

Introduction

Litton Poly Scientific for the past five years has been producing a silicon based multimode fiber optic switch for military use. Recently the need for a single mode switch has become important. The need for the switch comes from the expanding fiber optic communications networks in the private sector. Eventually the plan was to design a new smaller actuator for the switch and integrate several of these switches into a single package and market them as telecommunications devices.

Instead of designing a new switch using different optics it was suggested that the 62.5 μm core multimode optical fiber simply be replaced by 9.0 μm core single mode fiber. This however presents the problem of light loss due to fiber misalignment. With large core fiber misalignment is not a significant problem since the amount of misalignment is small compared to the fiber core diameter. The opposite is true for single mode fibers which have a small core. The goal of this paper is to analyze light loss for the single mode switch.

The Device

The device consists of an etched silicon base in which four 500 μm ball lenses and fibers are attached. The bases are etched using standard photolithographic procedures in four inch diameter silicon wafers. Once the base patterns are etched into the wafer the wafer is cut using a dicing saw. The bases are then sorted for defects, cleaned and used for the switch. A standard yield of 40 – 50 bases is not uncommon for one wafer. An illustration of the device is shown in fig. 1.

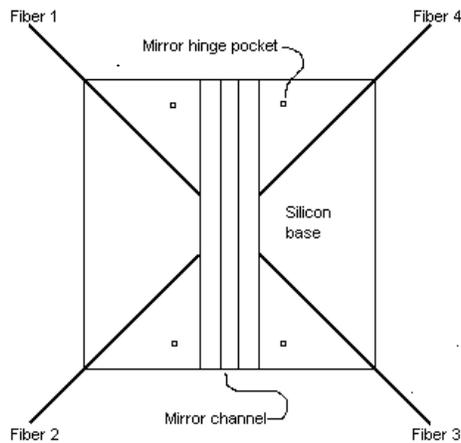


Fig. 1. Top view of switch base showing placement of fibers and lenses.

As far as the operation of the switch is concerned, in bypass mode light travels from fiber 1 to fiber 3 and from fiber 4 to fiber 2 through the coupling ball lenses. When the switch is activated a mirror is electrically actuated into the mirror channel. Light then travels from fiber 1 to fiber 2 and from fiber 4 to fiber 3 by reflection off the mirror.

The fiber used in the switch is $9\mu\text{m}$ core single mode fiber produced by Corning. This fiber has a numeric aperture of $\text{N.A.} = .13$ which means that the critical angle of light exiting the fiber is $\theta_c \approx 7.5^\circ$ or about .13 radians. Other specifications which the fiber has are the core radius $R = 4.5\mu\text{m}$ and a core concentricity of $1\mu\text{m}$ (meaning that the core is centered in the cladding to within $1\mu\text{m}$).

Sapphire ball lenses were used to couple the sending and receiving fibers. These lenses have a diameter of $500\mu\text{m}$, a focal length of $\sim 350\mu\text{m}$, an index of refraction of 1.76 and are anti-reflection coated. The focal length of the lenses was calculated using a paraxial approximation. An illustration of how the focal length is defined is provided below in fig 2. This approximation does not take aberration into consideration, which will be covered in the ray tracing section of this paper.

