Tapered Fiber Fabrication

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Adiabatically tapered optical fibers are widely used in applied optics research. However, they are hard to obtain commercially and are fragile, making them difficult to transport. Therefore, to perform experiments with these fibers, it is advantageous for the laboratory to be able to fabricate its own tapered fibers. After this process has been perfected, it also provides greater flexibility in that the laboratory can custom-make specific taper shapes for its particular needs.

Tapered optical fibers can be used to couple light into whispering gallery mode (WGM) microresonators [Rayleigh12, Garrett61, Benner80, Krauss90], an area that is receiving much interest at the moment. In a WGM optical resonator, which is a dielectric device, light of a specific wavelength (determined by the properties of the cavity) is confined by continuous total internal reflection. WGM resonators occur naturally in droplets [Qian86] and can be manufactured in the laboratory. These resonators have ultrahigh-Q factors of nearly ten million and can be fabricated by melting the tip of an optical fiber (fused silica) into nearly a perfect sphere [Braginsky89, Gorodetsky96, Vernooy98]. More recently, a group at Caltech has demonstrated ultrahigh-Q WGM resonators on a silicon chip [Armani03]. These devices combine the ultrahigh-Q factors of molten silica WGM devices with the ultra-small mode-volumes of microcavities. This unique combination

leads to very high intracavity intensities at low input powers. Both the large intracavity intensity and the large optical Q factor constitute the perfect regime for a large variety of interesting optical experiments, such as ultra-efficient nonlinear frequency conversion [Del'Haye07] or cavity optomechanics [Kippenberg07].

Optical fibers guide light through the process of total internal reflection. By a conservation of energy argument, an evanescent field extending outside of the boundary exists during total internal This reflection. evanescent field is exponentially decaying in intensity and therefore is difficult to utilize. One method of doing so, called frustrated total internal reflection, is an effect related to tunneling in quantum mechanics. Frustrated total internal reflection involves placing two highly polished surfaces within about one wavelength of each other so that the second can "pick up" the field from the first [Heald95]. Tapered fibers increase the strength of the evanescent field by confining the light into a small space. This increases the intensity of the field in the core of the fiber and results in more light being guided outside of the core. Then, light can be coupled into objects such as microresonators by means of frustrated total internal reflection.

Tapered optical fibers are useful for coupling light to WGM resonators for a few reasons. For one, if the fibers fulfill the adiabatic condition, coupling is low-loss. As long as the shape of the taper does not change too dramatically at any one point,



: Whispering Gallery Modes from Longest to Shortest Wavelength. As the wavelength of the light in the WGM resonator decreases, the mode moves closer to the surface of the cavity and decreases in spatial extent. Since the mode has such a strong dependence on the wavelength, the distribution is highly dependent on the phase velocity of the light in the cavity.

very little power will be lost through the fiber, allowing more to be coupled into the microresonator. For another, optical tapers allow for precise phase matching. Two phase-related conditions need to be met in order to obtain low-loss coupling. First, the phase of the light needs to match the resonance modes of the cavity [Spillane03]. Second, the phase-velocity of the light inside the WGM resonator and the light in the coupling fiber taper have to be matched as well. The phase velocity of light inside of tapered optical fibers can be controlled through the taper diameter as changing the taper diameter changes the propagation modes within the fiber [Spillane03]. A similar effect exists inside toroidal microresonators: Figure L is а representation of whispering gallery modes in microtoroids modeled in COMSOL®, an idea taken from a paper by Oxborrow [Oxborrow03]. The representation on the left corresponds to the longest wavelength; the one on the right corresponds to the shortest wavelength. As the wavelength of

light in the microcavity decreases, the mode moves further to the surface of the cavity and decreases in spatial extent. This wavelength dependent spatial mode distribution leads to a strong dependence of the phase velocity of the light.

