I. INTRODUCTION

Microscopic particle manipulation is increasingly employed by scientists and engineers exploring microscopic physics and constructing small devices. Ashkin demonstrated the trapping of particles and cells in water: Since then, optical tweezers have been used to explore the microscopic world of biology. Ashkin generalized his technique to manipulate neutral atoms: The past decade has seen a renaissance in physics generated by laser cooling and trapping of atoms.

We manipulate microscopic droplets and particles in the laboratory at atmospheric conditions. Weakly absorbing particles with relative refractive index greater than one can be manipulated by readily available lasers since the trap does not require laser tuning to a material resonance. We have also transported and trapped highly absorbing silver particles.

We have refined the technique for use in an undergraduate laboratory. The optical setup costs less than $1400 (excluding laser, optical table, and optical diagnostic equipment) and requires no machining. An optical table is not essential, we have constructed the trap on a 2 ft x 2 ft quarter-inch aluminum plate by gluing the optical components to the plate. Optical diagnostics including microscope, video camera, and recorder add less than $750 to the cost.

Undergraduates assisted in trap construction and characterization in addition to conducting numerous scattering experiments in the completed trap. The visual nature of the experiments intrigues students, who also appreciate that the experiments can be videotaped: This allows students to review the experiment and analyze the data at their leisure. The trap has been used in lab to teach advanced optical techniques and in lecture to demonstrate electrical forces and electromagnetic scattering.

This paper presents a brief outline of possible experiments in the trap, and in addition describes both the trap construction and a sample scattering experiment using the trap. Section II includes all the relevant equations for designing the trap. Section III describes laser requirements, construction of components, and a step-by-step alignment procedure for the trap. Section IV explains how to operate the trap. Section V introduces angular Mie scattering theory and describes the scattering experiments. Section VI contains a brief list of other experiments possible using the trap. The Appendix contains a parts list including vendors. The references include the address for a web site for a downloadable Mathematica notebook to generate angular scattering patterns.

II. TRAPPING THEORY

Figure 1 is a schematic of a particle (P) within the hollow fiber (HF) of the optical trap. The hollow fiber is indispensable for trap stability: The hollow fiber guides the laser beam by fiber modes suitable for trapping; the hollow fiber permits the relatively weak optical forces \( F_S \) and \( F_G \) to confine the particle by shielding it from the environment. The laser beams are coupled to the hollow fiber by low numerical aperture (NA) lenses near both fiber ends.

Very little of the light we observe is directly from its source. We perceive objects by reflection, and refraction of the light impinging on the object. These phenomena are lumped together and called scattering. According to Maxwell’s theory, light carries momentum in the direction of the light’s propagation. This is easily understood by Einstein’s photon model of light; when photons change direction due to a scatterer, then, according to Newton’s law, the scatterer experiences a reaction force. These reaction forces are optical forces. We adapt the terminology and notation for the optical forces \( F_S \) and \( F_G \) from standard optical tweezers’ terminology. Scattering forces \( F_S \) (which arise from momentum conservation of scattered photons and are proportional to laser intensity) provide the dominant force confining transparent particles along the fiber axis in the trap: We refer to optical forces along the fiber axis as scattering forces. An off-axis particle experiences a restoring force due to the radial dependence of the fields in the waveguide. These forces (which arise from the gradient of the electric field) confine the particle to the fiber axis: We refer to radial optical forces as gradient forces, \( F_G \).

Light is guided in the hollow fiber by grazing reflection, and the intensity of the lowest loss mode as a function of \( z \), along the fiber axis, and \( \rho \), the fiber radial direction, is

\[
I(\rho, z) = I_0 J_0(\chi \rho / \rho_0) e^{-z/\xi_0},
\]

where \( I_0 \) is the field intensity coupled to the fiber at the entrance \( z = 0 \) and \( \rho = 0 \), \( \chi \) is the first zero of the zero-order Bessel function.
Bessel function, $\rho_0$ is the fiber radius, and $z_0$ is the intensity decay constant given by

