High-reliability pump module for non-planar ring oscillator laser

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ABSTRACT

We propose and have demonstrated a prototype high-reliability pump module for pumping a Non-Planar Ring Oscillator (NPRO) laser suitable for space missions. The pump module consists of multiple fiber-coupled single-mode laser diodes and a fiber array micro-lens array based fiber combiner. The reported Single-Mode laser diode combiner laser pump module (LPM) provides a higher normalized brightness at the combined beam than multimode laser diode based LPMs. A higher brightness from the pump source is essential for efficient NPRO laser pumping and leads to higher reliability because higher efficiency requires a lower operating power for the laser diodes, which in turn increases the reliability and lifetime of the laser diodes. Single-mode laser diodes with Fiber Bragg Grating (FBG) stabilized wavelength permit the pump module to be operated without a thermal electric cooler (TEC) and this further improves the overall reliability of the pump module. The single-mode laser diode LPM is scalable in terms of the number of pump diodes and is capable of combining hundreds of fiber-coupled laser diodes. In the proof-of-concept demonstration, an e-beam written diffractive micro lens array, a custom fiber array, commercial 808nm single mode laser diodes, and a custom NPRO laser head are used. The reliability of the proposed LPM is discussed.

Keywords: NPRO Laser, Laser diode pump module, optical fiber array, micro lens array, reliability.

1. INTRODUCTION

Due to its narrow linewidth and stability, the Nd:YAG, Non-Planar Ring Oscillator (NPRO) laser[1] was chosen as the baseline laser for the metrology subsystem of JPL/NASA's Space Interferometry Mission (SIM). A fiber-coupled laser diode (LD) pumped NPRO laser was developed in a previous work [2] so that the temperature-controlled laser head module can be separated from the laser pump module (LPM). It, thus, permits an independent mechanical and thermal design of the LPM from that of the NPRO laser head. As there will be no service available to SIM over the entire mission, the LPM needs to be highly reliable. Roughly speaking, the LPM should have a lifetime (time before the device is worn out) on the order of 5 years and a reliability of ~99.7%, which corresponding to a random failure rate on the order of 10 FITs (Failures in Time=failures per 1 billion device hours). A 1 to 2W, 808nm laser diode normally can not meet this reliability and lifetime requirement. One way to increase the reliability and lifetime of the LPM is to combine multiple laser diode beams into a single pump beam.

There are several ways to combine multiple laser diodes together into an LPM. For example: (1) time multiplexing: in this method, several fiber-coupled, 1 to 2 W, multimode laser diodes are connected to the input of an optical fiber switch and the output fiber is connected to pump the NPRO laser; when the laser diode being used fails, the input is switched to a good laser diode and so on, (2) spatial multiplexing: one way to implement this method is to use fold mirrors to stack multiple laser diode beams into a larger collimated beam which is then coupled to a multi-mode fiber to pump the NPRO laser, (3) polarization multiplexing: in this method, a polarizing beam splitter is used to combine two linearly polarized laser diode beams into one beam and coupled into the multimode fiber to pump the NPRO laser, and (4) fiber multiplexing: in this method, a fiber combiner combines multiple fiber-coupled laser diodes into one multimode fiber to pump the NPRO laser. Among these methods, the two fiber based methods (1) and (4) are most attractive because there is no optics to align for adding a laser diode to the LPM.

However, due to the pump beam condition required for generating a single mode laser beam from the NPRO laser and the principle of conservation of energy, there is a constraint on the Entendu (product of the numerical aperture (NA) and the core diameter) of the multimode pump beam delivery fiber. Namely, the Entendu needs to be smaller than a certain value so that the beam waist diameter and the divergence angle of the pump beam inside the crystal is confined within the TEM00 mode of the NPRO laser beam before it is nearly depleted by absorption. In this respect, the fiber-switch is a better approach than the fiber combiner because the Entendu of the input fiber beam does not increase at the output of the LPM, whereas in the fiber combiner approach, the Entendu increases with the number of the input fibers and can exceed the maximum condition allowed for single mode lasing. On the other hand, the fiber switch approach involves moving parts, which can become a reliability issue itself.

In fact, just by coupling the bare laser diode beam into a multimode fiber increases the Entendu of the laser diode due to the non-circular symmetry of the Entendu of the bare multi-mode laser diode. When the beam emitting from a multimode laser diode with an elliptical Entendu profile is coupled into a circular multimode fiber, one can only match either the beam cross section or the angular distribution. That is if we correct the laser diode beam to be a circular beam in cross section, the angular distribution will not be circular symmetrical or vice versa. This means the Entendu of the input beam is smaller than that of the optical fiber. Thus, after the input beam is scrambled by the fiber the Entendu of the beam is increased. This does not happen in a fiber-coupled single-mode laser diode because the output beam of a bare single-mode laser diode is circularly symmetrical.

