

Laser Diode to Single-Mode Fiber Coupling with Ball Lenses

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Summary

The single-mode laser diode to single-mode fiber coupling efficiency is analyzed for couplers with ball lenses. A theory for the calculation of the coupling efficiency and the losses due to misalignments is presented including the effect of spherical aberration. It is shown that the spherical aberration of the lenses contributes very strongly to the coupling losses and limits the maximum coupling efficiency. The losses due to lens aberration are minimized for couplers consisting of ball lenses with small diameter and high refractive index, because the aberration losses decrease with decreasing focal length and increasing refractive index. The calculations are in very good agreement with experimental results.

1 Introduction

Optical fiber transmission systems using laser diodes (LD) and single-mode fibers (SMF) are very attractive for providing high bit rate long distance communication systems. In the wavelength region of 1.3 μm , or in case of dispersion shifted fibers in the region of 1.55 μm , the chromatic dispersion of the fibers is negligible and the possible repeater span is limited by the power demand of the receiver. It is obvious that a reduction of the coupling loss between LD and SMF directly increases the maximum repeater spacing. Therefore laser modules with high coupling efficiencies are required, which maintain the high efficiency under a variety of environmental conditions such as vibrations, mechanical shocks and temperature variations. This is a difficult task as a submicron accuracy is required for SMF-components.

In order to achieve a high coupling efficiency between LD and SMF the mode of the single-mode laser diode must be matched to the fundamental mode of the single-mode fiber. Due to the large beam divergence of the laser mode coupling units with one or two small ball lenses with diameters below 1 mm are commonly used. Although such lenses show a considerable amount of spherical aberration, this effect was usually ignored in designing LD to SMF couplers [1, 2], and only few papers dealt with these aberration effects [3-6]. The purpose of this paper is to give a quantitative determination of aberration losses of LD to SMF couplers and their dependence on the focal length and the refractive index of the employed ball lenses. Furthermore the influence of the spherical aberration on misalignment tolerances is studied.

In Section 2 the general theory is outlined followed by the determination of the lens function of ball lenses in Section 3. In Section 4 the coupling loss which is caused by the spherical aberration is evaluated, Section 5 presents the maximum possible coupling efficiencies of couplers with two ball lenses. In Section 6 the effect of misalignments is shown.

2 Theory

In Fig. 1 a LD to SMF coupling arrangement with two lenses is shown schematically. With the assumption of gaussian field distributions the elliptic near field of the LD is given by the function

$$\psi_1(x, y) = \sqrt{\frac{2}{\pi}} \frac{1}{\sqrt{w_{1x} \cdot w_{1y}}} \cdot \exp \left[-\left(\frac{x^2}{w_{1x}^2} + \frac{y^2}{w_{1y}^2} \right) \right] \quad (1)$$

with spot sizes w_{1x} in x-direction (perpendicular to the junction plane) and w_{1y} in y-direction (parallel to the junction plane). The field of the SMF is circular symmetric and is given by

$$\psi_f(r) = \sqrt{\frac{2}{\pi}} \frac{1}{w_f} \exp \left[-\frac{r^2}{w_f^2} \right] \quad (2)$$

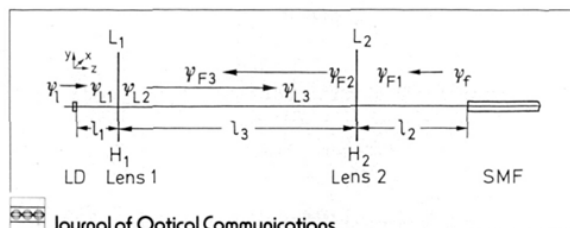


Fig. 1: Schematic diagram of a two lens coupling arrangement (LD = laser diode, SMF = single-mode fiber)

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with w_f as fiber spot size. Both fields are normalized to have unity power (A is the cross section area of the field):

$$\iint_A |\psi|^2 dA = 1. \quad (3)$$

The far fields ψ_{L1} and ψ_{F1} are calculated with the diffraction integral [7] with a series expansion of the phase terms to the 6th order. With wavelength λ , distance l_1 between LD and the principal plane H_1 of lens 1 (see Fig. 1) and the far field spot sizes $w_{L1x} = l_1 \cdot \lambda / (\pi \cdot w_{fx})$ and $w_{L1y} = l_1 \cdot \lambda / (\pi \cdot w_{fy})$ the field ψ_{L1} of the LD is given by the expression

$$\psi_{L1}(x, y) = \sqrt{\frac{2}{\pi}} \frac{1}{\sqrt{w_{L1x} \cdot w_{L1y}}} \cdot \exp \left[-\left(\frac{x^2}{w_{L1x}^2} + \frac{y^2}{w_{L1y}^2} \right) + j\phi_{L1}(x, y) \right] \quad (4)$$

with the phase term

$$\phi_{L1}(x, y) = -\frac{\pi(x^2 + y^2)}{\lambda \cdot l_1} \left[1 - \frac{x^2 + y^2}{4 \cdot l_1^2} + \frac{(x^2 + y^2)^2}{8 \cdot l_1^4} \right]. \quad (5)$$

The far field of the SMF is correspondingly given by

$$\psi_{F1}(r) = \sqrt{\frac{2}{\pi}} \frac{1}{w_{F1}} \cdot \exp \left[-\frac{r^2}{w_{F1}^2} + j\phi_{F1}(r) \right] \quad (6)$$

with the phase term

$$\phi_{F1}(r) = -\frac{\pi \cdot r^2}{\lambda \cdot l_2} \left[1 - \frac{r^2}{4 \cdot l_2^2} + \frac{r^4}{8 \cdot l_2^4} \right]. \quad (7)$$

Here l_2 is the distance between SMF and principal plane H_2 of lens 2 and $w_{F1} = l_1 \cdot \lambda / (\pi \cdot w_f)$ the far field spot size.

