Coupling light emitting diodes to multimode optical fibers

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Coupling Light Emitting Diodes to Multimode Optical Fibers

by

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Numerous interactions contributed significantly to this work. During the period when I was developing experimental methods, C.F. Flores provided insight and creative suggestions. He recommended optical coupling geometries for analysis. At the same time, D.A. Snyder provided valuable knowledge and recommendations for implementation. The simulation program, which I modified and applied in this study, was conceived and originally written by E. Rice. The simulation program was rewritten and generalized by E.E. Bergmann. I acknowledge the significant efforts of these two men. Useful discussions with D.R. Decker led to deeper understanding of the applicability of the simulation program and aided the comparison of simulation results with experimental results. I also acknowledge the support and encouragement of R.H. Knerr and D.J. Wasser.
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ABSTRACT

Experimental measurements of optical power launched into the core of a multimode optical fiber from a light emitting diode are compared to power values determined by a ray-tracing computer program. The simulation models the LED as a step-index optical fiber having a "core" emitting area slightly larger than the size of the current-defining contact. The optical power emitted from the source is assumed to be a function of the current density in the active layer of the diode. The current density, in turn, is assumed to have a constant value over the central 75% of the source area and to be a rapidly decreasing function of radius for the remaining source area. Power coupling is examined for three LED-to-fiber lensing geometries: a microspherically-lensed diode; a diode coupled through a larger, isolated, imaging lens; and a combined microsphere/imaging two-lens geometry. The coupling capability of the various lensing geometries is judged on their ability to couple power and on their sensitivity to alignment.

Modeled diode radiance (power per steradian per unit source area) decreases as \( \cos^3(\theta) \) rather than the first order cosine dependence of a Lambertian emitter. The simulated butt-coupled launched power differs from experiment by 0.5 dB when the fiber is laterally aligned with the diode. Predicted launched powers for any of the three lensing geometries generally
differ from experiment by 0.5 — 3.0 dB. The powers predicted during lateral
tolerance analysis for the microsphere coupling geometry deviate from
experiment by no more than 4.4 dB. Axial tolerances are predicted to be
values within a factor of three from the experimental tolerances. Again, the
worst performance is for microspherical lensing. Lateral tolerances are the
most accurately predicted parameter for LED-to-fiber coupling. For all
lensing geometries, lateral tolerances are within ± 50% of the experimental
tolerance.

The magnitude of the simulation's predictions differs from experiment
resulting from the simulation's tight angular distribution of power. Increasing
the power radiated at larger angles from the surface normal, making the
diode appear more Lambertian, should improve the model's ability to predict
LED-to-fiber coupling. An additional improvement would be to increase the
radiant flux density (power per unit source area) of the source.
1. Overview of LED-to Multimode Optical Fiber Coupling

Light Emitting Diodes (LEDs) are effective sources for fiber optic communication links of moderate bit rates (less than 200 Mb/s) and moderate lengths (less than 2 km). Design of communication links using LEDs must consider the coupling of the diodes into the optical fiber. This design issue results from the differing spatial characteristics of the LED emission and the fiber acceptance cone. A light emitting diode has a very divergent light emission. Its radiance (power per unit solid angle per unit source area) degrades to one-half its maximum value by moving from normal incidence to an observation angle of 60 degrees. In contrast, optical fiber exhibits a rather narrow angle of acceptance (12-20 degrees is typical). The optical fiber transmits only those rays incident on its core area with propagation angles less than the fiber's limiting acceptance angle.

This work examines LED-to-multimode optical fiber coupling using both experimentation and simulation. Coupling will be predicted using a ray-tracing simulation for several LED-to-fiber lensing geometries. The simulation results will be compared to experimental measurements of LED-to-fiber coupling in similarly-lensed configurations. The results of these comparisons will be used to evaluate the assumptions of the simulation model and recommend improvements to the simulation model.
1.1 Light Emitting Diodes as Optical Sources

Surface-emitting light emitting diodes used as optical fiber communication sources have evolved from homojunction broad-area devices with etched wells (Burrus and Dawson 1970) to double-heterojunction planar devices with current confinement (Keramidas, Berkstresser and Zipfel 1980; Escher et al. 1982). The devices examined in this study are double-heterostructure devices in the 0.87 μm wavelength Ga$_{1-x}$Al$_x$As/GaAs material system, although similar concepts and results apply to InGa$_x$As$_{1-x}$P/InP devices. The devices are grown by Liquid Phase Epitaxy on n-type GaAs substrates, and they consist of three epitaxial layers (Figure 1). Working downward from the substrate (upon which the window layer is grown prior to its removal), the first layer is a thick n-Ga$_{1-x}$Al$_x$As window layer. The next layer grown is the p-type GaAs active layer. The third layer is a p-Ga$_{1-x}$Al$_x$As confining layer. The window and confining layers form heterojunctions with the active layer. Thus, their larger bandgaps contain carriers within the active layer. In addition, the window layer provides support to the structure while maintaining transparency to the emitted radiation.

After epitaxial growth, the substrate is chemically etched; and contacts are provided on the top and bottom of the diode. The n-contact metallization
is applied directly to the n-type window layer. This contact extends radially-outward from a circular opening for the emitted light to escape. The bottom-side p-contact is a circular dot of photolithographically-controlled size. The size of the p-contact determines, to a large extent, the emitting region of the active layer, and isolation is placed around the p-contact to prevent unwanted currents. The currents can be assumed constant in the region of the active layer directly above the p-contact.

Photons are emitted within the active region of a light emitting diode when radiative recombination occurs. For high quantum efficiency and high power output, the types of recombination processes must be controlled. For thin active layer diodes, non-radiative surface recombination at the heterointerfaces reduces the quantum efficiency. For highly-doped active layers, non-radiative Auger recombination processes may also be introduced. The ratio of radiative to non-radiative recombination events is maximized. These recombination events are spontaneous, and the emitted photons have arbitrary orientation. However, the active region of a semiconductor diode has a high diameter-to-width aspect ratio. For this reason, the diode may be viewed as a surface of point sources. The LED active layer's radiance (power per unit area per unit steradian) within the source material decreases as a cosine function of the viewing angle. These emitter characteristics are termed Lambertian. An approximate model of a
light emitting diode represents the radiance emitted from the active region as the following decreasing function of viewing angle:

\[ B(\theta) = B(r) \cdot \cos(\theta) \]

where \( B(r) \) is the radiance of the diode junction at a given radius, \( r \), from the center of the emitting area (Miller and Kaminow 1988). The work of Lee and Dentai suggests that the light intensity profile, \( B(r) \), within the semiconductor material, above the active region, is proportional to the current density (Lee and Dentai 1978).

Thus, knowledge of the current distribution allows prediction of the light (optical power) distribution, and many competing factors internal to the diode influence the current distribution. These factors include, but are not limited to: doping concentrations, current densities, current confinement, layer thicknesses, differential bandgaps, diffusion lengths, and recombination processes. The active layer doping concentration influences the speed/power tradeoff. The high-level of active layer doping necessary for high-speed operation introduces non-radiative recombination processes, which reduce the power of the device. Alternatively, the low-doped active layer necessary for high-power operation reduces the speed of the device.

Since current density is directly related to the output power, as stated above, increased power is achieved by current confinement both parallel and
perpendicular to the junction plane. Parallel to the junction plane, current is confined by controlling the size of the p-contact by using dielectric isolation or Schottky barriers. The p-dot size can be made too small for a given current, causing the diode series resistance to increase. This decreases the output power by increasing the energy bandgap by internal heating. Perpendicular to the junction plane, current is confined by double heterojunctions, where the larger bandgap of the materials outside the active layer provides a potential barrier maintaining the carriers within the active layer. The current distribution in the plane of the junction will be modeled using the results of Joyce and Wemple. As more thoroughly discussed in section 2.2, this model allows for current to flow through the active layer in a region larger than the size of the p-contact. Current density in the active layer region directly above the p-contact is assumed constant; while, regions of the active layer radially outside of the p-contact have rapidly decreasing current density (Figure 5).