Toroidal microresonators [Armani03] are of particular interest to Dr. Schibli's laboratory for a variety of studies in the fields of cavity optomechanics, cavity quantum electrodynamics (cQED) and nonlinear optics. One of the students, David Miller, has been working on fabricating microtoroids for use with the tapered optical fibers.

Once light has been coupled into a microresonator, it will exhibit optomechanical coupling between the optical and mechanical properties of the microcavity. As the light builds up in the cavity, it will exert radiation pressure on the surfaces. Due to the small size of the cavity, the radiation pressure will start to cause mechanical motion. The mechanical motion of the walls of the cavity or of mirrors in the

cavity will cause a change in the optical field in the cavity in a process known as dynamic back-action, which is caused by momentum transfer. This process can result in either amplification or cooling (damping) of the system: amplification when power flows from the optical to the mechanical mode and cooling when power flows from the mechanical mode to the optical mode [Kippenberg07]. One use for this process is immediately apparent. The cooling process resulting from optomechanical coupling allows for the cooling of a mechanical system, not just individual atoms as in current laser cooling and magnetic trapping techniques [Kippenberg07].

Other applications of small nanomechanical oscillators involve testing limits of quantum and mechanical motion, made possible by the small mass of the cavities. Additionally, the wavelength and phase of the light within the microresonators is very precisely known due to the resonant modes of the cavity, making microresonators ideal candidates for high precision measurement. One application of this is towards determining the stability of fundamental constants [Antesberger09].

Applications of tapered optical fibers do not stop at microresonators. Another important use is in supercontiuum generation. Due to the confinement of light in an optical fiber, different wavelengths of light travel at different speeds leading to chromatic dispersion (see figure I above). This effect allows for a fine-tuning of the chromatic dispersion in tapered fibers where the diameter is easily controllable. Furthermore, tapered fibers confine light in small mode-volumes leading to large intensities. Thus, when laser light is sent down a tapered optical fiber, the large intensity will cause the refractive index to nonlinear, leading become to selfmodulation and four-wave mixing. These processes lead to a broadening of the optical spectrum of the light that was launched into the fiber taper. Broadening by as much as an octave in a process known as supercontinuum generation has been observed [Birks92]. Since the light still maintains high levels of spatial coherence, supercontiuum generation has important applications meteorology to and spectroscopy [Birks92].

As "The Shape of Fiber Tapers" by Birks and Li was used as a starting point for predicting which tapering parameters would result in which taper shape, but the model used in this experiment took into account more factors than this paper did. In order to improve upon the presented ideas, calculations were performed to determine the temperature of the fiber as it was pulled so this could be related to the viscosity.

To begin, the intensity of the laser needed to be found. By definition, intensity is the power divided by the area. In this case, assuming the scan speed of the laser is sufficiently faster than the pull rate of the fiber and slow enough that all sections of



: Taper Model Program. This is a screen shot of the tapering program developed in C++. The user can specify the taper parameters, the heating polynomial, and the laser power as well as the glass properties for fused silica. The program automatically updates to display the image of the taper (not drawn to scale), the total length of the taper, the minimum diameter of the taper, the steepest angle, and the peak temperature.

the fiber are illuminated, the intensity of the laser is

where P_{Laser} is the power of the laser, d_{Laser} is the diameter of the laser beam, and L(x) is the linear heating polynomial defined above.

From the intensity of the laser, the power level at the fiber can be calculated. Now, power is equal to the laser intensity times the area of the fiber. This becomes



where $P_{@Fiber}$ is the power on the fiber, R_{Fiber} is the radius of the fiber, and δI represents an infinitesimal unit of length along the fiber. This information can be used to calculate the net power gained by the fiber. This is described by

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where d_{eff} is the effective distance of a circular cross section and α is the absorption coefficient. This expression takes into account that some of the incident power is reflected back and not absorbed by the fiber.

