Improvement of laser to fiber coupling efficiency using microlens technique

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IMPROVEMENT OF LASER TO FIBER COUPLING EFFICIENCY USING MICROLENS TECHNIQUE

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ABSTRACT

The efficiency of coupling between semiconductor laser LD and single-mode optical fiber SMF was increased by a microlens of an appropriate focal length placed between laser and fiber. ZEMAX software was used to optimize the design of an optical system. The employed coupling system composed LD of 1.55 μm wavelength, achromatic doublet microlens and single-mode fiber, thermalized over the temperature range (243-343K). Main source causing the coupling loss have studied, these are misalignment during adjusting and fixing the position of fiber referring to the axial misalignment, lateral misalignment, angular misalignment error (tilt) and lateral and angular misalignment to gather .Achromatic doublet microlens of different types of glass material were selected. Significant coupling efficiency (95.5%) has been obtained for N-BAK4, N-SF10 microlens of radius of curvature 7.00900, -6.67800 μm, respectively. The effect of varying the field of view angle over the range (0-9^o) on the coupling efficiency was taken into account. Coma, astigmatism and spherical aberration were observed. Results shows that the misalignment error proves to be the predominant factor that affects the coupling scheme with precise adjusting accuracy relaxed misalignment tolerances should be employed in the coupling system.

Keywords: laser, fiber, coupling efficiency, microlens technique.

1. INTRODUCTION

The optical fiber and fiber sensor are novel sensors which develop very fast during the recent decades. They have been widely applied in many applications due to their durability, multiplexing capabilities, small size, wide bandth, ability to carry data in big size and electro-magnetic immunity [1]. Much attention is being given to the low-loss single mode fiber in the field of optical communication because of its very high bandwidth, making it a suitably long haul medium for large-capacity transmission systems [2]. In order to utilize fully this capacity, an efficient power coupling between semiconductor laser and single-mode fiber is necessary [2]. The matching between characteristic parameters of light source and optical fiber should be concerned when they are combined for higher coupling efficiency. Generally the characteristic parameters of optical fiber include the core diameter, NA (numerical aperture) and cut-off wavelength, while the parameters of light source comprise the light-emitting area and beam divergence [1]. Quantitatively evaluating the impacts of the factors can help researchers better understand the contribution of every factor thus they can optimize the parameters and adjust the coupling system components more precisely with less misalignment errors. Coupling of laser diode output into optical fiber can be achieved either directly in what is known as butt or direct coupling or using coupling optical systems such as lenses or fiber tapers [1]. A simple butt-joint method gives poor coupling efficiency, typically of the order of 10% because of mismatch of the laser and fiber fields [2]. In this article coupling system from laser diode to optical fiber using single focusing lens is established. Factors which might affect the efficiency are analyzed by theoretical study and simulation confirmation.

Fundamentals, method, results and discussions are detailed [1].

2. THEORETICAL BASIS

A. Coupling theory

According to mode coupling theory, the coupling from laser diode to optical fiber is the mode matching between them. The direct coupling is found to be inefficient (5-20%) due to the mismatching between the laser diode and the fiber mode field [1].

[illegible] (1)

This is the coupling efficiency between Gaussian elliptical beam and a monomode fiber of spot size W_f [2]. For a circular beam $W_{ox}=W_{oy}$and $R_x\ (z) = R_y\ (z)$ it is follows that

[illegible] (2)

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Where w(z) and w_f is the spot size of the beam and fiber respectively ,k is the wavenumber $R_x(z)$ and $R_y(z)$ are the curvature of the wavefronts of diffracted beam with respect to x and y direction as a function of z (separation from the laser)

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B- Factors analysis

There are several factors that might affect the coupling efficiency. By analyzing them and work out the tolerance range of l dB loss, the efficiency C is supposed to be evaluated from the in equation below [1]:

$$-10\lg\frac{P_{out}}{P_{in}} \leq 1\,dB \quad (3)$$

We can get the C as below: C $\geq$ 95 %.

(1) Misalignment tolerance

The process of establishing coupling system is associated with three kinds of misalignment regarding axial, lateral and angular misalignment.

(a) Axial misalignment

As shown in Figure-1, the axial misalignment S indicates the distance between the beam waist and the fiber tip.

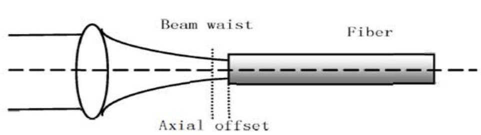

Figure-1. Axial misalignment.