Based on this circular symmetry property of the single mode laser diode, we propose to use it to build the LPM for pumping the NPRO laser. However, the commercial single-mode to multimode fiber combiner has its limitation in preserving the total Entendu due to the finite cladding thickness of a single mode fiber. To solve this problem, we propose and demonstrated a method that uses a fiber array and a matched micro lens array to combine fiber-coupled single-mode laser diodes.

In principle, approximately, 1000 single mode laser diodes can be combined without exceeding the Entendu requirement for pumping the NPRO laser. That yields approximately two order of magnitude more power than the multimode fiber combiner approach.

An additional useful feature of the single mode laser diode is that its wavelength can be stabilized with a passive Fiber Bragg Grating (FBG). This means no thermal electric cooler (TEC) is needed in the laser diode package to temperature-stabilize the wavelength and this can further improve the overall reliability of the laser diode package.

In the rest of this paper, we will describe the concept and a breadboard implementation of the proposed single-mode laser diode pump module approach.

2. CONCEPT

In this Section, we will first describe some background information needed to understand the requirement for pumping an NPRO laser. Then we will describe the concept of the proposed single-mode laser diode beam combiner LPM.

2.1 NPRO laser and Pump beam requirement for single mode lasing

The basic principle of NPRO laser is described in Ref [1]. In this section we will only discuss the requirement for the pump beam to generate a single mode NPRO laser beam. Figure 2.1-1 illustrates the beam geometry of the NPRO laser. In principle, to make the NPRO lase in single mode (TEM00) the 808nm pump beam needs to be focused into a volume smaller than the TEM00 mode of the NPRO laser and nearly depleted by absorption before it diverges beyond the boundary of the TEM00 mode. The Nd:YAG NPRO crystal depletes the pump fast, which means the pump beam can diverge beyond TEM00 mode after being nearly depleted. This NPRO pump beam requirement determines the maximum Entendu of the LPM output beam for single mode lasing. In other words, a better LPM architecture is one that preserves the total Entendu better. We will show later that the proposed single-mode laser diode beam combiner LPM is indeed better than other approaches in preserving the total Entendu.

The NPRO laser can emit at 1064nm or 1319nm depending on the optical coating on the NPRO crystal. SIM chose 1319nm to avoid the metrology beam interfering with the visible star light on the silicon detector, as the band gap wavelength of silicon is approximately 1100nm. A disadvantage of 1319nm over 1064nm NPRO laser is that it has a smaller quantum efficiency.

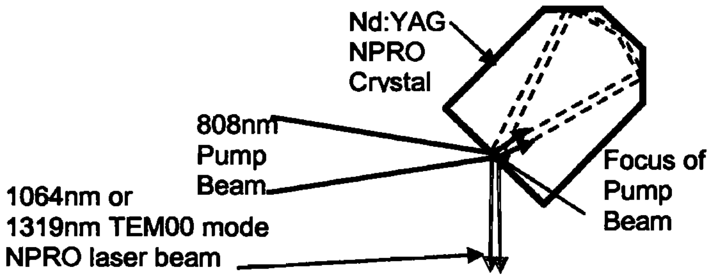


Figure 2.1-1 NPRO laser pump beam geometry

2.2 Single-mode laser diode LPM

Based on the limitation on the Entendu for the pump beam of the NPRO laser, a good pump module should preserve the Entendu as much as possible starting from the bare laser diode beam to the pump beam delivery fiber. A single-mode laser diode is better in this aspect because its elliptical mode can be converted into a circular mode matching that of a single-mode fiber. However, to combine multiple fiber-coupled single-mode laser diodes, the conventional fusion-based fiber combiner can not preserve the total Entendu because of the large cladding to core diameter ratio of a standard single-mode fiber. A different fiber beam combiner method is needed. We conceived a solution as described below.

Figure 2.2-1 illustrates the basic concept of a single-mode laser diode beam combiner LPM. Starting from the left of the illustration, the LPM consists of multiple fiber-coupled single-mode laser diodes, which are connected to a two-dimensional, closely-packed two-dimensional fiber array. The fiber beams from the array are then collimated by a matched two dimensional micro-lens array. The diameter of the lenslet in the micro lens array is the same as that of the cladding diameter of the fiber. As a result, the Entendu of each fiber is preserved as each individual fiber beam is expanded to fill the entire lenslet. To couple the beam into the pump beam delivery multimode fiber, the collimated fiber beams are focused with a bulk lens into the multi-mode fiber.

