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THE EFFECT OF THE COUPLING SCHEME ON COUPLING EFFICIENCY AND TOLERANT MISALIGNMENT OF SEMICONDUCTOR OPTICAL AMPLIFIERS MODULE

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ABSTRACT

Analysis on three different coupling systems, i.e., butt, single ball lens, and two ball lenses was carried out to study their effect in pigtailing a semiconductor optical amplifier (SOA) module. By placing the coupling system between the tips of two coupled single mode fiber parameters such as coupling efficiency and longitudinal tolerant with variation of working distance can be investigated. Result of the three schemes studied showed that two ball lenses is the most efficient for this application even with the assumption of an elliptical beam profile for the source fiber. We also observed an optimum range for the separation between the two lenses at which the coupling efficiency is maximal.

Keywords: coupling system, coupling efficiency, single mode fiber

INTRODUCTION

Photonic devices such as those widely employed in fiber-optic communications, optical sensing, and radio frequency (RF) photonics, they are known as a free space based photonic devices in which single mode or multi-mode pigtailed fiber collimators are used. This is because the coupling between two fiber collimators has a large working distance with low loss, which is critical for a practical free space intercomnected photonic devices modules. One of the most important requirements for these devices are the large misalignment tolerances, possibility of automating the alignment process between array of fibers and lenses, and reliable attachment of the coupling components. Therefore, it is of great importance to design an optical scheme with both high coupling efficiency and large tolerances. However, there are some difficulties in assembling of the collimator array regarding the multi-channel alignment and the requirements of submicron accuracy during alignment and attachment. The process of the alignment of fibers with the coupling components can be achieved in an active alignment process in which the input fiber or the fiber source is coupled into a receiver fiber. This process greatly enhanced the process of coupling with high accuracy for submicron alignment. In some applications, the coupling can be performed directly as face to face without any coupling media and also without a gap between the end faces of the two fiber, such as the common process of fusion splicing, but in some other case which require high coupling efficiency and a wide gap (long working distance), the butt or direct coupling is not adequate, therefore a certain type of coupling medium has to be inserted between the two fibers. Coupling using two GRIN lenses is reported to be efficient for this application [3]. But GRIN lenses are made of glass doped with some elements at their optical centers to have graded distributions of refractive index; therefore, they are very much affected by thermal and other environmental variation and show degradation in coupling efficiency and alignments due to the variation of the dopant distributions. In this work, a fiber-to-fiber optical scheme is designed with two ball lenses and compared with the use of single ball lens and butt coupling schemes for a semiconductor optical amplifiers (SOA's) which also can be applied to other photonic devices such as, isolators, circulators, attenuators, switches, and wavelength-division multiplexers/demultiplexers. Gaussian beam optics and ABCD ray tracing matrix are also employed to describe the mode field transformation between the to fiber tips. Coupling efficiency and misalignment tolerances are analyzed for better alignment. Laser welding is the powerful technique that makes the attachment of the coupling components such as small ball lenses feasible and strong to resist aging and environmental variations. All the parameters of the laser weld pulse have to be optimized for reliable weld yields

Semiconductor optical amplifiers (SOAs) are essentially laser diodes, without end mirrors, which have fiber attached to both ends. They amplify any optical signal that comes from either fiber and transmit an amplified version of the signal out of the second fiber. SOAs are typically constructed in a small package, and they work for 1310 nm and 1550 nm wavelength systems. In addition, they can transmit bidirectionally, making the reduced size of the device an advantage over other amplifiers.

THEORY

The arrangement of Figure 1, shows the source and receiver fibers as represented by SMF-1 and SMF-2 respectively, with the coupling system place between the two tips of the fibers.