The action of a ball lens is describes by a lens function L which relates the fields on both sides of the principal plane of the lens. The lens is therefore completely determined by the position of the principal plane and the lens function. Consequently the LD field ψ_{L2} just behind lens 1 is given by

$$\psi_{L2}(x, y) = L_1(x, y) \cdot \psi_{L1}(x, y) \quad (8)$$

and the field ψ_{F2} of the SMF in front of lens 2 (Fig. 1) by

$$\psi_{F2}(r) = \psi_{F1}(r) / L_2(r). \quad (9)$$

The fields ψ_{L3} and ψ_{F3} can be calculated with the diffraction integral [7] and ψ_{L2} and ψ_{F2} as generating functions.

In principle the coupling efficiency η is given by the overlap of the LD and the SMF fields in an arbitrary reference plane between LD and SMF, but in order to minimize the numerical effort the calculation should be carried out in the principal plane H_1 of lens 1. With a factor R_f which includes all reflection losses of the coupler the coupling efficiency is given by [8]

$$\eta = R_f \cdot \left| \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \psi_{L2}(x, y) \cdot \psi_{F3}^*(x, y) dx dy \right|^2 \quad (10)$$

with the normalized fields ψ_{L2} of the LD and ψ_{F3} of the SMF just behind the principal plane H_1 of lens 1 (see Fig. 1).

3 Lens function of a ball lens

In order to calculate the lens function L of a ball lens we follow the method given in [4]. As shown in Fig. 2 a light

ray is emitted from a point E at a distance l_E from the principal plane with an angle ϑ_E to the optical axis. The ray passes the ball lens (refractive index n_L , radius R_L and focal length $f_L = n_L \cdot R_L / (2 \cdot (n_L - 1))$) and crosses the optical axis at a point R at a distance l_R behind the principal plane. By applying Snell's law we find an expression for the distance l_R which is given by

$$\frac{1}{l_R} = \frac{\sin \vartheta_R}{l_E \cdot \sin \vartheta_E} \quad (11)$$

with

$$\vartheta_R = 2 \cdot \left[\arcsin \left(\frac{l_E}{R_L} \cdot \sin \vartheta_E \right) - \arcsin \left(\frac{l_E}{n_L \cdot R_L} \sin \vartheta_E \right) \right] - \vartheta_E. \quad (12)$$

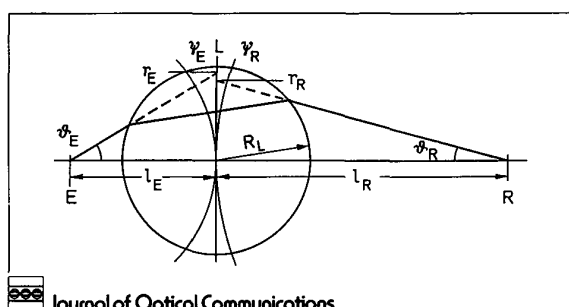


Fig. 2: Ray path through a ball lens

A series expansion of (11) and (12) yields

$$\frac{1}{l_R} = A_0 + A_2 \cdot \vartheta_E^2 + A_4 \cdot \vartheta_E^4 \quad (13)$$

with

$$A_0 = \frac{1}{f_L} - \frac{1}{l_E}, \quad (14)$$

$$A_2 = \frac{1}{8 \cdot f_L} \cdot \left[\left(\frac{n_L}{(n_L - 1)^2} - 1 \right) \frac{l_E^2}{f_L^2} + 4 \left(\frac{l_E}{f_L} - 1 \right) \right], \quad (15)$$

and

$$A_4 = \frac{1}{48 \cdot f_L} \left\{ \left[\frac{9}{40} \frac{n_L^5 - 1}{(n_L - 1)^5} - \frac{3n_L}{(n_L - 1)^5} - \frac{6}{10} \right] \frac{l_E^4}{f_L^4} + \frac{6n_L}{(n_L - 1)^2} \cdot \frac{l_E^3}{f_L^3} + 5 \cdot \left[1 - \frac{n_L}{(n_L - 1)^2} \right] \frac{l_E^2}{f_L^2} - 8 \cdot \frac{l_E}{f_L} + 2 \right\}. \quad (16)$$

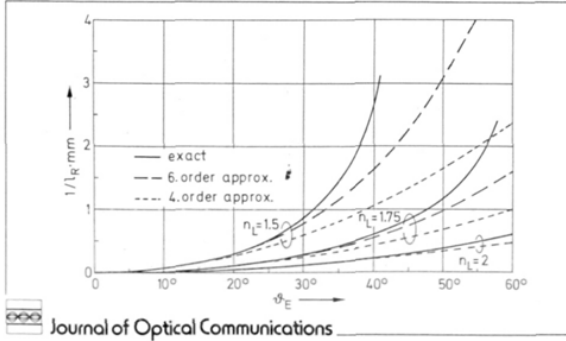


Fig. 3: Reciprocal value $1/l_R$ of the distance l_R vs. ray angle ϑ_E for ball lenses with $f = 0.291$ mm and three different refractive indices n_L ; the exact solution and the approximations of 4th and 6th order are plotted

