

Analysis of Efficiency and Misalignment Tolerances in Laser Diode Pigtailling Using Single Ball Lens

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Abstract: In this paper we present some investigations and analysis on coupling efficiency and misalignment tolerances in coupling of laser diode to single mode fiber using single ball lens of (diameter = 1mm, and refractive index $n = 1.8333$). It has been found that there should be an optimization for positioning of the ball lens between laser diode and the tip of the fiber. At some optimum positions, the coupling efficiency can reach maximum value over 90% when the ratio of the divergence angles ($M = \theta_x / \theta_y$) in both x and y directions respectively is (20/33) and the mode matching is very effective as it is illustrated by the effect of the lateral and angular offsets in both x and y directions on the misalignment tolerances. But when the ratio is ($M=8/33$) there is a reduction in coupling efficiency and the transformation is not effective. We also studied the effect of the transformed beam waist radii on the 1_dB axial, lateral and angular misalignment tolerances for the proposed coupling scheme and also noticed that the mode matching is very effective for ($M=20/33$). Our experimental results showed a significant relaxation in misalignment tolerances using single ball lens for coupling with optimum coupling efficiency of about 55% at a relaxed working distance in the range of (0.7 – 1.2 mm).

Keywords: ball lens, coupling efficiency, misalignment tolerances, mode matching

INTRODUCTION

Most of the production cost of the Photonic devices modules is due to the coupling and packaging process, therefore understanding the optimal coupling methods and determining the effective coupling schemes along with the packaging facilities is very important for reducing the devices cost. Laser welding proved to be the most effective tool for the automation of laser diode coupling and packaging process which yield a very reliable packaging and strong attachments of various components. The mismatch between the elliptical mode-field of the laser diode emission and the circular mode-field of the single mode fiber is the major cause of coupling loss. Different coupling schemes have been proposed, either discrete microlenses^[5] or fiber tapers are used. Butt coupling is the common and old direct coupling but this coupling scheme results in a very low coupling efficiency (5-25%). A coupling method using a cylindrical lens has been also reported^[3,14] for coupling laser diodes to single-mode fiber. It has been also reported that a combination of a cylindrical lens and Graded index (GRIN) rod lens^[12] can be employed to give a relaxed tolerances with high coupling efficiency. Another efficient coupling scheme with a hemispherical lens

fabricated on the fiber endface^[12]. The use of tapered hemispherical end single-mode fiber also reported to give efficient and reflection insensitive coupling^[11]. Fiber microlenses with different shapes and configurations (circular, cylindrical, hemispherical, and hyperbolic) reported to achieve good coupling efficiencies, however, the lens aberration can not be avoided which affect the coupling efficiency, moreover the asymmetrical formation of the microlenses severely affect the misalignment tolerances. Coupling of laser diode to single mode fiber using optical elements and lenses is associated with lot of difficulties regarding alignment, positioning, and fixing. Apart from the problem of lens aberrations that affect the coupling efficiency, single lens or a combination of confocal two lenses are promising methods for efficient couplings with wide lateral and angular misalignments, but these configurations have the problem of the attachments and fixing the components in an active alignment process. These requirements become feasible due to the advancement in laser applications, laser welding with two or three simultaneous beams with very small spot sizes can be employed for fixing lenses at their holders to the substrate during an active alignment process, and then the ferruled fiber tip (The fiber tip which is to be attached to the module is metallicity feruled to enable

the welding to the substrate via certain type of welding clips) is welded to the substrate using various types of welding clips. The possibility of deriving the pigtailed laser diode module during the alignment and welding process along with the measurement of the coupled power at the other end of the fiber provide an active alignment procedure for precise adjustments of all the coupling components in their optimum positions. Relaxed working distance (the separation between the coupling system and the ferruled fiber tip) and misalignment tolerances are advantageous of any packaged laser diode module which may enable inserting any optical component and allow flexibility in aging and environmental variation. For a butterfly laser diode module fig. (1), two simultaneous beams with very small spot sizes can be employed for fixing lenses at their holders to the substrate during an active alignment process, and then the ferruled fiber tip is welded to the substrate using various types of welding clips.

Experimental Procedure: Besides electronic circuitry, a typical transmitter consists of a diode laser with an optical isolator, a lens and a fiber pigtail. During production, these components are positioned and affixed by laser welding. Post weld shift along with other welding defects can be minimized or even eliminated by suitable selection of the material of welding tools such as fiber ferrule, welding clips, and the substrate. It is also reported that the laser beam parameters, the design of welding clips, and welding sequence have a very strong impact on the weld yields and hence the coupling efficiency.