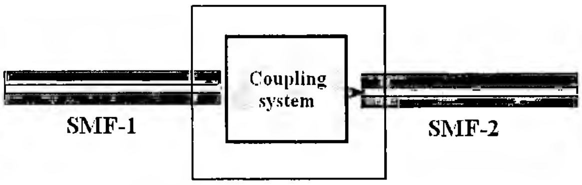

Figure 1: Fiber to fiber coupling arrangement

For simplicity, consider a circular mode that field of the laser diode is coupled into the source Therefore, the mode field of the source fiber can be expressed as follows [1]

$$\psi_s = \left(\frac{2}{\pi w_s}\right)^{1/2} \exp\left[-\left(\frac{x^2+y^2}{w_s^2}\right)\right] \exp\left[-j\frac{K_1}{2}\left(\frac{x^2+y^2}{R_s}\right)\right] \tag{1}$$

where; w_s *and* R_s are the mode field waist and wavefront radii before the transformation respectively. These parameters can be express in terms of the minimum waist of the mode field of the source fiber, w_{s0} as well as the distance to the coupling system between the two fiber tips, d as follows

$$w_s = w_{s0}\left[1+\left(\frac{d\lambda}{\pi w_{s0}^2}\right)^2\right]^{1/2} \tag{2}$$

$$R_s = d\left[1+\left(\frac{d\lambda}{\pi w_{s0}^2}\right)^2\right] \tag{3}$$

The transformed mode field of the source fiber is given as:

$$\psi_{2s} = \left(\frac{2}{\pi w_{2s}}\right)^{\frac{1}{2}} \exp\left[-\left(\frac{x^2+y^2}{w_{2s}{}^2}\right)\right]\exp\left[-j\frac{K_2}{2}\left(\frac{x^2+y^2}{R_{2s}}\right)\right] \tag{4}$$

where, $K_2 = 2\pi n/\lambda$, n is the refractive index of the coupling medium.

The transformation can be expressed in terms of the ABCD elements of the ray transfer matrix of the specified coupling components. From the values of A, B, C and D, one can calculate ω_{2s}, R_{2s} in terms of their counterparts before the transformation.

The receiver fiber is also a single mode fiber which can be expressed as;

$$\psi_r = \left(\frac{2}{\pi}\right)^{\frac{1}{2}} \frac{1}{w_r} \exp\left(-\frac{x^2+y^2}{w_r{}^2}\right) \tag{5}$$

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

$$\frac{w_r}{a} = 0.65 + \frac{1.619}{V^{\frac{3}{2}}} + \frac{2.879}{V^6} \tag{6}$$

where; a is the core radius of the fiber, V is the normalized frequency of the fiber, and for single mode fiber the value of V is in the range[2]; $1.9 \le V \le 2.405$
The coupling efficiency is expressed by the overlap integral [1,4]

$$\eta = \frac{\left|\iint \psi_{2s}\, \psi_r^* \, dxdy\right|^2}{\iint |\psi_{2s}|^2 dxdy \iint |\psi_r|^2 dxdy} \tag{7}$$

η depends on the degree of matching between the spot sizes and distributions of the source and receiver fiber mode fields.

EXPERIMENTAL PROCEDURE

In this research, we use the system of laser weld (LW4000S) which includes an Nd:YAG laser with dual laser beams, welding workstation and motorized stages for housing the packaged photonic module, with active alignment facilities, i.e., during the alignment of the two fiber tips the source fiber is connected with a laser diode module powered by a laser diode controller, during the alignment, the system continuously measures the coupled power at the free end of the receiver 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.2. The tips of the coupled fibers are metalized and ferruled inside Kovar ferrules to enable their attachment by laser welding to the main substrate using saddle-shaped welding clips. The parameters of the laser weld pulses are optimized for minimizing the post weld shifts and achieving the reliable weld yields.

