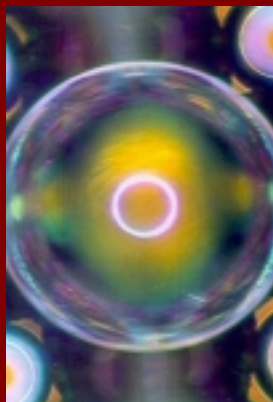


Choosing Ball or GRIN Lenses

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In modern telecommunication systems, micro-optic components couple light between fibers, from laser diodes to fibers and from fibers to detectors, as well as collimate light from fibers in thin film filter dense WDMs. Both ball lenses and graded index (GRIN) lenses may be employed in these roles. In this article lens properties are discussed and instances where one class of optic may be superior to another are noted.

A ball lens is spherically shaped, generally possesses a constant refractive index, and is made from commonly available glasses or other transparent optical substrates. Transmitted light changes direction at the curved boundaries, traversing the interior in straight lines. The focal length, measured from the center of the lens, and back focal length, measured from the surface of the lens, are shown in Figure 1. The focal length is dependent upon both the refractive index of the glass and the lens diameter (Tables 1 & 2). Placing a point source at the focal point of the lens results in collimated light.

Table 1. Dependence of Ball Lens' Focal Length Upon Refractive Index

Glass	Index (1550)	f	fb
SiO ₂	1.45	1.61 R	0.61 R
BK7	1.5	1.50 R	0.50 R
LaSFN9	1.8	1.13 R	0.13 R
LaSFN35	2.0	1.00 R	0.00

Table 2. Dependence of Focal Length Upon Radius for LaSFN9 Ball

Radius	f	f _b (mm)
1.0	1.13	0.13
0.5	0.56	0.06
0.2	0.23	0.03
0.1	0.11	0.01

The GRIN lens has a cylindrical shape and a refractive index distribution varying radially with a parabolic profile, with its maximum on the lens axis (we limit our discussion to lenses with radially varying index distributions). The light path curves throughout the lens, unlike the case for the ball lens. A common type of GRIN lens is illustrated, with 'pitch' $p = 0.25$. A point source located at one end of this lens will result in collimated light exiting the other end. Typical selections of length, diameter, and index are given in Table 3.

Table 3. Physical Dimensions of Typical GRIN Lenses ($p = .25$, wavelength = 1550 nm)

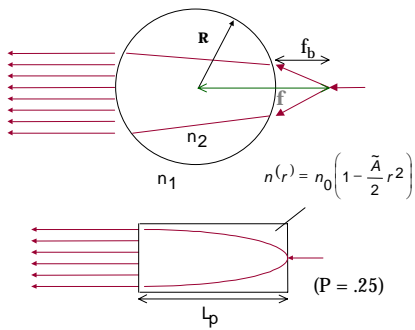
Radius	Length (mm)	NA	Peak Refractive Index
0.5	3.3	0.37	1.550
0.5	2.6	0.46	1.592
0.9	4.8	0.46	1.592
0.9	3.8	0.6	1.634
1.0	6.6	0.37	1.550
1.0	5.3	0.46	1.592
1.0	5.3	0.46	1.592

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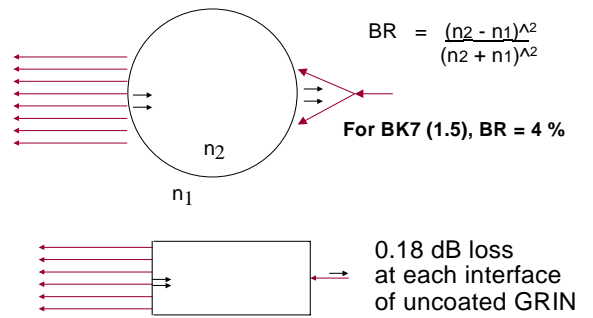
Ball and GRIN lenses share at least one difficulty. Light travelling between materials of different refractive index (e.g., air and glass), will be partially reflected (Figure 2). The amount reflected depends upon the refractive indices, angle of incidence and polarization state of the light. At normal (0°) incidence, light transiting between air and material with an index of 1.444 (fused silica at 1550 nm) will suffer an insertion loss of 0.15dB, as 3.3% is reflected. These reflections can cause a problem when launching light into a fiber from a laser diode, destabilizing its output. Such reflections back into the laser cavity are to be avoided, but there is another issue. Each reflection is a loss to the power budget of an optical link, and should be reduced in order to maximize signal strength. One approach to lessen insertion loss is to apply an anti-reflection (AR) coating, which consists of one or more thin layers of material deposited on the lens to suppress reflection and thereby enhance transmission. With multilayer AR coatings, it is possible to reduce the insertion loss at an optical interface to less than 0.004 dB over a wide range of wavelengths and incidence angles.