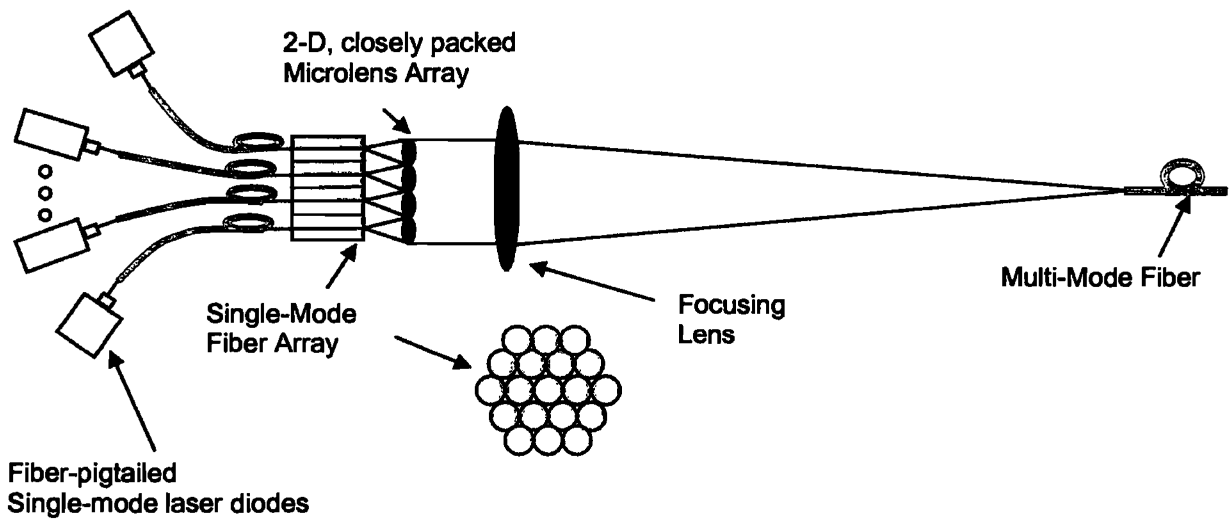


Figure 2.2-1 Concept illustration of a single mode laser diode beam combiner LPM

The focal length of the lens array is chosen according to the numerical aperture of the single mode fiber used and the desired filling factor of the fiber beam on the lenslet. It is normally in the sub-millimeter range. The focal length of the focusing lens is chosen to produce a focused beam within the core diameter and the acceptance angle of the multimode fiber. The focal length is normally a few millimeters.

A bonus of using single-mode laser diodes is that we can add a less temperature-sensitive Fiber Bragg Grating to stabilize its output wavelength so that no Thermal Electric Cooler (TEC) is needed in the laser diode package for wavelength stabilization. This can further improve the reliability of the LPM.

3. PROOF OF CONCEPT DEMONSTRATION

In this Section, we will describe a breadboard implementation of the single-mode laser diode combiner LPM. In the breadboard implementation, we started with a 7-fiber design to test the feasibility of the design. Then we demonstrated a 19-fiber combiner LPM and used it to pump a JPL-developed NPRO laser head. The detailed implementations are described below.

3.1 Design

To take advantage of JPL's e-beam capability and simplify the design for the proof-of-concept breadboard implementation, we modified the original design to replace the combination of micro lens array and focusing lens with a single diffractive micro lens array that performs both collimating and focusing functions at the same time. Figure 3.1-1 shows the schematic of this modified design. The diffractive micro lens array was designed and written with an e-beam machine at JPL's Microelectronics Device Laboratory (MDL). To match the diffractive micro lens array with the fiber array, the fiber positions are mapped first and then a diffractive micro lens array is designed and fabricated according to the mapped fiber positions.