The first two terms in (13) describe the lens law of geometrical optics, the other the spherical aberration of the ball lens.

$$A(r) = \left[1 + 2 \cdot B_3 \cdot r^2 + \left(3B_5 - \frac{B_3^2}{2} \right) r^4 \right] \cdot \exp \left\{ -\frac{r^4}{w_E^2} \left[2 \cdot B_3 + (2B_5 + B_3^2) \cdot r^2 \right] \right\} \quad (23)$$

In Fig. 3 the reciprocal value of l_R is plotted vs. the ray angle ϑ_E for ball lenses with focal length $f_L = 0.291$ mm and three different refractive indices $n_L = 1.5$, $n_L = 1.75$ and $n_L = 2.0$. For every refractive index a set of three curves is shown: $1/l_R$ calculated with the exact solution of (11) and with the 6th and 4th order approximation of (13) (4th order with $A_4 = 0$). The origin of the rays (point E) is placed in the focal plane of the lens, i.e. $l_1 = f$, so with ideal lenses, $1/l_R$ should be zero independent of the angle ϑ_E . As it is shown in Fig. 3, the ball lenses can be regarded as ideal lenses only at small angles ϑ_E , and at larger angles the spherical aberration dominates more and more. Especially for lenses with small refractive index n_L the spherical aberration has a strong effect.

It is also shown in Fig. 3 that the deviations between the exact solution and the power series expansions of $1/l_R$ are small for angles up to 20° which are typical half FWHM values of LD far fields. At small angles and for lenses with high refractive index the deviations are negligible. Even the 4th order series would describe the effect of spherical aberration sufficiently.

The radius r_R in Fig. 2 is given by

$$r_R = l_E \cdot \frac{\sin \vartheta_E}{\cos \vartheta_R} \quad (17)$$

If this equation is expanded into a series we find the expression

$$r_R = l_E \cdot (\vartheta_E + F_3 \cdot \vartheta_E^3 + F_5 \cdot \vartheta_E^5) \quad (18)$$

with

$$F_3 = \frac{l_E}{f_L} \cdot \left(\frac{l_E}{2 \cdot f_L} - 1 \right) + \frac{1}{3} \quad (19)$$

and

$$F_5 = \left[\frac{n_L}{8 \cdot (n_L - 1)^2} + \frac{1}{4} \right] \frac{l_E^4}{f_L^4} - \left[\frac{n_L}{8 \cdot (n_L - 1)^2} + \frac{7}{8} \right] \frac{l_E^3}{f_L^3} + \frac{l_E^2}{f_L^2} - \frac{l_E}{2 \cdot f_L} + \frac{2}{15} \quad (20)$$

For a given light source the fields ψ_E and ψ_R are completely determined by l_E , ϑ_E , l_R and r_R , and the lens function L is given by

$$L(r) = \frac{\psi_R(r)}{\psi_E(r)} = A(r) \cdot P(r) \quad (21)$$

with $A(r)$ as amplitude function and $P(r)$ as phase shift function. The amplitude function can be calculated with the help of

$$\int_0^{r_E} |\psi_E|^2 r \, dr = \int_0^{r_R} |\psi_R|^2 r \, dr \quad (22)$$

which means that the power of the incoming field ψ_E within a circle of radius r_E must be the same as the power of the outgoing field ψ_R within a circle of radius r_R . With the assumption of a circular symmetric gaussian field ψ_E the amplitude function $A(r)$ is given by

with the abbreviations

$$B_3 = \frac{\frac{1}{3} - F_3}{l_E^2} \quad (24)$$

and

$$B_5 = \frac{3 \cdot F_3^2 - F_3 - F_5 + \frac{2}{15}}{l_E^4} \quad (25)$$

As the field ψ_R deviates only little from a gaussian shape, $A(r)$ can be approximated by

$$A(r) = K \cdot \exp \left[-\frac{r^2}{w_E^2} (K^2 - 1) \right] \quad (26)$$

with

$$K = \left[1 + \left(F_3 - \frac{1}{3} \right) \cdot \frac{w_E^2}{l_E^2} + \left(F_5 - F_3 + \frac{1}{5} \right) \frac{w_E^4}{l_E^4} \right]^{-1} \quad (27)$$

In this approximation any field distortion is ignored, and ψ_R is regarded as a gaussian field with spot size

$$w_R = w_E / K \quad (28)$$

Therefore (26) and (27) describe only the change of the spot size from w_E to w_R .

The phase shift function $P(r)$ in (21) is given by

$$P(r) = \exp \left[j \frac{\pi \cdot r^2}{\lambda \cdot f_L} (1 + G_2 \cdot r^2 + G_4 \cdot r^4) \right] \quad (29)$$

with

$$G_2 = \frac{1}{8 \cdot l_E^2} \left[\left(\frac{n_L}{(n_L - 1)^2} - 3 \right) \frac{l_E^2}{f_L^2} + 10 \cdot \left(\frac{l_E}{f_L} - 1 \right) \right] \quad (30)$$

and

$$G_4 = f_L \cdot \left[\frac{A_4 - 2A_2 \cdot F_3}{l_E^4} - \frac{3 \cdot A_0^2 \cdot A_2}{4 \cdot l_E^2} + \frac{A_0^5}{8} + \frac{1}{8 \cdot l_E^5} \right]. \quad (31)$$

With these equations the lens function of a ball lens is completely described within an approximation of 6th order.