In order to calculate the power absorbed by the fiber, it is first necessary to calculate the effective distance from the integral





Cost A = x/R : Effective Distance Diagram. This figure defines the information needed to evaluate the integral to determine the effective distance of a circular crosssection.

Finally, to determine the temperature of the fiber, equate the power absorbed by the power to the power emitted in thermal equilibrium.



This derivation culminated in an interactive program simulating taper shapes (see figure II), which is available for download form Dr. Schibli's webpage at http://spot.colorado.

edu/~trs/downloads.shtml. This program allows the user to input the initial fiber radius, the pull length, coefficients for the heating polynomial, laser power, and laser focus size. Other parameters include the absorption coefficient, the coefficient for blackness found in the Stephan-Boltzmann equation, and viscosity parameters. This information is used to calculate taper length, minimum diameter, steepest half angle, and peak temperature and present a visual image of the taper.

In order for the tapered optical fibers to provide low-loss coupling, the taper must fulfill the adiabatic condition. This is a constraint placed on the maximum rate of change the taper's radius. Formally,



[Birks00], where r is the fiber radius, z is the coordinate along the fiber length, β_1 is the propagation of the fundamental LP₀₁ mode, and β_2 is the propagation constant of the LP₀₂ mode.

The propagation constants were calculated from Saleh and Teich's information on step-index fibers in *Fundamentals of Photonics*. It follows from their definitions that

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where a is the core radius, n_1 is the index of refraction of the fiber core, and n_2 is the index of refraction of the fiber. Since this expression is inversely related to the core radius, the angle can become steeper as the fiber becomes narrower. Thus, the worst case scenario is at the beginning of the taper and occurs for an angle of 10.5 mrad.



: Taper rig. The fiber is heated by a CO₂ laser beam, which passes through a lens configuration to be focused. It then encounters a galvanometer mirror that scans the beam across the fiber, which is tensioned and pulled by two translational stages.



: Photograph of real taper rig.

In order to taper an optical fiber, the fiber must be tensioned, heated, and pulled, as in figures IV and V. In the initial set up, an infrared laser beam was focused through a series of three lenses and scanned across the optical fiber using a galvanometer system with a gold-coated mirror suitable for infrared wavelengths. The fiber was held by two clamps attached to two translational stages (NRT150). The stages were operated by a stepper motor controller which was in turn run by an ActiveX program executed in Visual Basic. Two microcontrollers (Texas Instruments' MSP430f2012 Device's and Analog ADUC7020) were used to control the set up: the first was used to control the laser power and the second was used to give the galvanometer system its input scan function. The tapering rig, including additional changes and adjustments, will be examined in more detail in the following section.



The

common methods of heating optical fibers for tapering

: Coherent CO₂ Laser (10.6 μm wavelength). are by flame, CO₂ laser, microfurnace, and fusion splicer

[Ward06]. This fabrication process utilizes a Coherent Diamond C-30L CO₂ laser (figure VI). The laser source has the advantage of being clean and consistent with the ability to provide uniform heating if the scan speed of the laser exceeds the pull rate of the fiber [Birks00]. Additionally, the taper shape is extremely sensitive to the heating length [Birks00], and the use of a CO₂ laser provides a controllable method for specifying the heating length.

Birks and Li discuss which parameters control the shape of the fiber tapers. The C++ code developed for this project incorporates parameters such as temperature dependent viscosity ignored in this paper (see the predictions section). However, their assertion that the heating length, or "hot zone", has the most influence on the taper shape is accurate. The hot zone is currently being described by the linear polynomial

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where L_0 is the initial heating length, L_1 is a constant that can range from -1 to +1, and x is the pull length of the fiber. If desired, higher order terms could be added to this polynomial.

