Coupling and attachment of single mode fiber into laser diode transmitter

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In this paper we present some investigations and analysis of various parameters that contribute for increasing the coupling efficiency of laser diode to single mode fiber coupling using ball lenses coupling scheme. Dual beams from Nd:YAG laser welding system have been used for the alignment and welding of the coupling components in a butterfly configuration. The process of attachment of fiber to laser diode and welding of various coupling components, such as lens holders, fiber ferrule and welding clips have been performed in what is so called active alignment process, where the system continues measuring the coupled power during the process of coupling and welding of coupling components in their holder to each other and to the main substrate. The experimentally measured coupling efficiency using double ball lenses coupling scheme was found to be around 75% with relaxed axial, lateral and angular misalignment tolerances. From theoretical calculations we found that by optimizing the separations between various components, coupling efficiency can reach 100% with relaxed misalignment tolerances. From the effect of lateral and angular offsets as well as the 1-dB misalignment tolerances calculations, the mode fields of laser diode and single mode fiber have been found to be effectively matched.

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1. Introduction

Pigtailing of laser diode transmitter includes coupling to a fiber via certain optical system coupling schemes and module packaging processes [1,3]. Nevertheless, direct coupling of laser diode into single mode fiber found to be inefficient ~ (5-20%) due to the mismatching between the laser diode and single mode fiber mode fields. A lot of published work in employing different types of microlenses fabricated on the fiber tip from the fiber itself, reported to give significant coupling efficiencies [5,9], but the problem of asymmetries in forming the lens on the fiber tip makes them very sensitive to axial, lateral and angular offsets. Coupling of laser diode to single mode fiber using optical elements and lenses is associated with a lot of difficulties regarding alignment, positioning, and fixing, for coupling laser diode to single mode fiber with optimum coupling efficiency and relaxed misalignment tolerances, it is very necessary to adjust all the coupling components in their optimum position which require very high precession. Different coupling schemes have been studied theoretically and experimentally by many researchers to enhance the coupling efficiency [4,5]. Apart form the problem of lens aberrations that affect the coupling efficiency, single lens or a combination of two lenses are promising methods for improving the coupling efficiency with wide lateral and angular misalignments. Ball lenses of small diameters have been reported [7,8] to be suitable for coupling laser diodes to single mode fibers, but they have been found to be very stringent in alignment and positioning fixation. Those difficulties become feasible due to the vast development in laser applications, the process of the alignment and fixing of ball lenses inside their holder to the substrate in the path between the laser diode and the fiber can be performed using laser welding technique with dual Nd:YAG laser beams (LW 4000S, from Newport) fig.(1) which is employed in this research for coupling and packaging 1550nm laser diode module. Laser welding because of its low distortion of the workpiece, was examined by many researchers and research centers for the packaging of laser diode modules. 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. The fiber tip which must be attached to the module is metallically feruled to enable the welding to the substrate via certain type of welding clips. Relaxed working distance and misalignment tolerances are advantageous to any packaged laser diode module which may enable inserting any optical component and allow flexibility in aging and environmental variation. Here we report the use of dual ball lenses of very small sizes (1 mm diameter) for coupling 1550 nm high power laser diode transmitter for communication applications.

2. Theoretical aspects

It is well known that laser diode have elliptical emission which can be described by an elliptical Gaussian field distribution whereas single mode fibers can be described by circular Gaussian field distribution.

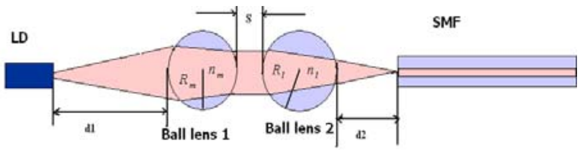

Fig.1 Dual ball lenses coupling of laser diode to single mode fiber.

The mode field of an elliptical emission from a laser diode is given as [1]:

$$\psi_L = \left(\frac{2}{\pi w_{1x} w_{1y}}\right)^{1/2} \exp\left[-\left(\frac{x^2}{w_{1x}^2} + \frac{y^2}{w_{1y}^2}\right)\right] \exp\left[-jK_1\left(\frac{x^2}{2R_{1x}} + \frac{y^2}{2R_{1y}}\right)\right] \quad (1)$$

$K_1 = 2\pi/\lambda_1$ is the wave number or the propagation constant in free space and λ is the wavelength in free space, w_{1x}, w_{1y} are the beam waist sizes perpendicular and parallel to the junction plane of the laser diode facet respectively, the beam waist sizes w_{1x}, w_{1y} are the waist radii defined at $1/e^2$ points of the emitted optical power in the transverse direction.

