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Optical Fibre Coupling of Laser Diode Arrays

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1 BACKGROUND

Diode laser technology has made extraordinary progress since the first semiconductor lasers were fabricated in 1962. The semiconductor lasers have been dominating the laser market for years due to their advantages over other lasers. These advantages include compactness and high efficiency, improvement in lifetime, diversity in wavelength covering visible to infrared bands, power scaling to kilowatts with diode arrays and the recent dramatic drop in price [1]. However, the laser beams emitting from the diode lasers have certain drawbacks that have to be overcome. They suffer from bad beam quality with divergent angle much bigger than that of the conventional lasers. The laser beams are also astigmatic with different radius, beam divergence and waist position in the directions parallel and perpendicular to the p-n junction. For almost all the applications, however, it is usually desirable for the laser beams to have symmetrical profiles with high quality and high power to produce a small but powerful spot. This is quite challenging for the diode lasers and therefore the laser beams from high power diode lasers need to be coupled and reshaped before being used.

There are three main methods to couple and reshape the diode laser beams. The first and most straightforward method is the use of lenses to focus the light, in which the laser beams are collimated and focused separately in the parallel and perpendicular directions. The second technique uses optical fibres in which the fibre-ends are positioned close to the laser strips. The light is coupled into and guided along the fibres. The resulting combination of the fibres in a bundle results in the compression of the beam. Another method to reshape the beam makes use of a tapered duct, which has a bigger entrance than exit plane, with gradually decreasing diameter. The light is reflected at the sides of the duct and as it is tapered, the duct compresses the light into the smaller area at the end-face. This project focuses mainly on the optical fibre coupling due to its advantages over the other two options.

2 OBJECTIVE

The objective of this project is to develop an efficient and low cost method of laser beam coupling and reshaping for high power laser diode arrays. The scopes include: (1) characterisation of laser beam from diode arrays; (2) design of lens, duct and fibre connector; fabrication of optical duct and fibre coupler; and (3) optimisation of specifications of optical components.

3 METHODOLOGY

Optical fibre coupling uses optical fibres to couple and guide the laser light from the laser strips to a circular beam with a small diameter compatible to the size of an individual emitter in the diode arrays. Each emitter of an array has its own fibre and at the output end, all fibres are combined in a circular shape. In this way, the diode laser beam can be effectively coupled, reduced and reshaped. Figure 1 shows an example of a fibre coupler using the so-called butted-end coupling.

Conventional optical ray tracing can be used to explain the wave guiding principle in the fibres. Referring to the right side in figure 2: n_1 is the refractive index of the core of the fibre and n_2 that of the fibre cladding, while n_0 is the refractive index outside the fibre. Light rays entering the fibre are refracted at the air/core interface according to Snell's law. The refracted ray of light hits the core/cladding interface and is totally reflected if the angle of incidence is bigger than the critical angle.

In the butted-end optical fibre coupling, the fibres have to be positioned close to the laser diode and carefully aligned with respect to the laser emitters. The direction of the fibres is perpendicular to the plane of the laser diode array. The type of fibre has to be matched with the diode laser.

Keywords: Laser diode array; Optical fibre coupling; Laser beam shaping

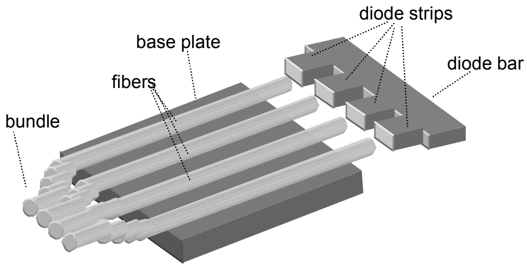

Figure 1 Example of a fibre coupler. The light from each strip is collected and guided by its fibre. All the fibres are then bundled together to form a circular spot.