A single ball lens made of LaSF N9, grade A, fine annealed optical glass with 1 mm diameter and a refractive index of 1.8333 is used to couple light from 1550nm laser diode to a single mode fiber. During the alignment process, the system continuously measures the output power of the diode laser at the free end of the fibers to determine coupling efficiency. A machine vision system pre-positions the housing, after the system locates the light in the fiber, alignment routines determine the optimum coupling position. The coupling parts are then fixed using two or three simultaneous laser beams from Nd: YAG laser. Normally for butterfly type modules the system is equipped with two beams as shown in the fig. (1) The laser pulse energy and duration as well as the sequence of the spot welds have to be adjusted to compensate the expected deformation and guarantee a well-performing welding joint without introducing unnecessary heat. The spot welds are placed symmetrically to reduce thermal influence, this process compensates for the stress introduced by the welds. The alignment process for all components and the spot-weld quality are monitored by

CCD cameras on the welding optics. The welding laser includes a pilot laser beam, which simplifies positioning the spots and the development of the welding process. During the active alignment and scanning process the coupled power is monitored continuously by the optical meter

Theoretical Considerations: It is well known that laser diodes have elliptical emission which can be described by elliptical Gaussian field distributions whereas single mode fibers that support the fundamental LP₀₁ mode that can be accurately described by circular Gaussian field distributions.

The laser field Ψ_{lL} before the ball lens and at a distance d_1 from the laser facet is given by^[1].

$$E_{lL} = \left(\frac{2}{\pi w_{lx} w_{ly}} \right)^{1/2} \exp \left[- \left(\frac{x^2}{w_{lx}^2} + \frac{y^2}{w_{ly}^2} \right) \right] \exp \left[-j k_1 \left(\frac{x^2}{2 R_{lx}} + \frac{y^2}{2 R_{ly}} \right) \right] \quad (1)$$

$k_1 = 2\pi / \lambda$ is the wave number or the propagation constant in free space and λ is the wavelength in free space, w_{lx} , w_{ly} are the beam waist radii perpendicular and parallel to the junction plane of the laser diode facet respectively, the beam waist sizes w_{lx} , w_{ly} are the waist radii defined at $1/e^2$ points of the emitted optical power in the transverse direction. R_{lx} , R_{ly} are the radii of wavefront curvature perpendicular and parallel to the junction plane respectively. w_{lx} , w_{ly} can be expressed in terms of its minimum waist sizes ω_{lx} , ω_{ly} . The mode field of the single mode fiber can be expressed as²:

$$E_f = \left(\frac{2}{\pi \omega_f^2} \right)^{1/2} \exp \left(- \frac{x^2 + y^2}{\omega_f^2} \right) \quad (2)$$

ω_f is waist radius of field at the single-mode fiber. After the ball lens, the laser mode field is get transformed to become:

$$E_{2L} = \left(\frac{2}{\pi w_{2x} w_{2y}} \right)^{1/2} \exp \left[- \left(\frac{x^2}{\omega_{2x}^2} + \frac{y^2}{\omega_{2y}^2} \right) \right] \exp \left[-j \frac{k_2}{2} \left(\frac{x^2}{R_{2x}} + \frac{y^2}{R_{2y}} \right) \right] \quad (3)$$

ω_{2x} , ω_{2y} are the transformed beam waists. R_{2x} and R_{2y} are the transformed radii of curvature in the X and Y directions; k_2 is the wave number in the coupling medium.

The coupling efficiency is expressed by the overlap integral^[1]

$$\frac{\left| \iint E_{2L} E_f^* dx dy \right|^2}{\iint |E_{2L}|^2 dx dy \iint |E_f|^2 dx dy} \quad (4)$$

After cube we get:

$$\eta = \eta = 4\omega_f^2 / \omega_{2x}\omega_{2y} \left[\left(1 + \omega_f^2 / \omega_{2x}^2\right)^2 + \left(k_2^2 \omega_f^4 / 4R_{2x}^2\right) \right]^{1/2} \left[\left(1 + \omega_f^2 / \omega_{2y}^2\right)^2 + \left(k_2^2 \omega_f^4 / 4R_{2y}^2\right) \right]^{-1/2} \quad (5)$$