R_{1x}, R_{1y} are the radii of wavefront curvature perpendicular and parallel to the junction plane.

The mode field of the single mode fiber can be approximated by a symmetric fundamental Gaussian beam [2] with its waist located at the fiber endface.

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

w_f is the spot size of the mode field in the fiber given by:

The transformed laser field ψ_{2L} at the fiber plane 2 is given by:

$$\psi_{2L} = \left(\frac{2}{\pi w_{2x} w_{2y}}\right)^{1/2} \exp\left[-\left(\frac{x^2}{\omega_{2x}^2} + \frac{y^2}{\omega_{2y}^2}\right)\right] \exp\left[-j\frac{K_2}{2}\left(\frac{x^2}{R_{2x}} + \frac{y^2}{R_{2y}}\right)\right] \quad (3)$$

$K_2 = (2\pi/\lambda)n_2$ is the wave number inside the fiber, n_2 is the refractive index of the fiber core.

The transformation can be described by using the complex beam parameter [2] as follows

$$\frac{1}{q_{1,2}} = \frac{1}{R_{1,2}} - i\frac{\lambda}{\pi n_{1,2}(w_{1,2}^2)} \quad (4)$$

Where the subscripts 1, 2 correspond to case before and after the coupling system, λ is the laser wavelength in free space.

The coupling matrix is represented by ABCD and from the values of the matrix elements, A, B, C and D, we can calculate ω_{2x}, ω_{2y}, R_{2x} *and* R_{2y} as follows

$$(w_{2x,2y})^2 = \frac{\left(A + B/R_{1x,1y}\right)^2 (w_{1x,1y})^4 + (\lambda_1 B)^2}{n(AD - BC)(w_{1x,1y})^2} \quad (5)$$

$$R_{2x,2y} = \frac{\left(A + B/R_{1x,1y}\right)^2 (w_{1x,1y})^4 + (\lambda_1 B)^2}{(A + B/R_{1x,1y})(C + D/R_{1x,1y})(w_{1x,1y})^4 + (\lambda_1^2 BD)} \quad (6)$$

Where,

$\lambda_1 = \lambda/\pi n_1$, and n_1 is the refractive index of the coupling system.

Coupling efficiency

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

$$\eta = \frac{\left|\iint \psi_{2L}\psi_f^* dxdy\right|^2}{\iint |\psi_{2L}|^2 dxdy \iint |\psi_f|^2 dxdy} \quad (7)$$

η depends on the degree of matching between the spot sizes and distributions of the laser and fiber mode fields. After substituting ψ_{2L} and ψ_f and integrating one gets in the absence of any lateral and angular misalignment:

$$\eta = 4w_f^2/w_{2x}w_{2y}\left[\left(1 + w_f^2/w_{2x}^2\right)^2 + \left(k_2^2 w_f^4 \big/ 4R_{2x}^2\right)\right]^{-1/2}\left[\left(1 + w_f^2/w_{2y}^2\right)^2 + \left(k_2^2 w_f^4 \big/ 4R_{2y}^2\right)\right]^{-1/2} \quad (8)$$

When the lateral offset is considered, analytical analysis suggests that the coupling efficiency is given as:

$$\eta' = \eta\exp\left(-2d_x^2/\omega_{2x}^2\left[\left(1+\omega_f^2/\omega_{2x}^2\right)^2 + \left(k_2^2\omega_f^4 \big/ 4R_{2x}^2\right)\right]^{-1/2} - 2d_y^2/\omega_{2y}^2\left[\left(1+\omega_f^2/\omega_{2y}^2\right)^2 + \left(k_2^2\omega_f^4 \big/ 4R_{2y}^2\right)\right]^{-1/2}\right) \quad (9)$$

