The Trajectory of an Anisotropic Particle Near a Light-Transmitting Optical Nanofiber

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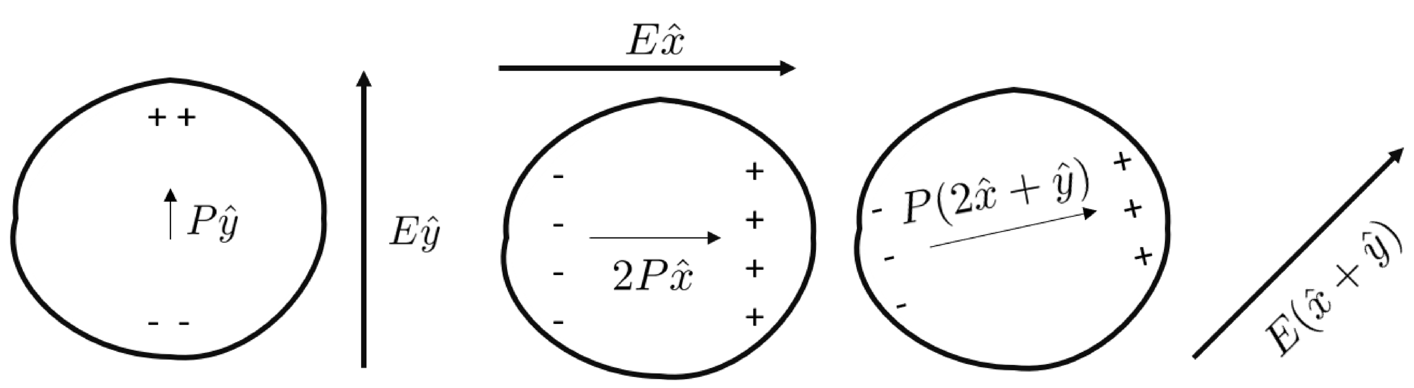
Anisotropic Particles

Anisotropic particles respond differently to electromagnetic fields depending on the direction of the field. They usually appear differently when looked at from different angles. The figure (obtained from [3]) below shows an anisotropic particle.

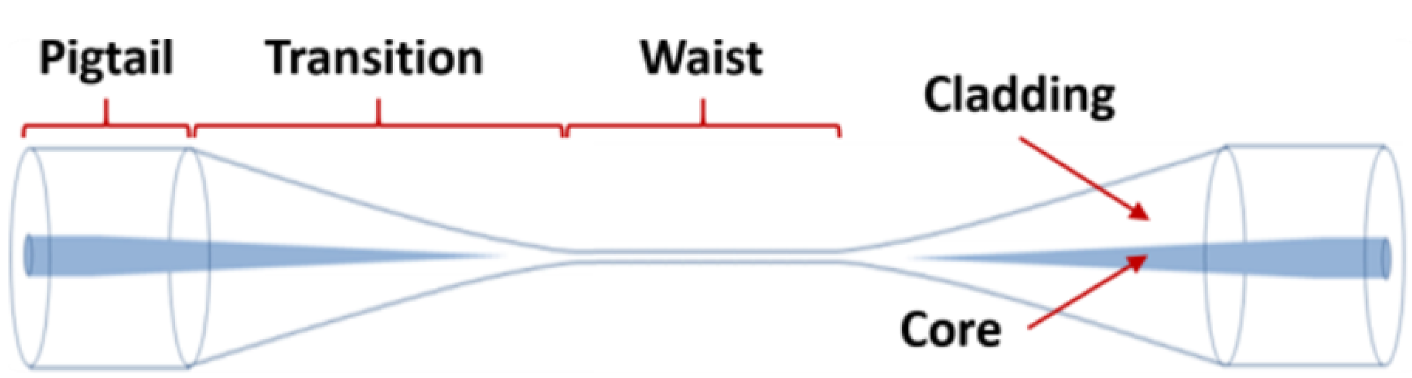
Most particles are anisotropic either because of their shape or the arrangement of their molecules. The following figure shows a hypothetical response of an anisotropic particle to an electric field:



The dipole moment $\vec{P}$ describes how charges redistribute themselves in response to an electric field $\vec{E}$. When the electric field is E in the y-direction the dipole moment is P in the y-direction. When the electric field is in the x-direction, the dipole moment is $2P$ in the x-direction. Our investigation deals with anisotropic particles with linear birefringence. This means we can determine the dipole moment when the electric field is $E\hat{x} + E\hat{y}$ by simply adding up the responses to both directions. In this case, we find that when the electric field is equal parts to the x and y directions, the dipole moment is more closely oriented with the x-direction. So the dipole moment is not always in the same direction as the electric field. The magnitude and direction of the response of the particle to the electric field depend on the direction of the electric field.

