Out-of-Plane Optical Coupling Between an Elliptical Gaussian Beam and an Angled Single-Mode Fiber

W. T. Chen and Lon A. Wang

Abstract—**An approximate analytical model is developed for calculating the out-of-plane coupling efficiency between an elliptical Gaussian beam from a laser diode and an angled single-mode fiber. The simulation results obtained from the model indicate that when a laser diode has no tilt the coupling efficiency varies with relative rotation angle at a period of π rather than remains constant, and the period changes from π toward 2π as the tilt angle of laser diode increases. A proof-of-principle experiment is performed to demonstrate the validity of the model as the elliptical factor becomes large. Potential applications by employing the model are discussed.**

Index Terms—**Angled fiber, elliptical Gaussian beam, optical coupling.**

I. INTRODUCTION

VARIOUS optical implementations of coupling light from a semiconductor laser diode into a single-mode fiber with high coupling efficiency and large misalignment tolerance have been investigated for decades [1]–[3]. Additionally, to meet the low bit-error-rate requirement for a long-haul high-speed fiber communication system, the reduction of external optical back reflection [4], [5] is considered as vital to optical coupling. It was demonstrated that the bit error rate of the system operating at 591.2 Mb/s over 100 km fiber distance could be improved from 10^{-4}, 10^{-11}, and down below 10^{-13} as the amount of back reflection decreased toward -10, -15, and -20 dB, respectively [6]. Many approaches have been employed for reducing back reflection. For example, back reflection in the order from -30 to -60 dB can be obtained by antireflection coating, index matching and 10° factitious misalignment [7]. Although further lower back reflection is generally achieved by using an optical isolator [8], such utilization may significantly increase the cost of an optical subassembly (OSA) module.

Conversely, the utilization of an angled facet fiber in the package of an OSA module for the reduction of back reflection would be more cost effective in performance and simpler in implementation. For example, it was reported that a packaged receptacle type laser could have a Gbit/s operation for 1.3 and 1.5 μm fiber system utilizing a 12° angled facet single-mode fiber [9]. The industry standard for the angled fiber is 8°, which has been shown to have back reflection below -50 dB when a symmetric Gaussian beam ($\lambda = 0.633$ μm, $W_{l0} = 2.2$ μm) is coupled into or out from a weakly guiding single-mode fiber ($W_{f0} = 2.75$ μm, $V = 2.2$) [7]. However, the utilization of an angled facet fiber causes one major problem in the packaging process because the optical coupling efficiency is strongly dependent upon the relative rotation angle, $\Delta\alpha$, where $\Delta\alpha$ is defined as the angle difference between an angled fiber module and a laser diode module. Since the relative rotation angle can be of any value, it is very difficult to optimize the coupling efficiency in the packaging processing of an OSA module.

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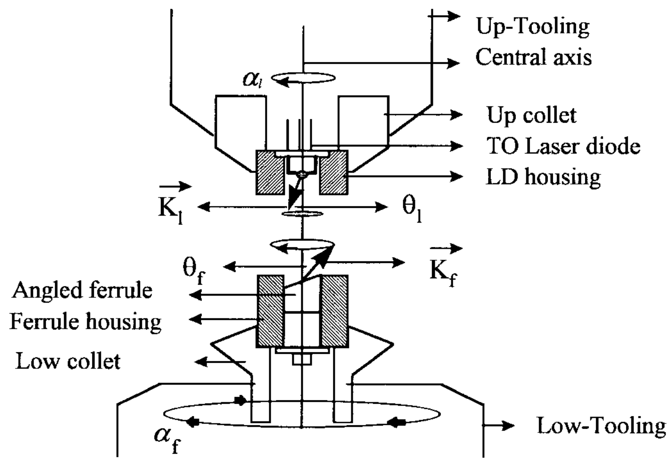

Fig. 1. Schematic diagram of an OSA packaging system for autoalignment and laser-welding.

Fig. 1 shows a system setup for packaging an OSA module. A laser diode module with stainless housing is clamped by up-collets and then put on an up-tooling. Similarly, an angled fiber module including Zirconium ferrule and stainless housing is clamped by low-collets, and then put on a low-tooling. Since the two modules are placed on the toolings possibly at any angle, the propagation directions of laser beam ($\vec{K}_1$) and fiber field ($\vec{K}_f$) may not be coplanar, i.e., $\Delta\alpha \neq 0$, $\Delta\alpha = \alpha_f - \alpha_1$. The coupling efficiency would therefore be dramatically different from the ones calculated based on symmetric and coplanar Gaussian beams. Therefore, to achieve the maximum coupling efficiency, either the angled fiber module or the laser diode module needs to be rotated. In each rotation, however, both longitudinal and transverse scannings are required, which is time-consuming and therefore certainly not cost-effective. To solve this problem, we present an approximate method of analyzing the coupling efficiency between an elliptical Gaussian beam and an angled-facet single-mode fiber when both are out-of-plane misaligned.