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, analytical analysis suggests that the coupling efficiency is given as:

$$\eta'' = \eta\exp - \frac{k_2^2 w_f^2}{2}\left(\phi_x^2\left[\left(1+\omega_f^2/\omega_{2x}^2\right)^2 + \left(k_2^2\omega_f^4 \big/ 4R_{2x}^2\right)\right]^{-1/2} + \phi_y^2\left[\left(1+\omega_f^2/\omega_{2y}^2\right)^2 + \left(k_2^2\omega_f^4 \big/ 4R_{2y}^2\right)\right]^{-1/2}\right) \quad (10)$$

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

1-dB Loss Misalignment Tolerances

The least critical alignment tolerance is the alignment of the two images along the optical axis. The 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. We modify the relations given by (**Joyce and Deloach, 1980**) for considering the elliptical emission of the laser diode to become as follows

$$\Delta z_{1dB} = 0.5\frac{\pi}{\lambda}\left(\sqrt{(\omega_{2x}{}^4+\omega_{2y}{}^4)/2}+\omega_f{}^2\right) \quad (11)$$

Similarly, expressions for lateral and angular alignment tolerances (displacement resulting in 1-dB coupling losses)

$$r_{1dB} = 0.33(\sqrt{(\omega_{2x}{}^4+\omega_{2y}{}^4)/2}+\omega_f{}^2)^{1/2} \quad (12)$$

And

$$\Delta\phi_{1dB} = 60\frac{\lambda}{\pi^2}\left(\sqrt{\frac{2}{\omega_{2x}{}^4+\omega_{2y}{}^4)}}+\frac{1}{\omega_f{}^2}\right)^{1/2} \quad (13)$$

3. Experiment

In our research we use the system of laser weld (LW4000S) which includes an Nd:YAG laser with dual laser beams, welding workstation and motorized stage for laser diode module housing which is connected to a laser diode controller for driving the laser diode module, with active alignment facilities, i.e., during the alignment of a laser diode transmitter module, the system continuously measures the output power of the diode laser at the free end of the fiber to determine the coupling efficiency. A machine vision system pre-positions the housing, and after the system locates the light in the fiber, alignment routines determine the optimum coupling position. The coupling parts are then fixed using two simultaneous laser beams from Nd: YAG laser schematically shown in fig.(1).

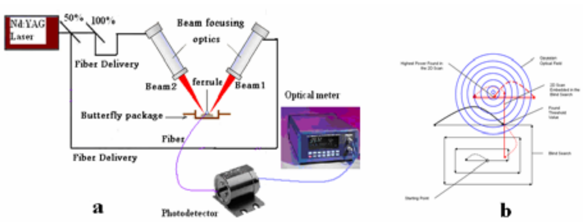

Fig. 2 a- Dual beam laser weld with active alignment. b- blind search in active alignment processes.

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. In addition, the spot welds can be viewed to determine optimum welding parameters. Two pneumatic grippers are equipped with the system, one for gripping the ferruled fiber tip at the position of maximum coupling power, the other is gripping the first lens which facing laser diode (collimating lens) the process of realignment and adjustment is performed before using laser welding to fix the lens in its holder to the substrate. The process is repeated for the second lens (focusing lens) before welding the second lens the alignment process and adjustment of the separations between the two lenses as well as between lenses and laser diode or the fiber tip have to be performed to assure maximum coupling efficiency with relaxed misalignment tolerances.

4. Results and discussion

Two ball lenses of (diameter =1 mm) and different refractive index are used. The first one which facing the laser diode has a refractive index of (nm=1.5) made of (BK7, Grade A Fine Annealed glass). The other lens which facing the fiber tip has a refractive index of (nl=1.8333) made of (LaSF N9, grade A, fine annealed optical glass) have been used for coupling 1550 nm laser diode into single mode fiber with core radius of 4µm. The obtained results show that coupling of laser diode to single mode fiber using double ball lenses is an efficient coupling scheme with relaxed working distance and misalignment tolerances. The simulation results, fig. (3) Show that by fixing the laser to first lens separation d1 at 3.5 mm (which is the optimum distance), and for more elliptical mode fields, i.e., ($\theta_x/\theta_y = 8/33$) of laser diode outputs, dual ball lenses coupling scheme shows higher coupling efficiency with large working distance, whereas for less elliptical outputs the coupling efficiency is less as illustrated in fig. (3). Moreover, the coupling efficiency and the working distance (fiber tip to second lens separation d2) can be controlled by variation of the separation between the two ball lenses (s). It has been found that at the optimum lenses separation (s=0.4 mm), the coupling efficiency is maximum at d2=3.5mm with a range of working distance d2 between (2mm-5 mm). The experimentally obtained working distance and misalignment tolerances are also tolerant as shown in Figs. (4,6) respectively.