The active layer thickness influences output power through two competing factors. Increased active layer thickness provides increased area for recombination to occur as carriers diffuse through the junction. (This effect is minimized since the minority carrier density decreases with distance from the junction.) Also, the active region absorbs its emitted radiation. Thus, increased active layer thickness may reduce output power. The ratio
of active layer width to diffusion length influences the interfacial surface non-radiative recombination (Tsang 1985).

In addition to these concerns influencing the current density and optical power within the semiconductor material, the semiconductor / air material interface affects the power distribution external to the diode material. Semiconductor materials have high refractive indices relative to air. (GaAs has a refractive index of 3.3 -3.65 depending on doping.) Light traversing a high to low refractive index boundary will be refracted toward higher angles from the interface normal. At incidence angles above the critical angle, light rays will be totally-internally reflected within the semiconductor material.

Due to the index of refraction difference at the GaAs/Air interface, radiance of the diode external to the GaAs is expected to degrade with a cosine dependence on viewing angle (Barnoski 1976). Thus, for GaAs, only rays having divergence angles less than or equal to 16 degrees will be emitted into the air above the semiconductor, while rays of higher divergence angle are totally-internally reflected. Further, the energy propagating at "angles" less than the 16 degree critical angle will be refracted throughout the full hemisphere (π radians) above the diode surface.
1.2 Optical Fiber Characteristics

An optical fiber is a dielectric waveguide of cylindrical cross-section consisting of an inner core region of higher refractive index than the surrounding cladding region (Figure 2). Electromagnetic radiation in the optical frequency range is contained within the fiber waveguide by total internal reflection within the core or at the core/cladding interface. Detailed presentations of the characteristics and operation of optical fiber waveguides are readily available in the literature (see for example, Miller and Kaminow 1988). Since this simulation of optical fiber light transmission is based on ray-tracing techniques, only the refractive index properties of optical fibers will be considered.

The refractive index profile of the core of an optical fiber typically has one of two characteristic patterns: step-function or graded-function of radius (Figure 2). In both cases, the central fiber core is of higher refractive index than the surrounding cladding material. In the conceptually simpler step-index fiber, the refractive index has a constant value in the core region and abruptly changes to a lower value at the core/cladding interface. The refractive index profile of this type of fiber has a step-function appearance. Optical energy propagates at various angles through a step-index fiber core, undergoing refraction at the core/cladding interface. A graded-index fiber,
on the other hand, has an index of refraction which is highest in value at the center of the core and diminishes toward the perimeter of the core. The variation of the core refractive index with radius may take on several forms, the most common being a parabolic profile. The core refractive index is always greater than the cladding refractive index. Optical energy propagates through this type of fiber by continuous refraction as the index continuously changes until total internal reflection occurs.

The conditions for total internal reflection indicate the requirements on rays within the fiber core to continue their propagation within the fiber. These internal conditions, in turn, dictate the requirements on light entering the fiber such that the light will propagate in the waveguide.

The angle a ray makes with the fiber axis when entering the fiber can be related to the ray's critical angle for total internal reflection. The angle of such an extreme ray is the half-angle of a cone of acceptable rays entering a fiber waveguide. The cone of acceptable rays describes the "numerical aperture" of the fiber which is defined to be \( NA = n \sin(\theta_c) \) for a step index fiber (where \( n \) is the index of the medium into which emission occurs) and \( NA = n_1 (2\Delta)^{1/2} \sqrt{1-(r/a)^2} \) for a parabolic graded-index fiber. For the graded index fiber, \( n_1 \) is the refractive index along the fiber axis, \( \Delta \) is a parameter determining the scale of the profile change, \( r \) is a given radial
position, and $a$ is the radius of the fiber core (Palais 1988).

Rays which enter the fiber at angles greater than that required for total internal reflection will not be retained within the fiber core. These rays may, however, be totally internally reflected at the cladding-to-buffer material interface. Such rays propagate a short distance through the fiber, but they soon diminish in power due to the high attenuation they encounter in the cladding material. In the experimental measurements for this study, long lengths of fiber are used to attenuate these cladding modes.

1.3 LED-to-Optical Fiber Coupling

A surface emitting LED is a highly divergent source as discussed in section 1.1 above. For fiber optic communication, the LED is coupled to a fiber waveguide that has a numerical aperture limiting the angular divergence of propagated rays. Therefore, significant optical power is lost upon LED-to-fiber coupling (coupling efficiencies are typically 5-10%). However, properly designed LEDs in combination with appropriate LED-to-fiber lensing provide sufficient power coupling for LEDs to serve as cost-effective light sources for moderate bit rate, moderate distance fiber optic communication.

Optical power is "Butt-coupled" into a fiber when the fiber is nearly "butted" against the LED surface in an attempt to capture emitted light before
it diverges outside the fiber core radius. This simple coupling technique provides near optimal coupling when the source radius is greater in size than the fiber core, since lenses cannot increase the radiance above that at the LED surface. In situations when the diode emitting area is smaller than the fiber core, lensing can be used to increase the power coupled. A source radius / fiber core radius ratio less than one is favorable, since equivalent currents channeled through smaller active regions increase the radiance of the diode. Lensing can be used to provide increased coupling into the fiber due to the increased radiance of the source (Tsang 1985).

The divergence of optical power emitted by an LED can be reduced (that is, the beam can be made more convergent), although the radiance (power per steradian per unit area) of the LED just above its active layer provides a limit to the radiance obtainable. Many lensing schemes have been used to increase coupled power between small area emitters and optical fibers. Lenses can be placed on the emitter surface, the fiber surface, or within the region between the source and fiber.

This study will examine three lensed coupling arrangements: a microspherically-lensed LED, an imaging geometry, and a two-lens geometry (Figure 3). A microspherically-lensed LED has a small (100-500 μm diameter) high refractive index lens mounted directly on the LED surface. A
convergent beam is created from the highly divergent, Lambertian LED emission, so that there is a very high coupling point axially removed from the LED surface. At positions near this point, launched power can be traded for lateral tolerance. An imaging geometry places a larger (approximately 1 mm diameter) high refractive index lens a distance just greater than the lens focal length from the LED surface. A real image of the LED is projected axially toward the fiber. Highest coupling occurs at the image point, and coupling can be traded for lateral tolerance with axial fiber movement. A two-lens geometry uses both a microspherical lens located on the LED and a larger imaging lens to provide a large lateral tolerance between the lenses. The results of computer simulation of coupling in these three lens configurations will be compared to experimental measurements. The lensing geometries will be evaluated for power coupled into multimode fiber and for sensitivity to misalignment.

2. Coupling Model

A ray-tracing computer program is modified to predict power coupling from a light-emitting diode into a multimode optical fiber. Light rays originate from point sources on the LED surface within an area defined by the diode's current distribution. Light rays emerge from all point sources in all angular directions from normal emission down to a limiting angle determined by the
program input. The location and propagation direction of the rays are traced through an optical system between the LED and fiber. The location and angle of propagation of all rays is compared to the dimensions and acceptance angle of the receiving fiber in the plane of the receiving fiber to determine which rays are successfully coupled into the fiber. The intensities of successfully coupled rays are summed and compared to the total power emitted by the diode into the hemisphere above its surface. The power coupled in all simulations for this study is then compared to the power butt-coupled into the fiber core.

2.1 Simulation Program Description

A ray tracing program designed to evaluate coupling loss between two optical fibers is used to predict LED-to-multimode optical fiber coupling. The program identifies rays by source location and propagation direction. Source location is specified by the two polar coordinates, \( r \) and \( \phi_1 \), in the source plane. A given ray's propagation direction is specified by the two angles, \( \theta \) and \( \phi_2 \), as shown in Figure 4. The program performs a four-dimensional, recursive integration over the parameters \( r \), \( \phi_1 \), \( \theta \), and \( \phi_2 \).

1. This AT&T Program is written in the C language and runs under MS-DOS. A recent improvement to the user interface expands the program's applicability beyond fiber-to-fiber coupling to include source-to-fiber and fiber-to-detector analyses. This thesis work provides initial results applying the program to LED-to-multimode fiber coupling.
Limits for these parameters are dictated by the coupling geometry as tabulated below.