ABCD ray tracing matrix can be used to express ω_{2x} , ω_{2y} and R_{2x} , R_{2y} in terms of their counterparts before transformations. When the lateral offset is considered, analytical analysis suggests that the coupling efficiency is given as:

$$\eta = \eta \exp \left(-2d_x^2 / \omega_{2x}^2 \left[\left(1 + \omega_f^2 / \omega_{2x}^2\right)^2 + \left(k_2^2 \omega_f^4 / 4R_{2x}^2\right) \right]^{-1/2} - 2d_y^2 / \omega_{2y}^2 \left[\left(1 + \omega_f^2 / \omega_{2y}^2\right)^2 + \left(k_2^2 \omega_f^4 / 4R_{2y}^2\right) \right]^{-1/2} \right) \quad (6)$$

Where, d_x is the lateral offset on x-axis and d_y is the lateral offset on y-axis

When the angular offset is considered

$$\eta = \eta \exp \left(-\frac{k_2^2 \omega_f^2}{2} \left\{ \eta^2 \left[\left(1 + \omega_f^2 / \omega_{2x}^2\right)^2 + \left(k_2^2 \omega_f^4 / 4R_{2x}^2\right) \right]^{-1/2} + \eta^2 \left[\left(1 + \omega_f^2 / \omega_{2y}^2\right)^2 + \left(k_2^2 \omega_f^4 / 4R_{2y}^2\right) \right]^{-1/2} \right\} \right) \quad (7)$$

Where ϕ_x , ϕ_y are the tilt angles in the x and y directions respectively.

The misalignment alignment tolerance can be defined as the displacement between the two beam waists along the optical axis which results in a 1-dB loss of coupling efficiency which is given in [7,8] for the case of equal waist radii of the laser beam in both x and y direction. We made a modification to be applied for the general case for axial misalignment tolerances as follows:

$$\Delta z_{1dB} = 0.5 \frac{\pi}{\lambda} \left(\sqrt{(w_{2x}^4 + w_{2y}^4) / 2 + w_f^2} \right) \quad (8)$$

For the lateral and angular alignment tolerances (displacement resulting in 1-dB coupling losses) can be expressed as:

$$\Delta r_{1dB} = 0.33 \left(\sqrt{(w_{2x}^4 + w_{2y}^4) / 2 + w_f^2} \right)^{1/2} \quad (9)$$

$$\Delta \theta_{1dB} = 60 \frac{\eta}{\lambda^2} \left(\sqrt{2(w_{2x}^4 + w_{2y}^4) + w_f^{-2}} \right)^{1/2} \quad (10)$$

RESULTS AND DISCUSSIONS

Theoretical calculation of coupling efficiency with working distance (separation of ball lens to single mode fiber) for the case of single ball lens coupling are shown in figs. (3,4) for different values of d_1 (the separation between the laser diode and the ball lens), which shows that at ($d = 0.2 - 0.25$ mm) the coupling efficiency is maximum with a wide range of