$$z_0 = 6.8 \frac{\rho_0^3}{\lambda^2} \frac{n^2 - 1}{n^2 + 1},$$  \quad (2)$$

where $n$ is the fiber’s wall refractive index relative to the ambient refractive index, and $\lambda$ is the ambient laser wavelength. For each individual beam, the trap is centered in the fiber and with the cylindrical coordinate system translated to the trap center the intensity sum, $I$, and difference, $\Delta I$, are

$$I(\rho, z) = 2I_0\rho^2(\chi\rho/\rho_0)e^{-t_{2\rho_0}} \cos \left( \frac{z}{z_0} \right),$$

$$\Delta I(\rho, z) = 2I_0\rho^2(\chi\rho/\rho_0)e^{-t_{2\rho_0}} \sin \left( \frac{z}{z_0} \right),$$

where $l$ is the fiber length and $I_0$ is the intensity at $\rho = 0$ of each individual beam. Theoretically, in excess of 98% of each beam can be guided into the lowest loss mode and an individual 100-mW beam coupled into a 20-μm-i.d.-fiber gives $I_0$ in excess of 1.4 GW/m². Figure 2(a) shows the intensity along the fiber axis ($\rho = 0$) for two 100-mW 780-nm beams coupled into an 8-mm-long 20-μm-i.d.-fiber. Figure 2(b) shows the radial dependence of the intensity at the trap center ($z = 0$). The radial intensity gradient provides the radial confinement while the balanced scattering forces at the trap center confine the particle longitudinally.

In principle, the optical forces on the particle can be determined exactly from the incident light through a complex and computationally intensive generalized Lorentz–Mie theory (GLMT), which combines the Mie scattering coefficients for the particle and the shape coefficients of the beam.

The two limiting regimes of particles much larger/smaller than the optical wavelength admit simple approximations for the optical forces: An appropriate measure of the size of a particle of radius $a$ is the size parameter, $x = 2\pi a/\lambda$. For small particles ($x < 1$) a dipole approximation is appropriate. For large particles ($x > 100$) a geometrical ray approximation is appropriate. Unfortunately, particles easily confined in our trap (with a 780-nm laser) are from 1 to 5 μm in radius, giving size parameters in the intermediate range 8 < $x$ < 40 for which neither approximation is accurate. Since the trap radial confinement is excellent, we assume that the particle is always located on the beam axis and we do not compute or measure gradient forces, which would require the full GLMT. For particles on the beam axis the GLMT reduces to a simple sum involving the Mie scattering coefficients, which also determine the observed far field scattering patterns observed in the reported experiment.

Mie scattering theory is an exact theory for scattering by homogeneous spherical scatterers from planar incident waves. The incident, internal, and scattered fields are written as infinite sums of appropriate functions in spherical coordinates. The coefficients, $a_n$ and $b_n$, of the expansion for the external field are the scattering coefficients: We adopt the notation and terminology of van de Hulst. The scattering coefficients, determined by matching the tangential field components at the boundary $r = a$ of the scatterer, are

$$a_n = \frac{m \psi_n(mx) \psi'_n(mx) - \psi_n(x) \psi'_n(mx)}{m \psi_n(mx) \xi'_n(x) - m \xi_n(x) \psi'_n(mx)},$$

$$b_n = \frac{\psi_n(mx) \psi'_n(mx) - m \psi_n(x) \psi'_n(mx)}{\psi_n(mx) \xi'_n(x) - m \xi_n(x) \psi'_n(mx)},$$

with $m$ the relative refractive index of the scatterer and primes denoting derivatives of the Ricatti–Bessel functions $\psi_n(r)$ and $\xi_n(r)$ with respect to their arguments.