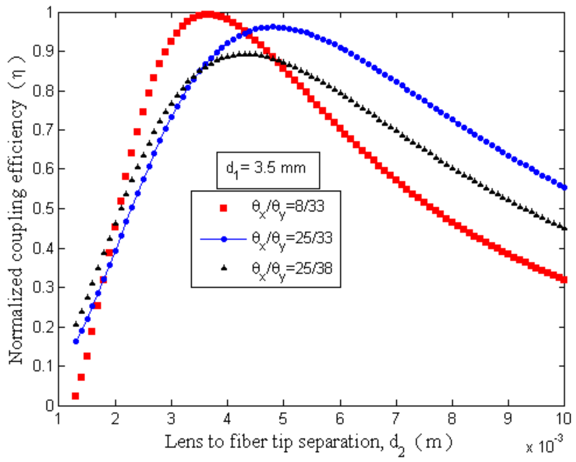

Fig. 3 Variation of coupling efficiency with laser divergence lens to fiber separation for different divergence ratios

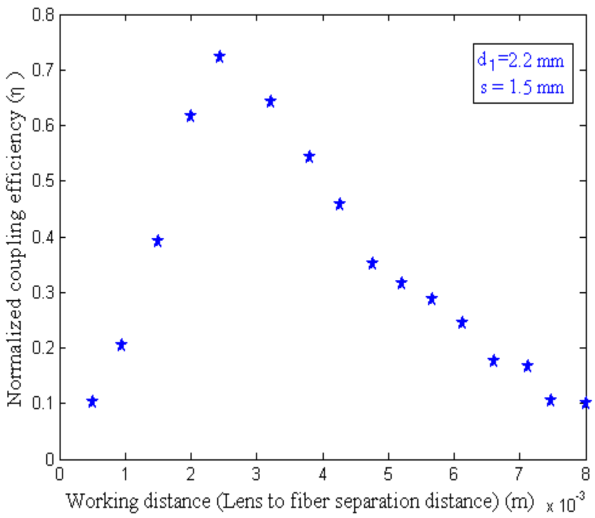

Fig. 4. Variation of coupling efficiency with working distance (experimentally)

By studying the effects of lateral, transversal and angular offsets on the coupling efficiency, we found that using double ball lenses coupling scheme is suitable to convert the elliptical laser beam distribution to nearly circular distribution which is clear from comparing the effect of lateral and transversal offsets on the coupling efficiency, it is clearly noticeable that the offset in both x and y directions, Fig. (5) and experimentally in fig.(6) give the same effect on the coupling efficiency which means that the transformed mode field of the laser diode is circular. The same effect have been also observed in the case of angular offset Fig. (8). Those effects are illustrated in three dimension in Ffigs. (7, 9).

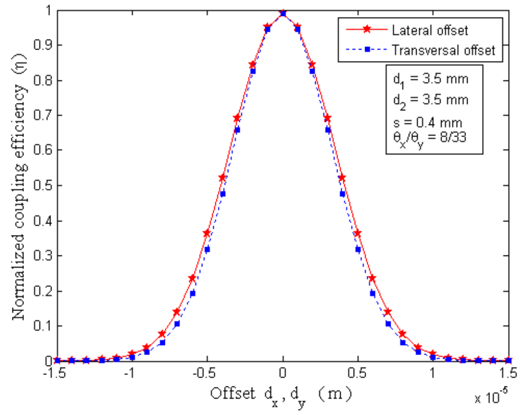

Fig. 5 Effect of lateral and transversal offsets on the coupling efficiency

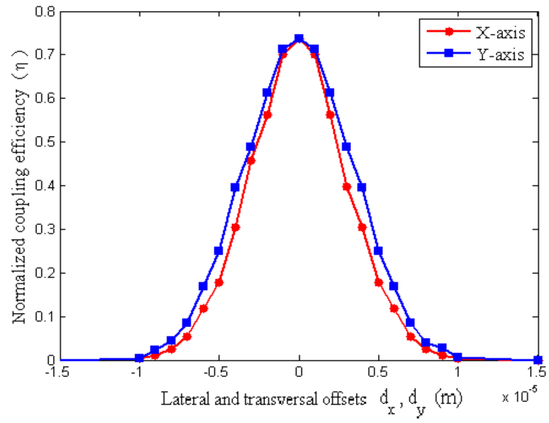

Fig. 6 The variation of coupling efficiency with the lateral and transversal offsets (experimentally)