When the axial misalignment is considered, the coupling loss is given by:

$$C_{lz} = \frac{1}{1+\left(\frac{\lambda L}{2\pi W^2}\right)^2} \quad (4)$$

We can infer from Equation (4) that coupling efficiency is not markedly influenced by axial misalignment. Nevertheless, large axial misalignment leads to oversize beam spot, which might bring in additional coupling loss [1].

Where: L is the axial misalignment of the beam waist and *W* is the spot size of light beam.

(b) Lateral misalignment

Figure-2 shows that the lateral misalignment is the displacement that light spot from the fiber core at the perpendicular facet of the fiber tip [1].

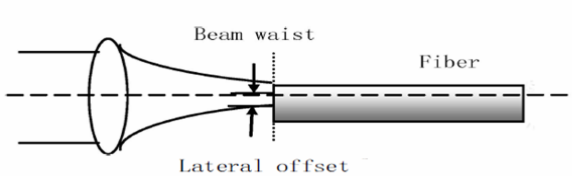

Figure-2. Lateral misalignment.

The coupling loss caused by lateral misalignment is given by:

$$C_{lx} = \exp\left(-\frac{x_L^2}{W^2}\right) \quad (5)$$

Where: x_L is the misalignment of the single-mode fiber.

It can be indicated from Equation (5) the coupling efficiency is very sensitive to lateral misalignment.

(c) Angular misalignment

As shown in Figure-3, the angular misalignment **Θ** is the angle from the beam axis and the fiber axis. This displacement leads to the increasing of incident angle and causes coupling loss due to the mismatching of *NA* [1].

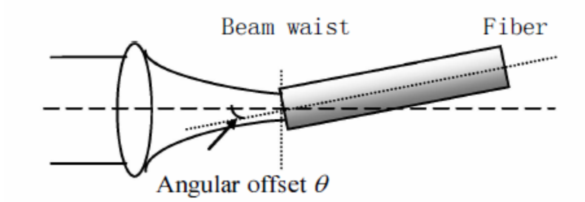

Figure-3. Angular misalignment.

The coupling loss caused by angular misalignment is given by:

$$C_\theta = \exp\left(-\frac{\pi^2 W^2 \theta^2}{\lambda^2}\right) \quad (6)$$

Where: *Θ* is the angular misalignment and λ is the laser diode emission wavelength.

With some calculation it can be inferred that the coupling efficiency is also very sensitive to angular displacement.

(2) Thermal effect

Frequently, optical system must perform over a wide temperature range. Due to the thermal expansion and the change of the index of refraction of the lens material with temperature, the performance of the system is affected. This is especially pronounced in the infrared region, where most materials suffer from a high *dn/dt*, the change of index with temperature. To maintain an acceptable image quality, in many cases refocusing will be necessary. This can be accomplished mechanically or optically. Specially, the mechanical adjustment can be done manually or by other means, such as feedback servo systems and others. Optically, the compensation can be achieved by selecting suitable optical materials and element powers [3, 5].

The changing parameters of a lens in housing are the following [3, 5]:

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Table-1. Lens and housing parameters change with temperature.

Temperature	T	(T+ΔT)
Lens radius	r	r (1+α_L ΔT)
Lens thickness	d	d (1+α_H ΔT)
Lens index of refraction	n	n+(dn/dT) ΔT
Housing (mount)	s	s (1+α_H ΔT)
Spacing between lens and detector		

Where: ΔT is the change in temperature, α_H is the coefficient of linear expansion for housing, α_L is the coefficient of linear expansion for lens and *dn/dT* is the change in refractive index with temperature.

2.1. Defocus with change in temperature

To simplify the procedure, thin elements are assumed. For an objective consisting of J thin elements mounted in housing, the focal shift is [4, 5]:

$$\Delta f = -\left[f^2 \sum_{j=1}^{j} \left(\frac{H_i}{fi} \right) + \alpha_H f \right] \Delta t \qquad (7)$$

where: $H_i = \frac{dN_i / dT}{(N_i - 1)} - \alpha_{Li}$: is thermal glass constant, f is focal length of system (assumed to be the length of the housing), f_i is the focal length of element i, dN_i / dT is the index change in element i, α_{Li} is the thermal expansion coefficient of element I and α is the thermal expansion coefficient of housing.

The defocusing distance Δ*f* is the separation of the lens focus from the detector. This is depicted in Figure-4, where a temperature increase is assumed. It is indicated that the focal length actually decreases with an increase in temperature; while the housing expands focus from the detector position is [4-6].

$$\Delta f = f \Delta t (T + \alpha_H) \qquad (8)$$

where, Δf is the change in the focal length for single thin lens.