The remaining paper is arranged as follows. In Section II, two methods of calculating the coupling efficiency are discussed. In Section III, we compare the simulation results of different modelings, and demonstrate the validity in a proof-of-principle experiment. It is found that our model can give a better fitting to the experiment results than the one previously reported. In Section IV, we discuss some potential applications by employing our model. Finally, we conclude our investigation in Section V.

II. Theory

A. Approximate Analytical Model

Since Kogelnik analyzed the coupling efficiency between two Gaussian beams [10], many coupling schemes which could lead to high coupling efficiency and large misalignment tolerance have been characterized [11]–[13]. Almost all these works assume two coupling beams in coplanar propagation. Recently Clement and Österberg have reported a modified new model to treat the coupling between a circularly symmetric Gaussian beam and an angled-facet single-mode fiber including out-of-plane misalignment [14]. Their results indicated that i) the normalized coupling efficiency varied with relative rotation angle at a period of 2π when a laser diode had a tilt, i.e., $\theta_1 \neq 0$ and ii) the coupling efficiency was independent of relative rotation angle when a laser diode had no tilt, i.e., $\theta_1 = 0$. However, as will be described later, such model may fail to predict the coupling efficiency of beams having a nonunity elliptical factor. It is noted that beams from many waveguide-based devices generally possess elliptical intensity profiles even the output ends are either tilted or angled [15], [16]. Therefore, it is important to include an elliptical factor in the calculation of coupling efficiency when such devices are employed.

Traditionally, an elliptical Gaussian beam is approximated as an equivalent circular Gaussian beam with its waist being substituted by the geometric mean of the two transverse components. Such approximation is also assumed in [14], [17], which may lead to the results significantly different from those when a truly elliptical Gaussian beam is treated. Here, we propose a method to analyze the coupling between an elliptical Gaussian beam and an angled-facet single-mode fiber when both are out-of-plane misaligned. The method is based on the variable separation and the projection of beam propagation direction, which results in a simpler derivation of coupling efficiency than that described in [14].

A general coupling scheme is shown in Fig. 2. The tilt angles of two coupling fields, defined respectively as θ_1 and θ_f for laser and fiber, are assumed small enough so that $\cos\theta_f$ and $\cos\theta_1$ are close to unity. By variable separation, the normalized electrical field of a Gaussian beam from a laser diode can be expressed as

$$E_1(x, y) = E_{1x}(x)E_{1y}(y) \tag{1}$$

and

$$E_{1x}(x) = \left(\frac{2}{\pi}\right)^{1/4}(W_{1x})^{-1/2} \cdot \exp\left\{-\frac{x^2}{W_{1x}^2} - ik\left(\frac{x^2}{2R_{1x}} + \theta_{1x}x\right)\right\} \tag{2}$$

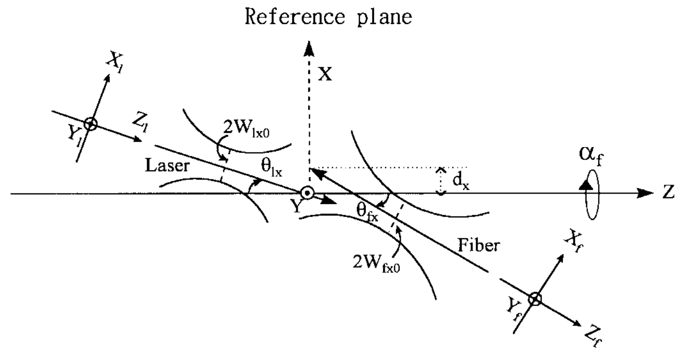

Fig. 2. Optical coupling scheme between a laser diode and an angled facet single-mode fiber.

$$E_{1y}(y) = \left(\frac{2}{\pi}\right)^{1/4}(W_{1y})^{-1/2} \cdot \exp\left\{-\frac{y^2}{W_{1y}^2} - ik\left(\frac{y^2}{2R_{1y}} + \theta_{1y}y\right)\right\} \tag{3}$$

where W_{lx}, W_{ly} are beam's radii, R_{lx}, R_{ly} are radii of curvature, and θ_{lx}, θ_{ly} are the tilt angles in the x direction and y direction, respectively.