Table 1
Ray-Tracing Integration Parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source Radius</td>
<td>r</td>
<td>0</td>
<td>User-Supplied Radius</td>
</tr>
<tr>
<td>Source Polar Angle</td>
<td>$\phi_1$</td>
<td>0</td>
<td>$2\pi$</td>
</tr>
<tr>
<td>Ray Axial Angle</td>
<td>$\theta$</td>
<td>0</td>
<td>User-Supplied &quot;NA&quot; of Source</td>
</tr>
<tr>
<td>Ray Polar Angle</td>
<td>$\phi_2$</td>
<td>0</td>
<td>$2\pi$</td>
</tr>
</tbody>
</table>

The rays traced through the system are chosen by the program to comprehensively cover variable values within the limits on the four integration variables previously described. Traces are done on rays in the following sequence:

$$\int_{0}^{r_{\text{max}}} \int_{0}^{2\pi} \int_{0}^{\theta_{\text{max}}} \int_{0}^{2\pi} (\text{Ray intensity & Acceptance}) \, d\phi_2 \, d\theta \, r \, d\phi_1 \, dr$$

As each ray is traced through the optical system, its position, direction, and intensity change due to the shapes and characteristics of material interfaces. Direction and intensity change due to refraction and reflection at optical interfaces, respectively. A ray's position, tracked by (x,y) coordinates
about the optical (z) axis, changes as the ray propagates. Its angles of propagation, $\theta$ and $\phi_2$, change due to refraction at material interfaces; and the ray’s intensity diminishes at each interface due to reflection loss. At the receiving element, each ray’s position and propagation angles are compared to the receiving element’s size and acceptance angle to determine if the ray is successfully accepted. The total intensity of accepted rays is calculated as a percentage of the intensity of all rays leaving the source’s surface.

The program reports the coupling loss (dB) for each coupling geometry and alignment situation described in the input file. The reference power used for reporting the power ratio is the sum of the number of all rays leaving the source under the specified conditions of source size and numerical aperture. (All source rays have initial intensity one.)

Weighting factors may be used to modify the magnitude (power) of accepted rays as functions of axial angle of propagation, $\theta$, or source radius position, $r$. They are exponential factors which are multiplied by the intensity immediately after integration of a given axial propagation angle or source radius value. The multiplicative weighting factors decrease from a value of one at integration variable values of zero to a value of $\exp \left( \frac{-c \cdot x}{x_{\text{limit}}} \right)$, where $x_{\text{limit}}$ is the maximum value of the integration variable and $c$ is a constant specified by the program user. The constant is chosen to improve the
simulation's agreement with experiment.

The user provides input to the program through a structured ASCII file describing the materials and geometry of surfaces along the optical path. For analysis of coupling between two optical fibers, information on the input and output fiber refractive indices, refractive index profiles, numerical apertures, and core sizes are given. Sections of the input file describe air gaps, spherical surfaces, apertures, and coatings encountered between the input and output optical fibers.

2.2 Application of Simulation to LED-to-Fiber Coupling

In order to apply this ray-tracing program to the LED-to-Multimode fiber coupling problem, I made changes to allow large values of input "fiber" refractive index and to include a weighting factor more accurately describing LED emitted power. In addition, I changed the output to report linear power values, relative power (dB), or linear power per steradian of solid angle subtended by the receiving element.

The LED can thus be described similarly to a step index optical fiber, with refractive index of 3.3 for GaAs. The emitting surface of the diode is not AR-coated. The angle of LED emission is limited to the critical angle for total internal reflection at the GaAs-to-air interface. This maximum angle of emission from the LED is then converted to an input "fiber" numerical
aperture using: \( na = n \sin(\theta_c) \). The "fiber core" radius specifies the region of the active layer which is a source of emitted radiation. As a first approximation, this "core" radius was taken to be the radius of the p-contact. However, I obtained better agreement with experiment by using an active region larger than the size of the p-contact. This increased active area is due to current spreading. Since the circular n-contact metallization has a larger radius than the circular p-contact dot, I allowed the radius of the active layer to extend beyond that of the p-contact. I assumed that the fields created by the potential between the contacts will spread carriers outward up to a radius limit defined by a straight line drawn between the n- and p-contact metallizations. Using \( r_1 \) as the radius of the p-contact metallization, I defined \( r_2 \) to be the radius of the emitting portion of the active layer, as described above. Then, using the results of Joyce and Wemple (1970), current density is assumed constant in the active region which lies directly above the p-contact; but current density in the active layer radially beyond the p-contact drops off at radial positions \( r \) outside the p-contact radius according to the equation:

\[
\frac{j}{j_1} = \left[ \frac{r_1}{r} \right]^2 \frac{\sin^2 \left[ \tan^{-1} (k) + k \ln \frac{r_2}{r_1} \right]}{\sin^2 \left[ \tan^{-1} (k) + k \ln \frac{r_2}{r} \right]}
\]
The factor $k$ is as described by Joyce and Wemple. The parameters for this modeled LED device are shown schematically in Figure 5.

2.3 LED Emission Profile Results

Radiance (power per steradian per unit source area) emitted by the LED active layer into the subsequent semiconductor material and into the air above the diode was predicted by simulation. The results reflect the decrease in radiance with viewing angle that is expected for a Lambertian emitter (Figure 7). A Lambertian source emits isotropically within the source medium. It has equal radiant intensity (power per unit area) across its surface when viewed perpendicular to the source surface. The Lambertian source will, however, show a decrease in radiance due to the decreasing effective source area when viewed obliquely. The predicted diode radiance decreases with viewing angle at a greater rate than the Lambertian cosine dependence (Figure 7).

The diode internal radiance distribution is refracted at the diode/air interface. As a result, power at divergence angles greater than the critical angle is internally reflected, and power at divergence angles less than the critical angle is refracted an amount determined by Snell's Law. For the relatively small angles involved, the resultant propagation angles in air are all equally increased by the GaAs/air refractive index ratio. As a result, the
radiance external to the diode will be less in magnitude, but it will show the
same functional dependence as the radiance internal to the diode. The
simulation program correctly predicts the external diode radiance relative to
the internal radiance (Figure 7).

The simulation program predicts that a properly aligned butt-coupled fiber
located 0.5 μm above the diode surface loses -13.3 dB of power during
coupling. The simulation's reference power is the power emitted by the LED
into the entire hemisphere above its surface. A 13.3 dB loss indicates that
4.7% coupling occurs. The model predicts that the butt-coupled geometry
has a 3 dB lateral tolerance of ±30 μm at an axial location of 254 μm (Figure 8).

2.4 Lensed LED Coupling Results

Power coupled, axial tolerance and lateral fiber tolerance were predicted
for microsphere lensing using lenses ranging in diameter from 60—300 μm
and in index from 1.7—1.9. The axial fiber tolerance results for various lens
materials indicate potential coupling improvement of 3 dB over butt coupled
for lens materials with refractive index of 1.9 or larger (Figure 10). Lower
index materials reach a peak coupling equal to butt-coupling. For all lens
materials, peak microspherically lensed coupling is axially removed from the
lens surface, and coupling degrades sharply beyond the optimal axial
coupling location. Optimal power coupling occurs at an axial separation of 
700 μm for a sapphire (n=1.7) 300 μm diameter lens and at axial separations 
of approximately 300 μm for GK-19 (n=1.9) or Zirconia (n=2.1) lenses of 
similar diameters.

Axial tolerance of microspherically lensed coupling is predicted by the 
model to have higher peak coupled powers as lens diameter is increased. 
The peak axial coupling location moves farther from the diode surface as 
lens diameter increases (Figure 11). Peak power coupled ranges from -1.0 
dB for a 60 μm diameter GK-19 lens to +3.0 dB for a 250 μm diameter GK-
19 lens. The peak axial coupling point is 70 μm for the 60 μm diameter lens 
and 300 μm for the 250 μm diameter lens.