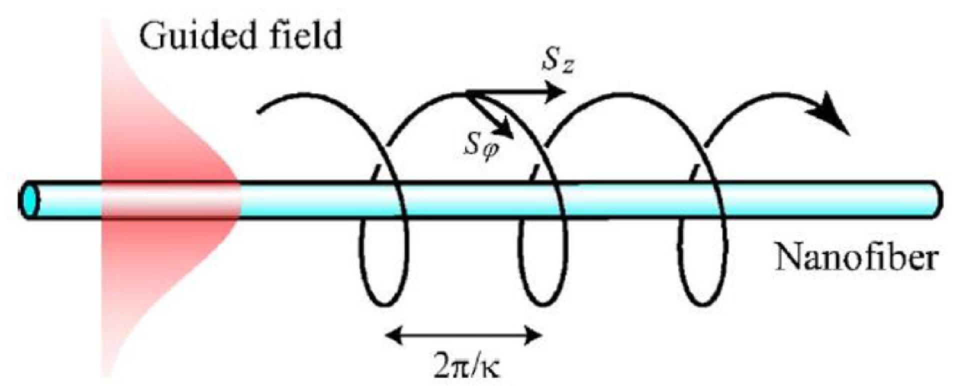
Optical Nanofiber

Optical nanofibers are created by heating and stretching normal optical fibers. The figure below (obtained from [1]) is a schematic of an optical nanofiber.



The "pigtail" has the dimensions of a normal optical fiber. It has a radius of about $10^{-3}m$. However, the "waist" of the optical nanofiber is about $10^{-6}m$. The cladding material guides the light as it is transmitted through the "core" of the fiber.

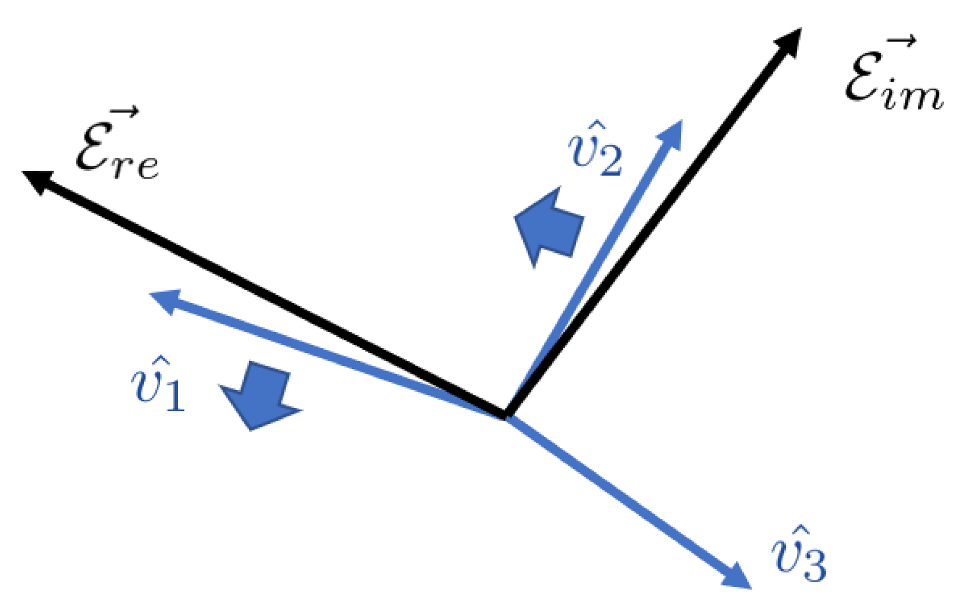
Due to the small size of the waist, light leaks out as it is transmitted through the fiber. The next figure (obtained from [2]) is an illustration of this



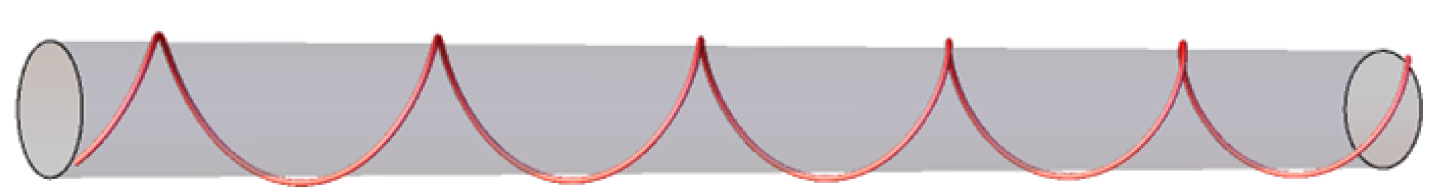
The light field outside the waist of the fiber can influence the motion of particles near the nanofiber. In this investigation, we model the behavior of an anisotropic particle near the waist of the nanofiber. We derived the force and torque on the particle and applied those equations to a specific anisotropic particle made of kyanite.

Behavior of Kyanite Particle in Electric Field of Nanofiber

The orientation of an anisotropic particle may be completely described by the direction of 3 perpendicular axes embedded in it body. As the particle rotates, these axes rotate along with it. In the diagram below these axes are $\hat{v}_1$, $\hat{v}_2$ and $\hat{v}_3$. Our analysis showed that for a certain choice of parameters, the torque on the particle causes one of its axes to remain perpendicular to the plane of rotation of the electric field while the other two spin in the same plane that the electric field does. In the diagram below, $\hat{v}_3$ is the axes perpendicular to the plane of the field while $\hat{v}_1$ and $\hat{v}_2$ spin in the same plane as the electric field.