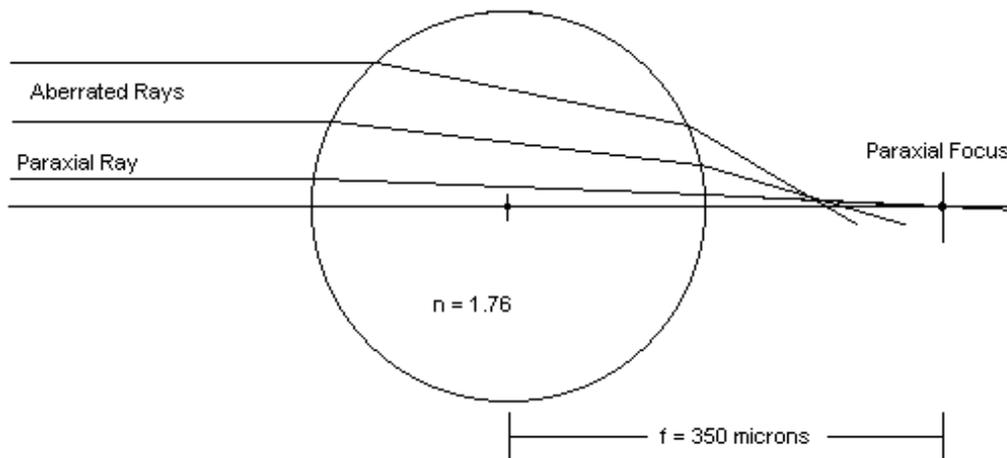


Fig. 2 Ray diagram of focal length.

Construction

After the bases are cut from the wafer they are cleaned with isopropyl alcohol and de-ionized water. The lens pockets are then inspected and lenses installed using epoxy. This is the first assembly step of the switch. Each base/lens set is then placed on a heated vacuum chuck where the installation of the fibers takes place.

The fibers are then placed in the v-grooves of the base and their distances from the lenses are adjusted to yield maximum output from the receiving fiber. A house built 1550 nm diode laser and HP intensity meter are used to optimize output. Once the optimum placement is determined the fibers are epoxied to the base. The heat in the vacuum chuck speeds the epoxies curing process.

As the epoxy dries it expands and tends to displace the fiber. A measurement to

determine the amount that the fiber is displaced is the fiber to lens height measurement. The optimal value for this measurement is $D = 188\mu\text{m}$ since the fiberradius is $62.5\mu\text{m}$ and lens radius is $250\mu\text{m}$. A distance D of $188\mu\text{m}$ puts the center of the fiber in line with the center of the lens.

The measurement of D was done with a digital indicator mounted on a stand. This particular indicator has an accuracy of $\pm 1\mu\text{m}$. First the height of the lens above the base was determined then the fiber height was determined. This was done with a microscope to ensure that the tip of the indicator was making contact with the top of the lens or fiber. The difference in these two values is D . Once D is calculated the fiber offset d , is calculated and is $d=188-D$.

The Optical System

The optical system for a single branch of the switch consists of a transmitting fiber two coupling lenses and a receiving fiber as shown in figs 2&3. Rays leaving the transmitting fiber pass through the two ball lenses and are imaged at the face of the receiving fiber. Neglecting aberration and any surface discontinuities of the lenses the fibers should be placed at the focal points of the lenses. This would form a 1:1 imaging system (a perfect image of the transmitting fiber would be formed at the focal point of the second lens). The fibers are placed approximately $100\mu\text{m}$ from the surface of the lens.

The first calculation of interest is the Rayleigh distance S . For distances smaller than S the light exiting the fiber may be considered as a set of parallel rays and the critical angle of exitance may be disregarded. For distances greater than S the light output may be considered as having an spherical wave front and the critical angle must be taken into consideration. An equation for this distance is given as.

$$S = \frac{D^2}{2\lambda}$$

Where D is the fiber core diameter ($D = 9\mu\text{m}$), a is the limiting angle of resolution and λ is the wavelength ($\lambda = 1550\text{nm}$). For the given diameter and wavelength $S = 26\mu\text{m}$ so the fiber to lens distance is above the Rayleigh limit. A diagram showing the different parameters above is shown below in fig. 3.

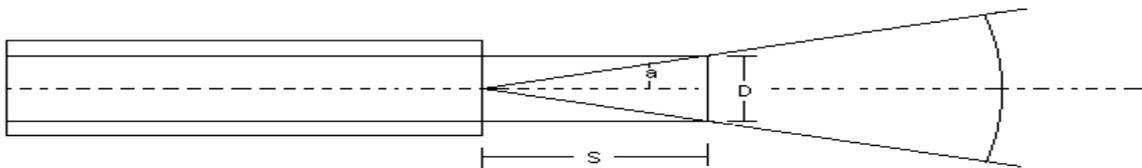


Fig. 3. Diagram showing fiber end, S , D and limiting angle of resolution a .

