Electromagnetic Simulation Optimizes Design of a Sub-20 nm Resolution Optical Microscope

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Recent advances in nanotechnology and nanoscience are highly dependent on our newly acquired ability to measure and manipulate individual structures on the nanoscale. A drawback of light microscopy is the fundamental limit of the attainable spatial resolution dictated by the laws of diffraction at about 250 nanometers. This diffraction limit arises from the fact that it is impossible to focus light to a spot smaller than half its wavelength. The challenge of breaking this limit has led to the development of near-field scanning optical microscopy (NSOM).

NSOM has extended optical measurements past the diffraction limit, making it possible for the first time to view objects and features in the 50 to 100 nanometer range. NSOM uses a very small light source that is scanned just over the surface of the sample. Illuminating the sample with the near-field of a small light source makes it possible to construct optical images with resolution beyond the usual diffraction limit. See (http://www.umich.edu/~protein/NSOM/Technique.html << link to diagram of NSOM) for additional information on the technique. Recent research has demonstrated that the use of apertureless probes can further improve spatial resolution to below 25 nanometers.[1-3] The next challenge is optimizing the tip design in order to strongly illuminate the sample at distances from the aperture that are hundreds of times closer than the dimension of the wavelength of the light that is employed. Trial and error methods are highly undesirable because of the great challenges involved in building and testing optics at nanometer scales. At Portland State University, funded by the NSF (IDBR #0500812), we are overcoming this problem by using a commercial finite different time domain electromagnetic simulator (XFDTD) to analyze tip performance without the need to build a physical model.

The optical probes originally used in NSOM were created by pulling an optical fiber to a final diameter of 25-100 nm, coating it with aluminum, and etching to provide a flat, circular endpoint, and aperture. Unfortunately, only a tiny fraction of the light coupled into the fiber is emitted by the aperture because, as light travels down a fiber, it can stop propagating with a nice round spot profile if the dimensions of the fiber shrink. After a critical dimension of the fiber is reached, other waveguide modes of propagation can continue, but they will dissipate very quickly as they travels down the tapered fiber. The low light throughput and finite skin depth of the metal limit the resolution to normally 50 to 100 nm. Light in the visible part of the spectrum will penetrate only so many nanometers into the fiber's metal coating before the fields dissipate. Metal coated fibers that are tapered to 10's of nm's at the end will confine the light down to the end, but at that point the light will be converted to a plasmon which barely makes it to the end in the form of a non-propagating field. The skin depth is the depth the electric field of the light will travel into the metal before it is cut down to 1/*e* of the original strength.

Need for finer spatial resolution

Many applications require spatial resolutions that are not attainable with the aperture technique. For example, a spatial resolution of at least 30 nm is desirable in spectroscopic imaging of photosynthetic membranes in order to resolve closely packed individual proteins in a lipid membrane. This has been accomplished by the use of laser-illuminated metal tips to provide a local excitation source for the spectroscopic response of the sample under investigation. Excitation light of proper polarization induces a strongly enhanced field at the tip. The highly localized excitation source has provided resolution levels of 15 nm to 25 nm, making it possible, for example, to resolve tightly packed chromophoric membrane proteins.

Unfortunately, the presence of the metal tip nanometers away from the fluorophore leads to fluorescent quenching. This results in a negative fluorescent image, essentially a dark spot at the chromophore position surrounded by a sharp halo of emission. Along with colleagues at Harvard University, we had overcome this problem by depositing a homogenous, nanometer-scale silicon oxide coating on near-field probes in order to minimize quenching.[4] An important advancement was achieved when electron beam assisted deposition (EBAD) demonstrated the ability to evenly deposit silicon oxide coatings on the complex three dimensional tips of the apertureless metal probes, which are typically only a few nanometers wide, in order to avoid fluorescent quenching. We used a focused ion beam (FIB)/scanning electron microscope (SEM) to grow dielectric material on a complex three-dimensional optical probe. A DualBeam FIB/SEM manufactured by FEI (Strata DB-235), which uses a liquid metal Gallium ion source accelerated to 30 kV with specimen currents from 1 pA to 20 nA, was utilized for the tip coating operation. We finally overcame the challenge of maintaining the integrity of the coating while achieving reasonably fast deposition rates. Using electron beam aided deposition, we were able to create a dielectric film with nanometer conformity over complex optical geometries.