In order to heat the fiber to a high temperature, the laser beam needed to be focused down to a radius of around 50 µm. The ABCD matrix method provided a convenient way to calculate Gaussian beam propagation. The ABCD matrix method uses the paraxial approximation to show a linear relationship between the radius of a beam and its angle of divergence before and after optical element. The an paraxial approximation assumes that the angles involved are small enough that $\sin\theta$ is approximately θ . Using this technique, different four-by-four matrices were used to represent different optical elements or a section of free-space propagation. These matrices were then multiplied together to form the "ABCD" matrix with the matrix the first element corresponding to encountered by the beam placed on the far right. Then, the radius and half-angle divergence of the beam before and after the optical elements were related by the equation:

where the primed coordinates represent the new radius and angle of divergence of the beam (see figure VII).



: Radius and Angle Definitions in the ABCD Matrix Method.

Only two element matrices were of interest for these calculations. The matrix representing propagation through a freespace region of length L is $\begin{array}{c} 1 \\ 0 \\ 1 \end{array}$, and the one for propagation through a thin lens $\begin{array}{c} 1 \\ 0 \\ 1 \end{array}$ (Kogelnik66].

Calculations showed that in order to focus the laser beam down to 50 µm with one lens, the focal length would be too short to provide enough useful working distance. Instead, a series of three lenses was used to avoid this problem. The first two acted as a beam expander and collimator, and the last one focused down the beam. In order to use the THORLABS ZnSe designed for infrared lenses wavelengths, the shortest and longest focal length lenses were selected for the beam expander. This turned out to be f = 50 mmfor the first lens and f = 200 mm for the second lens. Since these two lenses also needed to collimate the beam, $\theta' = 0$ in the ABCD matrix equation. From the laser specification sheet, r = 2.775 mm and θ = 3.775 mrad at a distance of 500 mm from the laser head. This left r' and L as the only unknowns, so the two equations were solved for these two parameters using the Mathematica[®] software. This yielded a spacing of 25.4 cm between the first two lenses and an expanded beam size with a radius of 10.4 mm. Since the beam was collimated after these two lenses, the placement of the third lens was less critical. However, a shorter focal length resulted in a tighter beam focus, so the third lens was selected to provide a small focal length that was not so small that it caused the beam focus to deviate from the fiber too much during the scan. The angle of convergence after the third lens was determined by basic geometry to be

by assuming the beam size was negligible at the focus in comparison to the initial radius after the lens. With an initial radius of about 10 mm and a focal length of 150 mm, θ = 66.8 mrad.

From Gaussian optics, the waist size, which is the radius at the focus, was given by



where λ is the wavelength of the light, θ is the angle of convergence, f is the focal length of the lens, and d is the diameter of the beam. In this case, $\omega_0 = 50.5 \mu m$, which was close to the target value.

From here, it was important to know how much the focus deviated from the fiber during the sweep. Assuming a 1 cm sweep when the beam's focus was initially positioned at the center of the sweep, the focus deviated from the fiber by 0.10 mm. This was again found from basic geometry. In order for this number to be meaningful, it was compared to the Rayleigh range, which is the distance it takes the beam to double in size and is given by

In this case, $z_R = 0.76$ mm, so the beam did not deviate from the focus too much during the scan, which provided nearly uniform heating as required.



: Galvanometer Mirror. This system consisted of a scanning mirror and a servo driver board and was used to scan the laser beam across the fiber. Next, the laser beam encountered the THORLABS galvanometer

system (GVS001). The galvanometer consisted of a goldcoated mirror that was controlled though a servo driver board. To set up the galvanometer

system, the scanning mirror was connected to the driver board, and the driver board was connected to a ± 12 power supply. The servo driver board interacted with a 12-bit precision analog microcontroller (ADCU7020), which transmitted the signal for the scanning polynomial. An inverting operational amplifier circuit was needed to connect between the microcontroller and the servo driver board to transmit the scanning function.

The optical fiber was held by two THORLABS 150 mm translational stages

(Apt150). Base plates and fiber clamps were custom machined to

attach to the translational stages. The base plates were aluminum plates with the correct hole pattern to attach to the



: Fiber Clamps and Translational Stages. The clamps tensioned the fiber and the stages pulled it during the tapering procedure.