The scattering force for an incident beam with unit intensity and ambient refractive index $n_b$ is $F_x = \pi a^2 (n_b/c) \times (Q_{ext} - (\cos \theta Q_{inc}))$, where the extinction efficiency...
III. TRAP CONSTRUCTION

Figure 3 is a schematic of the hollow fiber optical trap. It consists of a laser, steering mirror (SM), beam splitter (BS), two lenses (FL1 and FL2), and fiber. The cw laser requirements are adequate power to trap particles and satisfactory spatial beam quality to couple the laser beam to the fiber. We have constructed the trap using both a 780-nm diode and a 532-nm frequency doubled YAG laser. The diode laser in our laboratory is an older 500-mW single-mode laser. We believe that a cheaper functional diode laser can be constructed from a 200-mW diode with a user constructed current supply. The hollow fibers (commercial capillary tubing available at nominal cost) need to have their polyimide coating removed to view trapped particles. This coating can be burned off short sections with a butane lighter or propane torch. The fiber should be wiped clean with ethanol or methanol before use to reduce light scattering and heating. In practice, we have found that an 8-mm-long section of 20-\mu m-i.d. and 350-\mu m-o.d.-fiber provides an adequate trapping spring constant and reasonably easy alignment. Fibers can be cleaved to length using either a scorer or cleaver. The 350-\mu m-o.d. fiber is preferable to thinner fibers for its rigidity and enhanced ability to attenuate scattering from the external fiber wall and mount.

The maximum coupling efficiency of 98% is achieved with a lens with a focal length of

\[
f = \frac{2\pi\omega_0^2\rho_0}{3\lambda},
\]

where \(\omega_0\) is the laser spot size. We have achieved satisfactory coupling efficiency to a 20-\mu m fiber with a 40-mm lens for a 1.5-mm beam radius with both the 780- and 532-nm laser, and satisfactory trapping with laser powers from 20 mW to 1 W. Alignment at the lower laser powers requires practice.

The droplet source is a nebulizer, which delivers a mist of droplets between the coupling lens (FL1) and the fiber. The converging laser beam both funnels and propels the droplets into the fiber. For larger droplets we modified an asthmatic pneumatic nebulizer. For smaller droplets we have constructed a nebulizer by suspending a source chamber in the water bath of an ultrasonic room humidifier, see Fig. 4. Both sources work well, but the mist must be directed microscopically close to the fiber entrance at low flow velocities.

The asthmatic nebulizer, Fig. 5, was modified by first mounting the respirator head (comprising a source chamber, a compressed air inlet, and two mist outlets) and adding transfer tubing to one of the mist outlets and exhaust tubing to the other. The transfer tubing directs the mist to the fiber entrance and restriction clamps on both the exhaust and transfer tubes control the droplet flow to the fiber.

Figure 4 is a schematic for constructing a nebulizer using an ultrasonic room humidifier. A source chamber composed of a glass funnel (GF) with plastic sheathing (PS) glued to the funnel mouth is suspended in the water bath of an ultra-
glued with silicone to form saddles. The saddles are then glass microscope slide.

The fiber mount is crucial for ease of trap operation. The fiber mount must minimize fiber heating and light scattering to avoid disturbing the shallow longitudinal trap. Excessive heating manifests itself as difficulty in trapping the particles. The keys to avoiding heating problems are clean fibers, transparent mounts with minimal fiber contact, and careful fiber alignment. Figure 6 is a schematic for a fiber mount constructed from four cover slips (CSs) and a glass microscope slide (MS). Two pairs of cover slips are glued with silicone to form saddles. The saddles are then glued onto opposite faces of the microscope slide. With the assembly in a vise, the saddle positions can be visually adjusted (before the silicone sets) so that a fiber resting in the saddle is approximately level and perpendicular to the microscope slide. This mount facilitates fiber replacement and alignment since a new fiber placed on a previously aligned mount is automatically nearly aligned with the laser beam. Note that the top corners of the cover slips should not protrude more than the working distance of the microscope objective above the fiber. Once dry, the mount is glued to the face of a two-axis tilt stage with the saddles holding the fiber clear of the tilt stage.

The setup of the trap, particularly the alignment of the laser beams, is not trivial but with practice the complete construction and alignment takes less than 30 min. Note that care in preliminary positioning (A) is crucial for ease of alignment. Construction proceeds as a series of approximations with Fig. 3 and the caption is providing the optical component key.