Challenges of tip design

The next step was optimizing the metal tip design. This was accomplished by modeling Chance Prock Silbey (CPS) theory for an emitting Dipole aligned in close proximity to a metal substrate and then applying the results to the design of a metal tip.[5] In detecting the fluorescent signal from a molecule, the optimum distance from the chromophore to the metal tip is approximately 22 nm for a parallel emitting dipole or 24 nm for a perpendicular emitting dipole[6]. If the metal tip is closer than 3 to 5 nm, even with the coating, then the fluorescent signal is dramatically quenched, making it impossible to detect the signal. This sets up the primary challenge in tip design, optimizing the near-field tip design to deliver the highest possible electromagnetic field at the appropriate distance. Although we believe the tip molecule separation would be similar to the bulk metal – molecule situation, the tip's geometry requires

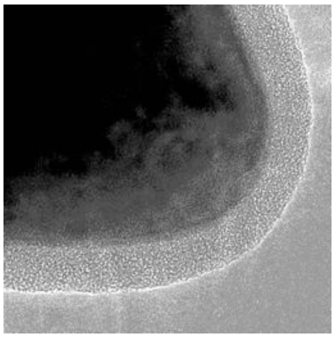

Figure 1. Transmission electron micrograph of a metal probe tip coated with 10 nm of electron beam grown $Si0_2$ to prevent fluorescence quenching by the metal.

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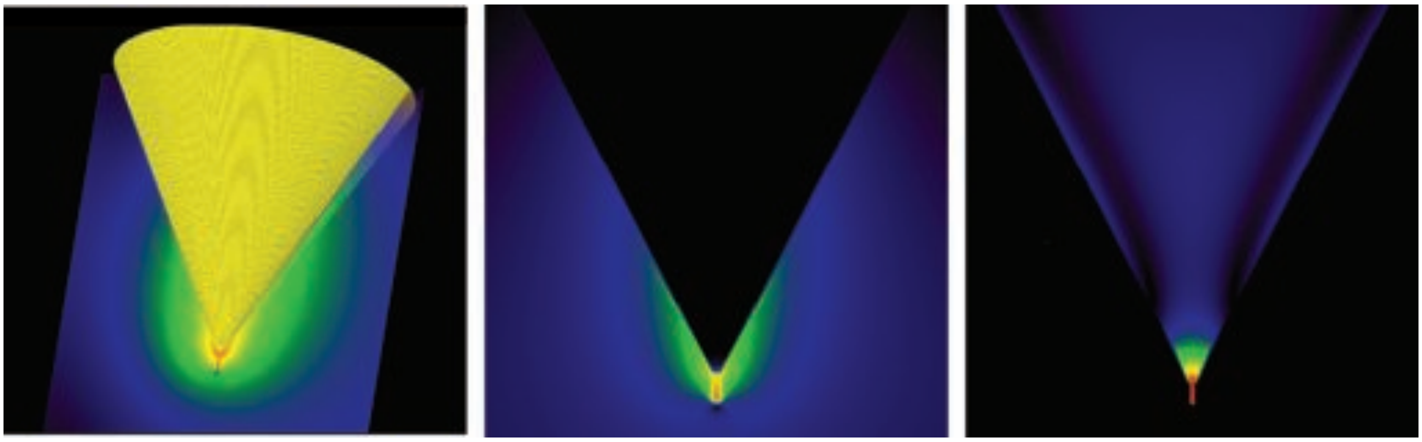

*Figure 2. FDTD modeling of a sharp TENOM probe tip, (a.) the 3D view of the probe tip with crossection of **E** the external electric field magnitude, (b.) the 2D side view of the **E** field distribution, (c.) and **J**, the current density magnitude. When a horizontally incident (vertical polarization) is applied this probe experiences an increase of local field instensity (|**E**|) of ~1000 times.*

careful modeling in order to determine this information. It would be very difficult and expensive to accomplish this objective using conventional build and test methods. The primary problem is the cost of fabricating the tips and the difficulty of performing field measurements at the nanometric scale.

