Fabrication of Probes for High Resolution Optical Microscopy

Physics 564 Applied Optics

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Abstract
Near Field Scanning Optical Microscopy (NSOM) is a technique used to overcome the diffraction limit of optical systems. The resolution of an optical system is ~λ/2—for an imaging system that uses visible light. NSOM uses a metal coated aluminum fiber optic tip to image features smaller than λ/2. This paper presents the theory behind the diffraction limit, the basics of the NSOM technique used by Dr. Andres La Rosa of Portland State University, and the basics of a Focused Ion Beam system (FIB). Finally, the technique used to make an aperture on the end of metal coated fiber optic tips is presented, along with the results of some experiments in making those apertures.

Introduction

Optical Limitations

The ultimate limiting factor in an optical system is diffraction. Diffraction is the deviation of rectilinear propagation of light. When a ray of light passes through an aperture, it spreads out in space. This spreading out of light leads to constructive and destructive interference. For light passing through a circular aperture, an Airy disk pattern results. Figure 1a shows an example of an Airy disk pattern and the corresponding intensity distribution. Figure 1b shows two Airy disks close together, yet still resolvable. Figure 1c illustrates that when the two intensity distributions are too close together, it is difficult to distinguish between them.

![Airy Discs](image)

Figure 1. Examples of airy disk patterns and their corresponding intensity distributions[1]

Lord Rayleigh gave criterion for the resolution (Δl) of two objects as being when “the center of one Airy disk falls on the first minimum of the Airy pattern of...” another object. [5] For a circular aperture in a diffraction limited system, the airy disk contains most (84%) of the power of the light source incident on the aperture. This lateral resolution for optical systems is determined by the diffraction limit. Figure 2 is the geometry for illustrating the diffraction limit.
The diffraction limit for an optical system with a circular aperture is: $\Delta l = \frac{1.22\lambda}{D}$ (1)

Where:
- $\Delta l =$ minimum lateral resolution
- $f =$ focal length of lens
- $\lambda =$ wavelength
- $D =$ diameter of lens

The numerical aperture (NA) is defined as: $NA = n\sin\theta \approx \frac{D}{2d}$ (2)

Where:
- $n =$ index of refraction surrounding lens
- $\theta =$ half angle subtended by lens

When the point, $P$ is far away from the lens, $d = f$. Thus the NA becomes:

$$NA = \frac{D}{2f}$$ (3)

Substituting equation (3) into equation (1) yields:

$$\Delta l = \frac{1.22\lambda}{2NA}$$ (4)

The maximum that NA can be is 1, which in turn gives a lateral resolution limit of:

$$\Delta l = \frac{1.22\lambda}{2} \approx \frac{\lambda}{2}$$ (5)
NSOM

Near Field Scanning optical Microscopy (NSOM) is a way to overcome the diffraction limit. The conventional limit for resolution using light is $\sim \lambda/2$, as previously shown. For a system using an incident wavelength of 500 nm, the resolution limit would be $\sim 250$ nm. In NSOM, the diffraction limit is overcome by working in the near field, and using very small apertures cut on the tip of fiber optic probes. The near field is when the light source is within one wavelength of the image plane. Thus the tip of the fiber has to be very close to the object being imaged. This close proximity requires very precise control of the tips elevation and movements.

NSOM uses an optical fiber as a waveguide for the incident light. The fiber is made up of an inner core with a radius on the order of 5 μm, with an outer cladding of 125 μm. The cladding is made of a material with an index of refraction that is lower than the index of refraction of the core material. This mismatch in refractive indices gives rise to total internal reflection, allowing light to propagate down a fiber’s core. The fiber that is used for the NSOM technique has the end pulled into a sharp cone. Light will not propagate down the core when it gets so small. However, the evanescent modes of light will. Figure 3 shows a cross section of a fiber optic cable with a light wave propagating in the core. The property of the wave and the fiber medium is such that the intensity of the wave is non-zero at the core-cladding interface. Some of the field, called the evanescent field, propagates in the cladding.

![Figure 3. Light wave propagating in a fiber illustrating the evanescent field](image)

When the fiber is pulled to a sharp point, the modes of the light wave cannot propagate, only the evanescent modes will continue. The point of the fiber is sectioned off; this creates an aperture. The diameter of the aperture is the lateral resolution of the NSOM technique. Figure 4 shows a fiber pulled to a point and with an aperture, and the resulting evanescent wave exiting the end.
When the fibers have been pulled to a point, only the core of the fiber is left at the very end. Aluminum is used to coat the fiber tip to keep the light contained within the tip. This aluminum coated fiber point is then sectioned off at the very end to create an aperture.

**Focused Ion Beam**

A Focused Ion Beam system (FIB) operates in a manner similar to an electron microscope. In an electron microscope, an electron is accelerated down a column under vacuum from the electron source to a target. The particle is accelerated by applying high electric fields to the source—typically a filament of some sort.