Fresnel Reflection

The first source of loss encountered by the light passing through the switch is due to reflection of light at the air-glass interfaces of the fibers and lenses. This reflection is due to the difference in refractive index of the media and is explained by Fresnel's equations. The fraction of light reflected at the interfaces is given by the following equations. R_p is the fraction of light reflected from the surface in which the polarization is parallel to the plane of incidence while R_s is the fraction of light reflected in which the polarization is perpendicular to the plane of incidence. The sum of the two R_i is the total fraction of light reflected.

$$\theta_r = \sin^{-1} \left\{ \left(\frac{n_1}{n_2} \right) \cdot \sin(\theta_i) \right\}$$
$$R_p = \frac{1}{2} \left[\frac{n_2 \cos(\theta_r) - n_1 \cos(\theta_i)}{n_2 \cos(\theta_r) + n_1 \cos(\theta_i)} \right]^2$$
$$R_s = \frac{1}{2} \left[\frac{n_2 \cos(\theta_i) - n_1 \cos(\theta_r)}{n_2 \cos(\theta_i) + n_1 \cos(\theta_r)} \right]^2$$

$$R_t = R_s + R_p$$

Where $n_1=1$ for air, $n_2=1.76$ for sapphire, θ_i and θ_r are the incident and refracted angles at the surface of the lens and R_t is the fraction of light reflected. Using a computer it was found that $R_t = .076$ and remains approximately constant for the angles varying between $0 \leq \theta \leq \theta_c$. The fraction of light transmitted is $T = 1 - R_t = .92$. This is the fraction of light transmitted at each air-glass interface. Since there are four air-glass interfaces the total transmission through the lenses is $T_L = T^4 = 0.73$. To find the total amount of loss due to reflection we have to take into account reflection at the fiber ends. The fraction of light transmitted at the fiber ends was calculated to be $T_F = .93$. The total fraction reflected is the product of the transmission coefficients $T = T_L T_F = .68$. This corresponds to a total loss of 1.6dB. The loss measurements taken were smaller than this as expected since the lenses have an anti-reflection coating on their surfaces. Refer to table 2 for these loss measurements.

Ray Tracing

For completion a ray tracing analysis of the system was done. A diagram of the rays leaving the transmitting fiber and their paths through the lens system is show in fig. 4 below.

Inspection of fig. 4 shows that ray 1 leaves the fiber parallel to the axis at the outer most extent of the core and after passing through the lens system falls $1.8\mu\text{m}$

above the receiving fiber axis. Ray 2 leaves the fiber from the center at the critical angle and falls $11\mu\text{m}$ below the receiving fiber axis. The reason that these two particular rays were chosen was to illustrate that spherical aberration is a major contributor to the measured losses. Choosing a lens with a smaller index of refraction will help to lessen this problem. See appendix A for the algorithm used to calculate the placement of the rays.

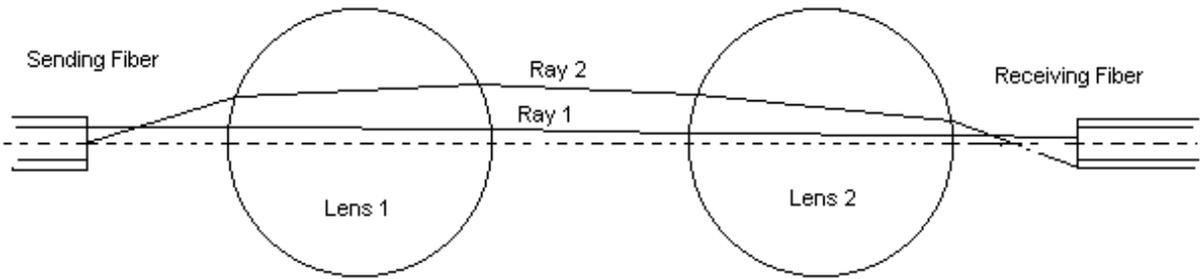


Fig. 4. Ray tracing diagram of optical assembly.