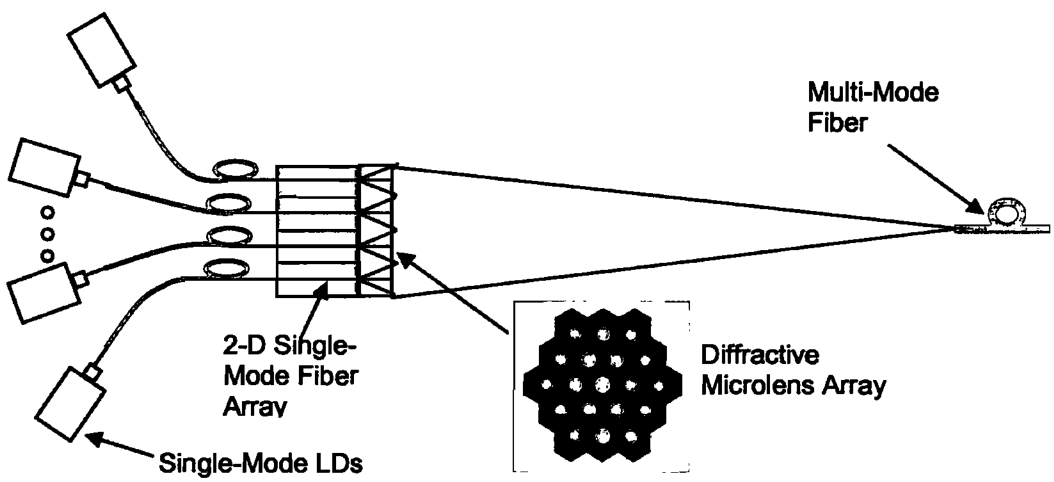


Figure 3.1-1 Single-mode laser diode beam combiner using diffractive lens array

Although the diffractive lens array is used in the proof-of-concept breadboard demonstration due to its advantage of not needing a focusing lens and that it can be designed and made in-house with fast turn around time. However, it has a lower and non-uniform throughput than the refractive lens array. Thus, the refractive micro lens array is preferred for applications where more efficiency is required.

Based on this design, we first implemented a 7-channel breadboard LPM and then a 19-channel to increase pump power so that we can characterize the NPRO laser at the desired output power level. The designs of the fiber array for the two implementations are different and will be described below.

3.2 7-channel demonstration

The first proof-of-concept demo consists of 7 commercial fiber-coupled, 808nm, single-mode, laser diodes and a custom-made, 7-channel, closely packed, fiber array (see Figure 3.2-1). These laser diodes do not have FBG in the output fiber. The fiber array is confined within a precision drilled hole and polished. The diffractive micro lens array was made by writing the diffractive lens pattern on a glass substrate coated with a layer of PMMA using an e-beam lithography system at JPL's MDL. The thickness of the glass substrate is designed to be equal to the back focal length of the lens array so that the focus alignment can be made by contacting the micro lens array to the fiber array. Figure 3.2-2 shows the experimental setup for aligning and characterizing the 7-channel single-mode laser diode beam combiner. The fiber array is mounted on an x-y-z stage and the micro lens array on a rotational stage. The micro lens array is placed against the fiber array, aligned to match the fiber array pattern, and a thin layer of index matching fluid is applied between the micro lens array and the fiber array to eliminate Fresnel reflections at the interface. A CCD camera is used to view the output beam pattern during alignment. The output of the combined beam is then coupled into a 100μm core diameter, 0.12NA multimode fiber.