Lateral tolerance results from simulated microspherical lensing indicate 
the increased power coupling and decreased lateral tolerance of higher 
index lens materials. Sapphire lenses of 300 μm diameter couple -1.0 dB 
relative power when aligned and have a ±80 μm 3 dB lateral tolerance. 
Higher index GK-19 and Zirconia lenses of similar diameter have +1.0 dB 
relative power coupling capability, but their 3 dB lateral tolerance is reduced 
to approximately ±45 μm (Figure 12). Simulation results as a function of lens 
diameter indicate that power coupled and 3 dB lateral fiber tolerance both 
decrease with decreasing lens diameter (Figure 14).
Power coupled, axial fiber tolerance, and lateral fiber tolerance were determined using the simulation model for Imaging Geometries using 1 mm Sapphire ($n=1.7$) and 1 mm GK-19 ($n=1.9$) lenses. Axial fiber tolerance results for Sapphire indicate maximum coupling of -1.0 dB occurs at a lens-fiber separation of 1550 $\mu$m (Figure 24). Lateral fiber tolerance results for the sapphire lens indicate peak power coupling of -6.7 and -2.0 dB for LED-lens/lens-fiber spacings of 254/1000 $\mu$m and 406/749 $\mu$m, respectively. The 3 dB lateral fiber tolerance of ±80 $\mu$m for the 254/1000 $\mu$m configuration exceeds the ±33 $\mu$m lateral tolerance of the 406/749 $\mu$m configuration (Figure 25). These findings indicate the power versus tolerance tradeoff.

LaSF-18 lenses ($n=1.9$) couple more power and have reduced lateral tolerances in comparison to the sapphire lens. The LaSF-18 254$\mu$m LED-lens / 851 $\mu$m lens-fiber configuration has +0.6 dB power coupling capability with respect to butt coupling and ±28 $\mu$m lateral tolerance. The LaSF-18 508$\mu$m LED-lens / 445 $\mu$m lens-fiber configuration has a -1.5 dB power coupling capability and a ±20 $\mu$m lateral tolerance (Figure 26).

Predictions of power coupled and lateral tolerances for the two-lens geometry were made for GK-19 ($n=1.9$) 250$\mu$m diameter microlenses combined with either 1 mm BK-7 ($n=1.5$) or 1 mm Sapphire ($n=1.7$) macrolenses. The lateral tolerances between the microlens and macrolens
as well as between the macrolens and fiber were determined. In all two-lens material and spacing geometries, the interlens lateral tolerance initially exceeds the macrolens-to-fiber lateral tolerance. For GK-19/BK-7 two-lens geometries with interlens spacings less than 800 μm, coupled powers of -4.0 dB with respect to butt-coupled values are attained when in alignment. The lateral tolerance between the lenses increases from approximately ±120 μm for the 762 μm lens-lens axial spacing / 485 μm macrolens-fiber spacing geometry (Figure 29) to approximately ±150 μm for the 250 μm / 250 μm geometry using the same lenses (Figure 27). The macrolens-to-fiber lateral tolerance simultaneously decreases from approximately ±80 μm for the 762 μm / 485 μm geometry (Figure 29) to approximately ±75 μm for the 250 μm / 250 μm geometry (Figure 27).

Simulation results for two-lens coupling with different macrolens materials indicates that a larger refractive index macrolens (Sapphire vs. BK-7) decreases the lateral interlens tolerance by approximately 30 μm, and increases the optimal power coupled by approximately 1.0 dB (Figures 27, 31).
3. Experimental Measurements of LED-to-Fiber Coupling

3.1 Light Emitting Diodes Studied

Small-area Double-Heterostructure GaAlAs Light Emitting Diodes have been extensively reviewed in the literature for use as sources for optical fiber communication (Burrus and Miller 1971; Tsang 1985; Miller and Kaminow 1988). The diodes used in this work are similar to the Burrus diode, except that the highly absorbing n-type GaAs substrate layer is replaced by a transmissive n-doped GaAlAs "window" layer. Thus, etching is not required; and a planar device results (Keramidas, Berkstresser and Zipfel 1980). These devices incorporate current confinement for increased current density by dielectric contact isolation which improves the power coupled into small core, limited NA optical fibers. At 60 mA d.c. typical operating current, 100 μW of optical power is normally coupled from the diodes used in this study into a 62.5 μm glass optical fiber having a numerical aperture of 0.29. The optical power emitted into the hemisphere above the diode was measured using an integrating sphere to be approximately 3 mW.

3.2 Measurements of Optical Coupling

The optical power coupled from a surface-emitting GaAlAs Double Heterostructure Light Emitting Diode into the core of a 62.5 μm glass optical fiber was measured using the test set schematically shown in Figure 6. For
these measurements, the emitting diodes were rigidly clamped, and they were d.c. biased using an HP6141C Current Source. The receiving optical fiber was mounted on a three-axis micrometer stage manufactured by Newport Research Corporation. The optical power, coupled through a one kilometer length of fiber to attenuate cladding mode power, was measured using an Anritsu Model ML93A Optical Power Meter and sensor Model MA95A. All work was performed on an air-suspension optical table.

Coupled power measurements were made in all three optical lensing configurations described in section 1.3. This required precise location and movement of a single lens as well as simultaneous use of two lenses. Two methods were used for locating lenses. For the first method, I epoxied lenses onto ultra-fine capillary tubes. These tube/lens assemblies were attached to a Line Tool Co. three-axis micrometer stage for precise movement. For the second technique, I epoxied small lenses directly onto the surface of the emitting diode. This second technique was initially used to measure coupling capability of a microspherically lensed LED and was subsequently used during measurement of coupling in a two-lens geometry.

Measurements made in the imaging and two-lens geometries required that both the fiber and the large lens be aligned in the plane of the diode junction to establish the optical axis. The initial alignment was established in
the following way:

1. The fiber was initially aligned with the LED to achieve an optimal Butt-coupled power. The power, fiber x-location, and fiber y-location were noted.

2. The fiber was then moved the minimum axial distance from the LED to allow the lens to be inserted. The lens was inserted in this close-coupled position, and the lens’ lateral position was optimized. The lens’ x-location and y-location were noted.

3. Working under a microscope, the lens was moved axially toward the LED to a near contact position, and the fiber was moved axially until it nearly contacted the lens. These lens and fiber axial (z) locations were used to establish proper LED-to-lens and lens-to-fiber axial spacings.

4. The fiber was backed out axially to establish the desired coupling distance, and the lens was backed out from the LED to establish the desired LED-to-lens and lens-to-fiber spacings.

5. Having established the desired axial positions of the lens and fiber, the optimal fiber lateral position was verified.

The lens designs, described in section 1.3, were compared for their power-coupling capability at various LED-to-lens, interlens, or lens-to-fiber
spacings. Power measurements made with various amounts of lateral (in the plane of the LED) or axial (along the optical axis) misalignment of one of the components enabled me to evaluate each lens configuration's sensitivity to alignment.

3.3 LED Butt-Coupled Into Multimode Fiber Results

Butt-coupling power from an LED into an optical fiber provides a repeatable reference power for comparison of coupling geometries. I measured optical power launched with the fiber laterally aligned and approximately 0.5 µm axially removed from the diode as part of the calibration steps preceding any lens-coupled measurements. The diodes used for this study typically had butt-coupled launched powers of -10.0 dBm.

I measured the sensitivity of butt-coupling to lateral fiber misalignment. Lateral scans of power coupled into the 62.5 µm core diameter fiber were completed on three diodes. These measurements were made at an axial distance of 254 µm so that the fiber would not hit the top-side wire bond of the diode. A typical single-axis lateral scan result for the butt-coupled configuration indicates that the 3 dB lateral fiber tolerance for butt-coupling is ±33 µm (Figure 8). Measurements of power coupled as a function of both x- and y-offset were taken at fiber displacement increments of 0.5 mils. A perspective plot of the power coupled as a function of simultaneous x- and y-
misalignment (Figure 9) shows the symmetry and high sensitivity of the butt-coupled arrangement.