Calculation of Loss Due to Fiber Misalignment

The problem of fiber misalignment is inherent in the design and construction of the switch. Misalignment losses arise from the use of epoxy. As the epoxy cures it tends to displace the fiber vertically from its optimal position. For multimode switches, which have large core diameters this is not a significant problem. This is because the fiber core diameter and thus the diameter of the spot created by the receiving fiber lens is large compared to fiber misalignment created by the epoxy, which is typically $1\mu\text{m} - 3\mu\text{m}$ (see fig. 5). With the single mode fiber, which has a core diameter of $9\mu\text{m}$, this misalignment can cause more significant losses.

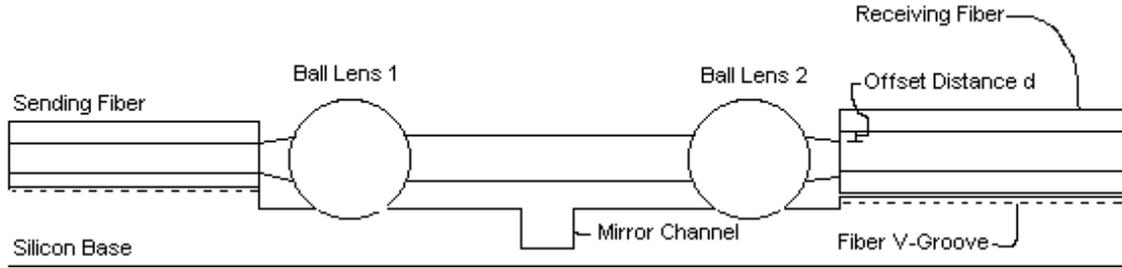


Fig 5. Side view of fiber lens system showing fiber and image displacement.

The goal of the analysis that has been done was to determine the fraction of power lost to misalignment. This was done by taking the power contained in the area of the image created by ball lens 2 and comparing it to the power that enters the end face of the receiving fiber. The power contained within the image is assumed to be within a circle of radius R , the fiber core radius. The power entering the end of the receiving fiber passes through an area of two offset circles (fig. 6). The intensity distribution in the sending fiber and image are assumed to be gaussian and have the form of eq.1.

$$(1) \quad I(\rho) = C \exp\left(\frac{-2\rho^2}{R^2}\right)$$

In eq.1 C is a normalization constant to be determined, R is the fiber core and image radius ($4.5 \mu\text{m}$ in this case) and ρ is the radial distance from the center of the image. The power is then the integral of the intensity across the cross sectional area of the fiber core (eq.2).

$$(2) \quad P = \iint I(\rho) \rho d\rho d\theta$$

To determine C and simplify further calculations it is necessary to normalize the power that the coupling beam carries. Normalizing the power we get (eq. 3).

$$(3) \quad P = 1 = C \int_0^{2\pi} d\theta \int_0^R \exp\left(\frac{-2\rho^2}{R^2}\right) \rho d\rho$$

Using $\int \exp\left(\frac{-2\rho^2}{R^2}\right) \rho d\rho = -\frac{R^2}{4} \exp\left(\frac{-2\rho^2}{R^2}\right)$ and solving for C.

$$C = \frac{1}{1.358 R^2}$$

This is the normalization constant, which will be used in the remaining power calculations. The power coupled to the receiving fiber is that contained within two circles of radius R, offset by distance d (fig. 6).

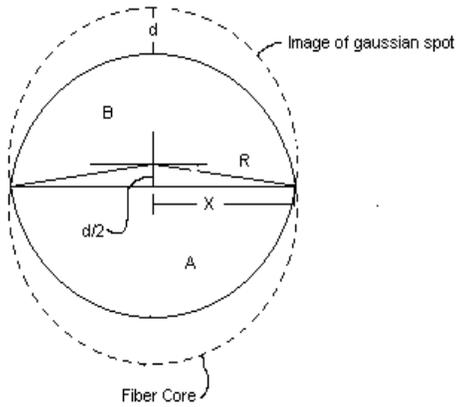


fig 6. Diagram of image circle offset distance d from fiber core circle.