THORLABS stages. The fiber clamps slid into a groove on the base plates and were secured with clamps along their bottoms. Each fiber clamp had a groove machined onto the top for the fiber. The top of the clamp had a Viton strip to secure the fiber and a magnetic set screw to control the clamping force.

The movement of the translational stages was controlled by a THORLABS stepper motor controller (BSC103). The software that came with the stepper motor controller provided insufficient capabilities to control the translational stages, so the ActiveX controls for the system had to be



: Graphical User Interface. This program is used to taper the fibers. The two panels at the top correspond to the two translational stages. The Reset and Go to 150 buttons were programmed to position the stages, and the taper button takes the information under the taper parameters section to determine the pull length and speed, the heating polynomial, and the laser power during a pull.

utilized. Although multiple programs are capable of interacting with ActiveX the code commands, used in this experiment was created in Microsoft Visual Basic 2008 Express Edition, which is freely available for download at http://www.microsoft.com/express/vb/Def ault.aspx.

In the code used for this experiment, the user interacted with a graphical user interface (see figure X) that was fairly simple to navigate. The two panels at the top of the screen represented the two translational stages. These panels allowed the user to view the absolute position of each stage, as well as "jog" the

stages by a small amount either forwards or backwards and view and edit the additional settings such as how the triggering system worked. Additional features were programmed into the ActiveX control to provide all of the necessary capabilities to taper the fibers. For the tapering set up, the stages needed to be at the far end of each translational stage so that the smallest possible section of fiber could be tensioned between them. Each stage's default "home" position was at the front of the stage, and every time the stepper motor controller was turned off, it forgot the location of the stages. Therefore, every time the stepper motor controller was turned back on, the

user had to click the programmed "reset" button that appeared on the graphical user interface. This button was set to take the stages back to their home position so the software could determine where they were and then move the stages back to 150 mm, the far end of the translational stage. Underneath this button is a "go to 150 mm" button. After the stages had been moved, this button automatically took them back to an absolute position of 150 mm, assuming the stepper motor controller had remained on. Beneath this button is the "taper" button. This button was programmed to interact with the numeric boxes seen to the right of the button. In these boxes, the user could specify the total taper length, and the acceleration and velocity of the tapering move. All three of these values described the total taper movement, so the distance, acceleration, and velocity for each stage was half of the values entered in the boxes. The taper button would not turn on until the microcontroller was also on to ensure that the fiber was not accidentally pulled without any application of laser power. The final button and numeric boxes on the graphical user interface allowed the user to specify parameters for the jog function. The default jog settings took steps at half of a millimeter, so the numeric boxes allowed the user to specify a smaller jog distance, acceleration, and velocity so that this method could be used to tension the fiber if necessary without breaking it or change the position of the stages without tapering a fiber. Hitting the "jog" button replaced the default parameters with the new ones. After that, the jog buttons were used on the top panels as before. Two more numeric boxes allowed the user to specify the constants in the heating polynomial, which were used by the microcontroller to heat the fiber via a calibration function. The final numeric box on the graphical user interface allowed the user to specify the laser power as a percentage from 0% to 100%. This value was then taken by the other microcontroller to regulate the laser power in the actual tapering experiment.

Since a CO_2 laser produces light at a wavelength around 10.6 μ m, the laser beam cannot be aligned by sight. The first step in getting the experimental set up aligned and functional involved making sure the laser beam, lenses, scanning mirror, and fiber were all at the same height. A height of three inches above the optical table was decided upon.

To begin, the laser beam had to come out of the laser head at a height of three inches level to the table. To get an initial estimate, New Focus posts were machined to around the correct height. The height and angle were further adjusted by burning holes in Kim Wipes (the CO2 laser's radiation is invisible to the human eye and CCD/CMOS cameras) until the holes were at a level of three inches both close to and far away from the laser head.