Similarly, the electric field distribution of an angled facet single-mode fiber can be written as

$$E_f(x, y) = E_{fx}(x)E_{fy}(y) \tag{4}$$

and

$$E_{fx}(x) = \left(\frac{2}{\pi}\right)^{1/4} W_f^{-1/2} \exp\left[-\frac{(x-d_x)^2}{W_f^2} - ik\left\{\frac{(x-d_x)^2}{2R_f} + \theta_{fx}(x-d_x)\right\}\right] \tag{5}$$

$$E_{fy}(y) = \left(\frac{2}{\pi}\right)^{1/4} W_f^{-1/2} \exp\left[-\frac{(y-d_y)^2}{W_f^2} - ik\left\{\frac{(y-d_y)^2}{2R_f} + \theta_{fy}(y-d_y)\right\}\right] \tag{6}$$

where d_x, d_y are transverse misalignments, and θ_{fx}, θ_{fy} are the tilt angles in x and y directions, respectively.

The optical coupling efficiency can then be calculated by using the overlapping integral on a reference plane, which is expressed as [18]

$$\eta = \eta_x \cdot \eta_y = \left\{\eta_z^{(x)}\eta_{d_x}^{(x)}\eta_\theta^{(x)}\eta^{(x)}{}_{z,\,dx,\,\theta}\right\} \cdot \left\{\eta_z^{(y)}\eta_{dy}^{(y)}\eta_\theta^{(y)}\eta^{(y)}{}_{z,\,dy,\,\theta}\right\}. \tag{7}$$

The θ_x and θ_y which denote the angular misalignments in the XZ plane and YZ plane, respectively, as described in [18], are replaced by

$$\theta_x = \theta_{fx} - \theta_{1x} \tag{8}$$

$$\theta_y = \theta_{fy} - \theta_{1y}. \tag{9}$$

Referring to Fig. 2, we initially set the two coupling fields coplanar, i.e., $\Delta\alpha = 0$. If the fiber and the laser diode are rotated by an angle α_f and α_1, respectively, as indicated in Fig. 1, the two beams then become out-of-plane misaligned.

When the fiber module is rotated, the angular misalignment in the direction of x and y axes, denoted as θ_{fx} and θ_{fy}, respectively, can be derived by projecting the fields into their x and y axial components.

$$\theta_{fx} = \sin^{-1}\left\{\frac{\sin(\theta_f)\cos(\alpha_f)}{\sqrt{1-[\sin(\theta_f)\sin(\alpha_f)]^2}}\right\} \tag{10}$$

$$\theta_{fy} = \sin^{-1}\left\{\frac{\sin(\theta_f)\sin(\alpha_f)}{\sqrt{1-[\sin(\theta_f)\cos(\alpha_f)]^2}}\right\} \tag{11}$$

where

$$\theta_f = \sin^{-1}\{n_f \cdot \sin(\theta_{fa})\} - \theta_{fa}. \tag{12}$$

θ_f and θ_1 denote again the tilt angles of fiber and laser modules, respectively, and θ_{fa} is the polished angle of the fiber.

Similarly, we can derive θ_{lx} and θ_{ly} of the laser module as

$$\theta_{1x} = \sin^{-1}\left\{\frac{\sin(\theta_1)\cos(\alpha_1)}{\sqrt{1-[\sin(\theta_1)\sin(\alpha_1)]^2}}\right\} \tag{13}$$

$$\theta_{1y} = \sin^{-1}\left\{\frac{\sin(\theta_1)\sin(\alpha_1)}{\sqrt{1-[\sin(\theta_1)\cos(\alpha_1)]^2}}\right\}. \tag{14}$$

For small-angle approximation, (8) and (9) can be written as

$$\theta_X = \theta_f \cos(\alpha_f) - \theta_1 \cos(\alpha_1) \tag{15}$$

$$\theta_y = \theta_f \sin(\alpha_f) - \theta_1 \sin(\alpha_1). \tag{16}$$

Substituting (15) and (16) into (7), we can obtain the coupling coefficient between an elliptical Gaussian beam and an angled facet single-mode fiber including out-of-plane misalignment

$$\begin{aligned}\eta &= \eta_x \cdot \eta_y \\ &= (\boldsymbol{\kappa}_x)^{1/2} \exp\Bigg\{-\boldsymbol{\kappa}_x\Bigg(\left(\frac{d_x^2}{2}\right)\left(\frac{1}{W_{1x}^2}+\frac{1}{W_{f0}^2}\right) \\ &\qquad + \left(\frac{k^2\theta_x^2}{8}\right)\left(W_{1x}^2+W_{f0}^2\right) \\ &\qquad + (d_x Z\theta_x)\left(\frac{1}{W_{1x}^2}+\frac{1}{W_{f0}^2}\right)\Bigg)\Bigg\} \\ &\quad \cdot (\boldsymbol{\kappa}_y)^{1/2} \exp\Bigg\{-\boldsymbol{\kappa}_y\Bigg(\left(\frac{d_y^2}{2}\right)\left(\frac{1}{W_{1y}^2}+\frac{1}{W_{f0}^2}\right) \\ &\qquad + \left(\frac{k^2\theta_y^2}{8}\right)\left(W_{1y}^2+W_{f0}^2\right) \\ &\qquad + (d_y Z\theta_y)\left(\frac{1}{W_{1y}^2}+\frac{1}{W_{f0}^2}\right)\Bigg)\Bigg\}\end{aligned} \tag{17}$$