The total power received by the fiber is contained within the overlap of the image circle and fiber core circle. First the power contained within the two radii lines and the beam circle (region A) will be calculated. Equation 2 will be used to determine the power flow in A. The integration with respect to the radial distance ρ is between 0 and the fiber radius $R=4.5\mu\text{m}$, however, the limits of integration with respect to θ must be changed since we are not integrating over an entire circle. The power in A is then.

$$P_A = \frac{1}{1.358 R^2} \int_{\pi+\theta_0}^{2\pi-\theta_0} d\theta \int_0^R \exp\left(\frac{-2\rho^2}{R^2}\right) \rho d\rho$$

The limits of integration for θ may be simplified by realizing that the intensity does

not vary with respect to θ . The new limits may be set to $\theta = 0$ and $\theta = (2\pi - \theta_0) - (\pi + \theta_0) = \pi - 2\theta_0$. The expression for P_A becomes.

$$P_A = \frac{1}{1.358R^2} \int_0^{\pi-2\theta_0} d\theta \int_0^R \exp\left(-\frac{2\rho^2}{R^2}\right) \rho d\rho$$

Now from figure 6 it can be seen that

$$\theta_0 = \sin^{-1}\left(\frac{d}{2R}\right)$$

Evaluation of the integral with $R = 4.5\mu\text{m}$ yields (eq. 4)

$$(4) \quad P_A = .1592\left[\pi - 2 \sin^{-1}\left(\frac{d}{2R}\right)\right]$$

This value of P_A is valid for displacements d which are less than the fiber core radius R

Now the power contained in the upper region B will be calculated. This calculation is more difficult since it involves integrating a truncated gaussian. Cartesian coordinates will be used since it is inconvenient to represent the fiber core circle using polar coordinates in the spot circle frame of reference. The integration will be done from the radius line R to the offset fiber core circle. So the limits of integration must be determined. For the y integration the lower limit is the radius line R . This line has the form.

$$y_0 = \frac{d}{2\sqrt{R^2 - \left(\frac{d}{2}\right)^2}} x$$

The upper limit is an offset circle and has the form.

$$y_1 = -d + \sqrt{R^2 - x^2}$$

The limits of integration for x are.

$$x_0 = -\sqrt{R^2 - \left(\frac{d}{2}\right)^2} \quad \text{and} \quad x_1 = 0$$

Finally with the limits of integration determined and using equation 2 the total power flow in region B is given by (eq. 5).

$$(5) \quad P_B = \frac{2}{1.358R^2} \int_{x_0}^{x_1} \int_{y_0}^{y_1} \exp\left(\frac{-2x^2}{R^2}\right) \exp\left(\frac{-2y^2}{R^2}\right) dy dx$$

Unfortunately there is no closed form solution for this integral with the existing limits. Integrating the y-gaussian yields an error function and the x integration requires integrating the product of the x-gaussian and the error function. Since there is no closed form for equation 5, a computer program using the trapezoid rule was used to evaluate the integral. The total power entering the fiber is then the sum of the two powers P_A and P_B .

$$P_T = P_A + P_B$$

Since the total power in the fiber has been normalized, calculation of the loss in dB has been simplified. The general equation for loss in dB is (eq. 6).

$$(6) \quad Loss = -10 \log\left(\frac{P_T}{P}\right) \quad \text{which reduces to} \quad Loss = -10 \log(P_T)$$

Table 1 summarizes the results of the above equations for different values of fiber displacement d.

Table 1

Displacement d [μm]	$P_{T\text{calc}}$	$Loss_{\text{calc}}$ [dB]
1	.93	.28
2	.83	.79
3	.69	1.64
4	.50	2.97

Where $P_{T\text{calc}}$ and $Loss_{\text{calc}}$ are the calculated power and loss respectively. The

experimental loss values are listed in table 2 and a plot showing the calculated and experimental values is given in fig. 7 on the next page.