3.4 Microspherically Lensed LED Coupling Results

Initial tests were performed by gluing microspherical lenses to the surface of the emitting diodes using optically transmissive epoxy having an index of refraction, \( n = 1.55 \). Five types of lenses were examined (Table 2). They had diameters from 60 \( \mu \text{m} \) to 300 \( \mu \text{m} \) and ranged in refractive index from 1.7 to 2.1. The lens material designations BK-7, LaSF-18, and GK-19 refer to optical materials defined by Schott Optical Glass, Inc. The lens' surface finish was Grade 10 or Grade 25 as rated by the Anti-Friction Bearing Manufacturer's Association (A.F.B.M.A.). An average of three lenses of each type were studied. Measurements were made to determine coupling capability and sensitivity to lateral and axial misalignment.

Axial tolerance data (Figures 10, 11) indicates that a refractive index of at least 1.9 is necessary for a lens of 250-300 \( \mu \text{m} \) diameter to cause convergence of the LED beam. These data show that sapphire, with a refractive index of 1.7, has insufficient refractive power to narrow the beam and cause an axial peak in power launched. These data also indicate that GK-19 glass (\( n = 1.9 \)) and zirconia (\( n = 2.1 \)) have increasing ability to converge the beam. It is important to restate at this point that the radiance of the
Table 2

Microspherical Lenses Examined

<table>
<thead>
<tr>
<th>Material</th>
<th>Refractive Index</th>
<th>Diameter (µm)</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sapphire</td>
<td>1.7</td>
<td>300</td>
<td>25</td>
</tr>
<tr>
<td>GK19</td>
<td>1.9</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>250</td>
<td>10</td>
</tr>
<tr>
<td>Zirconia</td>
<td>2.1</td>
<td>300</td>
<td>25</td>
</tr>
</tbody>
</table>

emitted light cannot be increased. Rather, the LED output is a rapidly diverging beam; the lenses only affect the beam divergence. Radiance at the peak power point cannot exceed the radiance emitted by the LED (Tsang 1985).

For materials of sufficiently high refractive index to refract the LED emission, smaller diameter lenses cause greater convergence. The glass material, GK-19, with a refractive index of 1.9, can cause an axial peak in power for the LED in this study when the GK-19 lens diameter is at least 100 µm. The 60 µm diameter lens curve has no axial power peak, the 100 µm diameter lens curve peaks at z=40 µm, and the 250 µm diameter lens curve peaks at z=100 µm (Figure 11).

The trends of increased launched power and decreased alignment
tolerance as functions of increased lens refractive index are noted in lateral
tolerance results (Figures 13, 15). Data are presented for various Sapphire,
GK-19, and Zirconia lens diameters. The increasing ability of higher index
lenses to more effectively narrow the beam is evident by comparing lateral
tolerance data for nearly equivalent diameter lenses of sapphire, GK-19, and
zirconia. This is manifested by higher launched powers and smaller lateral
tolerances. Based on the GK-19 data, larger diameter lenses have greater
ability to collimate the LED output.

Experimental results of power coupled and lateral tolerance for diodes
lensed with microsphere lenses located above the diode surface on capillary
tubes are documented in Figure 16. Mounting the lenses on capillary tubes
allowed precise location of the lenses. Measurements using the lenses on
capillary tubes directly measured 3 dB lateral tolerance. Experimentally-
determined lateral tolerance results for diodes having microspherical lenses
epoxied on their surface are plotted in Figures 18-22. The tests providing
these data were organized to study the shape of the lateral tolerance curve
for each lens. Typically one diode, but in no cases more than two diodes,
were studied for lateral tolerance. For each diode studied, lateral tolerance
was measured in the ±x and ±y lateral directions. These four or eight lateral
tolerance measurements at each axial fiber location were averaged for these
plots. The error bars are drawn to ±1 standard deviation determined from
these measurements.

The LED and lens have been properly (laterally) aligned for all data presented to this point. Further studies examine the effects of lateral misalignments of the lens with respect to the active area of the LED. Such results are useful for evaluating variations in coupling which could be expected in manufacture of emitting diodes with attached spherical lenses when the diode's top-surface lens-locating feature is misaligned from the bottom-surface electrical contact. In Figure 17, I compare reduction in coupled power and lateral tolerance which is caused by this diode contact-to-lens misalignment. (Data for lenses that are properly centered are plotted with small bullets. Data for LED active area-to-lens lateral misalignment of 20 \( \mu \text{m} \) are plotted with triangles, and data for diode-to-lens misalignment of 40 \( \mu \text{m} \) are plotted with boxes.)

In the left column of plots in this figure, reduction in coupled power is plotted as a function of the axial separation between the lens and fiber. As expected, the axial location for acceptable coupled power moves farther from the LED as the refractive index of the lens decreases. These data indicate the greater decrease in coupled power occurring for lower index materials as a result of the lens-LED misalignment. This last result is due to the lower ability of the lower index lenses to refract the angularly-diverging
light from a poorly aligned contact.

The right-hand column of plots shows the lateral fiber offset resulting in a 3 dB drop in coupled power as a function of axial lens-fiber separation. The results indicate that greater lateral tolerance exists for lens materials of lower index. Also, lateral fiber tolerance degrades more sharply for lower index lenses as the lens and LED are laterally misaligned. The lateral tolerance is greatly reduced for low index lenses when misalignment occurs due to the lens material's inability to redirect angularly diverging light. The lateral tolerance becomes asymmetric with the smaller value greatly suffering with p/n contact misalignment for lenses of low index.

3.5 LED Lensed with an Imaging Sphere Results

Spherical lenses with diameters on the order of 1mm have been used to couple light from a GaAlAs LED into a 62.5µm core diameter multimode optical fiber in an "imaging" geometry. An imaging sphere is spatially removed from both the source and fiber, and an image of the source is created in the vicinity of the entrance plane of the fiber (positioning the image precisely on the fiber plane decreases lateral tolerances). Lenses with refractive indices of 1.5, 1.7, and 1.9 were considered, and none of the lenses were anti-reflection (AR) coated. The lenses were evaluated for their ability to couple optical power as well as provide both lateral and axial
tolerances.

Variables for the imaging geometry include: lens material, lens size, LED-to-lens spacing, lens-fiber spacing, LED lateral misalignment, lens lateral misalignment, lens axial misalignment, fiber lateral misalignment, and fiber axial misalignment. My measurements provide information on the effects of LED-to-lens spacing, lens-to-fiber spacing, and fiber lateral misalignment on coupled power.

Results for LED-to-lens separation (Figure 23) indicate that BK-7 glass (n=1.5) has insufficient refractive power to bring significant LED radiation within the fiber's NA. However, higher index sapphire (n=1.7) and LaSF-18 (n=1.9) provide acceptable powers at LED-to-lens separations which are practical for most packaging applications. For these measurements, lens-fiber separation was optimized for each LED-to-lens position measurement.

An additional power penalty, which must be considered in evaluating all tolerances involved in packaging a 1 mm imaging lens design, is caused by variation from the nominal axial lens-to-fiber separation. This loss can be significant as demonstrated by the results for a 1 mm sapphire lens (Figure 24).