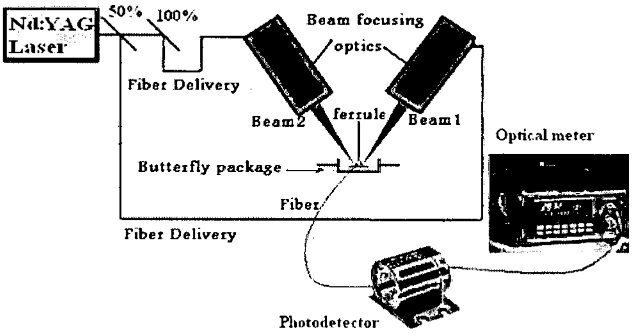

Figure 2: Dual beams Nd:YAG laser welding for butterfly modules

RESULTS AND DISCUSSION

Three coupling configurations have been analyzed for coupling a single mode fiber into a single mode fiber. For the direct coupling scheme, the variation of the coupling efficiency with the working distance is shown in Figure 3. This figure illustrates that the coupling efficiency can be maximum if the ends of the two fibers brought to contact without any offset and tilts but it deceases dramatically with increasing the separation between the two fibers (working distance). However, at a working distance of $100\mu m$, the coupling efficiency reduced to around 40% of its maximum value.

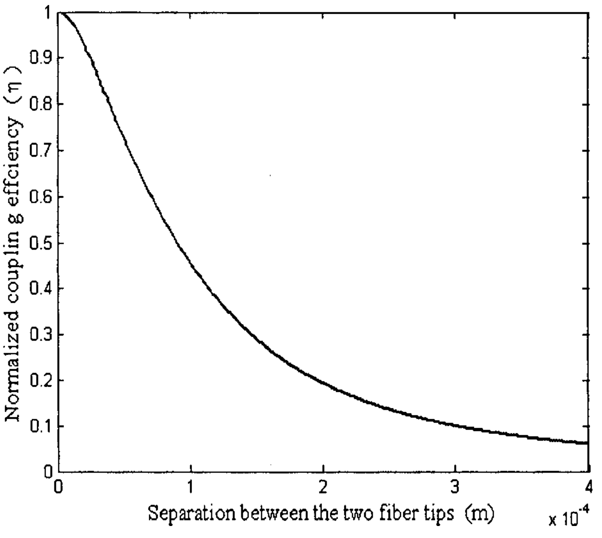

Figure 3: Coupling efficiency versus the separation between the two fiber ends

Single ball lens coupling scheme provides significant enhancements to both the coupling efficiency and the working distance, as shown in Figures 4 for two cases using ball lenses with similar radius (0.5 mm) and different refractive indices, i.e., 1.5 and 1.8313. Both cases provided high coupling efficiency and wide working distance. However, the ball lens with higher refractive index gave high coupling efficiency even at zero working distance. Moreover, ball lenses with higher refractive indices are more preferred because they are suitable for minimizing the spherical aberration.

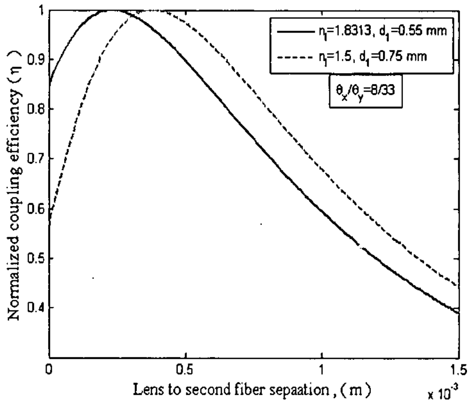

Figure 4 Variation of the coupling efficiency with the working distance using single ball lens with different refractive indices.

For the case of two ball lenses with (0.5 mm) radii and the first has a refractive index of (1.5) whereas the second has a refractive index of (1.8313) and keeping the distance between the source fiber and the first lens equal to its focal length (0.75 mm) , for different values of lenses separation distances, it has been found that there is an optimum value of 1 mm at which the coupling efficiency has a stable variation with the distance between the second lens and the receiver fiber (working distance) and it can reach unity at a working distance around (0.8 mm) as shown in Figure 6. Again considering the ball lenses to be of same high refractive indices, i.e., 1.8313, shows a better variation of coupling efficiency with working distance at coupling distance (first fiber to first lens separation) of 0.55 mm which is the focal length of the first lens. From the different values of lenses separation distances, the optimum value is found to be also 1 mm. However, comparing to the first case, here the coupling efficiency is more than 50% even at a zero working distance.