Table 2

Switch	Displacement d [μm]	P_{Texp}	Loss_{exp} [dB]
1	1	.77	1.14
2	1	.76	1.19
2	3	.55	2.58

As can be seen, the calculated loss in dB is much smaller than the measured loss. This suggests that there are some other factors that are causing light not to make it through the switch. The possible causes for the losses will be discussed in the conclusion. The error bars in fig. 7 are based on the $\pm 1\mu\text{m}$ accuracy of the indicator used to measure d .

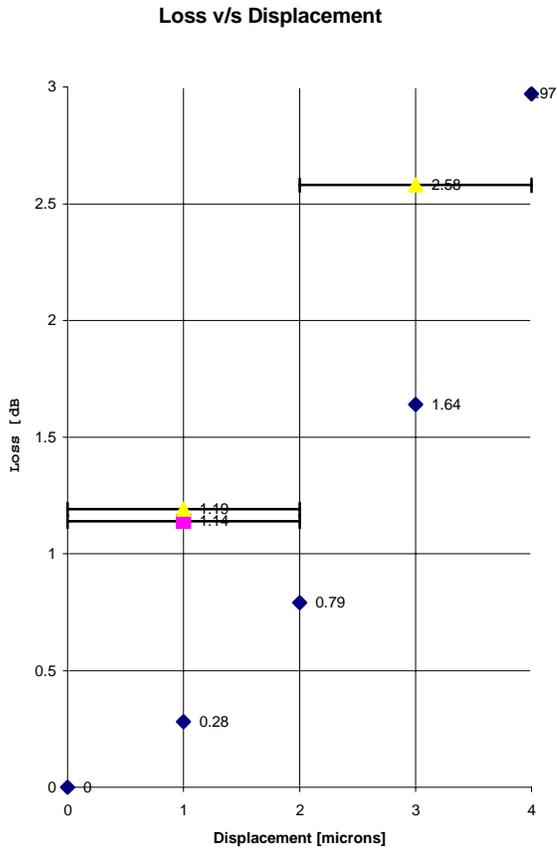


Fig. 7. Plot of loss v/s displacement for calculated and experimental values.

Conclusions

The calculated losses due to misalignment are only a fraction of the measured loss. From the above graph the difference is particularly noticeable for small misalignment. This indicates that there is some other source of loss independent the misalignment. Sources such as reflection at the fiber ends and off the surfaces of the lenses are presumably small since there are anti reflection coatings on the lenses. An optical matching gel should be used between the fibers and lenses to reduce reflection loss. From the ray tracing analysis it is evident that spherical aberration could result in the measured losses. The easiest solution to the problem of aberration is to choose a lens with a smaller index of refraction and thus a longer focal length while keeping the lens size the same. An index of refraction of ~ 1.6 should help to lessen the problem. Another source of loss could be light scattering from imperfections on the surface of the lens. A higher-grade lens with fewer imperfections would help to solve this problem. To find the sources of losses more accurately would require the construction, measurement and characterization of a large number of switches in order to build reasonably reliable statistics.

Appendix A

The purpose of this appendix is to provide the reader with the equations used to calculate the placement of the rays. To make calculations as simple as possible a math program on the computer is recommended. The equations provided are general, meaning that they can be used with systems that have different size fibers, lenses and spatial parameters as well as different indices of refraction for the lenses. A separate ray tracing diagram denoting the different parameters is included on the last page.

The algorithm used consists of a series of variables dependent on the initial spatial parameters. There are nine initial spatial parameters, which are listed below.

x_o = distance between end face of sending fiber and center of first lens.

x_1 = distance between center of second lens and receiving fiber end face.

R = radius of ball lens.

r = radial distance from center of fiber. (r was chosen to be the fiber radius on the diagram)

d = distance of fiber offset from axis. (note that this parameter is not shown on the diagram)

n_1 = index of refraction of air = 1.

n_2 = index of refraction of sapphire = 1.76.

θ = angle at which ray leaves sending fiber.