In addition to the power degradations caused by variation in LED-to-lens and lens-to-fiber axial spacings, the coupled power will drop when there is
Table 3

Lateral Fiber Tolerance Comparison for Imaging Geometry

<table>
<thead>
<tr>
<th>Lens</th>
<th>LED-Lens Separation μm (mils)</th>
<th>Lens-Fiber Separation μm (mils)</th>
<th>Optimal Lens-Fiber Separation</th>
<th>Rel Pwr dB</th>
<th>3 dB Fiber Lat Tol ±μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaSF-18</td>
<td>254 (10)</td>
<td>749 (29.5)</td>
<td>1.3</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>800 (31.5)</td>
<td>*</td>
<td>1.1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>851 (33.5)</td>
<td>1.2</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>564 (22.2)</td>
<td>1.4</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>612 (24.1)</td>
<td>*</td>
<td>1.1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>665 (26.2)</td>
<td>1.4</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>691 (27.2)</td>
<td>1.6</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>508 (20)</td>
<td>445 (17.5)</td>
<td>1.9</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>495 (19.5)</td>
<td>*</td>
<td>1.4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>546 (21.5)</td>
<td>2.0</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>635 (25)</td>
<td>330 (13)</td>
<td>3.6</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>406 (16)</td>
<td>*</td>
<td>2.2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>457 (18)</td>
<td>2.9</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Sapphire</td>
<td>254 (10)</td>
<td>1016 (40)</td>
<td>1.5</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1067 (42)</td>
<td>*</td>
<td>1.2</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>356 (14)</td>
<td>818 (32.2)</td>
<td>1.4</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>869 (34.2)</td>
<td>*</td>
<td>1.2</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>406 (16)</td>
<td>749 (29.5)</td>
<td>1.3</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>800 (31.5)</td>
<td>*</td>
<td>1.1</td>
<td>33</td>
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<tr>
<td></td>
<td>508 (20)</td>
<td>597 (23.5)</td>
<td>1.4</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>648 (25.5)</td>
<td>*</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>635 (25)</td>
<td>495 (19.5)</td>
<td>1.9</td>
<td>22</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>549 (21.6)</td>
<td>*</td>
<td>1.3</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>599 (23.6)</td>
<td>-</td>
<td>22</td>
<td></td>
</tr>
</tbody>
</table>
lateral misalignment between the components (Table 3). That is, coupled power drops if any of the elements (LED, lens, or fiber) is not centered along the optical axis. If an LED is packaged in a connectorized package, LED-to-lens lateral alignment will remain fixed during multiple insertions of a fiber. In this implementation, the lens-to-fiber lateral alignment will vary. Lateral tolerances have been measured at geometries where the fiber is axially slightly removed from its optimal power point. This slight offset increases lateral tolerance, though there is a corresponding power penalty. These data show that for both lens types, lateral fiber tolerance decreases as the lens is moved farther from the LED.

3.6 Two-Lens LED Coupling Results

A two-lens LED-to-fiber coupling design, as presented in section 1.3, has four optical components: LED, microlens, macrolens, and fiber. A brief study of the capabilities of a two-lens design was completed. Light-emitting diodes with integrally-mounted 250 μm diameter GK-19 lenses were used for these studies. The macrolens, mounted on a capillary tube mounted to a three axis micrometer stage as discussed in section 3.2, allowed coupling and lateral tolerances to be studied as functions of interlens and macrolens-to-fiber spacings.

The results given in Table 4 show the tradeoff between coupled power
and lateral tolerance that exists for the two-lens design. Note that interlens
tolerance exceeds fiber lateral tolerance and that the two-lens lateral fiber
tolerance exceeds that of imaging or microspherical geometries. Further
investigation concentrated on use of the BK7 macrolens because of the
greater lateral tolerances it provides.

Table 4

Coupling Results for Two-Lens Approach

<table>
<thead>
<tr>
<th>Integral Lens Type</th>
<th>Interlens Spacing μm (mils)</th>
<th>Macrolens Description</th>
<th>Macrolens Power Drop (dB)</th>
<th>Interlens Lat. Tol. ±μm</th>
<th>Fiber Lat. Tol. ±μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>GK19/250</td>
<td>250 (10)</td>
<td>BK7/1mm/25</td>
<td>3.0</td>
<td>122</td>
<td>98</td>
</tr>
<tr>
<td>GK19/250</td>
<td>250 (10)</td>
<td>Sapphire/1mm/10</td>
<td>1.8</td>
<td>102</td>
<td>91</td>
</tr>
</tbody>
</table>

The two-lens design using a BK7 macrolens could provide coupled power
within 0.6 dB of the maximum power coupled using only a microlens. Table
5 lists data on the power coupled and lateral tolerances for the two-lens
design using a BK7 macrolens at a variety of spacings. Note that the 3 dB
lateral fiber tolerance remained nearly constant at ± 100 μm, while the 3 dB
interlens lateral tolerance varied from ± 65 to ± 130 μm. The greater lateral
tolerance in a two-lens design exists between the two lenses, where the
power-to-tolerance tradeoff is least sensitive.
Table 5
Coupling in a Two-Lens Arrangement Using a BK-7 1mm Diameter Macrolens

<table>
<thead>
<tr>
<th>Interlens Separation μm (mils)</th>
<th>Macrolens-to-Fiber Separation μm (mils)</th>
<th>Power Drop 1 (dB)</th>
<th>3 dB Lat. Tol. Between Lenses ±μm</th>
<th>3 dB Fiber Lat. Tol. ±μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>203 (8)</td>
<td>148 (5.8)</td>
<td>2.7</td>
<td>125</td>
<td>100</td>
</tr>
<tr>
<td>254 (10)</td>
<td>148 (5.8)</td>
<td>2.8</td>
<td>120</td>
<td>102</td>
</tr>
<tr>
<td>254 (10)</td>
<td>254 (10)</td>
<td>2.9</td>
<td>130</td>
<td>105</td>
</tr>
<tr>
<td>254 (10)</td>
<td>305 (12)</td>
<td>3.0</td>
<td>130</td>
<td>na</td>
</tr>
<tr>
<td>305 (12)</td>
<td>135 (5.3)</td>
<td>2.8</td>
<td>120</td>
<td>104</td>
</tr>
<tr>
<td>356 (14)</td>
<td>226 (8.9)</td>
<td>2.9</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>406 (16)</td>
<td>302 (11.9)</td>
<td>2.9</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>457 (18)</td>
<td>345 (13.6)</td>
<td>2.8</td>
<td>115</td>
<td>100</td>
</tr>
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<td>508 (20)</td>
<td>356 (14)</td>
<td>2.8</td>
<td>110</td>
<td>100</td>
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<tr>
<td>559 (22)</td>
<td>399 (15.7)</td>
<td>2.7</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>610 (24)</td>
<td>439 (17.3)</td>
<td>2.6</td>
<td>105</td>
<td>na</td>
</tr>
<tr>
<td>660 (26)</td>
<td>455 (17.9)</td>
<td>2.5</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>711 (28)</td>
<td>495 (19.5)</td>
<td>2.4</td>
<td>95</td>
<td>100</td>
</tr>
<tr>
<td>762 (30)</td>
<td>485 (19.1)</td>
<td>2.4</td>
<td>90</td>
<td>104</td>
</tr>
<tr>
<td>813 (32)</td>
<td>516 (20.3)</td>
<td>2.3</td>
<td>90</td>
<td>114</td>
</tr>
<tr>
<td>864 (34)</td>
<td>737 (29)</td>
<td>2.2</td>
<td>70</td>
<td>112</td>
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<td>914 (36)</td>
<td>686 (27)</td>
<td>2.0</td>
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</tr>
<tr>
<td>965 (38)</td>
<td>658 (25.9)</td>
<td>1.9</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>1321 (52)</td>
<td>584 (23)</td>
<td>0.6</td>
<td>70</td>
<td>45</td>
</tr>
</tbody>
</table>

Note 1: Reduction in coupled power from the axial peak of the microlensed LED (-11.78 dBm).
Note 2: Optimal geometry found by optimizing both the macrolens and fiber along three axes.
4. Discussion

4.1 Comments on the LED Model

Computer simulations indicate the proper equivalence between internal and external diode radiance; however, both internal and external radiance results deviate from the expected Lambertian profile by a factor $\cos^2(\theta)$ (Figure 7). The greater angular degradation of the simulation indicates that the step index fiber model for the diode does not "emit" sufficient photons at large angles. This deficiency results from the different aspect ratios of a fiber core and a diode active area. The fiber core is infinitely deeper than it is wide, while the diode active layer is far thinner than it is broad (typically 1 $\mu$m thick and 50$\mu$m diameter wide). This thickness difference causes energy emitted from a fiber core to be relatively more concentrated about the surface normal due to wave propagation along the fiber axis. Emission from a flat diode active layer, on the other hand, can be viewed as coming from a surface of point sources. This energy profile pattern will be richer in wide angle emission.