In a FIB system, the particle is a charged atom, which is substantially larger than an electron. The source for a FIB system is called an emitter (as in ion emitter) or a tip, and is also a filament, but with a few added features. Figure 5 shows a typical filament used by FEI in their FIB systems.
The filament is a wire that is connected in a triangle shape between the two posts. Electrodes connect to these posts and current is passed by them thru the filament to heat the emitter. Attached to the filament is a coil reservoir, and attached to the coil is a wire (tip) which has been etched to a very sharp point. A material is then used to coat the tip and coil reservoir. The material which coats the wire is usually Gallium (Ga), although many different materials can be used, historically Ga has been the easiest and most versatile.

The tip is surrounded by an electrode called the suppressor. A voltage can be applied to the suppressor to decrease or increase the electric field with respect to the extractor. The extractor is a circular electrode with a small hole in the center that allows the ions to pass through it. A high voltage, typically 5kV to 15 kV, is applied to it. This extraction voltage is at a lower potential than the tip, so that positive ions are pulled away from the tip towards the extractor. But they have enough energy to pass through the hole in the center of the electrode. The tip has a high voltage applied to it, typically 5kV to 50kV. The voltage is called the acceleration voltage, and it, minus the extractor voltage, gives the ions their kinetic energy. If the tip has an acceleration voltage of 45 kV, and the extractor has a voltage of 10 kV, the ions will travel down the column with a kinetic energy of 35 keV. Figure 6 is a diagram of a typical FIB system.

![Diagram of a typical FIB system](image)

Figure 6. Schematic showing the different elements of a FIB system[^3]
Method

Optical Fibers that have been pulled to a point and coated with aluminum were taken to FEI Co. to have the end sectioned off, effectively creating an aperture. The system used at FEI is a Nova Nano lab Dual Beam system; it has both a FIB and a Scanning Electron Microscope (SEM). The aluminum coated fiber tips were prepared for sectioning by being placed on double sided copper tape adhering to an aluminum disk. Carbon paint was used to ensure electrical contact and vibration stabilization near the tip. The purpose of having electrical contact is so the tips do not charge up.

The FIB system has built in software programs for making various patterns—and for sectioning. The method used to section the fiber tips is called “cross sectioning”. The FIB beam is rastered back and forth in a serpentine pattern from bottom to top of a predefined rectangular area. The beam makes more passes on the last line rastered than on the first. This has the effect of creating a stair-stepped pattern in the material, as shown in Figure 7 and Figure 8. The purpose of using this pattern to section the tips is to minimize the re-deposition of sputtered material (in this case aluminum and silicon dioxide of the fiber tips).

![Direction of Raster](image)

Figure 7. Stair-stepped cross section diagram for sectioning fiber tips.

![Figure 8. SEM image of cross-section pattern made in Aluminum](image)
Results

Figure 9 is an image of a tip that was etched, coated and sectioned in Dr. A. La Rosa’s laboratory, at Portland State University. The dark circle in the center is the fiber core, surrounded by the lighter, aluminum coating. The core is on the order of 75 to 100 nm.

![Figure 9. Aluminum coated fiber tip made in DR. La Rosa’s laboratory](image)

Figure 10 shows the initial results of the sectioning of the fiber tips. Figure 10a is an image of a fiber tip pre-sectioning. Figure 10b is an image of the fiber tip post sectioning. Figure 10c is an end-on image of the fiber with aperture diameters shown by yellow lines. The black in the image is silicon dioxide, or optical fiber. The lighter material is the aluminum coating of the tip. In a FIB system, dielectrics often image as much darker in contrast compared to a conductor. This is due to much less secondary electrons being collected from a dielectric, than from a conductor. This high contrast phenomenon is effective in trying to determine if the tip sectioned has an aperture the right size, and if the fiber and aluminum is present.

![Figure 10. FIB image of aluminum coated fiber tip. a-pre-etch. b-post-etch. c-post-etched end view](image)
Conclusions

Some of the problems that have occurred already are apertures that are not perpendicular to the length of the fiber, and the aluminum coating not being uniform on the very tip of the fiber. Regarding the aperture not being perpendicular, with some practice aligning the fiber with lines placed by software, this problem was overcome. The largest impediment so far has been the aluminum coating either not sticking, or not being applied at the last few microns of the tip. This problem should be readily overcome as more tips are etched and coated.

Achieving resolution that overcomes the diffraction limit has already been done. NSOM is an attractive alternative to other methods of nanoscale imaging such as SEM and TEM. With more practice, the production of high quality, small aperture fiber probes will occur in the near future. The FIB is an effective tool for sectioning off the ends of the fiber probes, and should be able to reliably etch apertures on the order of tens of nanometers.
Reference List