where

$$\begin{aligned}\boldsymbol{\kappa}_x &= \left\{\boldsymbol{\eta}_z^{(x)}\right\}^2 \\ \boldsymbol{\kappa}_y &= \left\{\boldsymbol{\eta}_z^{(y)}\right\}^2\end{aligned} \tag{18}$$

and $\eta_x^{(x)}$ and $\eta_z^{(y)}$ indicate the coupling efficiency without any kinds of misalignment in the x and y directions, respectively.

One special situation is that the two coupling beams have circularly symmetric Gaussian profiles and both laser and fiber beam waists coincide on the fiber end. Then, (17) can be reduced to

$$\begin{aligned}\eta = \boldsymbol{\kappa} \exp\Bigg\{-\kappa\Bigg(\left(\frac{d^2}{2}\right)+\left(\frac{1}{W_{10}^2}+\frac{1}{W_{10}^2}\right) \\ +\left(\frac{k^2\theta_{\text{eff}}^2}{8}\right)\left(W_{10}^2+W_{f0}^2\right)\Bigg)\Bigg\}\end{aligned} \tag{19}$$

where

$$\theta_{\text{eff}} = \left(\theta_x^2+\theta_y^2\right)^{1/2} = \left[\theta_f^2+\theta_1^2-2\theta_f\theta_1\cos(\Delta\alpha)\right]^{1/2} \tag{20}$$

$$\boldsymbol{\kappa} = \frac{4}{\left(\dfrac{W_{10}}{W_{f0}}+\dfrac{W_{f0}}{W_{10}}\right)^2} \tag{21}$$

and $\Delta\alpha = \alpha_f - \alpha_1$.

The effective angular misalignment θ_{eff} is introduced to take an out-of-plane misalignment into consideration in a way such that the out-of-plane model can be equivalently treated as the coplane one. This result is the same as (14) of [14]. It is noted that our model is also based on small-angle assumption, but derived in a simpler way. Moreover, the model can simulate more accurately on the elliptical beam coupling, as examined further on. To compare the difference of the results obtained with and without the assumption, an exact and numerical formulation of coupling efficiency should be developed.

B. Exact Numerical Model

The exact numerical formulation of coupling efficiency is derived directly from the overlapping integral of two coupling fields

$$\eta = \frac{\left|\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_1 \cdot E_f^* \, dx\, dy\right|^2}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_1 \cdot E_1^* \, dx\, dy \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_f \cdot E_f^* \, dx\, dy} \tag{22}$$

where the electrical fields of laser diode and angled fiber are expressed in their propagation coordinates as $E_1(X_1, Y_1, Z_1)$ and $E_f(X_f, Y_f, Z_f)$, respectively (refer to Fig. 2). Unlike (17), no approximation is made in (22). With the use of propagation characteristics of a Gaussian beam and coordinate transformation, the exact numerical coupling efficiency can be obtained in some reference plane, (X, Y, Z).

III. Simulation and Proof-of-Principle Experiment

We first consider the situation that a laser diode has no tilt $\theta_1 = 0°$. The solid and the dash lines in Fig. 3 show the simulation results obtained by using the approximate analytical and the exact numerical models, respectively, with various elliptical ratios. W_x and W_y denote the beam waists in x and y directions, respectively, of either a laser diode or a fiber. The elliptical ratio is defined as W_y/W_x. In the simulation, the waist of laser diode is assumed 5 μm in x direction, and the fiber is 8° angled. The two models agree with each other very well, better than 99.7% accuracy, indicating that