For these reasons, we used FDTD to model the near-field response of proposed designs. Electromagnetic simulation takes only a small fraction of the time and expense involved in building and testing apertureless tips. Simulation also provides more information than physical experiments by yielding results at every point in the solution domain, far exceeding the results that can be achieved with physical measurements. We picked XFDTD software from Remcom, Inc., State College, Pennsylvania, because of its ability to mesh complicated geometries. Adaptive meshing capabilities reduce solution times while maintaining high levels of accuracy by automatically adjusting the mesh to provide more cells in areas with high transients and reducing cells in areas where there is less variation. In addition, the use of a parallel computational code allows for multiple computers to be connected in order to perform calculations faster as well as use larger workspaces.

Using simulation to iterate to an optimized design

We began by simulating an existing tip design in order to validate the accuracy of the method. We divided the initial design into cubic cells with the appropriate frequency dependent behavior. An absorbing boundary condition was used. The incident excitation field was set to an electric field strength of 1 V/m at 800 nm wavelength and the space was discretized with 3 nm cubes. The material of the tip was defined to be Au and the spacer was SiO_2. The electromagnetic field in each cell under plane wave illumination was calculated by the software through time domain integration of Maxwell's equations. The intensity enhancement at the end of the tip is 100 without the spacer, approximately 5 nm in front of the tip. When the 9 nm SiO_2 spacer is present, the enhancement is reduced to 50. This is still high enough for near-field imaging at 5 nm in front of the tip. These results matched the experimental measurements so we began using XFDTD in an effort to optimize the tip design.

Normally apertureless near-field optical probes require direct illumination of the tip apex in order to generate a sub-diffraction limited light spot. A large background signal originates from the emission of many chromophores in the far-field illuminated volume. Typically, tips with a high field enhancement are used in order to overcome this background contribution. Another way to overcome this problem is to non-radiatively propagate a field to the end of the tip where the energy of the field could emit radiatively, eliminating the background contribution. Under certain conditions the energy carried by photons of light is transferred to packets of electrons, called plasmons, on a metal's surface. The light's energy is transferred to driving the electrons resonantly through attenuated total reflection at very specific conditions.

Guided by electromagnetic simulations, we designed a tip that takes advantage of this technique[4], which was created by A. Otto in the late 1960s.The angle of the prism, tip shaft length, and gap

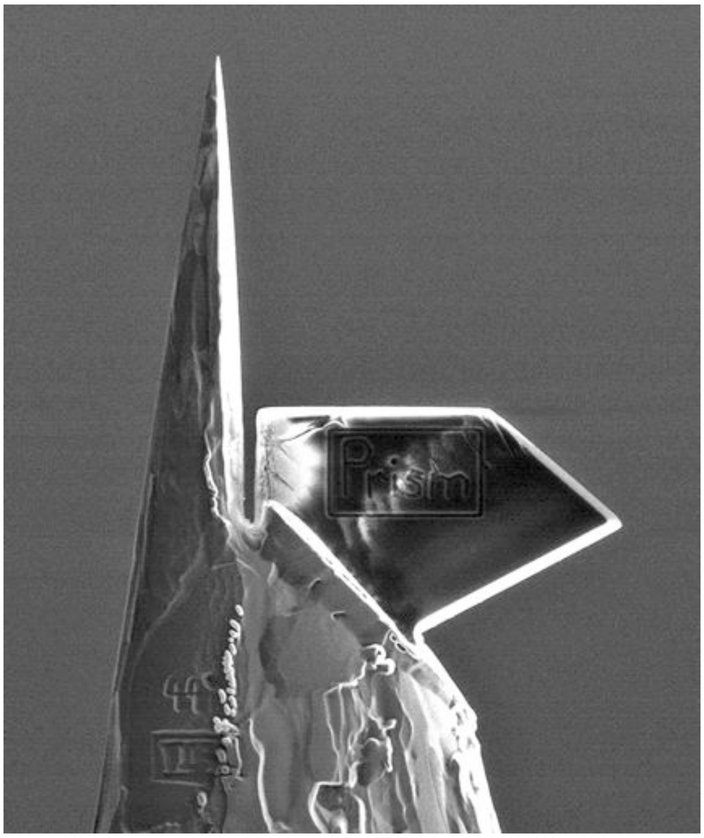

Figure 3. This novel NSOM probe takes advantage of a non-radiatively coupled focused spot of light that creates a resonant Plasmon which dramatically improves signal to noise. Light enters the prism and the end of the tip creates a strong localized field.