The lenses came next in the alignment process. The first lens was placed half a meter away from the laser head since

lens calculations assumed that distance. The second lens was placed at approximately 25.4 cm away from the first, which was the distance needed to collimate the beam from the ABCD calculations. The placement was fine tuned by again testing the beam size on Kim Wipes.

The location of the third lens was less critical since the laser beam was collimated coming out of the second lens. The third lens was placed close to the second and on a New Focus single-axis, 1inch translational stage to allow for fine tuning of its focal position.

The galvanometer mirror needed to be as close to the third lens as possible. If the mirror was placed close to the lens, that let more of the 15 cm focal length be between the mirror and the fiber, decreasing the angle the mirror had to sweep. This meant that the focus of the laser beam would deviate from the fiber less, giving more uniform heating. Also, it reduced the intensity of the light on the gold-coated mirror to kept it within the mirror specifications. The mirror was put in place and aligned first using a visible laser and then fine-tuned by the glow of the fiber as the CO₂ laser swept across it.

Finally, the fiber clamps on the translational stages had to be at the right height. The original base plates were not thick enough, so spacers were machined to ensure that the fiber was at the right height. Additionally, the fiber had to lie straight between the two clamps, so that involved careful measurement and adjustment by trial and error.

The lens calculations in the preceding section were performed before the galvanometer system arrived. Upon seeing the galvanometer mirror, it became apparent that the expanded beam size was too large for the mirror. This was further evidenced by the asymmetric tapers in the first few tapering attempts, indicating that one side of the fiber was receiving more power than the other. In order to fix this problem, the beam expander was removed and the laser beam was allowed to expand through free space until reaching a 7 mm diameter aperture to ensure the beam was circular. Then, the beam passed through the f = 150 mm lens and was scanned across the fiber as before. The beam size was greater at the fiber by a factor of about four; however, since the beam was more diffuse at the galvanometer mirror, the power could be increased to compensate for the larger focus size without harming the mirror.

Once the set up was completed and aligned, the actual tapering process was simple to perform. THORLABS SMF fiber optic cable had to be stripped and cleaned with isopropanol in preparation. After everything was turned on, the user needed to open the Visual Basic program, set the tapering parameters, and hit start. The program controlled the laser power, sweeping polynomial, and stage movement and automatically stopped everything at the end. The beam block also needed to be placed after the fiber to ensure that no stray laser beams left the experiment.

The final tapers should be between 3 and 4 microns in diameter. The human eye cannot resolve at that level, so some sort of magnification is required to characterize the taper shapes. One method is the optical microscope.



: Optical Microscope. The microscope consists of an objective lens and eyepiece, two foci, and two segments of collimated beam. Its magnification and resolution are described in the text.

The traditional optical microscope is a configuration consisting of four lenses. The first is the objective lens; the other three form the eyepiece. In this design, the on-axis beam of light is collimated between the objective lens and the first eyepiece lens and again between the last two eyepiece lenses. This system can be analyzed by using the ABCD matrix method and Mathematica[®] as before. Using the constraints that there must be a focus at either end of the lens configuration and that two segments have collimated on-axis beams, the magnification of the optical microscope is

From this relationship, the objective lens and second eyepiece lens should have long focal lengths and the other two short focal lengths in order to increase the magnification power of the microscope.

The resolution of the microscope is just as important as its magnification capabilities. Since the microscope used to image the tapered fibers involved a camera attached to a display screen,

The resolution of an optical microscope is also limited by the numerical aperture of the objective lens. For a Gaussian beam such as a laser,

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where λ_0 is the wavelength and d is the diameter of the lens. From this,

[optical microscope].