The variation for some other values of the separation between the two lenses is shown for the two cases, where the variation has large fluctuations despite that the coupling efficiency can reach unity at some points but it is not preferred because of this fluctuation that affects the reliability of the coupled device.

To better understand the effect of the separation between the two ball lens on the coupling efficiency, the distance from the coupling system to both the source and receiver fibers are fixed at the optimum values that give best results, i.e., 0.55mm and 0.8 mm respectively. The variation of the coupling efficiency with the separation between the two lenses for ball lenses of same refractive indices is shown in Figure 8, where it is clearly observed that there is an optimum range centered at (s = 1mm) at which the coupling efficiency is maximum and can reach unity. Fig. 8 shows the same illustration for a case of different refractive indices at the optimum coupling parameters mentioned above, i.e., 0.75mm coupling distance (focal length of the first ball lens), 0.8mm working distance. The first case clearly shows a better effect and a little bit wider range of lenses separation.

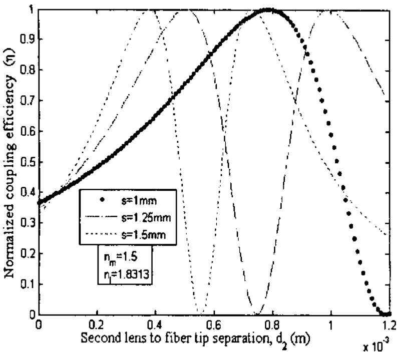

Figure 5: Variation of coupling efficiency with the working distance in fiber to fiber coupling using two ball lens with different refractive indices

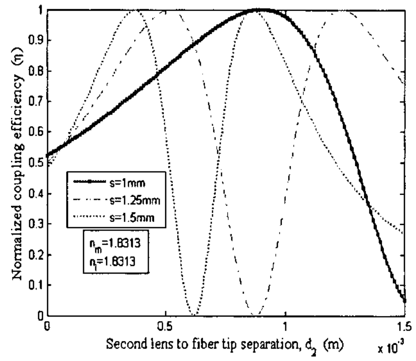

Figure 6 Variation of coupling efficiency with the working distance in fiber to fiber coupling using two ball lens with same refractive indices

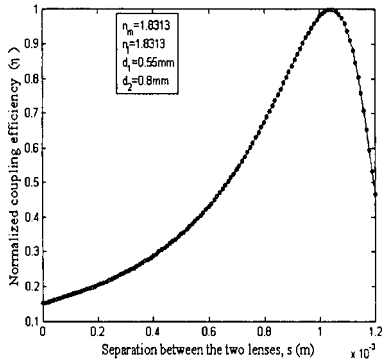

Figure 7: Effect of the separation between the two ball lenses with same refractive indices on the efficiency of fiber to fiber coupling

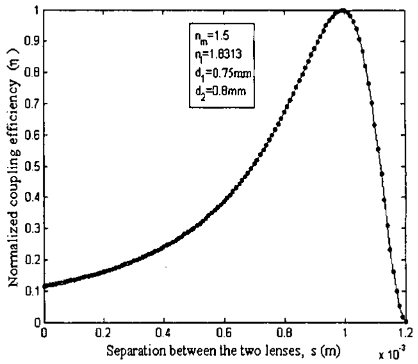

Figure 8: Effect of the separation between the two ball lenses with different refractive indices on the efficiency of fiber to fiber coupling