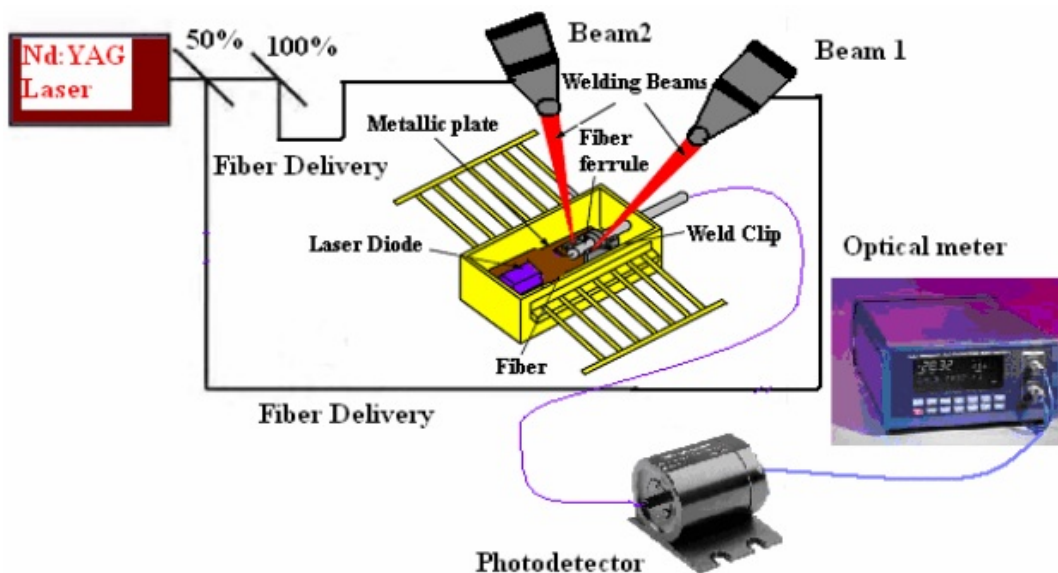


Fig. 1: Active alignment and dual laser beam weld for butterfly module

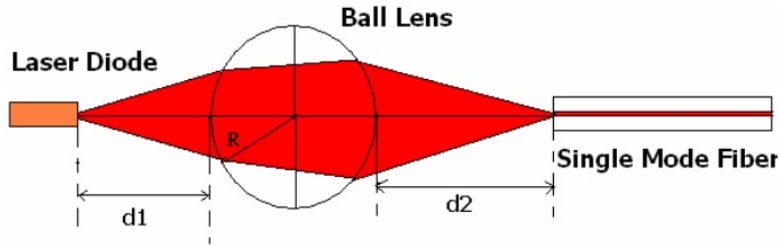


Fig. 2: Single ball lens coupling

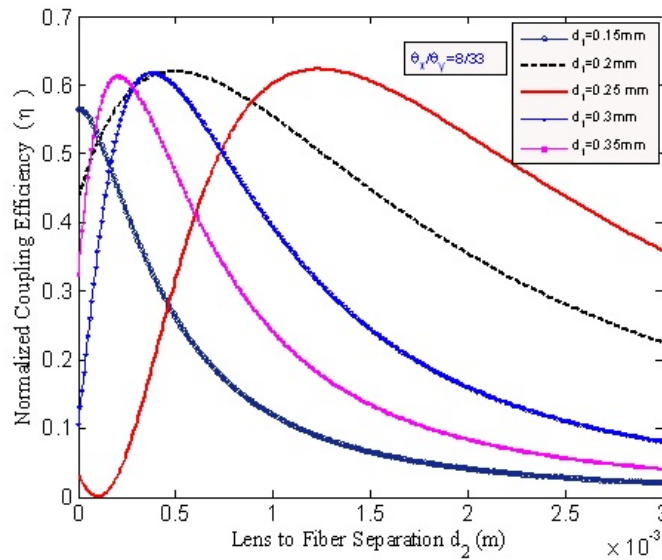


Fig. 3: Coupling efficiency versus the working distance d_2 , for ($M=8/33$)

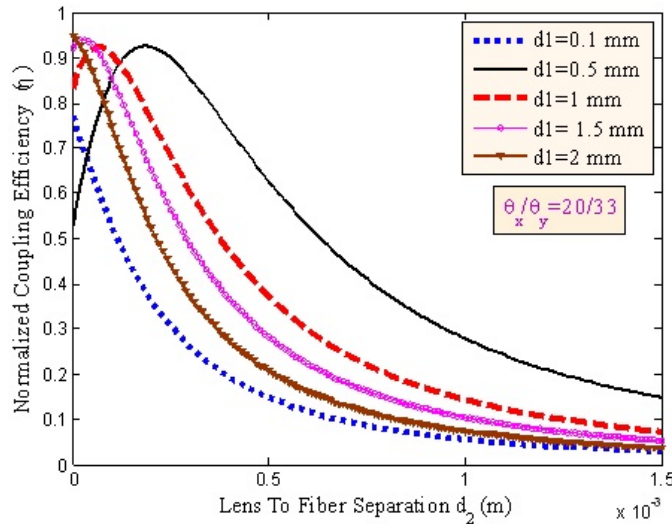


Fig. 4: coupling efficiency versus the working distance d_2 , for ($M=20/33$)

relaxed working distance. Experimentally we found that the obtained coupling efficiency can reach up to 55% at optimum position ($d_1=1.5$ mm and $d_2=0.7-1.2$ mm) as shown in fig. (15). if the divergence ratio of the elliptical mode field of the laser diode is ($20/33$) the

coupling efficiency can reach maximum value around 90% at optimum position of the ball lens with respect to both laser diode facet and the tip of the single mode fiber, whereas for a ratio of ($8/33$) the coupling efficiency is about 60% with relaxed working