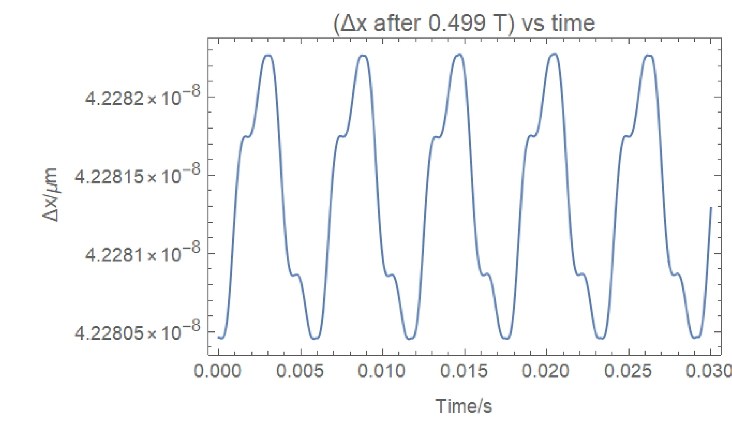


The vectors $\vec{\epsilon_{re}}$ and $\vec{\epsilon_{im}}$ are vectors that describe the plane of rotation of the electric field. At every given point near the nanofiber, the electric field is constantly spinning. Our analysis also showed that the particle takes a helical trajectory around the nanofiber. This is illustrated in the picture below:

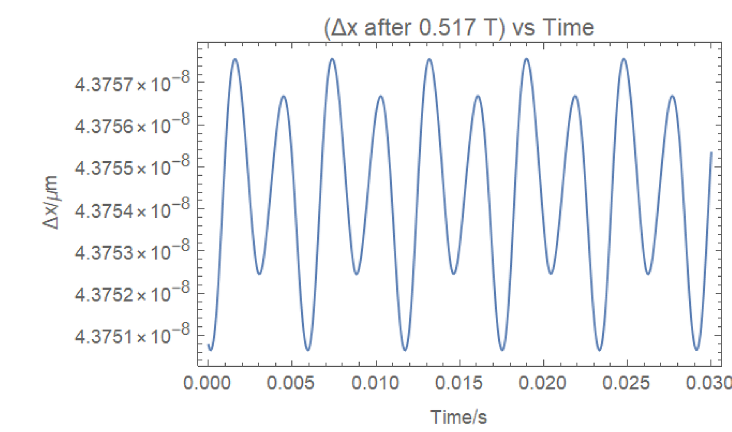


The red tube is the trajectory of the particle and the cylinder represents the waist of the nanofiber. As the particle traverses this trajectory, it spins rapidly. Our analysis also showed that the period of the spin of the particle is small ($\approx 10^{-2}$s) compared to the period of revolution ($\approx 10^{6}$s) around the nanofiber. So the particle spins about one of its axis many times before it orbits the fiber once.

As the particle traverses its trajectory, small oscillations in the force cause it to vibrate, but the vibrations are too small to be perceived in the previous figure. We are able to view these vibrations by isolating their effect on the trajectory of the particle. One way to do this is to plot the change in the x-coordinate of the particle over a time interval over which deviations in its rate of increase are caused by oscillations in the force on the particle.



This figure shows the difference in the x-coordinate of the particle between time t and time $t + 0.5T$ as the particle begins its journey around the nanofiber where T is the period of the spin of the particle. The amplitude of the vibrations corresponds to the amplitude of the oscillations in this figure - about $10^{-12}\mu$m. For comparison, the radius of the nanofiber is 1μm and the radius of the particle is about 0.1μm. Hence, the amplitude of the vibrations is much smaller than any length scale in the experiment. If we choose a different time-interval over which to measure the change in the x-coordinate of the particle, we get oscillatory behavior of a different nature:



The significance of this change in pattern is not fully understood because we are not analyzing the vibrations directly.

Remarks

One possible next step may be to probe these results in the lab. This work suggests that for bi-axial anisotropic particles like kyanite, there are three regimes of behavior depending on which of its axes are perpendicular to the plane of the electric field. The differences between these regimes may lead to different vibrations as the particle traverses its helical trajectory around the nanofiber. However, the vibrations of the particle are small (of the order $10^{-12}\mu$m) and may not be detectable in the lab even if they are present.

References

[1] Cindy Liza Esporlas et al. "Ultrathin Optical Fibers: Guided Modes, Angular Momentum, and Applications". In: *The Review of Laser Engineering* 46 (May 2018), p. 92.

[2] Thomas Nieddu, Vandna Gokhroo, and Sile Nic Chormaic. "Optical nanofibres and neutral atoms". In: *Journal of Optics* 18.5 (Mar. 2016), p. 053001. DOI: 10.1088/2040-8978/18/5/053001. URL: https://doi.org/10.1088%2F2040-8978%2F18%2F5%2F053001.

[3] Wikipedia contributors. *Birefringence — Wikipedia, The Free Encyclopedia*. [Online; accessed 3-April-2021]. 2021. URL: https://en.wikipedia.org/w/index.php?title=Birefringence&oldid=1003604662.