The model predicts a 13.3 dB optical power loss when butt-coupling the diode into an optical fiber located 0.5 $\mu$m from the diode surface. This means that 4.7% of the LED's total emitted power is captured by the 62.5 $\mu$m fiber core. Experimental measurements indicate that 2.3% of the diode's
total emitted power is butt-coupled into the fiber. The simulation's butt-coupled power for a diode-to-fiber separation of 254 $\mu$m underestimates the experimentally measured power by 0.5 dB, indicating that the simulation predicts a coupled power that is 90% of the experimentally-determined power (Figure 8). The combination of the simulation's greater percentage of power coupled and lower absolute power coupled suggests that the LED model is deficient both in large angle power emission and in power density.

The simulation's butt-coupled lateral fiber tolerance is 90% of the experimentally determined value (Figure 8). An increased angular distribution of emitted power would increase the simulation's predicted lateral tolerance, making the results more closely resemble experimental results.

4.2 Accuracy of Lensed-Coupling Simulations

Simulation results of power coupled as a function of axial fiber position in the microspherically-lensed geometry have trends similar to experimental results; however, simulation results consistently overestimate peak axial power coupled by approximately 2.5 dB (Table 6). Overestimated peak axial powers occur since the low angularly-divergent diode emission can be made convergent. High power coupling occurs when the fiber is located axially near the position of minimum beam width. The simulation's predicted peak power axial positions are twice as large as experimentally determined
values (Table 6). The shape of the simulation's axial power coupling curves is similar to experiment for the higher index GK-19 and zirconia lenses (Figure 10). The predicted axial coupling curve for the lower index sapphire lens has lower power values than experiment for axial separations less than 600 µm (Figure 10). The model's axial coupling predictions for microspherically-lensed diodes could be improved if the diode were given a greater angular distribution of power. Power emitted at higher angles from normal emission would be hard for the low index sapphire lens to collimate, and power of high emission angle would bring peak coupling locations closer to the lens for higher index lens materials.

Predicted microspherically-lensed power coupled at axial lens-fiber

<table>
<thead>
<tr>
<th>Lens Material</th>
<th>Lens Size µm</th>
<th>Rel Pwr dB</th>
<th>Axial Peak µm</th>
<th>Axial 3 dB</th>
<th>Experiment Pwr Peak µm</th>
<th>Axial 3 dB</th>
<th>Comparison Pwr Peak dB</th>
<th>Axial ratio</th>
<th>Comparison Axial ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sapphire</td>
<td>300</td>
<td>0.0</td>
<td>700</td>
<td>550</td>
<td>-2.2</td>
<td>400</td>
<td>1080</td>
<td>2.2</td>
<td>1.75</td>
</tr>
<tr>
<td>GK-19</td>
<td>250</td>
<td>3.0</td>
<td>300</td>
<td>275</td>
<td>0.3</td>
<td>100</td>
<td>550</td>
<td>2.7</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zirconia</td>
<td>300</td>
<td>3.0</td>
<td>300</td>
<td>275</td>
<td>0.25</td>
<td>200</td>
<td>550</td>
<td>2.75</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 6
Comparison of Results for Axial Tolerance of Microspherical Lens Geometry
separations of 500 \( \mu \text{m} \) overestimates experimental results slightly (0.4 dB) for the sapphire lens and overestimates experimental results moderately (3.0–4.0 dB) for GK-19 or zirconia lenses. The simulation program predicts lateral fiber tolerances that are 5% too large for sapphire 300 \( \mu \text{m} \) diameter lenses and 40% too small for GK-19 or zirconia lenses of similar diameter (Table 7, Figure 16).

Table 7

Comparison of Lateral Tolerance Results for Microspherical Lensing Geometry

<table>
<thead>
<tr>
<th>Material</th>
<th>Size (( \mu \text{m} ))</th>
<th>Simulation Rel Pwr (( \pm \mu \text{m} ))</th>
<th>Experimental Rel Pwr (( \pm \mu \text{m} ))</th>
<th>Comparison Pwr ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sapphire</td>
<td>300</td>
<td>-0.8, 80</td>
<td>-1.2, 76</td>
<td>+0.4, 1.05</td>
</tr>
<tr>
<td>GK-19</td>
<td>250</td>
<td>0.8, 55</td>
<td>-2.2, 86</td>
<td>+3.0, 0.64</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>-7.4, 50</td>
<td>-9.4, 82</td>
<td>+2.0, 0.61</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>-12.7, 20</td>
<td>-11.8, 100</td>
<td>-0.9, 0.20</td>
</tr>
<tr>
<td>Zirconia</td>
<td>300</td>
<td>1.3, 40</td>
<td>-3.1, 65</td>
<td>+4.4, 0.62</td>
</tr>
</tbody>
</table>

The simulation results indicate increasing power coupling accuracy and decreasing lateral tolerance accuracy for GK-19 lenses as the lens diameter decreases (Table 7). Comparison of experimental results of microspherically-lensed lateral tolerance which include \( \pm 1 \) standard deviation error bars to simulation results of microspherically-lensed lateral...
tolerance indicates that the simulation results are not within the uncertainty of the experimental measurements, with the exception of the results for the GK-19 100 μm diameter lens (Figures 18-22).

Simulation of the axial tolerance of the imaging geometry overestimates the peak power coupled by 0.2 dB, predicts an axial peak power coupling location that is 45% farther from the diode than the experimental value, and predicts the axial movement producing a 3 dB loss from the peak power which is 5% in error (Figure 24). Predicted lateral fiber tolerances for the imaging geometry are generally about 80% of the experimental value (Table 8).

Table 8

Lateral Fiber Tolerance for Imaging Geometry

<table>
<thead>
<tr>
<th>Lens Material</th>
<th>LED to Lens</th>
<th>Lens to Fiber</th>
<th>Simulation</th>
<th>Experiment</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μm</td>
<td>μm</td>
<td>Rel 3 dB</td>
<td>Rel 3 dB</td>
<td>Rel 3 dB</td>
</tr>
<tr>
<td>Sapphire</td>
<td>254</td>
<td>1000</td>
<td>-5.5</td>
<td>85</td>
<td>-1.75</td>
</tr>
<tr>
<td></td>
<td>406</td>
<td>749</td>
<td>-2.0</td>
<td>30</td>
<td>-1.25</td>
</tr>
<tr>
<td>LaSF-18</td>
<td>254</td>
<td>851</td>
<td>0.6</td>
<td>30</td>
<td>-1.2</td>
</tr>
<tr>
<td></td>
<td>508</td>
<td>445</td>
<td>-1.5</td>
<td>20</td>
<td>-2.0</td>
</tr>
</tbody>
</table>
Modifying the LED model to have greater power at large divergence angles would increase the lateral tolerance, increasing correspondence of simulation results with experiment.

Simulation results for two-lens coupling estimate coupled power with a systematic 2.0 dB error and estimate lateral tolerances within 50% of the true values (Table 9).

