Imaging Interferometric Nanoscopy to the Limits of Available Frequency Space

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Optical microscopy remains the dominant technology for imaging, but diffraction effects severely limit its applicability to nanoscale objects. Imaging interferometric microscopy (IIM) allows the acquisition of high-resolution optical images using a low *NA* objective using multiple sub-images, off-axis illumination, interferometric reconstruction and digital image processing. We have previously demonstrated a resolution approaching the free-space linear systems limit ($\lambda/4$) with a modest $NA = 0.4$ objective [1-3].

Here, we report the use of illumination propagating beyond the total-internal reflection (TIR) angle in a transparent substrate. The evanescent wave associated with the TIR extends beyond the substrate into the sample region where it is scattered by the sub-wavelength sample structure into propagating waves that provide information on the details of the object at spatial frequencies up to $(n_{sub}+NA)/\lambda$ with a normal object plane and $(n_{sub}+1)/\lambda$ with a tilted optical axis.

The resolution limit, by combining sub-images corresponding to all available (free space) regions in frequency space is $\lambda/4$. Taking advantage of evanescent illumination, this is extended to $\lambda/[2(n_{sub}+1)]$ as illustrated in Fig. 1 which shows the required frequency space coverage and parsing for a Manhattan geometry object with CDs of 180- (center) and 150-nm (right).The circles in Figs. 1(b) and 1(c) correspond to the bandpass limits of various microscopy configurations. Experimentally, we used α_{ill} (in the glass) of 76° and a tilt angle θ_{tilt} of 35° and achieved $N_{eff} = n_{sub}\sin(a_{ill}) + \sin\left(\theta_{tilt} + \sin^{-1} NA\right) \sim 2.32$.

The resolution of patterns with 150-nm CD features is beyond the half-pitch free-space linear systems limit of $\lambda/4 \sim 158$ nm, clearly demonstrating the evanescent coupling. The reconstructed image for 150 nm CD structures is shown in Fig 2 (a); the corresponding model in Fig 2 (b); and experimental and simulation crosscuts in Fig 2 (c).

The resolvable dimensions for typical source wavelengths are shown in the Table I. The columns labeled by n_{max} reflect the largest index transparent material at each wavelength. Other materials may further expand the available resolution. At a 193-nm wavelength, the resolution approaches typical SEM resolutions without requiring vacuum and indeed being fully compatible with water immersion. These resolutions are well beyond the current established perceptions of microscopy capabilities and suggest that advances in optical microscopy will have important impacts across a broad swath of science and technology.

Table I. Resolution limits (grating half-pitch) for various optical configurations at widely available laser wavelengths. (all dimensions in nm).

λ	IIM (air; λ/4)	½-immersion (λ/2(*n*+1); *n* = 1.5)	full immersion (λ/4*n*; *n* = 1.5)	½–immersion (n_{max})	full immersion (n_{max})
1064	266	213	177	116	74 (*n* = 3.6; Si)
633	158	127	106	74	48 (*n* = 3.3; GaP)
488	122	98	81	71	50 (*n* = 2.45, GaN)
193	48	39	32	34	27 (*n* = 1.8; polymer)

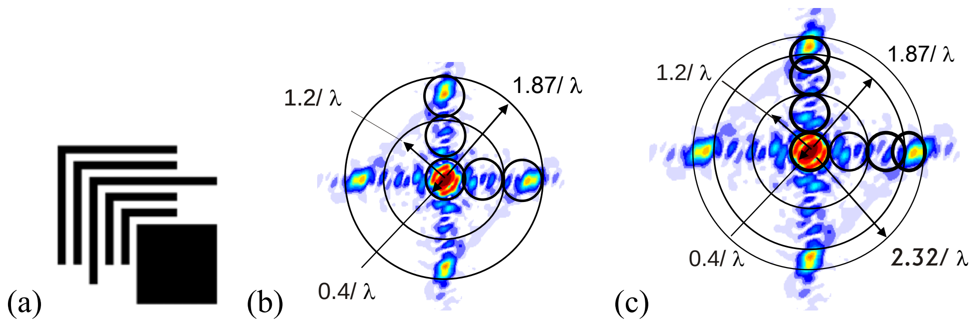

Fig. 1. Frequency-space visualization of IIM. a) Manhattan structure test pattern; scaled to different sizes as indicated; b) frequency space coverage for the structure with CD = 180 nm; c) frequency space coverage for the structure with CD = 150 nm.

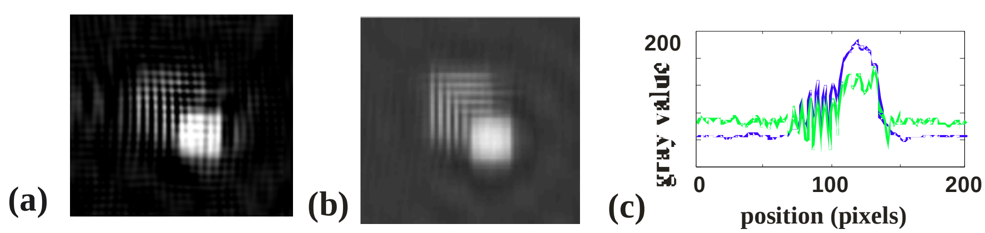

Fig. 2. IIM of a 150 nm structure using evanescent illumination and a tilted optical system. a) experimental composite (full) image; b) simulation of the full image; c) experimental and simulation cross-cuts of the full images.

References

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