(A) Preliminary positioning: (I) Position the laser with the steering mirrors (SMs) to an appropriate height typically dictated by the height of the microscope objective (MO). (II) Roughly position the beam splitter (BS) and mirrors (M1 and M2) so that the counterpropagating beams visually overlap. (III) Block Beam2 and make Beam1 parallel to the tapped holes of the optical table. (IV) Use a carpenter’s combination square to ensure Beam1 is parallel and level to the optical table at the desired height. (V) Unblock Beam2 and align it to overlap Beam1. Beam overlap is checked by blocking and unblocking the beams and checking the spot locations on marked cards hung on the mirrors. (VI) Locate the fiber mount between the mirrors (M1 and M2). (VII) Adjust the height of the fiber mount so the saddles are centered in the beam. (VIII) Place a cleaved and stripped fiber on the fiber mount with tweezers. (IX) Check to see that the fiber is level and parallel to the laser beams. (X) Position the lenses FL1 and FL2 (glued to 1/2-in. posts attached to the two \(xyz\)-translation stages) normal to the laser beams one focal length from each fiber end.

(B) Rough alignment of Beam1: (I) Block Beam2, translate lens FL2 out of the beam, and hang a marked card on mirror M2 with Beam1 centered on the mark. (II) Use the \(xyz\)-translation stage to adjust lens FL1 until the focused laser beam illuminates the fiber: The illumination is clearly visible. (III) Inspect the fiber to ensure that it is not clogged and that both ends are cleanly cleaved using a low power microscope: The laser beam and fiber will not couple if either end is gouged, but small shards are acceptable. (IV) Adjust lens FL1 until the fiber diffraction pattern (see Fig. 7) appears. The diffraction pattern should be symmetric; a nonsymmetric pattern indicates that the fiber and laser beam are not parallel. Rotationally adjust the fiber mount until the fiber and laser beam are parallel. (V) Search for the diffraction ring of the fiber-wall mode (see Fig. 8) by translating lens FL1 vertically downwards. Patience and occasional horizontal adjustment are required. If rings do not appear after repeated trials, replace the fiber since it is probably either poorly cleaved or clogged.

(C) Fine alignment of Beam1 to maximize coupling to the fiber hollow core: (I) Make fine adjustments to the focus and lateral position of lens FL1 to reduce the background scattering and make the rings more distinct. When this adjustment is completed a central Gaussian-like glow will appear concentric with the rings. This is the diffraction pattern from...
light coupled into the center of the fiber. (II) Rotate the fiber, using small adjustments of the tilt stage, so that the rings become more concentric with the mark on the card. (III) Re-adjust lens FL1 to maximize the central spot and reduce the background scattering. (IV) Repeat steps II and III until the rings are concentric with the mark on the card with a clear diffraction pattern. As this adjustment proceeds, the laser coupling to the hollow core of the fiber should improve, i.e., the central spot intensity should increase while the rings should decrease in both number and intensity. Figure 8 shows the diffraction rings and Gaussian spot of a well-aligned laser beam. (V) Check the alignment by verifying that the laser spot is centered on lens FL1. If the laser spot is above the lens center then the fiber is low and needs to be raised. Reposition the fiber vertically and/or horizontally as required and restart from stage B step IV.

(D) Alignment of Beam2: The second laser beam is easier to align because the aligned laser beam, Beam1, can be used as a guide to check the rough alignment of the second laser beam, Beam2. (I) Unblock Beam2 and check the alignment with Beam1 at several locations with a thin translucent card. (II) Adjust the beam splitter (BS) and mirror M2 so that Beam2 is centered on the diffraction pattern of Beam1 at several locations. (III) Block Beam1 and translate lens FL1 out of the beam path to avoid focusing the diffraction pattern of Beam2. (IV) Hang a marked card on mirror M2 to view the diffraction pattern. (V) Align Beam2 following the procedure outlined for Beam1 in C but do not adjust the fiber. (VI) Realign Beam1 examining the diffraction pattern with a card between lens FL2 and the fiber. As a check the laser beams should be near the center of each lens, FL1 and FL2.