: Microscope

A Pyle View 7" wide screen TFT LCD monitor was used to view the microscope image in conjunction with a Supercircuit PC302XS camera. For this screen, the pixel spacing of 1440x234 limited the resolution more than the wavelength of the light and the numerical aperture. However, the magnification gained by a series of four lenses did not provide any additional magnification or resolution over the shorter focal length camera lens. Thus, to construct the microscope, the 6 mm lens was removed from the camera and placed at the opposite end of a lens tube that was approximately 6.5 in long. With this configuration, the full diameter of a fiber before tapering filled the display screen, which provided the appropriate magnification and resolution to view tapers.

The lens tube was mounted on a THORLABS three-axis, 1-inch translational stage using a custom-machined mount. The three axes were used to find the fiber, bring the fiber into focus, and scan across the

fiber. The fiber was illuminated with a blue light emitting diode during imaging, since the shorter wavelength of blue light provides better resolution.

Later on, the microscope was revised to allow for imaging during tapering. In order to do this, the microscope mount was placed on an arm that was attached to the stage, and the microscope was placed in a vertical position to be out of the way of the laser beam.

In the process of troubleshooting the tapering process, some general principles on how to create good tapers have been found.

First, the fiber needs to be quite clean. Dirt and other impurities on the fiber surface will result in non-uniform heating and thus inconsistently shaped tapers. Along the same lines, if the fiber has been scored, cracked, or otherwise damaged during the stripping process, it will quickly break and not taper at all. Fortunately, the blue LED used in the microscope and the microscope itself help illuminate surface defects.

Second, faster laser san speeds tend to results in smoother tapers. At the lower scan speeds, violent vibrations can be viewed on the microscope screen as the fiber is being tapered. These vibrations cause bottlenecking in the final taper shape, which of course might violate the adiabatic conditions.



: Tapered Fiber. This image was taken by David Miller at the Colorado Nanofabrication Laboratory. On the right, the fiber is at its full diameter of 125 μm. On the left, it has been tapered down to between 5 and 10 microns. In this image, it is also visible that the fiber tapered more on one side than the other.

Third, the power level of the laser needs to be carefully selected. There is a lower limit where the power is too low and the fiber readily breaks, and there is an upper limit where the fiber becomes too soft and melts apart. Power levels just below the upper limit produce smoother tapers. Fortunately, current data supports a linear relationship between the scan length and the amount of power needed for a given scan speed. This information is currently being implemented into the ActiveX and microcontroller programs so the user does not need to specify it each time.

Figure XIII above, taken by David Miller at the Colorado Nanofabrication Laboratory, represents a fiber taper of a few microns achieved by taking this information into consideration. A few conditions in the tapering rig need to be fine-tuned to obtain better fibers. First, the optimal balance between scan speed and laser power needs to be found. This will probably entail changing the power throughout the scan as the scan length changes and the fiber diameter decreases. This is currently being implemented.

The fiber tends to taper more towards the side closest to the laser. In the future, this should be fixed or corrected for in the adiabatic condition, which would reduce the maximum angle.

The fiber also needs to be isolated from air flow within the room. It is possible to view the fiber oscillating on the microscope screen when it is not shielded.

As the taper shapes visibly improve, the shapes should be tested against the computer model to verify good agreement. Also, the adiabatic condition should be tested by sending light through the fiber while it is being tapered and monitoring the transmitted power at the other end.

After the tapers are perfected, the next phase will involve using them to perform other experiments. Of particular interest is their use in coupling light into microresonators, as discussed in the introduction. Possible uses of the tapred fibers and microtoroids in Dr. Schibli's lab include optical frequency comb generation, telecommunications, atomic and molecular sensors, and quantum electrodynamics, to name a few. In order to advance these experiments, a way to calculate the whispering gallery modes for the toroidal microcavities would be helpful. Oxborrow highlights the use of COMSOL[®] to aid in these calculations in his paper on the subject (see figure I at the beginning of this paper). Earlier this summer, COMSOL[®] hosted a seminar in Denver, Colorado meant as in introduction to its software. This was attended to investigate COMSOL[®] as a future option for these types of calculations.

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