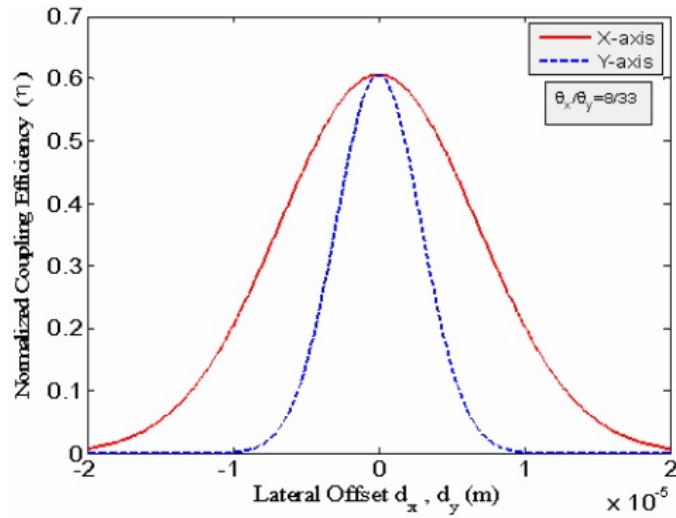


Fig. 5: The variation of coupling efficiency with the lateral offsets for ($M=8/33$)

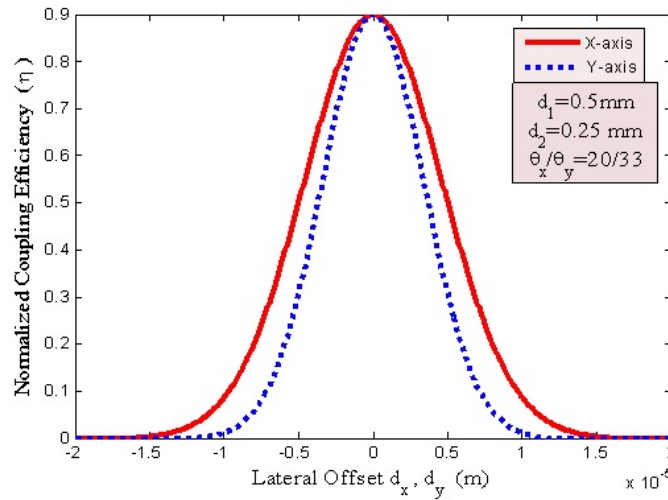


Fig. 6: The variation of coupling efficiency with the lateral offsets for ($M=20/33$)

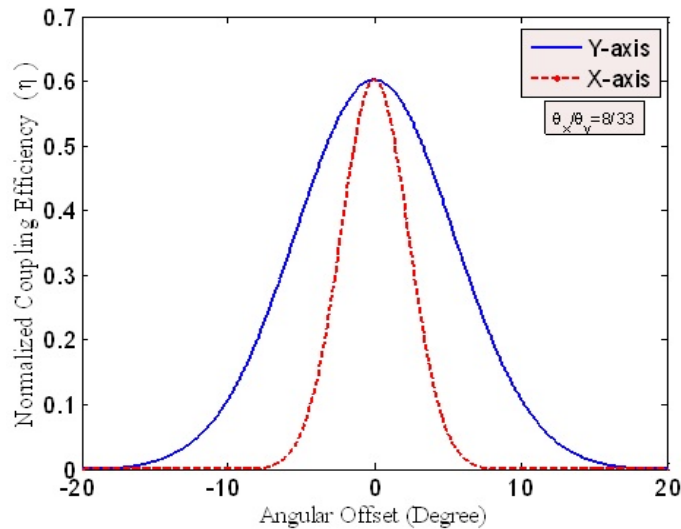


Fig. 7: The variation of coupling efficiency with the angular offsets for ($M=8/33$)

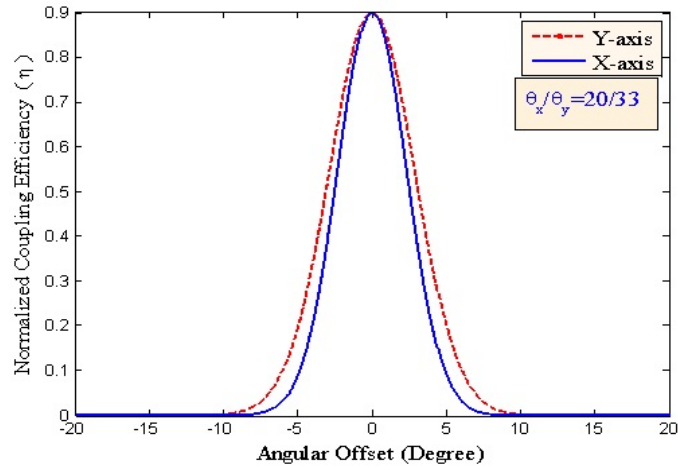


Fig. 8: The variation of coupling efficiency with the angular offsets for ($M=20/33$)