4 Coupling loss due to spherical aberration

In order to calculate the contribution to the coupling loss which solely originates from the spherical aberration of ball lenses, the overlap of two fields is studied for coupling with ball lenses of different refractive indices and focal lengths: first, a gaussian beam of small spot size which is transformed by a ball lens, and second, a plane gaussian beam of matched spot size as a reference field. The overlap is calculated with (10) with $\psi_{L2} = L \cdot \psi_{L1}$ as circular symmetric far field of a LD ($w = 1 \mu\text{m}$) or SMF ($w = 5 \mu\text{m}$) multiplied with the lens function L . The field ψ_{F3} is assumed to have a zero phase and the same spot size as the field ψ_{L2} , i.e. $w_{F3} = w_{L2} = w_{L1}/K$ (see (28)). Therefore the only coupling loss results from the spherical aberration of the employed lens.

The results are shown in Fig. 4 as overlap η_g vs. the focal length f_L of the ball lens. Two spot sizes, $w_1 = 1 \mu\text{m}$ and $w_2 = 5 \mu\text{m}$, and three different refractive indices, $n_{L1} = 1.57$, $n_{L2} = 1.75$ and $n_{L3} = 1.91$ are used as parameters. Reflection losses are ignored. The curves clearly

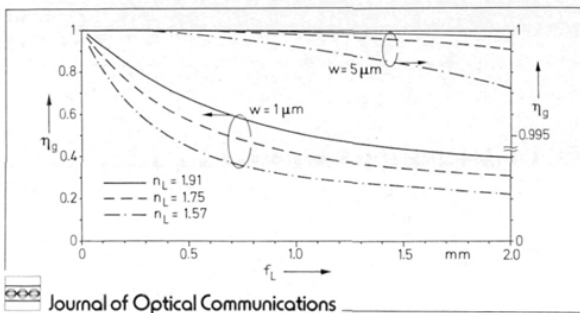


Fig. 4: Coupling efficiency η_g vs. focal length f_L of the ball lens for coupling a gaussian beam wave of spot size w to a plane gaussian beam wave of matched spot size; n_L is the refractive index of the lens; ($\lambda = 1.3 \mu\text{m}$)

indicate that the overlap, i.e. the coupling efficiency, increases with decreasing focal length and increasing refractive index of the ball lens.

This dependence can be explained by the fact that the spherical aberration originates from differences in optical path lengths at different ray angles. For ball lenses with equal refractive index the relation $\Delta l/f_L$ of the path length difference Δl to the focal length f_L is constant, i.e. the absolute value of Δl and therefore the aberration loss increase with increasing focal length. The dependence of η_g on the refractive index of the lenses is determined by the stronger refraction of the rays at the surface of a lens with

larger refractive index. The ray angle inside the lens and therefore the path length difference Δl decreases with increasing refractive index (see (13) to (16)). Thus, the aberration losses decrease with increasing refractive index.

In case of the SMF to plane wave coupling ($w = w_2 = 5 \mu\text{m}$) the coupling efficiency exceeds 99% throughout, and the ball lenses can be regarded as ideal lenses. This is a simple but very accurate approximation of the actual lens action. The reason for the negligible effect of the spherical aberration is given by the small divergence angle of the SMF radiation, which causes the last two terms on the right side of (13) not to effect the lens law of geometrical optics given by the first terms.

The curves in Fig. 4 are calculated with a series expansion of the phase terms of the fields and the lens function up to order r^6 . However, in most cases an expansion up to order r^4 should be sufficient, because the main part of the spherical aberration is described by the 4th order term.

5 Efficiency of a two lens LD to SMF coupler

The efficiency of the two lens coupler of Fig. 1 is calculated with the overlap integral in (10). Because of the small divergence of the SMF fundamental mode lens 2 acts nearly as an ideal lens and the field ψ_{F3} can be calculated by simple gaussian beam optics [9]. With w_f as the spot size of the SMF fundamental mode f_2 as focal length of lens 2 and the distances shown in Fig. 1 the field ψ_{F3} is given by

$$\psi_{F3}(r) = \sqrt{\frac{2}{\pi}} \cdot \frac{1}{w_{F3}} \cdot \exp \left[-\frac{r^2}{w_{F3}^2} + j \frac{\pi \cdot r^2}{\lambda \cdot l_3} \left(1 - \frac{l_e}{l_3} \frac{w_{F1}^2}{w_e^2 + w_{F1}^2} \right) \right] \quad (32)$$

with the abbreviations

$$w_{F1} = \left[\left(\frac{l_2 \cdot \lambda}{\pi \cdot w_f} \right)^2 + w_f^2 \right]^{\frac{1}{2}}, \quad (33)$$

$$l_e = \left[\left(\frac{l_2 \cdot \lambda}{\pi \cdot w_f \cdot w_{F1}} \right)^2 \cdot \frac{1}{l_2} + \frac{1}{l_3} - \frac{1}{f_2} \right]^{-1}, \quad (34)$$

$$w_e = \frac{l_e \cdot \lambda}{\pi \cdot w_{F1}}, \quad (35)$$

and

$$w_{F3} = \left[\left(\frac{l_2 \cdot \lambda}{\pi \cdot w_{F1}} \right)^2 + \left(\frac{l_3}{l_e} w_{F1} \right)^2 \right]^{\frac{1}{2}}. \quad (36)$$

As an example, the coupling of a LD with spot size $w_1 = 1 \mu\text{m}$ to a SMF with spot size $w_f = 5 \mu\text{m}$ is studied. The focal length of lens 2 is chosen to $f_2 = 1.377 \text{ mm}$ and is kept constant, while the focal length f_1 of lens 1 is varied. The distance between the principal planes of the lenses is $l_3 = 5 \text{ mm}$. Reflection losses are ignored.