The set of variables will now be listed. Variables not shown in the diagram will be explained below.

$$H = \left(\frac{1}{R} \right) \cdot \left[x_o \sin(\theta) + (r + d) \cos(\theta) \right]$$

H is a variable used to calculate the angle of incidence on the first lens.

$$\alpha = \sin^{-1}(H)$$

$$\beta = 2\alpha - \theta - 2 \sin^{-1} \left[\left(\frac{n_1}{n_2} \right) \cdot \sin(\alpha) \right]$$

$$A = R \sin \left[2 \sin^{-1} \left[\left(\frac{n_1}{n_2} \right) \cdot H \right] - (\alpha - \theta) \right]$$

$$\chi = \theta - \alpha + 2 \sin^{-1} \left[\left(\frac{n_1}{n_2} \right) \cdot \sin(\alpha) \right]$$

$$\delta = \frac{(\pi - \chi)}{2}$$

$$n = \frac{A}{\tan(\delta)}$$

$$L = \frac{A}{\tan(\beta)}$$

L is a variable used in the calculation of h_3 and θ_2 .

$$m = L - R - D - n$$

m is also a variable used in the calculation of h_3 and θ_2 .

$$\phi = \sin^{-1} \left[\left(\frac{m}{R} \right) \cdot \sin(\beta) \right]$$

$$\gamma = \sin^{-1} \left[\left(\frac{n_1}{n_2} \right) \cdot \sin(\phi) \right]$$

$$\eta = 2\gamma - \phi + \beta$$

$$t = \pi - \phi$$

$$\kappa = \phi - \eta$$

$$x_d = R \left[\frac{\sin(t)}{\sin(\kappa)} \right]$$

$$\varepsilon = x_i - x_d$$

Finally the distance above or below the axis. If ε is positive the ray will fall below the axis and if ε is negative the ray will fall above the axis.

$$H = \varepsilon \tan(\kappa)$$

Vita for Jonathan Scot Grimsley

I was born in Alexandria Virginia October 14, 1969. I lived in the D.C. area until I 1984 when I moved to the Roanoke area with my parents. What a culture shock! While in the Roanoke area I went to high school at Northside High School and hated every second of it. It was during this time, however, that I became interested in the field of physics. It was my 10th grade year and Halley's comet came through. My parents bought me a telescope for Christmas that year and my interest in the physical sciences exploded. Also throughout school I have had an interest in things that are mechanical (cars, mechanical gadgets anything that does something) and electronics. After graduating from high school I attended Virginia Western Community College. This experience was almost as entertaining as high school (I say sarcastically) and my grades at VWCC probably reflected that. After two years at VWCC I was lucky enough to be accepted into the Physics department at Virginia Tech. This is where the doldrums of high school and VWCC ended. While at Tech I became a member of the astronomy club and the Society of Physics Students and attended the various parties and observing sessions that these organizations held. It was during this time that I was having the most fun since I was finally having some of the questions about how things work answered. You know mechanics, e&m, quantum mechanics and lets not forget optics. My original intentions were to study astrophysics but once I realized that there were NO jobs there I focussed my attention on the other fields of physics. During my senior year as undergraduate student I worked in a high-energy physics lab in the basement of Robeson Hall (the physics building) designing, building and testing muon detectors. This group eventually sent me to Japan to help install the detectors at an accelerator facility. The trip was all expenses paid and lasted three weeks (SWEET). After graduation I was accepted as a graduate student at the Virginia Tech Physics department where I did the industrial physics program. This program was good in that it allowed me to do an internship at a local corporation. I did mine at Litton Poly Scientific in Blacksburg VA. Once my internship was over with I returned to classes and wrote the above report for completion of my degree. By now you are probably wondering how someone can start in astrophysics, work in high-energy physics and write a masters report in the field of optics. The answer is this. I am like a kid in a candy store when it comes to physics. I like it all. This is probably why I have recently taken an interest in acoustics and have learned the theory of how high fidelity loudspeaker systems are designed. The knowledge that I have obtained from studying math and physics has allowed me to do this. I feel that with a physics background one can investigate any physical subject (acoustics, material science, the engineering fields, electronics) and have a reasonable idea as to what is going on. Given time and research a person with a physics background can understand and master any of the above.