Transport of Intensity Equation for Characterizing Nanostructures and Applications for Laser Cooling Experiments

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Abstract:

Laser cooling has become a popular topic at the forefront of scientific research in recent years. Scientists continue to achieve colder material temperatures using laser cooling methods. Despite this, how a sample's temperature profile evolves during such experiments is a subfield that has yet to be extensively covered. To learn more, research was conducted into the phase retrieval method called transport of intensity equation (TIE), its calibration with nanostructures, and its prospects for laser cooling experiments. The acquired phase information from TIE coupled with the characterization of a material's temperature dependent refractive index can allow for accurate temperature-profile data to be collected.

Introduction:

In the realm of nanotechnology, being able to quickly and accurately determine a structure's dimensions is extremely useful. One popular method to do this is atomic force microscopy (AFM). However, using this method has several disadvantages including the time needed to acquire data and the cost of entry. Another method is to determine the dimensions via phase information utilizing a quantitative phase imaging (QPI) technique. This phase information can be collected through experiments involving interferometry and lasers; however, these setups are typically complex and rely on environmental factors [1]. An alternative QPI approach that avoids these contingencies and offers a more accessible solution is to use TIE, as shown in Figure 1. TIE possesses several strengths: it only needs an intensity measurement to obtain phase, works with partially coherent light sources, collects data extremely fast, and has high flexibility in its setup construction [2]. Due to these reasons, TIE was chosen as the best candidate to be implemented in laser cooling experiments. However, for this prospect to be explored, a well-calibrated TIE setup is of utmost importance. Experiments were conducted to properly calibrate a TIE setup to quickly obtain phase information from photoresist samples.

$$-k\frac{\partial I(\boldsymbol{r})}{\partial z} = \nabla \cdot \left[I(\boldsymbol{r})\, \nabla\phi(\boldsymbol{r}) \right]$$

Figure 1: Transport of intensity equation from Jialin Zhang, et al. [3].

Summary of Research:

For the TIE setup, an unconventional, infinitely corrected microscope was chosen because of the accessibility of the optical components. The setup was assembled according to the simplified diagram shown in Figure 2. The light source was a white LED with peak emission intensities at 450 and 545 nm. An aperture and condenser lens focused the light to the sample, which is a glass substrate topped with polymer photoresists fabricated in a grid-like pattern. After passing through the sample, the objective lens collected the light and formed an initial image. The light then passed through the tube lens where a dichroic filter was attached to eliminate intensities at wavelengths below 500 nm. The camera position moved along the z-axis to capture both in-focus and defocused images.

These images were analyzed using modified MATLAB codes provided in [2], where an intensity derivative was calculated using finite difference method before being applied to a TIE solver to obtain the phase information. Several algorithms have been developed to solve TIE, but the universal solution presented by Zhang et al. was chosen here primarily due to its excellent solution convergence [3]. In Figure 3, the phase contrast between the photoresist and the background can be seen in a 2D map.

After experimentally determining pixel size, the last step in the process is to take this phase data and convert it into a height profile for the photoresist using equations provided in [1]. The resulting graph, shown in Figure 4, indicates the photoresist is approximately 20 μm wide and 263 nm tall at its highest point. These values agree with AFM data, taken three years prior, showing a maximum height of 261 nm. However, the AFM data does not indicate a fluctuation of height as strong as Figure 4 does. Countless photoresists were profiled, and the discrepancy is thought to be attributed to two factors: most samples have sustained physical damage over the years, and the background phase contains non-uniform noise.

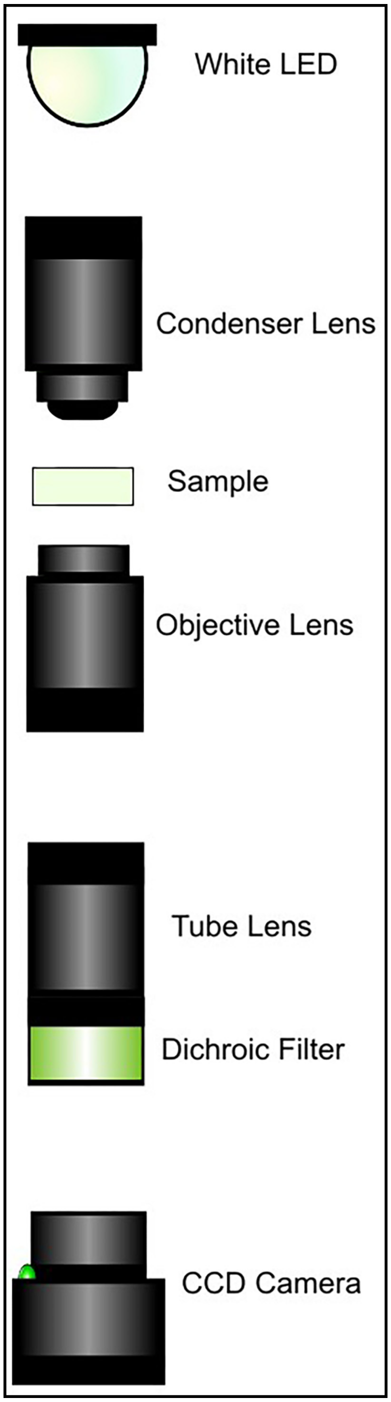

Figure 2: Experimental setup for TIE.

Conclusions and Future Steps:

Ultimately, more data would need to be collected on separate samples to affirm that the data collection process is replicable and applicable to a wider range of imaging subjects. Additionally, further computational work can be done to mitigate background noise when collecting and processing phase data to ensure proper calibration is achieved.

Looking ahead, a well-calibrated TIE experimental setup not only offers scientists a reliable method for obtaining the dimensions of nanostructures, but it is also a powerful tool to quickly extract phase information for various applications. In fact, the article by Zuo, et al. outlines a slightly more complex optical setup that allows for the collection of focused and defocused images simultaneously [2]. This method would allow for nearly instantaneous phase measurements and has several prospects in laser cooling applications. Alongside the research into TIE, an extensive Python code was developed to automate the collection of fluorescence data from rare-earth doped fluoride glass samples using a 2D grid, motorized stage, and spectrometer with Lightfield software [4]. Coupling the code with TIE would allow for seamless temperature-profile data to be collected which could help to expand the range of laser cooling experiments being conducted in the future.

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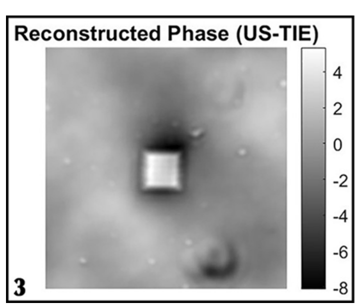

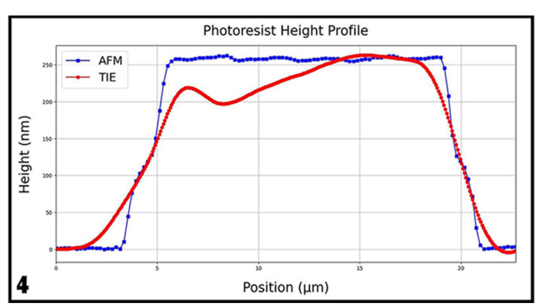

Figure 3, left: Phase reconstruction utilizing Matlab codes provided in Chao Zuo, et al. [2]. Figure 4, right: Height profile of a photoresist.