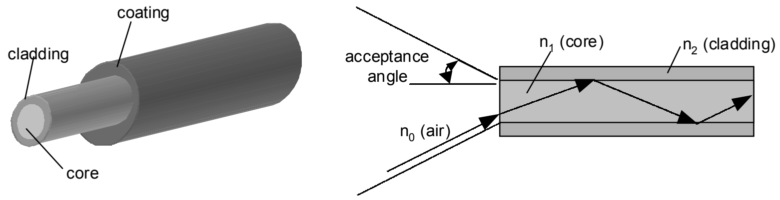

Figure 2 Structure of an optical fibre. Left: an optical fibre consists of a core and a cladding, which is protected by a polymer coating. Right: the maximum angle of acceptance for an optical fibre is determined by the refractive indices of the core and the cladding of the fibre.

A fibre with higher numerical aperture (*N.A.*) has a bigger acceptance angle to couple the light of the laser diode. The divergence of the beam leaving the fibre will be higher as well. A bigger fibre diameter makes the alignment less sensitive, but results in a bigger beam size. The fibre-ends have to be free of dust and scratches to decrease scattering loss. The butted-end coupling is simple and low cost while the coupling efficiency remains reasonably high.

The fibre ends are normally flat and perpendicular to the fibre. However, different shapes of the fibre ends are sometimes used, in order to increase the angle of acceptance of the fibres and thus the coupling efficiency. For example, the fibre-ends can have a hemispherical or tapered shape. An optical fibre coupler with tapered fibre ends in the fast-axis direction can automatically reduce the divergent angle, and an efficiency of 98% can be achieved.

Alternatively, the coupling efficiency of the optical fibre coupling can be improved by inserting certain optical components between the laser diode array and the fibre array, while keeping the coupling fibre end surface flat. For instance, an optical fibre positioned transversely in front of the coupler can be used as a cylindrical lens, as patented in reference [6]. The fibre used as the cylindrical lens can be the same as the coupling optical fibres. The function of this fibre is to effectively compress the divergence in the perpendicular direction because the beam is almost diffraction limited. Therefore, the efficiency for unchanged *N.A.* of the fibres goes up. One can also use optical fibres with lower *N.A.* for equal coupling efficiency. The method of introducing the fibre cylinder as a cylindrical lens to compress the beam divergence is simple and low cost, but the difficulty in depositing a layer of anti-reflection coating on the surface of the fibre affects the total coupling efficiency.

Another method to decrease the divergence in both the fast and the slow axis is by using a micro-lens array in front of the fibre ends. The micro-lens array has to be custom-made for each laser-diode type and therefore, this method will be expensive.

A more complicated approach with high coupling efficiency involves the fabrication of the fibre base and the laser diode array on the same Si substrate. In this case, the laser emitters are fabricated on a GaAs substrate first. Then the chips are mounted on the Si substrate using solder balls. The Si substrate is finally etched with fibre alignment V-grooves. As it can be seen, this approach can be employed only at the same time as the laser diode array is being fabricated.

The optical fibre coupler designed and developed in this project has two major components: a base and a bundle of optical fibres uniformly aligned on the base and cabled with a standard SMA905 connector as the output end. The number, 19, of the fibres is the same as that of the emitters in a diode laser array from Coherent. Both the diode laser array and the optical fibre coupler are fixed in a same copper box. The alignment between the coupler and the array must be done in such a way that the array has very good thermal conduction to the bottom of the copper holder, through which the array is cooled by a TEC cooler. Therefore, it is quite understandable that the array should be always fixed in the box followed by the alignment of the coupler against the array. The joining of the coupler to the holder can be done using normal epoxy glue.

The base is used to hold the optical fibres steadily, and precisely in close-proximity positions to the laser diode array. To realise this, precisely positioned slots were cut on a flat surface with spacing equal to the pitch of the emitters in the laser diode array. The shape of the slots can be square, half circular or V-shaped. The material of the base can be plastic or metal. Considering the plastic materials usually have high absorption for the laser beam and cannot withstand high temperature, the better choice is the metallic ones like copper and stainless steel. The cutting of the slots on the base can be done using micro-machining technologies; both EDM and laser micro-machining technologies were employed in this project. The laser micro-machining technology is efficient in the cutting on plastic materials, while the EDM technology is the better choice for the slots cutting on metallic materials. The size of the half-circular slots cut in this project is 250 μm in diameter and 20 mm long with error less than 5 μm.