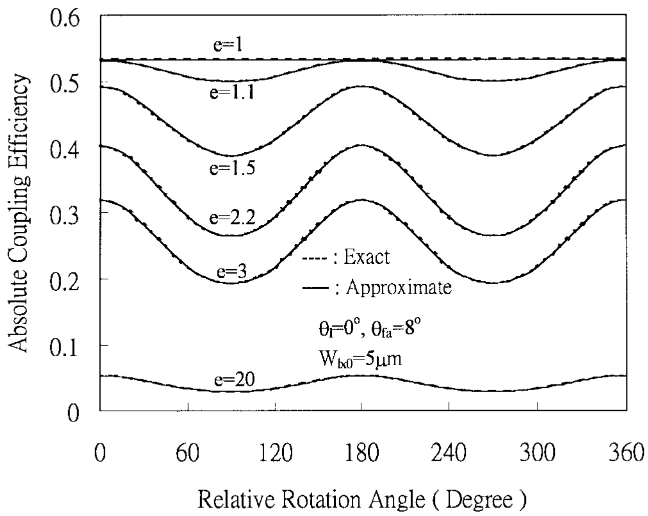

Fig. 3. Calculated absolute coupling efficiencies versus relative rotation angles based on different models when there is no laser tilt angle. The top straight line is also the result from Clement and Österberg's model.

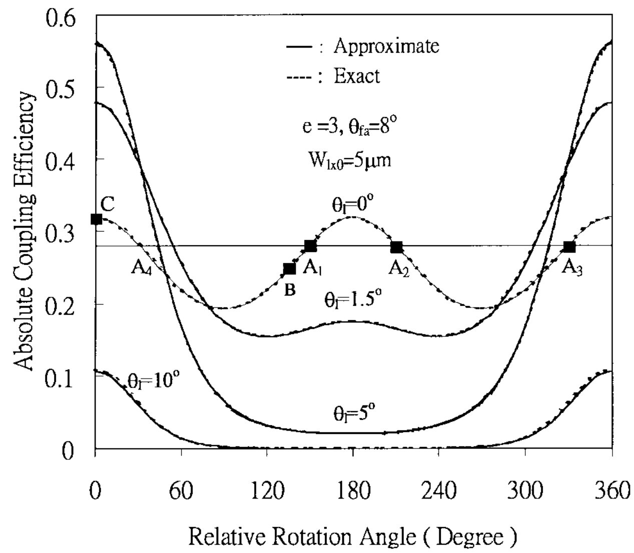

Fig. 4. Calculated absolute coupling efficiencies versus relative rotation angles for various tilt angles. Both curves overlap together.

the approximate analytical model is sufficiently applicable in such simulation. It is noted that, implicitly implied in [14], the coupling efficiency is independent of relative rotation angle $\triangle\alpha$ if the laser diode has no tilt (see also Fig. 5). Both approximate and exact models, however, indicate that the coupling efficiency varies with $\triangle\alpha$ at a period of π. Moreover, it is noted that at $\triangle\alpha = 90°$ the normalized coupling efficiency can vary by as much as 2.2 dB when the elliptical ratio is increased by three times.

In practical packaging, it is very difficult to maintain the concentricity of a laser diode module, i.e., θ_1 is usually nonzero. Shown in Fig. 4 are the typical effects of various θ_1 on coupling efficiencies as the elliptical ratio is set, for example, at 3 and the fiber is 8° angled. It is noted that the period of variation changes from π to 2π as θ_1 is increased beyond 3°. Unlike the previous results reported in [14], there are two minima where their locations move separately from 90 and 270° toward 180°, and merge together to have nearly constant efficiencies as θ_1 increases. When the tilt of laser diode is more than 1.5°, it is shown that only less than 30% of the maximum coupling power can be launched to the angled-facet single-mode fiber over a wide relative rotation angles ranging from 90 to 270°.

It can be shown that the π-to-2π period turning points occur, for example, at $\theta_1 = 2.2$ and 4.5° for $\theta_{fa} = 6$ and 12°, respectively, from our analysis by using $e = 3$. Moreover, the maximum coupling efficiency $\eta_{\max}$, which occurs at $\theta_1 = \theta_f$ when $\Delta\alpha = 0$, is only dependent on elliptical ratio, and can be expressed as

$$\boldsymbol{\eta}_{\max} = (\boldsymbol{\kappa}_{x0}\boldsymbol{\kappa}_{y0})^{1/2} \tag{23}$$

where

$$\kappa_{x0} = \frac{4}{\left(\dfrac{W_{1x0}}{W_{f0}} + \dfrac{W_{f0}}{W_{1x0}}\right)^2}, \kappa_{y0} = \frac{4}{\left(\dfrac{eW_{1x0}}{W_{f0}} + \dfrac{W_{f0}}{eW_{1x0}}\right)^2}. \tag{24}$$

The relative error of coupling efficiencies, $\triangle\varepsilon_{\text{app.}}$, derived from these two models is defined as $\triangle\varepsilon_{\text{app.}} \equiv (\eta_{\text{approximate}} - \eta_{\text{exact}})/\eta_{\text{exact}}$. It is found that the approximate analytical model agrees well with the exact one within 1.5% error as θ_1 is less than 5°, but errors may be beyond 6% as θ_1 is ~10°. It is noted that the maximum relative error occurs at $\triangle\alpha = 180°$ due to the maximum total tilt angle.

