Subdiffraction-Scale Surface Roughness Impact upon Spectroscopic Microscopy Detection of Internal Refractive Index Fluctuations: Applications to Early-State Cancer Detection

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Despite the fundamental diffraction limit of optical microscopy, we previously established that three-dimensional (3-D) subdiffraction-scale refractive-index (RI) fluctuations internal to a linear, label-free dielectric medium can be detected in the far zone with spectroscopic microscopy (Cherkezyan et al., PRL 111, 033903 (2013)). However, in our prior work, the air-medium interface was assumed to be a smooth plane.

The present work investigates how an air-medium interface having random nanoscale surface height variations (i.e., surface roughness) impacts the ability of our proposed spectroscopic microscopy technique to detect the desired RI fluctuations internal to the dielectric medium beneath the surface. Although light scattering from rough surfaces has been well investigated, the spectral characteristics of rough-surface reflectance intensity at a far-field image plane have not been clearly described and validated.

To this end, we have derived a general analytical expression for the spectral characteristic, $I_s(k)$, of the far-zone bright-field microscope image of a randomly rough surface of an underlying homogenous dielectric medium. Here, we assumed nanometer-scale surface height fluctuations characterized by an exponential spatial correlation in the lateral directions. The derived analytical expression was rigorously validated by numerically synthesizing the bright-field microscope image of the rough surface from near fields computed using a 3-D full-vector finite-difference time-domain (FDTD) solution of Maxwell's equations implemented with nanometer-scale voxels. We determined that $I_s(k)$ calculated from the analytical theory agreed very well with that obtained from the FDTD simulation. Furthermore, we have determined that, by analyzing $I_s(k)$, we can quantify the statistics of a randomly rough surface of an underlying homogenous dielectric medium.

Overall, the present work could favorably impact the ability of spectroscopic microscopy to detect and quantify internal RI fluctuations in dielectric media having subdiffraction-scale surface roughness. In the context of spectroscopic microscopy of biological cells, this would improve the sensitivity and specificity of the technique when applied to early-stage cancer detection.