Figure 1. Ball Lens and GRIN Lens



“A point source located at one end of this lens will result in collimated light exiting the other end.”

Figure 2. Back Reflection



Systems with GRIN or ball lenses gain greatly from AR coatings, since loss occurs at both interfaces, and can be much larger than the 0.15 dB cited for SiO₂. Figure 3 illustrates results obtained for both lens types after application of AR coatings by DSI, in contrast to the loss for uncoated optics. The GRIN plot shows the return loss, improved from around -13 dB, while the ball lens plot has the associated insertion loss plotted against wavelength.

If both lens types can be protected against back reflection losses, what distinguishes one over the other? Ball lenses are available from a number of vendors and can be much smaller than GRIN lenses, leading to reduced package sizes. (At DSI, we have coated ball lenses as small as 250 microns). The cost of ball lenses is also less than that of GRIN lenses. However, up to this point, the GRIN lens has been heavily favored, and been employed in higher-end systems more frequently.

Figure 3a. AR Coated GRIN Lens Performance

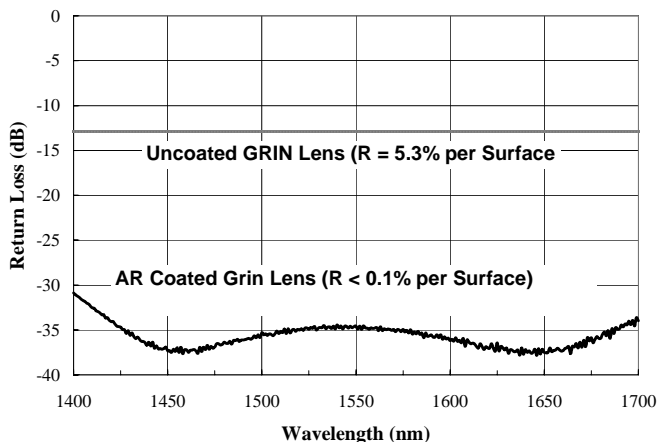
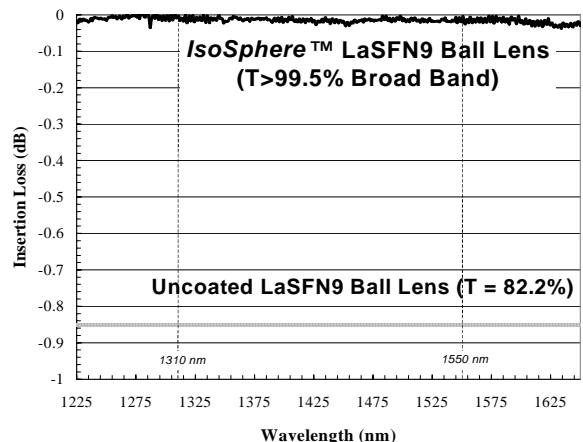