In Fig. 5 the coupling efficiency is shown as a function of the focal length ratio f_2/f_1 of both lenses (with $f_2 = \text{const.}$). Two sets of curves are plotted with the refractive indices $n_1 = 1.57$, $n_1 = 1.75$, and $n_1 = 1.91$ of lens 1 as parameters. In the lower set the SMF front face is placed in the focal plane of lens 2, i.e. $l_2 = f_2$, and only the distance l_1 is

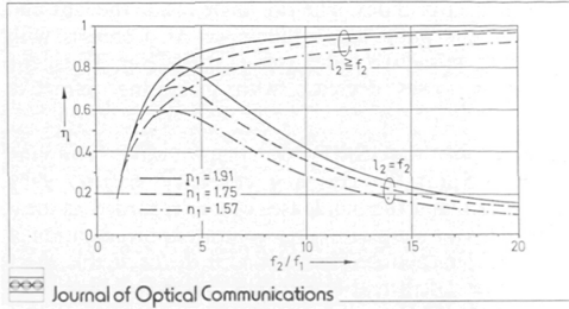


Fig. 5: Maximum coupling efficiency η vs. focal length ratio f_2/f_1 of lenses 2 and 1 ($f_2 = 1.377 \text{ mm} = \text{const.}$) for 3 refractive indices n_1 of ball lens 1; for the upper set of curves the distances l_1 and l_2 ($> f_2$) are adjusted for maximum η , and for the lower set $l_2 = f_2$ is fixed and only l_1 is adjusted; (parameters: $l_3 = 5 \text{ mm}$, $w_1 = 1 \mu\text{m}$, $w_f = 5 \mu\text{m}$, $\lambda = 1.3 \mu\text{m}$)

adjusted for maximum η . In this case the maximum coupling efficiencies are achieved for f_2/f_1 values slightly smaller than the confocal ratio $f_2/f_1 = w_f/w_1 = 5$. In the other set of curves both distances l_1 as well as l_2 are adjusted for maximum η with the condition $l_2 > f_2$. At small f_2/f_1 values these curves are identical to the former ones. At higher values, however, the coupling efficiency increases more and more.

This increase can be explained by the reduction of aberration loss with decreasing radius and focal length of lens 1, as it is shown in Fig. 4. Furtheron for a coupler with a high f_2/f_1 ratio the best coupling efficiency is achieved when the conditions $l_1 < f_1$ and $l_2 > f_2$ for the distances l_1 and l_2 are fulfilled, which means that the LD beam diverges from lens 1 to lens 2 (the beam width increases in propagation direction). Lens 1 therefore refracts the LD beam less than in the confocal case with a nearly parallel beam in the region between the lenses. This reduced beam refraction causes a reduction of aberration loss of lens 1. The missing refraction must of course be compensated by lens 2 which now has a greater part of the total beam refraction. But the loss due to spherical aberration of lens 2 increases only by a very small amount because the divergence angles at lens 2 remain small. So at last a net reduction in aberration loss occurs.

It is well known that coupling units with only a single lens always exhibit a lower coupling efficiency than couplers with two lenses (with the lens of the single lens coupler as lens 1). This fact can also be explained by the arguments given above. In a single lens coupler the LD beam wave is converging from the lens to the SMF, so the lens must refract the LD beam stronger than even in a confocal two lens coupler. The result is a higher aberration loss and a lower coupling efficiency.

In order to prove the gaussian beam optics approximation ((19)–(23)), the curves in Fig. 5 are checked by a calculation which additionally takes the spherical aberration of lens 2 into account. In this calculation all fields are assumed to be circular symmetric. The field ψ_{F1} is given by (6) and (7) with spot size w_{F1} and the field ψ_{F2} is calculated with (9). The lens function L_2 is given by (21) with the data of lens 2. The field ψ_{F3} at a distance l_3 from the principal plane H_2 of lens 2 is then calculated with the diffraction integral

$$\psi_{F3}(r) = \frac{\sqrt{8 \cdot \pi} \cdot \exp \left[j \frac{\pi \cdot r^2}{\lambda \cdot l_3} \right]}{\lambda \cdot l_3 \cdot w_{F3}} \int_0^\infty \exp \left[-\frac{Q^2}{w_{F2}^2} - j(D_2 Q^2 + D_4 Q^4 + D_6 Q^6) \right] \cdot J_0(D_1 \cdot Q) \cdot Q \cdot dQ \quad (37)$$

with J_0 as the Bessel function of zero order and the abbreviations

$$D_1 = \frac{2 \cdot \pi \cdot r}{\lambda \cdot l_3}, \quad (38)$$

$$D_2 = \frac{\pi}{\lambda} \left(\frac{1}{f_2} - \frac{1}{l_2} - \frac{1}{l_3} \right), \quad (39)$$

$$D_4 = \frac{\pi}{\lambda \cdot f_2} \left(G_{22} + \frac{f_2}{4 \cdot l_2^3} \right), \quad (40)$$

and

$$D_6 = \frac{\pi}{\lambda \cdot f_2} \left(G_{42} - \frac{f_2}{8 \cdot l_2^5} \right). \quad (41)$$

The functions G_{22} and G_{42} are given by (30) and (31) with the parameters of lens 2 and the subscripts changed to 2.