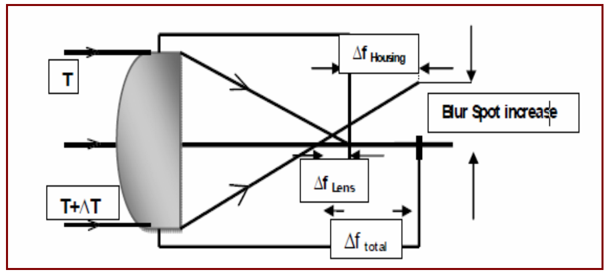

Figure-4. Focus error parameters.

(3) Field of view effect

Field of view (FOV) is one of the specifications for an optical system. It is the angular measure of the volume of space within which the system can respond to the presence of a target, and it is determined by the field stop. FOV is not related to the size of the AS or the EP; it depends on the linear dimension (d_f) of the field stop and on the effective focal length f of the imager from the objective to the detector. If FOV is a small angle, [7]:

$$FOV \approx d_f / f \qquad (9)$$

3. RESULTS AND DISCUSSIONS

A .Simulation and experiment

In order to confirm the impacts of the mentioned factors that might have an influence on the coupling efficiency, a system composed of laser diode, double lens and optical fiber is employed in this research. The laser beam spot diameter is 3mm with zero divergence angles, and the wavelength λ is 1.55μm. Numerical aperture of the fiber is 0.14; the core and cladding diameter are 8.3μm and 125μm. The focal length of the double lens is 20mm. During the alignment of the laser beam transmitting, the system continuously measures the output power at the free end of the fiber to determine the coupling efficiency. Meanwhile we use the optics simulation software ZEMAX to simulate the coupling system. According to the parameters mentioned above, we set the ZEMAX as below in Table-2:

Table-2. System parameter.

Surf: Type (Unit : mm)		Radius		Thickness		glass	Semi-diameter		Conic	
OBJ	Standard	Infinity		Infinity			0.000		0.00	
STO	Standard	Infinity		5.00			2.000		0.00	
2*	Standard	7.009		3.524	V	N-BAK4	6.250	U	0.00	
3*	Standard	-6.678		3.810	V	N-SF10	6.250	U	0.00	
4*	Standard	44.363		13.632			6.250	U	-1.00	V
IMA	Standard	Infinity		-			0.002	U	0.00	

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Furthermore the X, Y, Z position and Tilt in the settings could be designed to simulate the axial, lateral and angular displacement. In view of the axial displacement, the simulation and experiment result is shown in Figure-5.

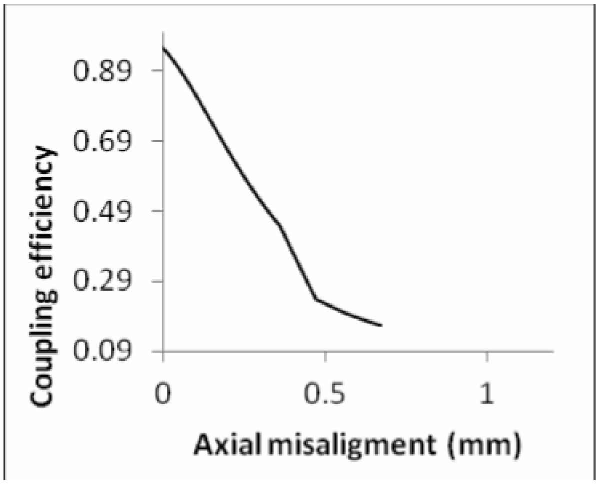

Figure-5. Effect of axial misalignment.

We see that in simulation the axial offset has larger tolerance while the experimental result is more restricted. Some other loss during coupling like light reflecting in real experiment could explain this. The graph also shows that the coupling efficiency is not very sensitive to the axial displacement and when the misalignment arrives 310μm, the coupling efficiency drops to 50.61%, and the misalignment tolerance 100μm for -0.241 dB coupling loss. Likewise, lateral displacement is taken into consideration. Simulation and experiment result is shown in Figure-6:

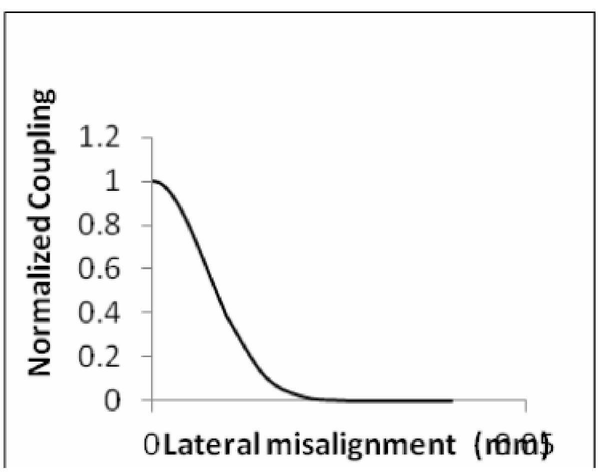

Figure-6. Effect of lateral misalignment.