Figure 3b. Coated Ball Lens Broadband AR Performance



Given the reduced size, availability, and cost benefits, why haven't ball lenses been utilized more widely in telecommunications? In part, due to coating technologies first applied, which helped inhibit ball lens usage. Evaporation, a useful technique elsewhere, has limitations in coating balls and other complex optical surfaces. In evaporative coating, parts to be coated are positioned in a vacuum chamber evacuated to 10^{-6} Torr or less. Coating materials are heated inside the chamber until they evaporate. With few air molecules in the chamber, material boils out from the source, eventually recondensing onto surfaces with direct lines of sight to the source. The deposition rate is highly dependent upon the angular orientation between surface and source, as well as the distance. Spheres coated by evaporation must be turned to coat both sides and resemble the earth floating in space: North and South Poles are covered (Figure 4's 'icecap' coating), while the equators are bare, unprotected. The coatings are not completely uniform even across the caps. A ball lens with such a coating has its useful optical axis designated by a red dot, and must be rotated (and fixed) carefully in its package. Thus, an additional alignment is introduced to the production process. A minimum lens diameter is mandated, as it is not easy to flip precisely a group of very small spheres. Due to these limitations, ball lenses have been employed without any AR protection, raising both insertion and return loss, or else they may have been displaced by an alternative without these problems.

Up to now, the GRIN lens has been heavily favored due to factors such as geometry and ease of use. Evaporation, or better yet, sputtering, can be employed to AR coat the ends of GRIN lenses (Figure 3a results). Either process can coat the flat ends of GRIN lenses; thus, the coated surface is readily identifiable during device assembly and no rotational alignment is necessary.

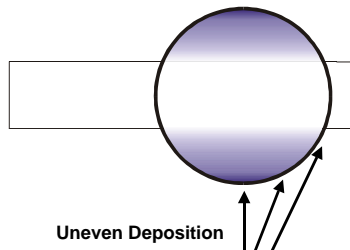
Table 4. Ray Matrix Results

	GRIN	Ball Lens
Coupling Efficiency	47	69 %
Minimum Package Size	9.1	4.6 mm
Beam Cut Off by Lens	37	8 %
R = 0.5 mm, Laser Diode has $2 \omega_{ox} = 1 \mu\text{m}$, $2 \omega_{oy} = 3 \mu\text{m}$		
Single mode fiber, $2\omega_o = 10.4 \mu\text{m}$		

Newer coating technology is causing a re-evaluation of the relative merits of ball and GRIN lenses, especially in light of the lower costs associated with ball lenses. DSI has developed the *IsoDyn*TM low pressure chemical vapor deposition (LPCVD) process, which is distinctive in the optical coating industry. As depicted in Figure 5, it is similar to processes employed by the semiconductor industry, and provides uniform, multilayer coatings over complex three-dimensional shapes. Deposition is induced by a chemical reaction occurring at the substrate surface. Thus there is no angular dependence, and the resultant coating is uniform over the surface to within 1%.

Figure 4.

Evaporation Produces Non-Uniform "ICECAP" Ball Lenses



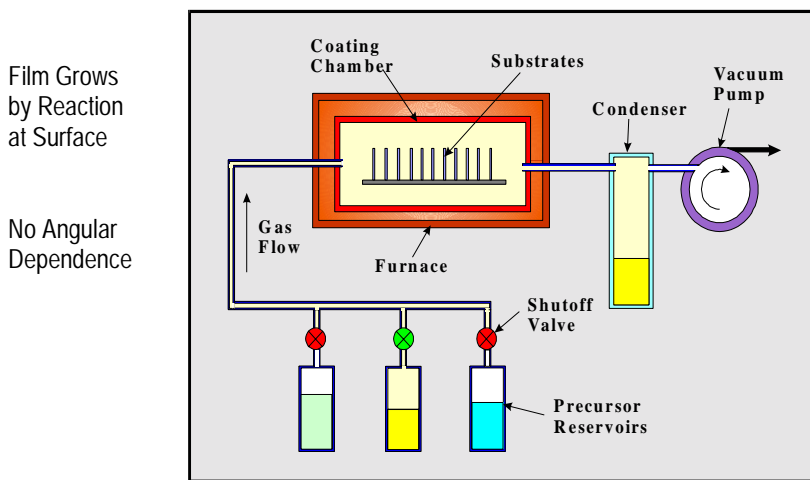
*IsoSphere*TM AR-coated ball lenses are completely covered, and have losses less than 0.01dB (99.75% T) per surface, over broad wavelength ranges (Figure 3b). They are much less expensive than GRIN lenses, fabricated from a wide range of substrate with consequent diversity of refractive index, and help to reduce package size. Finally, alignment labor is dramatically reduced when using these lenses, as no rotational orientation is required.