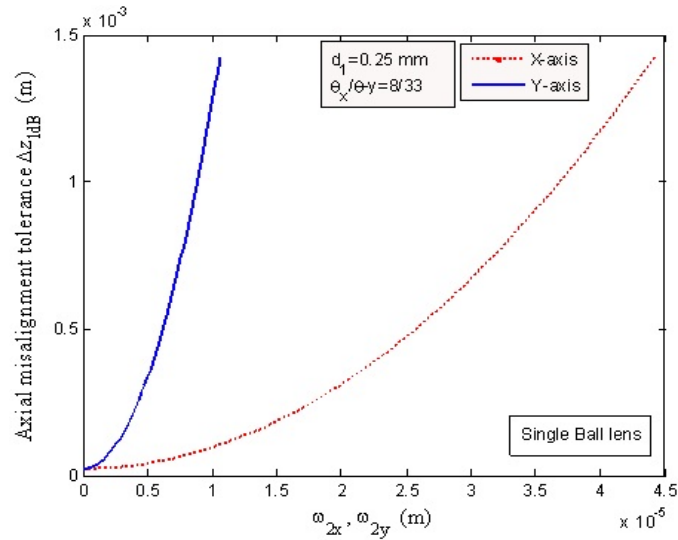


Fig. 9: 1_{dB} axial misalignment tolerance for $M=8/33$

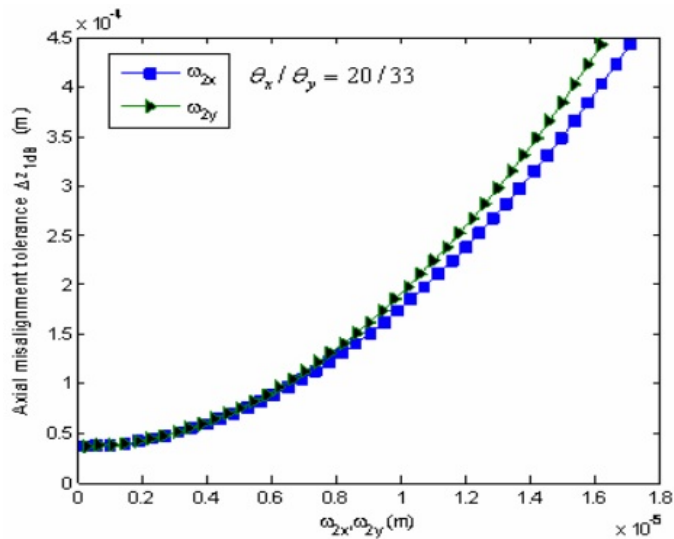


Fig. 10: 1_{dB} axial misalignment tolerance for $M=20/33$

distance despite that single ball lens is efficient but not sufficient for fully matching the mode fields of the elliptical laser diode mode field with the circular one of the single mode fiber. But for the case of ($M=20/33$). The effect of lateral and angular offset on coupling efficiency is shown for both M values in figs. (5,6,7 and 8) respectively. The effect of the change of the transformed beam waist sizes ω_{2x} , ω_{2y} on axial, lateral and angular 1-dB misalignment tolerances is calculated and plotted in figs. (9, 10, 11, 12, 13 and 14) respectively, which show that

after the transformation occurred to the mod field of the laser diode due to the passage through the ball lens, both beam waist radii in x and y directions become almost similar and have nearly the same effect on the misalignment tolerances. it is clear from the figures of offsets and 1-dB misalignment tolerances that the change in both x and y directions seems to be similar which means that the elliptical mode field of the laser diode has been effectively transformed to circular mode field and hence the mode matching is very effective.