The optical power can be attenuated due to the introduction of optical fibres in the power coupling. Typical loss is due to absorption of the optical fibres, scattering of impurities and defects inside the fibre core, power leaking from the core-cladding interface, and fibre end surface reflection because of index mismatch. Especially, in the case of fibre coupling the power from the laser diodes, light loss also comes from the mismatch between the divergence of the diode laser beams and the acceptance angle of the optical fibres, and the mechanical misalignment of the optical fibres against the laser diode arrays. The absorption and scattering loss is distance-dependent and negligible for the purpose of coupling with length in the order of meters. The end surface reflection, usually about 4% for the air/silica interface, can be reduced by depositing the ends with anti-reflection coating. The loss due to the mismatch of the laser beam divergence with the acceptance angle can be minimised by choosing suitable optical fibres. The most important and significant part of the loss in the optical fibre coupling is contributed by the misalignment of the optical fibres against the laser diode arrays.

The misalignment in the coupling of the optical fibres to diode laser arrays exists in five ways. They are linear misalignments in the parallel, perpendicular and axial directions and angular misalignments in the parallel and perpendicular directions. The most sensitive misalignments in the fibre coupling are the linear misalignments in the parallel and perpendicular directions. The main sources for these lateral and transverse misalignments are summarised in the following:

- Variation in fibre cladding diameter;
- Fibre core eccentricity;
- Mechanic fabrication error of the base slots;
- Diode laser lithography misalignment;

- Position offset of optical fibre against the slots during the alignment; and
- Different thermal coefficients for different materials.

All the misalignments except the position offset can be easily controlled to be less than 5 μm for coupling of a 200 μm optical fibre to a standard commercial diode laser. The position offset of the optical fibres to the individual slots, however, is difficult to reduce to such a level. This is because there is no automatic method right now to complete the alignment of the optical fibres to the slots, which is unfortunately manually done one by one.

4 RESULTS

The optical fibre coupler developed in this project is shown in figure 3 together with the laser diode array from Coherent. The optical fibres selected for the coupling of the laser beam from the Coherent diode array are from 3M with the following parameters:

- Materials(core/cladding): silica/TECS hard clad;
- Core size: 220 μm;
- Fibre size (core +cladding): 230 μm;
- Numerical aperture: 0.37;
- Absorption: 6 dB/km.

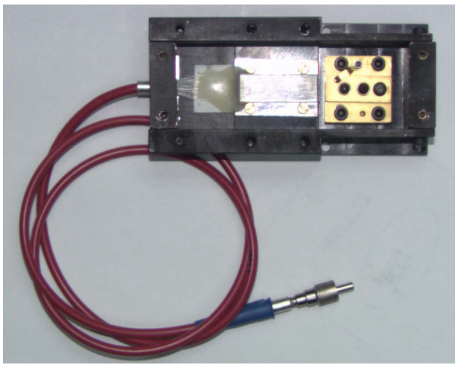

Figure 3 An optical fibre-coupled diode laser array with the fibre coupler developed in this project.

The diode array has the following specifications:

- Total output power: 20 W at current of 24 A;
- Operation wavelength: 808 nm at 24 A with a temperature shift of 0.3 nm/C^o;
- Beam divergence(FWMH): 10^o in the parallel direction and 40^o in the perpendicular direction;
- Length of the array: 10 mm;
- Number of emitters: 19;
- Size of emitters: 150 μm in the parallel direction and 1 μm in the perpendicular direction.

The alignment of the fibres to the base is shown in figure 4 and the positions of the optical fibres were measured with a microscope in both the parallel and perpendicular directions. The position offset is shown in figure 5, where it can be seen that the average offset is within 5 μm with a maximum value of 18 μm for number 14 fibre.