In order to calculate the coupling efficiency as given by (10) a double numerical integral must be evaluated, which takes much longer time for computation than a single integral. But the calculation showed that the results are within a deviation of less than 1% the same as given by the gaussian beam optics in Fig. 5, verifying the validity of this approximation.

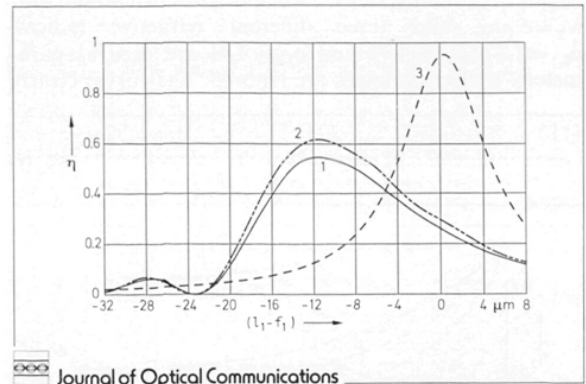


Fig. 6: Coupling efficiency η of a LD to SMF coupler with two ball lenses vs. axial displacement $l_1 - f_1$ of the LD: measured curve 1 (the small ripples which are caused by reflections at lens 1 have been omitted), calculated curve 2, and calculated curve neglecting aberration 3; reflection losses are ignored; (parameters: $\lambda = 1.3 \mu\text{m}$, $w_1 = 0.8 \mu\text{m}$, $w_2 = 1.0 \mu\text{m}$, $w_f = 5 \mu\text{m}$, $n_1 = 1.75$, $f_1 = 0.291 \text{ mm}$, $f_2 = 1.377 \text{ mm}$, $l_2 = f_2$, $l_3 = 5 \text{ mm}$)

Figure 6 shows η vs. the axial displacement $l_1 - f_1$ of the LD for a two lens coupling unit with the parameters given in Table 1. Three curves are shown: an experimentally measured curve 1), a curve calculated with the proposed theory 2), and, for comparison, a curve calculated with the conventional gaussian beam optics neglecting aberration 3). Reflection losses are ignored in all curves, i.e. for determining the coupling efficiency in the experiment (curve 1) the reference power was measured between lens 2 and the SMF, so the measured efficiencies had to be corrected only for the low reflection loss of the SMF.

Table 1: Parameters of the coupling unit.

λ	$= 1.3 \mu\text{m}$
f_1	$= 0.291 \text{ mm}$
n_1	$= 1.75$ (LaF22 sphere with 0.5 mm diameter)
f_2	$= 1.377 \text{ mm}$ (SK5 sphere with 2 mm diameter)
l_2	$= f_2$
l_3	$= 5.0 \text{ mm}$
w_f	$= 5.0 \mu\text{m}$
w_{1x}	$= 0.8 \mu\text{m}$ (calculated from the FWHM-angles of the measured far field of the Hitachi HL 1321 AC laser diode)
w_{1y}	$= 1.0 \mu\text{m}$

The curves in Fig. 6 clearly show that the coupling efficiency is essentially determined by the spherical aberration of the ball lenses, especially of lens 1. For maximum η the LD must be placed closer to the lens than in the case of coupling with ideal lenses, because the spherical

angles α and β . For a given set of optical elements the coupling efficiency now depends on the parameters $l_1, l_2, l_3, d_k, d_f, d_{f1}, \alpha$, and β . In order to calculate the coupling efficiency η , (10) is evaluated with modified field functions ψ_{L2} and ψ_{F3} which now include these misalignments.

With the offset d_k of lens 1 in y-direction (Fig. 7) the field ψ_{L2} is given by

$$\psi_{L2}(x, y, d_k) = \sqrt{\frac{2}{\pi}} \cdot \frac{A(x, y)}{\sqrt{w_{L1x} \cdot w_{L1y}}} \cdot \exp \left[-\left(\frac{x^2}{w_{L1x}^2} + \frac{y^2}{w_{L1y}^2} \right) \right] \cdot \exp \left[-j \frac{\pi}{\lambda} \left\{ \frac{x^2 + y^2}{l_1} \left(1 - \frac{x^2 + y^2}{4 \cdot l_1^2} + \frac{(x^2 + y^2)^2}{8 \cdot l_1^4} \right) - \frac{x^2 + y_d^2}{f_1} (1 + G_2 \cdot (x^2 + y_d^2) + G_4 \cdot (x^2 + y_d^2)^2) \right\} \right] \quad (42)$$

with $y_d = y - d_k$ and $A(x, y)$ given by (23).