between the prism and metal were carefully engineered to achieve resonance. When the plasmon reaches the tip end it generates a strong evanescent field within a region on the order of the tip end diameter. Evanescent waves are formed when sinusoidal waves are internally reflected off an interface at an angle greater than the critical angle so that total internal reflection occurs. The intensity of evanescent waves decays exponentially as they move further from the interface at which they are formed. This eliminates the signal generated by far-field illumination, increasing the signal to background ratio. We are currently evaluating the performance of these tips and working to improve their design to deliver even higher levels of performance. ■

For more information, contact Remcom: Email: info@remcom.com; Web site: www.remcom.com. For a comprehensive review paper on the subject see A. Bouhelier, *Field-Enhanced Scanning Near-Field Optical Microscopy,* Microscopy Research and Technique 69:563–579 (2006).

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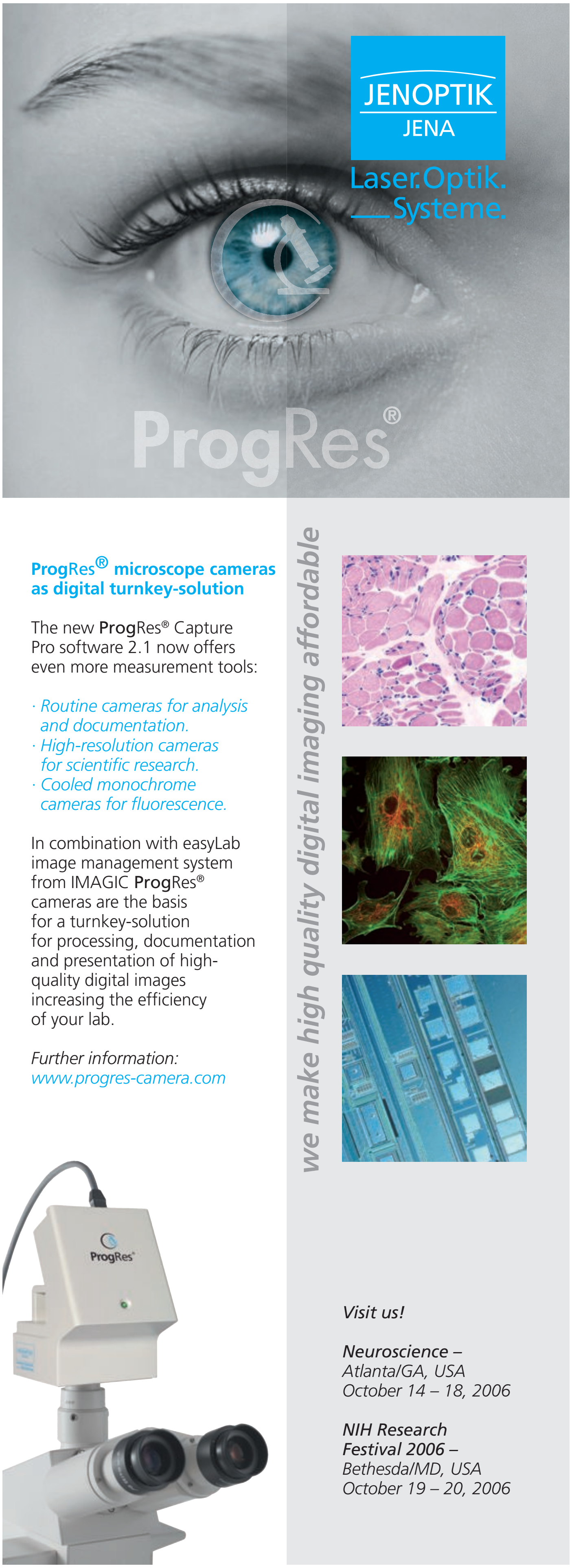

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