The fibres from the coupler has been bundled in a cable and terminated with a standard SM905 connector. Outside the bundle there is a standard furcation tubing to protect the fibres. The connection of the fibre bundle with the SMA905 connector and the end preparation were done in a way as described in Ref. [10]. The resulting cable has an output emitting size of 1.15 mm.

The optical fibre coupler has been characterized by measuring the laser power output as a function of the driving current, as shown in figure 6. The upper line is the laser power measured directly from the diode array and the lower line from output end of the fibre bundle. From the graph, we can see that the lasing threshold current is 8A and the power increases linearly with the driving current. The power has approximate slope efficiencies of 1.24W/A and 1.07 W/A, respectively for both lines. This indicates a coupling efficiency of 86% has been

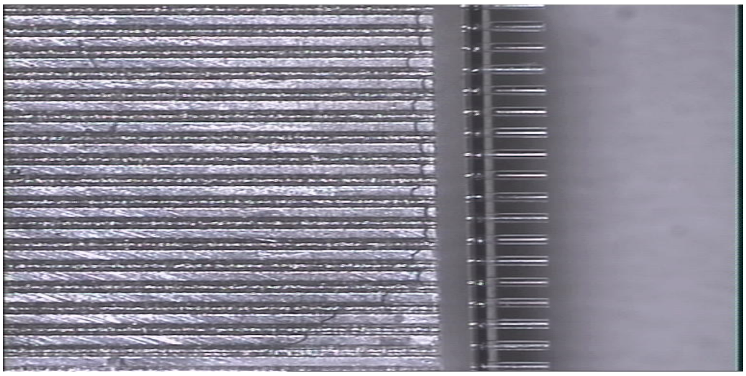

Figure 4 The alignment of optical fibres to the micro-slots on the coupler base.

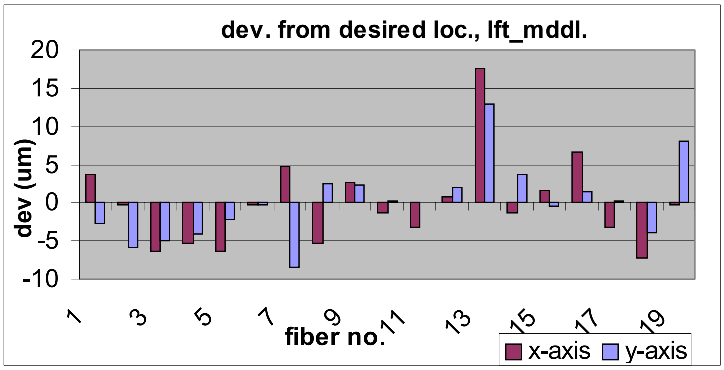

Figure 5 Position offset of the optical fibres to the desired location measured from the side of the coupler.

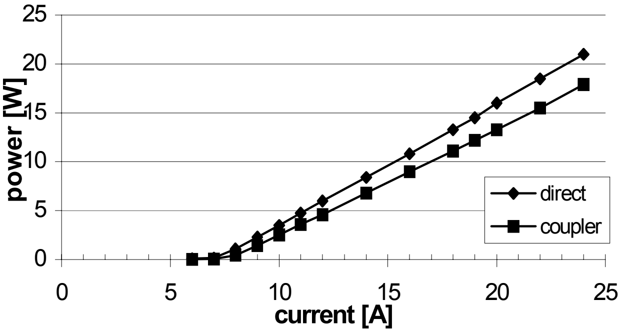

Figure 6 The coupled and the direct power as a function of driving current.

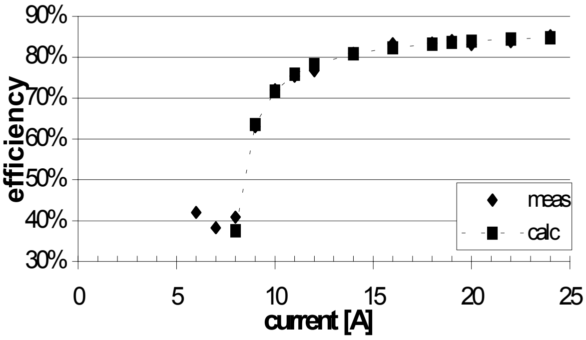

Figure 7 Coupling efficiency as a function of the driving current.

achieved. More detailed calculation of the coupling efficiency is shown in figure 7.