Taking the offsets d_f and d_{f1} and the tilt angles α and β (all in y-direction) into account (see Fig. 7) the field ψ_{F3} is given within the gaussian beam approximation by

$$\psi_{F3}(x, y, d_f, d_{f1}, \alpha, \beta) = \sqrt{\frac{2}{\pi}} \cdot \frac{1}{w_{F3}} \exp \left[-\frac{x^2 + y^2}{w_{F3}^2} \right] \cdot \exp \left[j \frac{\pi}{\lambda} \cdot \left\{ \frac{x^2 + y_m^2}{l_3} \left(1 - \frac{l_e}{l_3} \frac{w_{F1}^2}{w_c^2 + w_{F1}^2} \right) - 2 \cdot y \cdot \gamma \right\} \right] \quad (43)$$

aberration can partly be compensated by a defocus [5]. The shapes of curves 1) and 2) are nearly identical, even at small distances between LD and lens 1 (small l_1 values), where a second maximum of η appears. This additional small maximum is directly caused by the spherical aberration, it is not present in case of the coupling with ideal lenses (curve (3)). The only difference between curves 1) and 2) is given in the maximum coupling efficiency of 62% for curve 2) and 55% for curve 1). But this difference is believed to result from deviations of the actual LD field from a gaussian shape, which is one of the basic assumptions of the calculation. Hence, losses occur in the experiment, which are not considered in the calculation.

6 Effect of misalignments

In practice optical coupling arrangements are never perfectly aligned. It is therefore useful to extend the coupling theory to include misalignment effects. On the one hand, the additional losses due to misalignments of the optical elements can be calculated, and, on the other hand, fabrication and adjustment tolerances can be given.

Figure 7 shows a schematic diagram of a coupling arrangement with transverse offsets d_k, d_f and d_{f1} and tilt

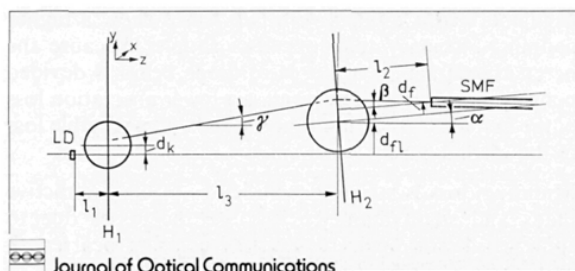


Fig. 7: Schematic diagram of a two lens coupling unit with transverse offsets d_k of the ball lens 1, d_{f1} of the SMF lens 2 axis, d_f of the SMF, and tilt angles α of the SMF lens 2 axis and β of the SMF

with $y_m = y - d_{f1} - d_f - l_2 \cdot \beta + l_3 \cdot \gamma$, $\gamma = \alpha + d_f/f_2 - (1 - l_2/f_2) \cdot \beta$, and the other abbreviations given by (32) to (35). For offsets and tilt angles in x-direction only the x and the y coordinates have to be changed

As an example the effect of the transversal offsets d_k and d_f of the ball lens 1 and the SMF on the coupling efficiency η is studied, respectively. The coupling efficiency is calculated with the fields given by (42) and (43) for a coupling unit as shown schematically in Fig. 7 with the parameters given in Table 1. The results are compared to measurements.

The dependence of the normalized coupling efficiency η_N on the transversal offset d_k is shown in Fig. 8. Two different curves are achieved for an offset in x- and y-direction because the LD has an elliptic near field: Curves 1) and 2) show η_N vs. d_k as calculated with the proposed theory. The measured results are inserted as crosses for the offset in y-direction and as circles for the offset in x-direction. In addition, calculations with the gaussian beam optics approximation are shown as curves 3) and 4).

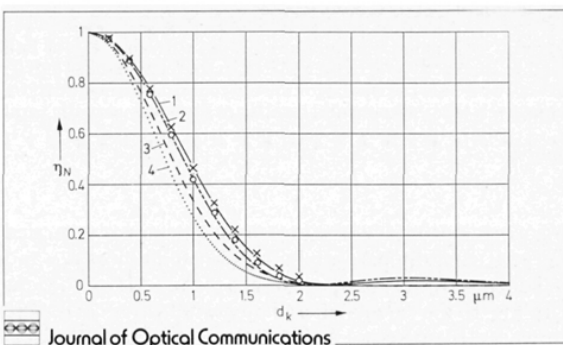


Fig. 8: Normalized coupling efficiency η_N vs. the transversal offset d_k of ball lens 1; curves 1 and 2 are calculated with the proposed theory for an offset in x- and y-direction, respectively; curves 3 (y-dir.) and 4 (x-dir.) are calculated with the gaussian beam optics approximation neglecting spherical aberration; the measured results are inserted as $\times$ for the offset in y-direction and as $\circ$ for the offset in x-direction; (parameters: see Fig. 6)

Fig. 8 shows a very good agreement between proposed theory and experiment. For this special coupling unit the spherical aberration causes an increase of the offset tolerance d_{ke} at the $1/e$ drop of η_N from $0.95 \mu\text{m}$ to $1.17 \mu\text{m}$ in the x-direction and from $1.04 \mu\text{m}$ to $1.25 \mu\text{m}$ in the y-direction. So the actual offset tolerances are approx. 20% larger than the predictions given by the gaussian beam optics calculation.

The dependence of the normalized coupling efficiency η_N on the transversal offset d_f of the SMF is shown in Fig. 9. Again, for curves are shown for the calculations, and crosses and circles for the measured results. Here, the spherical aberration increases the offset d_{fe} at the $1/e$ drop of η_N again by approx. 20% from $4.35 \mu\text{m}$ to $5.3 \mu\text{m}$ in x-direction and from $4.75 \mu\text{m}$ to $5.65 \mu\text{m}$ in y-direction.