Table 9
Lateral Tolerances of Two-Lens Geometry

<table>
<thead>
<tr>
<th>Macro-Lens (size)</th>
<th>Lens-Lens µm</th>
<th>Lens-Fiber µm</th>
<th>Rel Pwr Tol (dB)</th>
<th>Simulation Lens Tol ±μm</th>
<th>Fiber Tol ±μm</th>
<th>Experiment Lens Tol ±μm</th>
<th>Fiber Tol ±μm</th>
<th>Comparison Lens Tol ±μm</th>
<th>Fiber Tol ±μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK-7 (1mm)</td>
<td>250</td>
<td>250</td>
<td>-4.0</td>
<td>150</td>
<td>75</td>
<td>-1.7</td>
<td>130</td>
<td>105</td>
<td>-2.3</td>
</tr>
<tr>
<td></td>
<td>508</td>
<td>356</td>
<td>-4.0</td>
<td>140</td>
<td>75</td>
<td>-1.5</td>
<td>110</td>
<td>100</td>
<td>-2.5</td>
</tr>
<tr>
<td></td>
<td>762</td>
<td>485</td>
<td>-3.6</td>
<td>120</td>
<td>80</td>
<td>-1.2</td>
<td>90</td>
<td>104</td>
<td>-2.4</td>
</tr>
<tr>
<td></td>
<td>965</td>
<td>658</td>
<td>-2.1</td>
<td>95</td>
<td>85</td>
<td>-0.7</td>
<td>65</td>
<td>100</td>
<td>-1.4</td>
</tr>
<tr>
<td>Sapp (1mm)</td>
<td>250</td>
<td>90</td>
<td>-3.0</td>
<td>120</td>
<td>65</td>
<td>-1.0</td>
<td>102</td>
<td>91</td>
<td>-2.0</td>
</tr>
</tbody>
</table>

The lateral tolerance results are too large for the microlens-to-macrolens tolerance, and they are too low to the macrolens-to-fiber tolerance. These patterns result when coupling a restricted angular beam through a two-lens system. The initial lens nearly collimates the beam pattern. A large second lens can move large distances laterally and still capture the optical power.
The fiber, however, loses power coupling more quickly when moving laterally in a more tightly-restricted angular beam.

4.3 Recommendations for Future Work

The results of this study simulating LED-to-fiber coupling using a step-index fiber model for the emitting diode properly predict trends in coupling parameters. Power coupling accuracy varies from 0.2 dB to 4.4 dB and tolerance predictions range from ±5 % to 75% in accuracy. Interpretation of the results suggests that the model should be revised to increase the surface radiant flux density (power per unit area) of the diode and to increase the angular divergence of emission. The increased surface radiant flux density could be achieved by decreasing the radius of the active layer of the diode. This decrease should occur only over the central portion of the active region which has constant emitted ray density. Increased angular divergence could be achieved using weighting factors in the beam direction angle integration to increase the emitted power at large angles sufficiently to produce Lambertian emission patterns.
Figure 1: Light Emitting Diode as an Optical Source
The half-angle, $\theta$, of the acceptance cone is defined such that the internal reflection angle, $\phi$, is the critical angle for Total Internal Reflection.

Index of Refraction Profiles for Step-Index and Graded-Index Fibers are of the form:

Figure 2: Optical Fiber Coupling Characteristics
Figure 3: LED-to-Fiber Lensing Geometries
Source Location Parameters: $r, \phi_1$

Ray Direction Parameters: $\theta, \phi_2$

Figure 4: Ray Parameter Notation for Simulation Program
Model Parameters:

- core radius = $r_2$
- $n_a = n \sin (\theta_{sub \ c})$
- $n = 3.3$

Figure 5: Step Index Fiber Model of a Light Emitting Diode
Figure 6: LED-to-Fiber Coupling Test Set
Figure 7: Simulation Results; Normalized LED Internal and External Radiance
Figure 8: Lateral Fiber Tolerance of Butt-Coupled Geometry
Figure 9: Experimental Lateral Tolerance of Butt-Coupled Geometry
Figure 10: Axial Tolerance for Microsphere Lens Materials
Figure 11: Axial Tolerance using Microsphere Lenses of Various Diameters
Figure 12: Simulation Results; Lateral Fiber Tolerance using Microsphere Lenses of Various Materials
Figure 13: Experimental Results; Lateral Fiber Tolerance using Microsphere Lenses of Various Materials
Figure 14: Simulation Results; Lateral Fiber Tolerance for Microsphere Lenses of Various Diameters
Figure 15: Experimental Results; Lateral Fiber Tolerance for Microsphere Lenses of Various Diameters

Axial Lens–Fiber Separation = 500 um

Legend: ▼ 60 um diameter GK19
□ 100 um diameter GK19
○ 250 um diameter GK19
Figure 16: Experimental Launched Power and Lateral Fiber Tolerance for Microspherically-Lensed Diodes
Sapphire 300 μm, Grade 25

GK19 300 μm, Grade 10

GK19 250 μm, Grade 10

Zirconia 300 μm, Grade 10

- lens centered over LED contact

△ 20 μm p/n contact offset

□ 40 μm p/n contact offset

Figure 17: Experimental Results; Effect of p/n Contact Misalignment on Fiber Coupling of Microspherically-Lensed LEDs
Figure 18: Fiber Lateral Tolerance for LEDs Microspherically Lensed using 300 um diameter Sapphire Lenses
Figure 19  Fiber Lateral Tolerance for LEDs Microspherically Lensed using 300 um diameter Zirconia Lenses
Figure 20: Fiber Lateral Tolerance for LEDs Microspherically-Lensed using GK-19 250 um diameter Lens
Figure 21: Fiber Lateral Tolerance for LEDs Microspherically Lensed using GK-19 100 um diameter Lens
Figure 22: Fiber Lateral Tolerance for LEDs Microspherically-Lensed using GK-19 60 um diameter Lens
Figure 23: Experimental Results; LED-to-Lens Axial Tolerance of Imaging Geometry
Axial LED-to-Lens spacing = 250 um

Legend:
- Simulation Results
- Experimental Results

Figure 24: Axial Fiber Tolerance of Sapphire Imaging Geometry
Figure 25: Lateral Fiber Tolerance for Imaging Geometry using 1mm Sapphire Lenses
Figure 26: Lateral Fiber Tolerance for Imaging Geometry using 1mm LaSF-18 Glass Lenses

Legend for LED_lens / lens_fiber Spacings:
254/851 um: ○ Simul ● Exper
508/445 um △ Simul ▲ Exper
Conditions: GK-19 250 um Microlens
BK-7 1 mm Macro lens
250 um lens-lens spacing
250 um macro lens-fiber spacing

Legend:
- Simul. Lens-Lens
- Simul. Lens-Fiber
- Exper. Lens-Lens
- Exper. Lens-Fiber

Figure 27: Lateral Tolerances of Two-Lens GK-19 / BK-7
250/250 Geometry
Conditions: GK-19 250 um Microlens; 
BK7 1 mm Macrolens; 
508 um Lens-Lens spacing' 
356 um macrolens-fiber spacing

Legend:
- Simul. Lens-Lens      - Exper. Lens-Lens
- Simul. Lens-Fiber     - Exper. Lens-Fiber

Figure 28: Lateral Tolerances of 
Two-Lens GK-19 / BK7 
508/356 Geometry
Figure 29: Lateral Tolerances of Two-Lens GK-19 / BK7 762/485 Geometry
Figure 30: Lateral Tolerances of Two-Lens GK-19/BK7 965/658 Geometry
Figure 31: Lateral Tolerance of Two-Lens GK–19 / Sapphire 250 / 90 Geometry
REFERENCES


Mr. Stephen J. Wetzel was born in Allentown, Pennsylvania in 1960. His parents are the late Doris A. (Graver) Wetzel and the Reverend Willard W. Wetzel, currently of Northampton, Pennsylvania. Mr. Wetzel received an A.B. in Physics, Magna cum laude, from Franklin & Marshall College, Lancaster, Pennsylvania, in 1983. He has been employed by AT&T Bell Laboratories since 1984, and currently works at the AT&T location in Breinigsville, Pennsylvania. Mr. Wetzel has been involved in the design, introduction to manufacture, and qualification of optical multiplexers and optical data link products. He has been responsible for optical subassembly design, and he has specified a light-emitting diode for use as both the transmitting and receiving device in a data link product. Mr. Wetzel has developed a procedure to qualify data link transceivers for wave solder assembly. Mr. Wetzel has published the following articles on optical networking and optical data link design: S.Y. Suh et al., Aug. 1987, Active star coupler based fiber-optic local area network, *Journal of Lightwave Technology*, LT-5 (8): 1050-1061; and C.F. Flores, et al., 1987, ODL RS-232-2/02X: a single fiber RS-232 optical modem, in *EFOC/LAN 87 Proceedings*, 173-176. Mr. Wetzel was elected to Phi Beta Kappa in 1983, and he is a member of the Sigma Pi Sigma National Physics Honor Society.
END
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TITLE