The efficiency of the coupler is what really interests us, which is desirable to be as high as possible. It is dependent on a number of factors, like the alignment, the type of fibre, the laser characteristics, losses in the fibre, surface finish and contamination of the fibre-ends. In the simplest approximation, all these factors are independent from the lasing power. Therefore, the efficiency is expected to be constant for different lasing powers. This was confirmed by experiments while aligning the fibre coupler. However, after mounting the fibre coupler in its final stage, we measured that the efficiency is now a function of the power as shown in figure 7. A possible reason for the variation of the efficiency is that during the mounting of the fibre coupler, a very thin white layer of glue has been deposited on the fibre-ends. We have used a fast curing (Localite) glue to pre-position the fibres on the base, which produces this white looking layer around the neighboring region of the glued zone. Some of the laser light may be absorbed by this layer. And also as it is very thin, the absorption by the layer could be saturable. Therefore, there may be a maximum of power that can be absorbed.

The output power from the optical fibre coupled diode array has been extensively tested against time. The temperature of the optical fibre coupler was also monitored during the test. It is found that the power coupled from the diode array by the optical fibre coupler is quite stable. The fluctuation of the power is less than 1%. The stability is solely determined by the diode array itself. Temperature of the coupler rises slightly as the driving current increases being 25^{o} C at 10 A and 26.5^{o} C at 15 A.

The laser output beam from the bundle of 19 fibres has a minimum size of 1.15 mm with a half divergence angle of 21.7^{o}. The optical fibres used solely determine the output beam quality. For example, its beam size is five times of the core diameter for a bundle of 19 fibres in our case, and its divergence is equal to the acceptance angle of the optical fibres. We should note here that the optical fibres used in our coupler have an unnecessarily large core diameter of 0.22 mm. This is because the size of the laser diode emitters in the parallel direction is only the fibres. Considering alignment margin 0.15 mm, much smaller than the core of of 0.005 mm on either side, optical fibres with a core diameter of 0.16 mm should be large enough for effective coupling. Taking the cladding thickness of 0.01 mm into account, a beam size of 0.85 mm is achievable for the laser diode bar used in the project. Unfortunately these optical fibres with special sizes are not commercially available.

In order to reduce the diameter further to achieve small light spot in the optical fibre coupling, special optical components are necessary to compress the beams from the emitters first. This compression must be done individually for each emitter because the product of divergence with size of a light source can not be reduced by any optical component. However, we can decrease one by sacrificing the other while keeping the product unchanged. If the emitters are dealt with individually, this product will be many times (50) smaller than that of the whole bar. It is particularly important to do so in the parallel direction with respect to the diode array orientation where the ratio of the product to that in the perpendicular direction is 50 for each emitter or 2500 for the whole laser diode bar. Fortunately, its half divergence angle of 5^{o} is relatively small so that it can be increased 2-3 times without introducing mismatch to optical fibres. Therefore the beam dimension in the parallel direction can be compressed by increasing its divergence angle. To reduce the laser beams from the emitters individually, each emitter requires a separate set of components with dimensions compatible with the size of the emitter. In this case micro-lenses may be the best choice. Basically, two arrays of micro-lenses are needed. The first array of micro-lenses has larger focus length to collimate the laser beams, and the second array has smaller focus length to focus them. The spot size reduction of the focused beams is roughly equal to the ratio of focus lengths. However, the fabrication of the micro lens arrays is difficult and expensive. In fact, we have designed such a micro lens system that combines both the collimating array and the focusing array on a single piece of glass plate. Ray tracing results show it can half the beam size in the parallel direction.