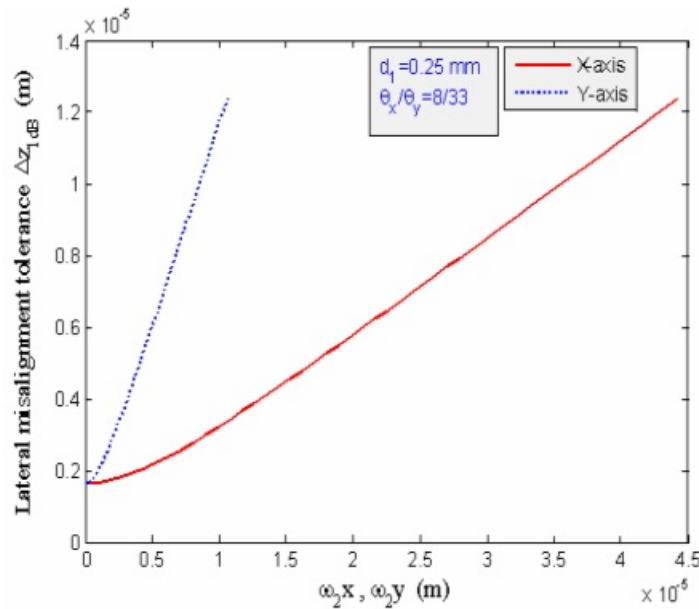


Fig. 11: 1_dB lateral misalignment Tolerance for $M=8/33$

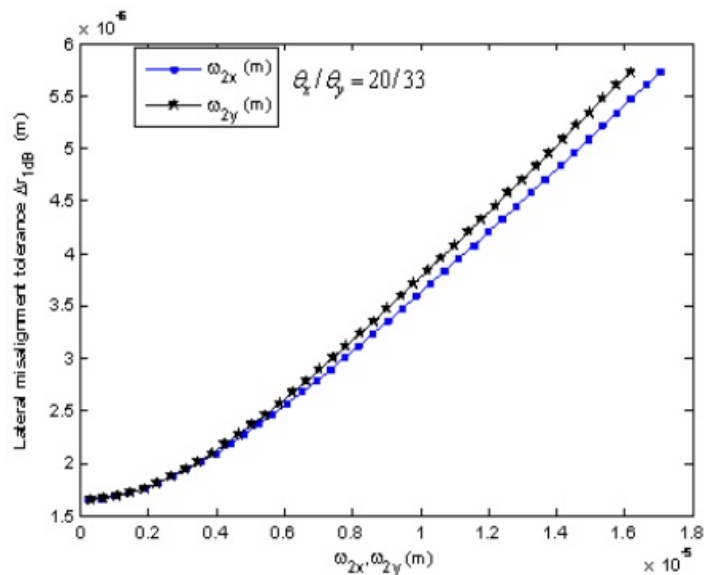


Fig. 12: 1_dB lateral misalignment Tolerance for $M=20/33$

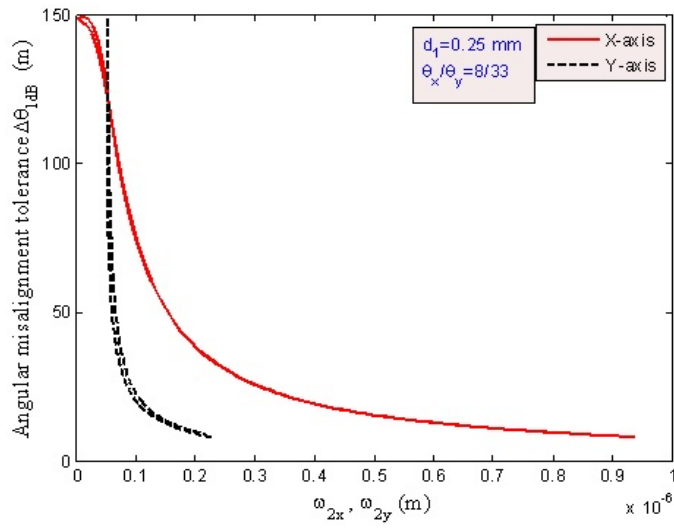


Fig. 13: 1_{dB} angular misalignment tolerance for M=8/33

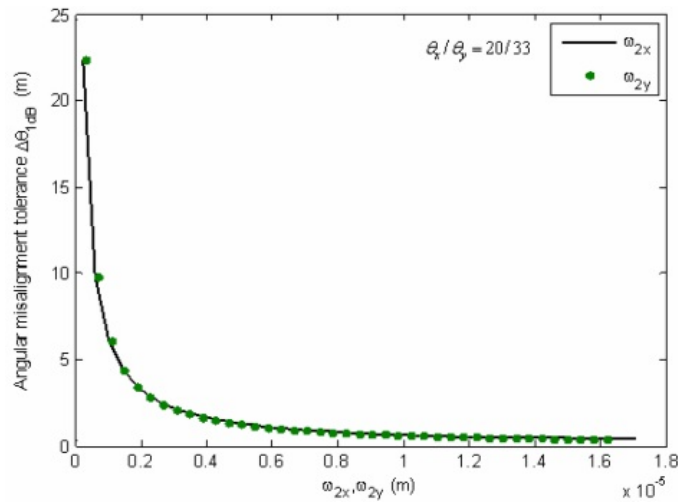


Fig. 14: 1_{dB} angular misalignment tolerance for M=20/33

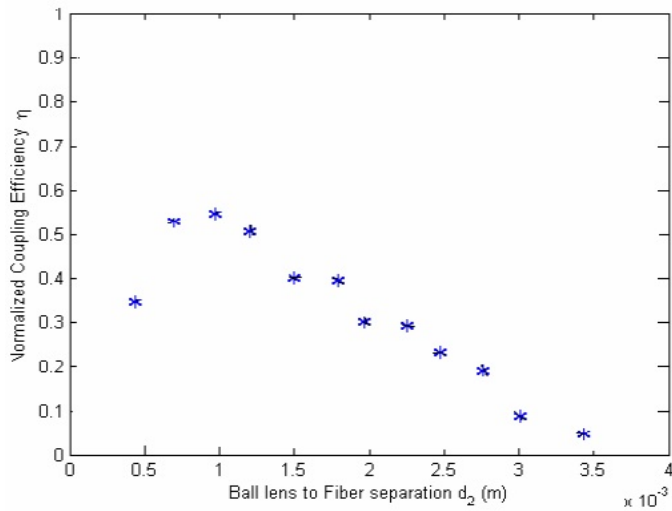


Fig. 15: Coupling efficiency versus the working distance d_2 , Exp.

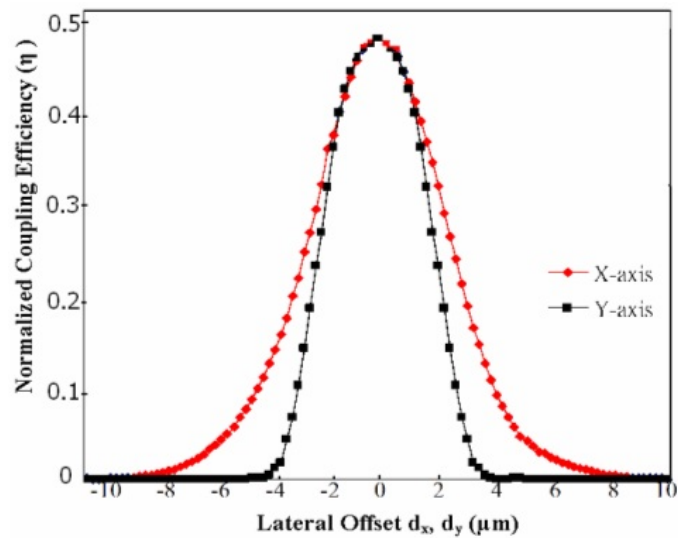


Fig. 16: The variation of coupling efficiency with the lateral offsets, Exp.

Conclusion: Theoretical results shows that for coupling 1550nm laser diode into a single mode fiber using single ball lens if the divergence ratio of the elliptical emission of the laser diode is (20/33) the coupling efficiency can reach maximum value around 90% at optimum position of the ball lens with respect to both laser diode facet and the tip of the single mode fiber, whereas for a ratio of (8/33) the coupling efficiency is about 60% with relaxed working distance despite that single ball lens is efficient but not sufficient for fully matching the mode fields of the elliptical laser diode mode field with the circular one of the single mode fiber. But for the case of (M=20/33) it is clear from the figures of offsets and 1-dB misalignment tolerances that the change in both x and y directions seems to be similar which means that the elliptical mode field of the laser diode has been effectively transformed to circular and hence the mode matching is very effective.

Laser welding technique with dual simultaneous Nd:YAG laser beams is applied for pigtailling 1550nm butterfly laser diode module. Single ball lens has been fixed inside its holders to the module substrate using certain types of welding clips, the ferruled fiber tip is also fixed at the optimum position that give maximum coupling efficiency with tolerant working distance using saddle shaped welding clip.

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