IV. TRAP OPERATION

We have trapped many materials including salt and sugar crystals from solution, glycerin droplets, 1- to 3-μm dielectric spheres, glass beads, and silver particles. Solid particles are mixed with water in the source chamber of the nebulizer. The resulting droplets, containing suspended particles, evaporate to leave the desired material.

As a preliminary test a 50–50 solution of glycerin and water is particularly easy to trap. Glycerin alone is too viscous for the nebulizer and needs to be thinned with water, which evaporates rapidly leaving a slowly evaporating glycerin droplet in the trap.

Fill the nebulizer source chamber. Turn the nebulizer on, direct the flow toward the fiber end, and minimize the droplet flow using the restriction clamps. Scattering from the droplets illuminates the converging laser beam, enabling the mist location and density to be visually inspected with the naked eye or through a low power microscope and adjusted. The scattered light from the mist is intense; the intensity can be reduced for comfortable viewing using colored plastic sheets listed in the optical diagnostic appendix. Note that for efficient collection the droplet stream must be microscopically close to the fiber end.

The naked eye can detect occasional particles entering and traveling down the fiber to the trap center. A microscope is then positioned to view the trapped particle under low power. Larger droplets are formed by coalescing the original droplet with additional trapped droplets. Multiple trapped droplets can be encouraged to coalesce by momentarily blocking one trap beam. The trap is sufficiently stable to trap salt crystals for hours and glycerin droplets until they evaporate into the Rayleigh regime. The longitudinal spring constant has been measured by perturbing the droplet from the trap center, videotaping the return, and extracting the spring constant from the resulting data. The minimum total power required to operate the trap with the frequency doubled YAG is 20 mW, or 10 mW at each fiber end.

Many experiments are possible with this basic trap setup, including trap characterization, coalescence time, one-
dimensional Brownian motion, morphology-dependent resonance, and Mie scattering observations. The basic Mie scattering observation experiment is described in the following.

V. SCATTERING EXPERIMENT AND THEORY

Scattering patterns from trapped droplets, Fig. 9 is a typical example, are readily observed in the lab, projected on a screen for presentation, or recorded for later analysis using a minimally modified optical microscope.

We modified an American Optical microscope (model 10) by removing the illumination source and mechanical specimen stage. The horseshoe leg of this microscope allows the objective to be directly above the fiber, and the objective turret allows easy interchange of objectives during observation. The trapped particle can be viewed directly, projected on a screen, or videotaped by replacing the eyepiece with a video camera. Figure 9 was recorded with a 45×, 0.45 NA objective. The scattering pattern becomes visible (and fills the field of view) by slight defocusing of the objective from minimum image size.

In general, the angular scattering pattern of a spherical scatterer depends upon polarization, size parameter, and relative refractive index. The experiment we describe, to illustrate one possible use of the trap, videotapes the evolution of the scattering pattern of a small glycerin droplet as it slowly evaporates into the Rayleigh scattering regime in the trap. The videotape record is subsequently analyzed to compute droplet size as a function of time.

Fig. 9. The angular scattering intensity from an approximately 3-μm glycerin droplet illuminated with a 780-nm trapping laser. The central vertical symmetry axis is at θ=0°.

Scattering is simplest for very small particles giving the familiar symmetric dipole scattering pattern. At slightly larger size parameters, the forward lobe becomes more intense than the rear. Further size increases generate intensity maxima (or fringes) in the scattering pattern. The number of these fringes increases with the size parameter. For large particles the fringes can be understood as interference effects, due to multiple reflections of the internal fields, in the geometrical ray optics approximation.

Figure 10 shows the standard scattering geometry and spherical coordinate systems: θ, the scattering angle, is measured from the incident radiation direction, z, while the incident propagation direction, r, and the observation direction, t, from the scatterer’s center define the scattering plane. In Fig. 10 the scattering plane is the plane of the figure.