The result is similar and both indicate that the lateral misalignment has great impact on coupling efficiency. When the misalignment arrives 8μm, the coupling efficiency drops to 51.2772%, and the misalignment tolerance 0.5μm for -0.21352 dB coupling loss.

Likewise, we have studied the angular misalignment. Model parameters are set as follow: light core diameter is 8.3μm and the NA is 5.5. Simulation and experiment result is shown in Figure-7.

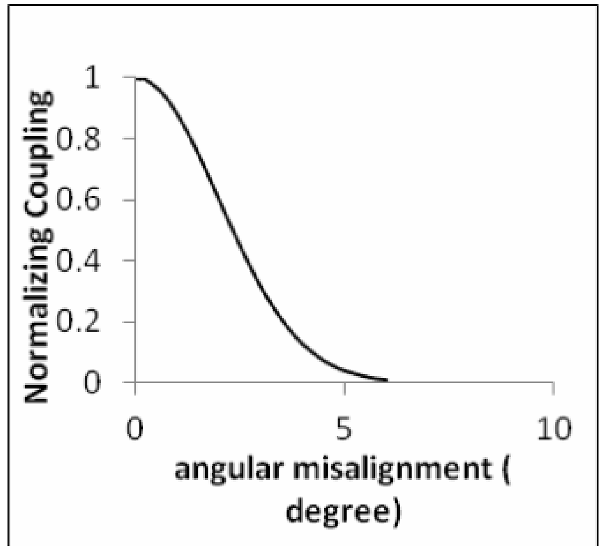

Figure-7. Effect of angular misalignment.

The experiment data shows a severe decline since in the practical experiment angular misalignment would bring in additional lateral offset. In Fig.7 the coupling efficiency declines to 51.1% when the angular offset arrives 2.2° and misalignment tolerance is 0.1° for-0.2029dB coupling loss.

Likewise, we have studied the lateral and the angular misalignment. The effect of combination of lateral and angular misalignment on the coupling efficiency. The result shows this as the lateral misalignment and angular misalignment increased, the coupling efficiency decreased for all value of tilt (0.2-0.3^{o}) also it is clear that as the value increased the coupling efficiency will decreased. The effect of combination of lateral and angular misalignment on the coupling efficiency is larger than the effect of indicial lateral misalignment or angular misalignment as show in Figure-8.

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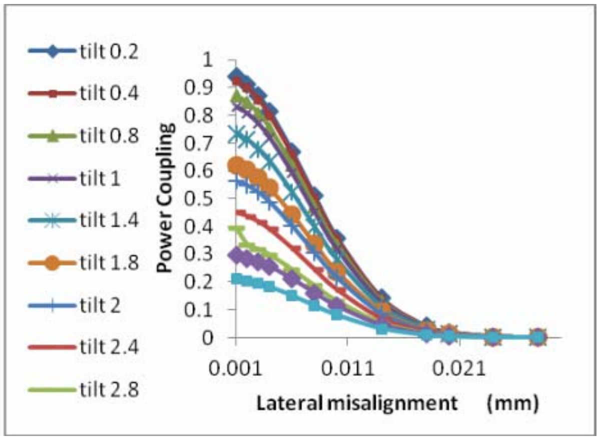

Figure-8. Effect of lateral and angular misalignment.

The effect of environment temperature in the range (-20-70°C) on the performance of the lens coupling design was also studied .The perfect system with all losses (i.e. tilt = lateral = axial = 0) were selected, then a change in the temperature of the environment was done. From Figure-9, it is shown that as the environment temperature increased, the coupling efficiency decreased, this behavior belong to the variation of optical design editor parameter (radius of curvature, thickness, focal length) of the optical elements (lenses) in the design so all the result change and quality analysis parameter values changed also.