Let us look at coupling a laser diode to single mode fiber by means of a single lens, utilizing parameters from commercially available products. Using ray matrix theory combined with wave optics, we have examined the performance of a laser diode-lens-fiber system (Figure 6). Optical efficiency and package size are two measures of how well these tasks are performed. A typical laser diode with dimensions of 1 x 3 microns was used. Anisotropic emission from a laser diode corresponds to an elliptical beam pattern in the far field, and was taken into account in the ray matrix calculations. Due to the large divergence of laser diodes, it is advantageous to employ an asymmetrical arrangement by locating the laser considerably closer to the lens, and thus the fiber correspondingly farther from the lens. For beam diameters exiting the coupling lens which exceed the lens aperture, the energy outside the diameter of the lens is lost, and the coupling efficiency factor was corrected for this effect. This correction is significant for GRIN lenses coupled to highly divergent laser diode sources, and limits the diode-to-fiber coupling efficiency using a single lens.

“The maximum achievable coupling efficiency of the ball lens is significantly higher.”

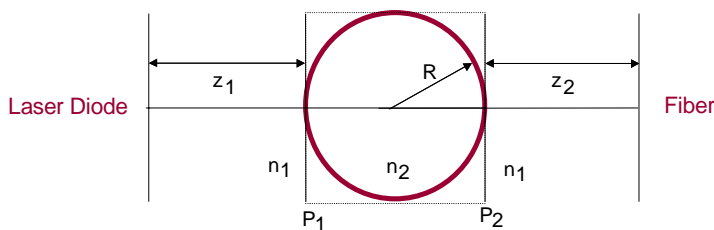
Consider the case of a 0.5 mm radius ball or GRIN lens coupled to a 1550 nm diode. The ball is fabricated from LaSFN9 glass; the GRIN lens has a length of 2.6 mm, pitch of 0.25, and NA of 0.46. For each case, the lens-diode separation is selected for maximum coupling efficiency. As shown in Figure 7, the maximum achievable coupling efficiency of the ball lens is significantly higher (69% vs. 47%) and the lens-fiber distance shorter than with the GRIN lens. The minimum package size (the total diode-fiber distance, or laser-lens + lens-fiber distance + lens length) for the ball is half that for the GRIN, or 4.6 rather than 9.1 mm, due to the stronger focusing power of the ball. The GRIN lens cuts off or "clips" a significant fraction of the asymmetric beam from the laser diode (37%) compared to the ball (8%). Employing an even larger NA (0.6) GRIN lens, with larger diameter (1.8 mm D, 3.8 mm length), merely increases the coupling efficiency to 57%, with package size inflated to 12.9 mm.

Figure 5. LPCVD Uniformly Coats Complex Shapes



Ball lenses have enjoyed cost and size advantages relative to GRIN lenses, but the perceived relative ease in use often led to the choice of GRIN lens in telecommunications applications. Due to improvements in ball lens coating technology, this preference has diminished. In some cases, ball lenses may even yield higher coupling efficiencies as well as smaller packages. This is causing a reassessment of the relative merits, and has led to an increase in the numbers of ball lenses employed.

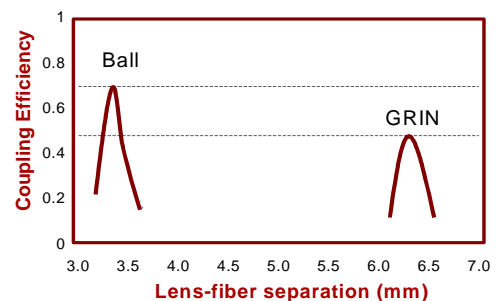
Figure 6. Ball Lens – Laser Diode Coupling



Distances for Laser Diode-Fiber Coupling Using GRIN, Ball Lenses

Notation Based Upon Siegman Lasers

Figure 7. Coupling Efficiency



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