Mie scattering theory provides explicit formulas for the scattering from a spherical droplet. If the polarization of the incident radiation is perpendicular to the scattering plane (i.e., parallel to E1 in Fig. 10) the scattered field intensity is

\[ I_1 = \frac{\lambda^2}{4\pi r^2} \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[ a_n \pi_n(\cos \theta) + b_n \tau_n(\cos \theta) \right] \]

while if the polarization is parallel to E2 in Fig. 10 the scattered field intensity is

\[ I_2 = \frac{\lambda^2}{4\pi r^2} \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[ a_n \pi_n(\cos \theta) + b_n \tau_n(\cos \theta) \right] \]

where the Legendre polynomials, \( \pi_n(\cos \theta) = P_n^{1(1)}(\cos \theta) / \sin \theta \) and \( \tau_n(\cos \theta) = (d/d\theta)P_n^{1(1)}(\cos \theta) \), define the angular dependence while the scattering coefficients \( a_n \) and \( b_n \) are defined by (5). The functions \( G_1(\theta) \) and \( G_2(\theta) \) are the angular efficiencies.

The counterpropagating trap beams provide two sources of incident radiation in our experiment. We do not expect and have not observed any coherence effects between the beams: The laser is not frequency stabilized and no special effort is made to mechanically stabilize the optical components. The sum, \( C(\theta) = G_1(\theta) + G_2(\pi - \theta) \), of the two appropriate patterns gives a symmetric scattering pattern for either (i = 1 or 2) input polarization. Intensity maxima/minima appear at \( \theta = 90° \), splitting the central fringe as the size parameter increases: The new fringes then migrate out toward the right and left (\( \theta = 0° \) and \( \theta = 180° \)) sides of the pattern. Experimentally the NA of the microscope objective limits the angle range seen in the experimental scattering pattern. As a result, in the experiment the number of scattering fringes is non-monotonic in time.
The scattering experiment described in this article determines the size of an evaporating ethylene or diethylene glycol droplet by recording the scattering pattern on videotape, and later counting the number of fringes in the scattering pattern. The schematic of the experimental setup, Fig. 3, shows a microscope objects for collecting and observing the scattering pattern.

The experiment sizing the glycerin droplets is initiated by capturing and coalescing droplets from the nebulizer mist until there is a glycerin droplet showing between five and ten fringes in the trap: such a droplet is between 2 and 5 \( \mu m \). The evolution of the angular scattering pattern is then videotaped as the droplet evaporates. It is important that the droplet is stable during the run and that the recording continues until the droplet passes into the symmetric dipole regime. The NA of the objective limits the field of view and as the droplet evaporates fringes migrate into the visible scattering pattern: This results in several droplet sizes having the same number of fringes \textit{visible} within this limited field of view. However, provided the recording extends down close to the Rayleigh regime, it is always possible to work backward from the well-determined size at the end of the run.

The analysis is performed by calculating the theoretical fringe pattern (for the appropriate refractive index and visible angle range) over a range of size parameters which includes the anticipated experimental size parameter range. Mathematica code, which calculates fringe patterns, is provided on our web site. Figure 11 shows sample output from the program for a glycerin droplet, from size parameter 5.2 to 5.4. The code is fully documented taking as input the refractive index, NA, size parameter range, and size parameter resolution and returning as output a sequence of images of the theoretical scattering patterns.

Figure 12 shows the experimentally determined droplet radius as a function of time. The sizing process has numerous sources of error. There is experimental error determining the number of fringes from the videotaped images. In addition, uncertainty is introduced because the number of scattering fringes remains constant within small ranges of size parameters. The error bars in Fig. 12 indicate this size range.

For particles of this size the dominant thermal effects should be absorptive laser heating and evaporative cooling. As a reasonable approximation, the time dependence of the droplet radius, \( a(t) \), should be determined by a simple power balance between these effects. Absorptive heating is approximately proportional to droplet volume. Evaporative cooling is proportional to the volume rate of change; surface area times the radius time rate of change. A heat balance gives a simple first-order ordinary differential equation for the radius \( a(t) \) with decaying exponential solutions,

\[
La^2 \frac{da}{dt} = -ia^3. \tag{13}
\]

The superimposed curve in Fig. 12 is a least-squares fit of an exponential.

