top in the first-order image. (B, C) The DF scattering intensity crosscuts at the positions of 550 (green-square) nm and 740 nm (red-square). Two bandpass filters of 550 nm and 740 nm were used to find the positions in the first-order image.