Fig. 5 depicts the difference between the Clement and Österberg (CÖ) model and ours for various laser tilt angles θ_1. Without loss of generality, the elliptical ratio and the beam waist of laser diode are set to 3 and 5 μm, respectively. In the CÖ's model, an average beam waist W_1, i.e., $W_1 = (W_{lx}W_{ly})^1/2$ is used in (19) while ours is based on (17). The results obtained from the two models are quite different for small tilt angles, however, become similar in variation as the tilt angle θ_1 increases because the influence of the elliptical factor becomes less dominant as compared to the tilt angle.

Similarly, the relative error of coupling efficiencies, $\Delta\varepsilon_{\text{C\&Ö}}$, can be calculated by using these two models for various θ_1, where $\Delta\varepsilon_{\text{C\&Ö}} \equiv (\eta_{\text{C\&Ö}} - \eta_{\text{approximate}})/\eta_{\text{approximate}}$. The maximum relative errors are found to be ~50% ($\Delta\alpha = 90°$, 270°) and ~77% ($\Delta\alpha = 180°$) for $\theta_1 \leq 1°$ and $\theta_1 = 5°$, respectively. It is noted that the maximum relative errors of these two models occur at $\Delta\alpha \sim 90°$ and ~270° for tilt angles smaller than 1°, but at $\Delta\alpha = 180°$ for large tilt angles. Moreover, from our analysis, the relative error $\Delta\varepsilon_{\text{C\&Ö}}$ increases with elliptical ratio.

An experimental setup shown in Fig. 1 was used for proof-of-principle. Two types of laser diodes at 1.3-μm-wavelength, hereafter called type A and B, were used. Each was mounted on a stainless housing by laser welding to form a laser diode module. The tilt angle of laser diode module θ_1 was precalibrated as reference. A Zr_2O_3 ferrule with single-mode fiber inside was polished at 8°, and then mounted on another stainless housing to form an angled fiber module. A beam profiler (Merchantech Corp.) was used for beam waist measurement. Ten pieces of Type A laser diodes were measured,

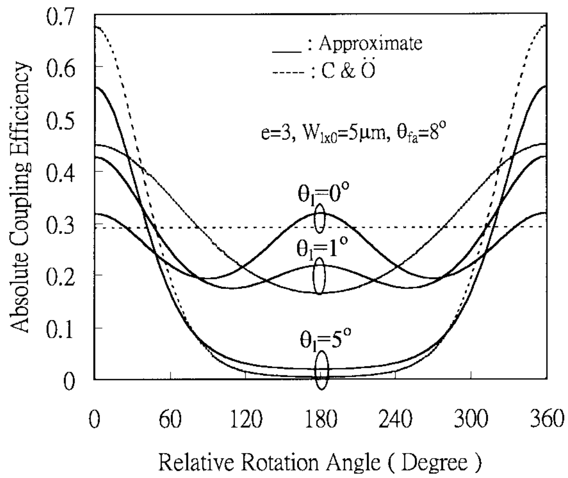

Fig. 5. Calculated absolute coupling efficiency variations based on different models.

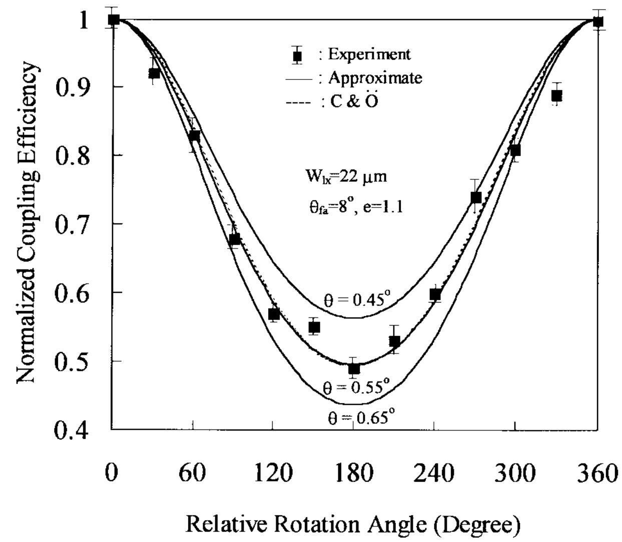

Fig. 6. Experiment and simulation results for type A laser diode.