CONCLUSIONS

Coupling and pigtailing processes of a semiconductor optical amplifier module have been discussed for three different coupling configurations. Despite that the butt coupling is the simplest and can provide high coupling efficiency, but the working distance is very tight to allow the insertion of the amplifier chip or other optical components. Single ball lens can provide enhancement to both the coupling efficiency and working distance but the problem of positioning the lens regarding to the amplifier chip between the two fiber tips arises. Because if the lens is before the chip the focusing to the second fiber will not be effective and if it is after the chip the collimation from the first fiber will not be effective. Therefore, a dual ball lenses coupling scheme is devised to solve that conflict by positioning the chip between the two lenses. Moreover, this coupling scheme provides a maximum coupling efficiency with wide misalignment tolerances that can be significantly controlled by the variation of lenses separations. The attachments of all coupling components have been done using laser welding with dual Nd:YAG laser beams during active alignment processes. The fibers tips have been metalized and encapsulated inside metallic ferrules to enable its weldability to the main substrate. Laser welding beam parameters have been 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.

REFERENCES

[1] A. Yariv and P. Yeh, *Photonics; Optical Electronics in Modern Communications*, 6th Ed., chap. 2, Oxford University Press, New York, 2007.

[2] Saleh and M. Teich, *Fundamentals of Photonics*, John Wiley & Sons, USA & Canada, 1991.

[3] M. Saruwatari and T. Sugie T.," Efficient Laser Diode to Single-mode Fiber Coupling Using a Combination of Two Lenses in Confocal Condition," *J of Quantum Elec.*, Vol.**QE-17,** No.6, 1981.

[4] S. Sarker, K. Thyagaralan and A. Kumar, "Gaussian approximation of the fundamental mode in single mode elliptic core fibers," *Opt. Comm.*Vol. **49,** No.3, pp. 178-183,1984.

[5] K. Holger and D. Karsten, "Loss Analysis of Laser Diode to Single-Mode Fiber Couplers with Glass spheres or Silicon Plano-Convex Lenses," *J. of LightWave Tech.*,, Vol. **8**, No.5, 1990.

[6] V. Shah L. Curtis, R. Vodhanel, D. Bour and W. Young," Efficient Power Coupling from 980nm, broad area laser to single-Mode Fiber Using a wedge-Shaped Fiber Endace",*J of Lightwave Tech.*, Vol.**8,** No.9, pp.1313-1318,1990.

[7] W. Joyce and B. Deloach, "Alignment of Gaussian Beams," *J. Appl. Opt.*, Vol. **23**, No. 23, p 4187-4196, 1984.

[8] L. Reith, W. Mann, G. Lalk, R Krchnavek, N. Andreadakis and C. Zah, "Relaxed-Tolerance Optoelectronic Device Packaging", *J. of LightWave Tech.*, Vol. **9**, No. 4, pp. 477-484, 1991.

[9] C. Edwards, H. Presby and C. Dragone, "Ideal microlenses for laser-to-fiber coupling", *J. Lightwave Tech.*, V.**11,** No. 2, pp. 252-257, 1993.

[10] H.Yang, S Huang, C. Lee, T. Lay and W. Cheng, "High Coupling Tapered Hyperbolic Fiber Microlens and Taper Assymetry Effect," J. Lightwave Tech., Vol. 22, No. 5, pp.1395-1401, 2004.

[11] Y. Murakami, J. Yamada, J. Sakai, and T Kimura, "Microlens tipped on a single-mode fiber end in GaAsP laser coupling improvement,". *Electron. Lett.*, Vol. **16**, No.6, pp: 321-322, 1980.

[12] Y, Odagiri, M. Seki, H. Nomura, M. Sugimoto, and K. Kobayashj,"Practical 1.5 µm LD-isolator-single-mode- fiber module using a V-grooved diamond heatsink," in Proc. 6th Eur. Conf. Optical Communication, (York, U.K.), pp. 282- 285, 1980.

[13] E. Weidel, "New coupling method for GaAs laser-fiber coupling," *Electron Lett.*, vol.**11**, pp: 436-437, 1975.