**VI. CONCLUSION**

The optical trap has proved to be a valuable educational and research tool. Student response is enthusiastic, with both students and faculty enjoying many hours developing and using the trap.

Numerous other experiments can be performed in the trap. Longitudinal trapping forces can be measured by videotaping (frame-by-frame review gives the particle velocity) trapped particles. We have recorded interesting dynamic motion of salt crystals at low laser power in the trap. Droplet coalescence times can be measured by observing the total scattering. We have used the trap to construct and observe a microchemical reactor. We measured mixing times by observing the quenching of fluorescence from a laser dye doped droplet coalescing with a potassium iodine droplet.

Removing one of the beams from the trap makes a deposition apparatus. We deposit onto a cover slip mounted on an \( xyz \)-translational stage located behind the fiber exit end. Both
single particles and 2- to 10-μm structures can be deposited. Deposition can be observed in real time by placing a horizontal microscope directly behind the cover slip. The deposition is subsequently analyzed with an optical microscope.

**ACKNOWLEDGMENT**

The authors would like to thank Michael Renn for access to equipment and for including an optical trapping experiment in his undergraduate optics laboratory.

**APPENDIX**

The components of the optical trap and optical diagnostic equipment are listed. Suppliers are identified to assist the reader; no Michigan Technological University endorsement is implied. Prices are current as of 1999.

**1. Optical trap**

1. Optical Base #BA2, 4 @ $9 each, Thorlabs, Inc., P.O. Box 366, Newton, NJ 07860, (201) 679-7227.
2. Optical Base #BA15, 1 @ $6.25, Thorlabs, Inc. (see item 1).
3. Magnetic Base, #MB175, 2 @ $39.50 each, Thorlabs, Inc. (see item 1).
4. Post holder, #PH3-ST, 5 @ $7.20 each, Thorlabs, Inc. (see item 1).
5. Post, #TR3, 7 @ $5.35 each, Thorlabs, Inc. (see item 1).
6. Post, #TR1.5, 2 @ $4.35 each, Thorlabs, Inc. (see item 1).
7. Clamps, #RA90, 2 @ $11.00 each, Thorlabs, Inc. (see item 1).
8. Kinematic mirror mounts, #KM-S, 4 @ $38.00 each, Thorlabs, Inc. (see item 1).
9. Kinematic mirror mounts, #KM1H, 1 @ $48.00 each, Thorlabs, Inc. (see item 1).
10. Beam splitter appropriate for laser wavelength, #03BT054 or 03BTF058, 1 @ approximately $50, Melles Griot, 4665 Nautilus Court South, Boulder, CO 80301, (800) 326-4363.
11. XYZ translator mount, #MT-XYZ, 2 @ $215 each, or preferably M-460A-XYZ-LH, 2 @ $550 and AJS-0.5, 6 @ $22 each, Newport Corp., 1791 Deer Ave., Irvine, CA 92606, (714) 863-3144.

**2. Optical diagnostics**

1. Used microscope with objectives and without illuminator and glass slide stage American Optical model 10, 1 @ approximately $500, National Microscope Exchange, Redmond, WA, (800) 851-7635.
2. Video Camera, #H52569, 1 @ $147, Edmund Scientific Co. (see item 12).
3. Color plastic sheets used for optical filters, #H40675, 1 @ $9.90, Edmund Scientific Co. (see item 12).
4. VCR recorder, 1 @ approximately $100.

**3. Special tools**

1. Fiber Cleaver, #FBC-001, 1 @ $160, Seicor Corp., 489 Seicor Park, Hickory, NC 28603, (828) 327-500.
2. Tweezers, #D31345, 1 @ $12.95, Edmund Scientific Co. (see item 12).

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Footnotes:

I tried to teach Fermi to fish, and it seemed to me he liked it. However, he once returned from Chicago with a lake fishing rod and reel. I told him that it was not suitable for mountain streams, but to no avail. Fermi developed a theory on how trout should bite and on how to catch them. The theory was disproved by experiment, but this did not impress him in the least. Ultimately he abandoned fishing, but not his theory.