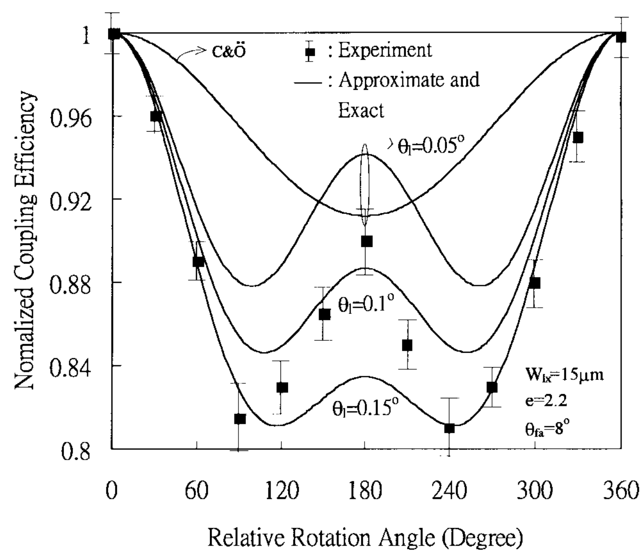

Fig. 7. Experiment and simulation results for type B laser diodes.

which had an average waist of 22 μm in the x direction and an elliptical ratio of 1.1. Similarly, the average beam waist of six pieces of type B laser diodes was 15 μm, and the elliptical ratio was 2.2. Using a Dukane-5020 auto-alignment and laser-welding package system, the laser diode and angled fiber modules were clamped by up and low collets, respectively. For each laser diode installed we successively rotated the angled fiber module at a step of 30° while keeping the laser diode module fixed. At each rotation step, an auto-alignment scanning was proceeded to find out the maximum coupling efficiency. Note that all laser diodes were operated in an automatic power control mode.

Fig. 6 shows the experiment results and the simulation fitting for type A laser diode at three different tilt laser angles, i.e., 0.45, 0.55, and 0.65°. All the measured and calculated coupling efficiencies which are all normalized to their maximum values vary with relative rotation angle at a period of 2π. The calculated coupling efficiencies are obtained by using the CÖ model and our approximate one. It is apparent that the difference between these two models is negligible since the laser diode had an elliptical ratio of $\sim$1 and a large tilt angle. About 3 dB deviation in coupling efficiency is seen in Fig. 6 when the angled fiber module is rotated one cycle. The minimum coupling efficiency occurs when the fiber module is rotated to 180°, i.e., $\alpha_f = 180°$. The experiment results are in excellent agreement with the simulation ones.

The result of employing type B laser diode is shown in Fig. 7. It is found that the measured coupling efficiency varies with relative rotation angle also at a period of 2π; however, there are two minima instead of one in a period as indicated by the CÖ model. The two minima occur at 90 and 240°. Three different coupling models, namely, CÖ, approximate, and exact ones, are used to fit the measured results using three angles. The tilt angle of $\sim$0.1° is found a better fit. Clearly, it is shown the approximate and the exact models are more suitable to describe the experiment results than CÖ's.

IV. Discussion

Based on the approximate coupling model, two potential applications are presented. The first one is for fast search of the optimal coupling efficiency between an elliptical Gaussian beam and an angled facet fiber in a packaging process. Since the laser diode and angled fiber modules may be placed at any direction in the toolings, the optical coupling efficiency may be deviated from its maximum value. It is therefore desirable to quickly find the optimal position with steps as few as possible. As shown in Fig. 4, three measurands, namely, efficiencies $\eta(A_1)$, $\eta(B)$, and the difference of relative rotation angle $\Delta\alpha_{A_1B}(\Delta\alpha_{A_1B} = \alpha_B - \alpha_{A_1})$, are required when (17) is applied to finding the maximum efficiency at, e.g., location C. First, A_1 is chosen and $\eta(A1)$ is measured. There are two and four possible locations of A_1 in 2π- and π-periods, respectively, if all the related parameters including W_{f0}, W_{lx0}, e, θ_1, and θ_{fa} are predetermined. Fig. 4 indicates four possible locations, A_1, A_2, A_3, and A_4, for a period of π. Secondly, a second point B is chosen and $\eta(B)$ is measured. If the sign of slope $\overline{AB}$ is known, only one and two locations of the maximum efficiency are possible for 2π-and π-periods, respectively. By applying the model, it is then apparent that point C can be found by rotating the low-tooling twice for a period of 2π, and three times for a period of π. Note that in order to avoid the sign change of slope $\overline{AB}\Delta\alpha_{AB}$ should be taken as small as possible. On the other hand, when the tilt angles of laser diodes have a spread, θ_1 needs to be calculated by utilizing $\eta(A)$, $\eta(B)$, and $\Delta\alpha_{AB}$ each time, which may be time-consuming. In practice, fortunately the deviation of θ_1 of OSA packages is usually small from industry mass production; therefore, an average θ_1 could be obtained from a few selected samples.