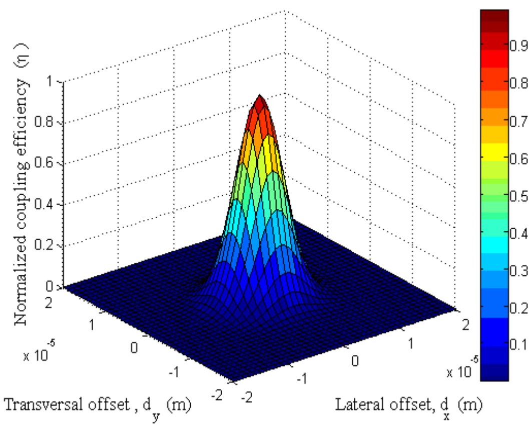

Fig. 7 Three dimensional illustration of the variation of coupling efficiency with the lateral and transversal offsets

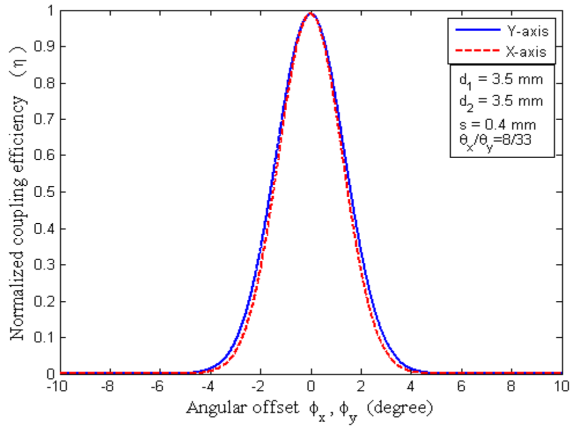

Fig.8 The variation of coupling efficiency with the angular offsets

By analyzing the effect of transformed beam waist radii on x and y axis of the laser diode on the 1-dB axial, lateral and angular misalignment tolerances, Figs. (10, 11, 12) respectively, it has been found that up to certain limits the misalignment tolerances are increasing with the increase of both radii and also give an evidence that by using double ball lenses the effect of both radii on the 1-dB misalignment tolerances is almost the same, which means that the mode matching is effective.

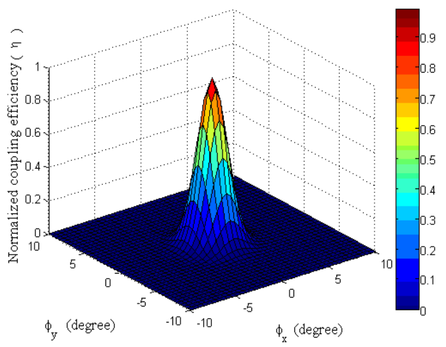

Fig.9 Three dimensional illustration of the variation of coupling efficiency with the angular offsets

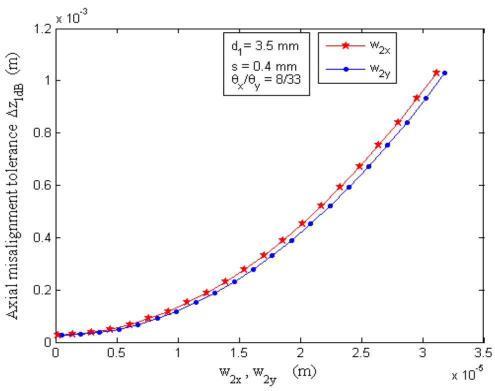

Fig. 10 The1-dB axial misalignment tolerances with variation of the transformed beam waist radii