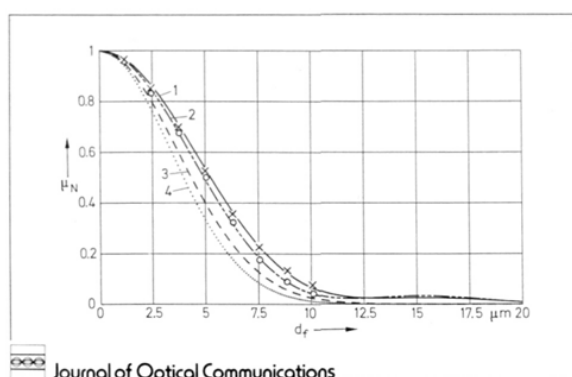


Fig. 9: Normalized coupling efficiency η_N vs. the transversal offset d_f of the SMF; parameters are given in Fig. 8

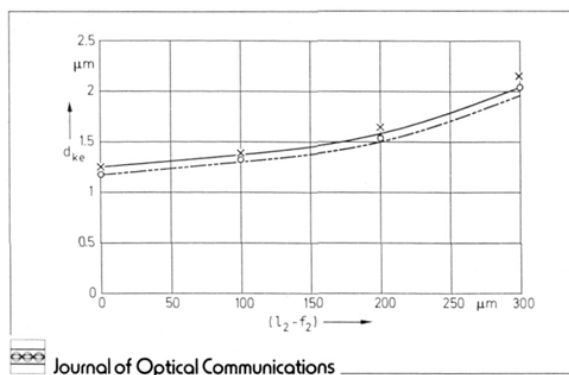


Fig. 10: Calculated and measured offset tolerance d_{ke} of ball lens 1 vs. distance $l_2 - f_2$ of the SMF from the focal plane of lens 2; curves 1 and 2 are calculated for the offset in y- and in x-direction, respectively; the experimental results are shown as $\times$ (y-dir.) and as $\circ$ (x-dir.); (parameters: see Fig. 6, l_1 is adjusted for maximum η)

It is worth noting that the measurements must be carried out very carefully because both offset tolerances d_{ke} and d_{fe} depend strongly on the distance of the SMF to the lens 2. In Fig. 10 the calculated and measured values of d_{ke} are shown vs. the distance $l_2 - f_2$ of the SMF from the focal plane of lens 2 (see Fig. 1). The curves indicate nearly a doubling of the d_{ke} values with a change of the distance $l_2 - f_2$ of only $300 \mu\text{m}$. If the position of the SMF in the measurement set up, i.e. the distance $l_2 - f_2$, is not precisely known, then the calculated and the measured d_{ke} values could differ by an amount which is much greater than

given by the difference between the simple gaussian beam optics approximation and the calculation including the spherical aberration as described above. This fact occurs especially, when a coupler is adjusted for the absolute maximum coupling efficiency, because then the distance $l_2 - f_2$ differs nearly always from zero. E.g. for the coupler discussed here, the distance $l_2 - f_2$ would be approximately $120 \mu\text{m}$, when l_1 as well as l_2 are adjusted for maximum η .

The same argumentation holds for the dependence of the offset tolerance d_{fe} on the distance $l_2 - f_2$ of the SMF from the focal plane of lens 2. As it is shown in Fig. 11, the d_{fe} values change from just below $6 \mu\text{m}$ to approx. $4 \mu\text{m}$ for a change of $l_2 - f_2$ of $300 \mu\text{m}$.

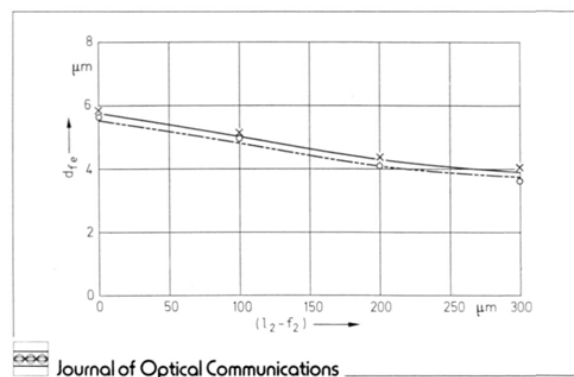


Fig. 11: Calculated and measured offset tolerance d_{fe} of the SMF vs. distance $l_2 - f_2$ of the SMF from the focal plane of lens 2; parameters are given in Fig. 10

The theory was also applied to the extensive experimental data given in Ref. 2. The calculations also showed a very good agreement with the measurements in nearly all cases.

7 Conclusion

A theory for the calculation of the coupling efficiency between a laser diode and a single-mode fiber including the losses due to misalignments and the spherical aberration is presented for coupling units with ball lenses.

It is shown that the coupling loss is mainly caused by the spherical aberration of the ball lens which is placed directly in front of the laser diode (lens 1 in Fig. 1) and which must collect the high numerical aperture radiation of the laser diode. A second lens in front of the single-mode fiber (lens 2 in Fig. 1) on the other hand can nearly always be regarded as ideal lens and therefore causes only negligible loss. Couplers with two lenses show a higher coupling efficiency than one lens coupler, because the necessary refraction of the laser diode beam is divided between both lenses. The result is a lower aberration loss of the first lens (at the laser diode) and still negligible loss of the second lens.

Minimum loss is achieved with lenses of high refractive index and small diameter, because the losses due to spherical aberration decrease with decreasing focal length and increasing refractive index of the ball lens.

A comparison of the calculated and measured coupling efficiencies and offset tolerances for a coupling arrangement with two ball lenses showed an excellent agreement.

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