The second application is for the inspection of concentricity between the up and low collets in an OSA package system. A Michelson interferometer is commonly used for such inspection. However, to the best of our knowledge, there is still no inspection method to characterize the parallelism of clamp surfaces between up and low collets. It is found that the approximate analytical model can be used to tackle with this problem, and is described as follows. Given a precalibrated laser diode module and an angled fiber module, one can calculate the ratio of the maximum and the minimum coupling efficiencies over a rotation period. From (19), the ratio is derived as

$$\frac{\eta_{\min}}{\eta_{\max}} = \exp\left\{-\kappa\left(\frac{k^2\theta_T\theta_f}{2}\left(W_{10}^2 + W_{f0}^2\right)\right)\right\} \tag{25}$$

where θ_T is the tilt angle between up and low collects. If $\theta_T = 0$, then complete parallelism between the collets results.

It is noted that the use of a laser diode having nearly unity elliptical factor is preferred since the analysis can be simplified. Fig. 8 indicates that the tilt angle can be characterized by measuring the coupling efficiency ratio over a rotation period using, for example, a type A laser diode. Assumed $\theta_1 \cong 0°$ and the fiber module is 8° angled. The ratio increases as the tilt angle decreases, and is close to unity when both collets are parallel to each other. The accuracy of concentricity inspection is expected to be less than 0.1° as estimated from the results shown in Fig. 6.

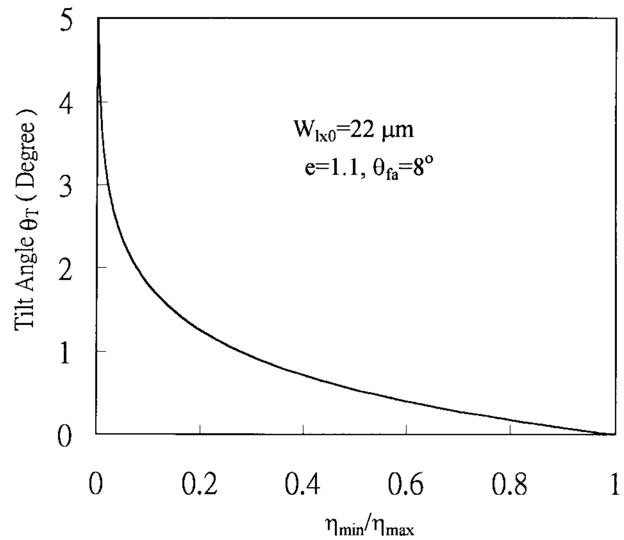

Fig. 8. Variation of relative tilt angle versus efficiency ratio.

V. Conclusion

The utilization of an angled facet fiber is considered as cost effective in reducing back reflection when packaging an OSA module. However, it is generally time consuming to search the maximum coupling efficiency owing to the strong dependence of coupling efficiency on relative rotation angle. We find the coupling efficiency varies significantly with an elliptical factor, and the previous treatments by employing circular Gaussian beam with geometric mean spot size may not be appropriate. An approximate analytical model is therefore developed for calculating the coupling efficiency between an elliptical Gaussian beam and an angled-facet single-mode fiber when the two fields are out-of-plane misaligned. Within small-angle approximation, the results obtained from the model are in good agreement with those from the exact numerical one. Both results show the coupling efficiencies vary with relative rotation angle at a period of π rather than remain constant when a laser diode has no tilt with respect to the central axis of the package system. As the tilt angle of laser diode increases, the period of coupling efficiency variation is shown to change from π toward 2π. Moreover, the maximum coupling efficiency is dependent only on elliptical ratio, and occurs at $\theta_1 = \theta_f$ when $\Delta\alpha = 0$.

Instead of utilizing the Hankel transformation as shown by Clement and Österberg, we derive an approximate analytical model based on the separation of variable and the projection of beam propagation direction to calculate the out-of-plane elliptical-beam to angled-fiber coupling. Simulation results show that for an elliptical ratio of 3 and tilt angles θ_1 less than 1°: 1) there are only 0.25% relative error between the approximate and exact models and 2) the maximum relative error between CÖ's and ours can be as high as 50% in coupling efficiency. In a proof-of-principle experiment, a laser diode with an elliptical ratio of 2.2 is found to have two minimum efficiencies within a period of 2π relative rotation angle, and exhibits a local maximum at $\Delta\alpha = 180°$ rather than a minimum as calculated by employing Clement and Österberg's model. The approximate model, therefore, can be used to simulate the results much more accurately. In addition, we propose two potential applications based on the approximate model. One is for quick search of the optimal coupling efficiency, and the other is for the concentricity inspection between up and low collets in an OSA package system.

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