In contrast with the beams in the parallel direction, the dealing of the beams in the perpendicular direction is much easier, because they are almost diffraction-limited. Their product of divergence with size is much smaller, although the divergence is 3-4 times larger. With a single micro cylindrical lens, all the beams in this direction can be well re-shaped for coupling with optical fibres with small core and low NA. The use of a single lens alone in the perpendicular direction, however, is not recommended. This is because the lens insertion enlarges the distance of the fibre ends to the diodes and therefore enlarges the beam size in the parallel direction. In our project, the optical fibres are end-butted directly with the emitters, neither the micro-lens arrays in the parallel direction nor the single cylindrical lens in the perpendicular direction is used.

5 CONCLUSION

We have shown in this report that an optical fibre coupler has been successfully designed and fabricated. The coupled laser beam is from a laser diode bar from Coherent, which has 19 laser emitters in an array of 10 mm with spacing of 0.25 mm between the emitters. The size of each emitter is 0.001 wide and 0.15 mm long. Correspondingly, the coupler has an array of 19 optical fibres fixed in a metallic base with periodic slots. The maximum power obtained from the output of the fibre bundle is 18 W for the maximum input power of 21 W from the laser diode bar. This implies that an optical fibre coupling efficiency of 86% has been achieved, very close to the theoretical value of 88% for the diode array and the optical fibres we used, under the assumption of perfect alignment. The minor difference indicates that the optical fibres to the coupler base slots and the fibre array to the laser diode bar are well aligned, and the influence on the coupling efficiency of misalignment contributed from the optical fibres and the fabrication of the base is negligible.

6 INDUSTRIAL SIGNIFICANCE

The research and development of the optical fibre coupling for the high power diode arrays is significant in terms of industrial applications. Firstly, it can be used directly in **materials processing**. Although diode laser arrays have their advantages over conventional lasers like long life time, high reliability and excellent stability, they would still have little applications, due to their poor beam quality. Optical fibre coupling and reshaping can help to improve their beam quality. Coupling the laser power individually from each emitter of the arrays will increase the beam density by many times to meet the materials processing requirements. Industrial laser systems based on the high power diode laser arrays with optical fibre coupling will greatly simplify the system structure, reduce the cost and enhance the flexibility. These systems are particularly useful in heat treatment, welding, cutting and biomedical applications.

The optical fibre coupling technology for the diode laser arrays can also boost the **laser industry** itself. One of the future trends in solid state laser is that the commonly used pump lamp will be eventually replaced by the laser diode arrays. In this case, the laser diode arrays can be arranged with respect to laser crystal transversely (side-pump) or longitudinally (end-pump). The end-pump configuration is particularly attractive due to its excellent beam quality and high power conversion efficiency. The challenge is to collect as much as possible diode power and focus it into a small spot on the crystal end. With the help of optical fibre coupling developed in this project, the spot size of the laser diode array can be easily reduced by a factor of 10 with coupling efficiency of 87%. This spot size can be further reduced to, say about 0.65 mm, in order to match the single pump mode.

The optical fibre coupling is also one of the most important technologies in today's **optical fibre communications**, which occupy the biggest portion of the photonics market. High power diode laser coupled with optical fibre is always desirable in optical fibre lasers and fibre amplifiers for transmission signal boost and relay. The optical fibre array coupling technology is especially useful for the future dense wavelength-division and multiplexing (DWDM) communications. Two examples can be given here. First, the DWDM transceivers will include hundreds of wavelengths emitted from diode arrays, each of them needs to couple and deliver into a single fibre, and this array of fibres needs to combine to form a bundle that will be finally connected to a single fibre that carries all the wavelength signals. The other example is the application in multiplexing/demultiplexing devices. One of the most promising devices is arrayed waveguide grating that has hundreds of micro-channels uniformly arranged to combine/separate wavelength signals. The alignment and coupling using optical fibres to its massive input and output ports is a key aspect of this device.

In a word, the optical fibre coupling technology not only expands the application of laser diodes in the established industry, but also is applicable and desirable for emerging fields in Photonics like DWDM communications. It is a highly value-added technology.

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