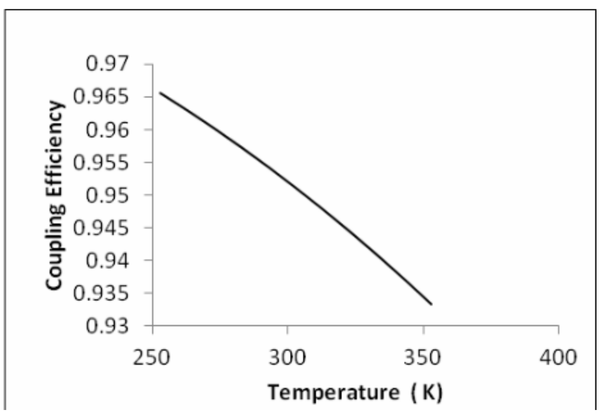

Figure-9. Effect of temperature.

When the temperature arrived to 70°C the coupling efficiency decline to 93.7%.

Finally, the effect of field of view within the range (0°-9°) on the power coupling efficiency was investigated. Figure-10 show the effect of field of view on power coupling and we can noted that coupling efficiency decreasing exponential when the field of view increasing.

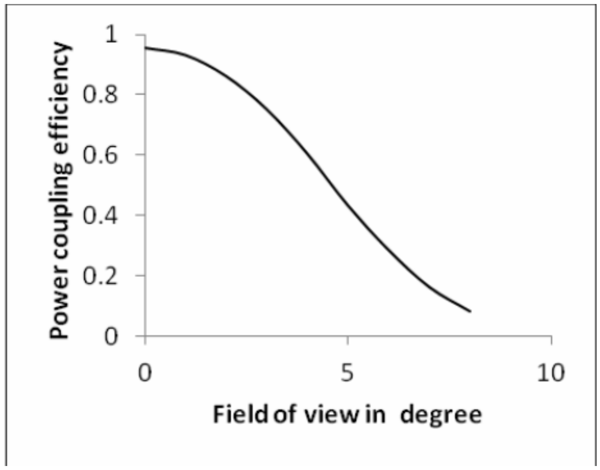

Figure-10. Effect of field of view.

B. DISCUSSIONS

According to the analysis above, it is found that a coupled lens improves the coupling efficiency and it is more stable than a non-lensed fiber. A LD-SMF coupling efficiency of 95% is achieved with for N-BAK4, N-SF10 microlens of radius of curvature 7.00900, -6.67800 mm. The lateral offset tolerance is more important in laser diode module fabrication than the angular misalignment tolerance. A degradation in coupling efficiency as the temperature increased (243-343K), the dependence of coupling efficiency on wavelength at the optimal working parameters is depicted.

The results shown that the lateral misalignment tolerance is more important in laser diode module fabrication than the angular misalignment tolerance. However, it is important to note that the angular misalignment tolerances cause no problem in laser diode fabrication and construction processes, because the angular misalignment of the light beam can compensate by adjusting the other lens during the assembling process.

Further, the influence of environment temperature over the range (243-343K) on coupling efficiency and other contribution factors which affect the coupling are analyzed and their tolerance has been worked out. The coupling efficiency would escalate as the temperature deceases in a certain range.

Finally the effect of varying the field of view angle (0-9°) on the coupling efficiency also investigated. Results illustrate that increasing the field of view angle will decrease the coupling efficiency.

4. CONCLUSIONS

In this paper, the coupling optics in case of laser diode into optical fiber via an achromatic doublet microlens simulated while related experiments are also done to optimize the parameter of the components in the system. Possible factors which cause loss and affect the coupling efficiency are analyzed and confirmed by experiments. According to the analysis result, the misalignment error proves to be the predominant factor that affects the coupling efficiency, indicating that the coupling scheme with precise adjusting accuracy and relaxed misalignment tolerances should be employed in the coupling system. From the result one conclude that the coupling efficiency is more sensitive to lateral misalignment more sensitive to lateral misalignment than axial misalignment and both vanishes C=0 at 22 μm and 122μ m, respectively. The effect of accumulate misalignment (lateral and angular misalignment) reduce the coupling efficiency and increasing the sensitivity of the coupling design. The coupling efficiency is affected by increase tilt value for each lateral misalignment value. The study of environment temperature on the coupling shows that this system is athermalized (very low sensitive to the temperature variation). This was due to the best choice is happened because the right choice of optical thermal material which has of low thermal expansion coefficient in our design. So this Therefore the proposed design was is very good for athermaliztion application study .The coupling system was very sensitive to the field of view increment The chromatic focal shift is (0.45 λ) which this is indicate that this design is achromatic and athermalized system.

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