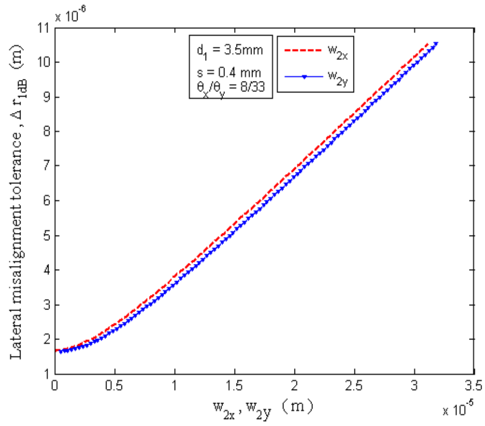

Fig. 11 The1-dB lateral misalignment tolerances with variation of the transformed beam waist radii

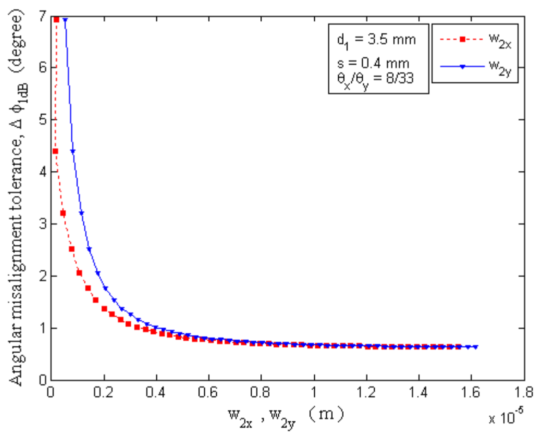

Fig. 12 The1-dB angular misalignment tolerances with variation of the transformed beam waist radii.

Laser welding technique with dual simultaneous Nd:YAG laser beams is applied for pigtailing 1550nm butterfly laser diode module. Two ball lenses have been fixed inside their 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 as shown in Fig. (13). Despite that the theoretical simulations of double ball lenses coupling scheme predict a nearly 100% coupling efficiency, Fig. (3) with very tolerant working distance and misalignment offsets (Lateral and angular), the experimentally obtained coupling efficiency, Fig. (4) is around 75% due to some practical limitations regarding the separations between the ball lenses as well as that from the coupling system to laser diode facet which were not easy to be brought to the ranges used in simulations, and there are some losses due to reflections and absorption by the coupling media which are ignored in the simulation.

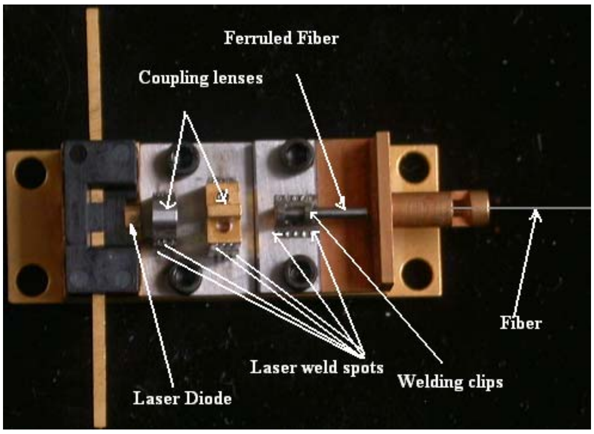

Fig. 13 A ready pigtailed laser diode module

5. Conclusions

Double ball lenses coupling scheme proved to be an efficient and tolerant coupling method in which the elliptical mode field of the laser diode is found to be effectively matched with the circular mode field of the single mode fiber which is the main requirement for getting high coupling efficiency with wide misalignment tolerances in laser diode transmitters.

The experimental value of the coupling efficiency is quite high (75%) comparing to the published values for other coupling schemes and it can be also further enhanced by optimizing the parameters of the coupling scheme as shown by simulations. Laser welding technique with dual Nd:YAG laser beams has been employed for the attachment and fixing all the coupling components in their holder and to the main substrate inside the packaged laser diode module (1550 nm). For employing laser welding technique in packaging of photonic devices that include sensitive optical components in very small size modules, laser welding beam parameters have to be optimized to get good and strong weld yields with less heat affected zone to prevent the damage that may happen to those components and at the same time achieving a very localized and strong weld yields.

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