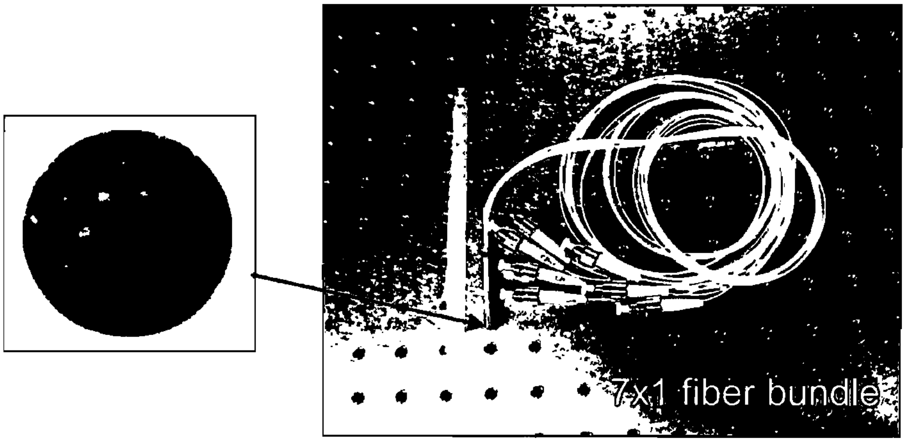


Figure 3.2-1 7x1 single-mode fiber array

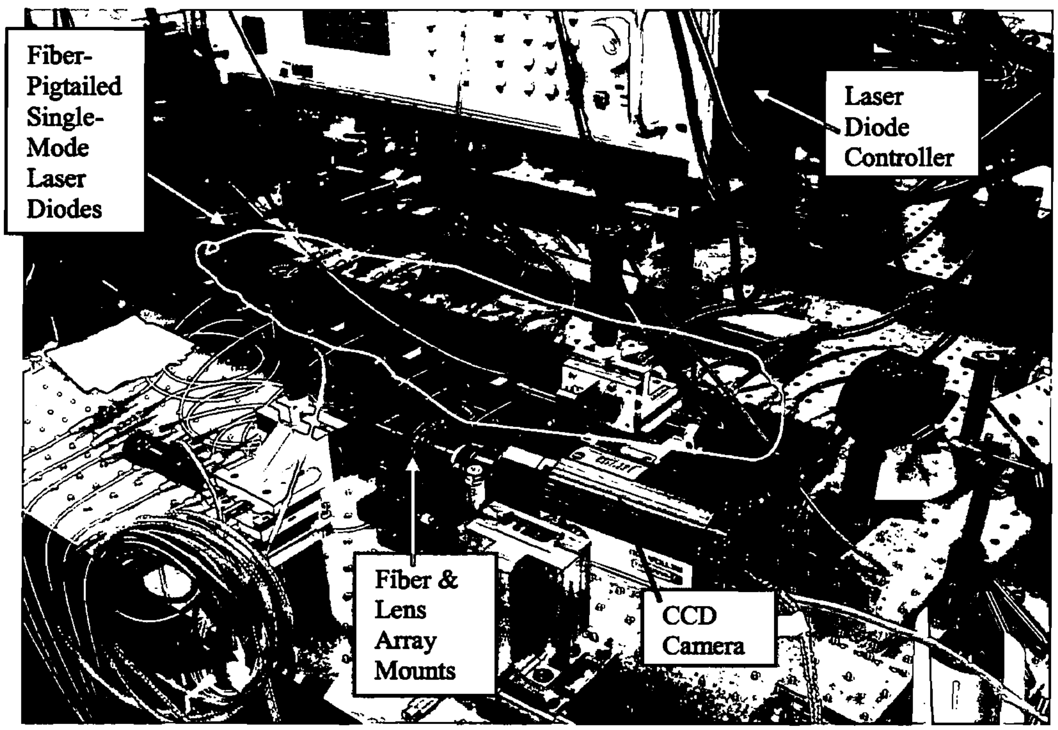
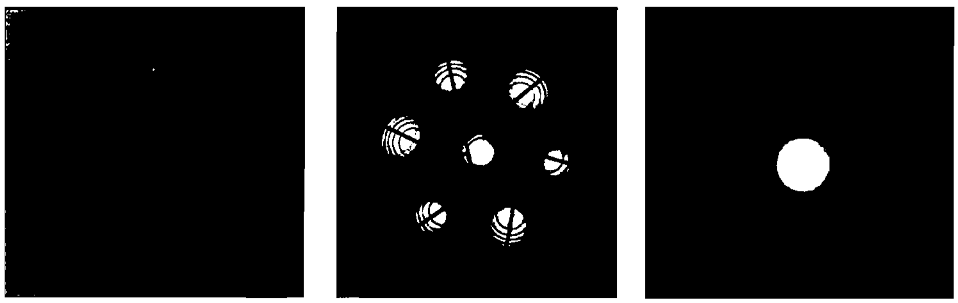


Figure 3.2-2 Experimental setup for characterizing the 7-channel single mode laser diode beam combiner.

In an ideal closely packed fiber array, the fibers should make contact with adjacent fibers. Figure 3.2-3a shows some fibers are not making contact with adjacent fibers. To solve this problem, the micro lens array was designed to match the actual positions of the fibers in the fiber array. Figure 3.2-3b shows the beam pattern (bright spots) overlaid on the lens array pattern (rings). The diffractive ring patterns are designed to focus and deflect each fiber beam to converge at a common spot on the focal plane. For example, the center beam coincides with the center diffractive ring so that it is not deflected, while the 6 surrounding beams are offset from the center of the diffractive rings so that they are deflected towards the center of the focal plane. In Figure 3.2-3b, the red line, which passes through the center of a beam and the center of a lens (concentric rings), indicates the actual direction that each beam is deflected by its corresponding lenslet. A perfectly matched fiber and lens array is achieved when these lines intersect at the center of the array. It is clear from Figure 3.2-3b this is not yet achieved. As a result, the combined beam size is bigger than the theoretical possible size.

The result of this combined spot is shown in Figure 3.2-3c. The coupling efficiency of the combined beam to the output fiber was measured to be ~74%, which is similar to the coupling efficiency of a typical commercial fiber coupled multimode laser diode. From Figure 3.2-3b and the discussion above, there is still room to improve this coupling efficiency by better matching the pattern of the micro lens array and the fiber array.



(a) 7-fiber array (b) beam pattern on lens array (c) Combined beam pattern

Figure 3.2-3 Experimental results of 7-fiber single mode laser diode beam combiner.

3.3 19-channel demonstration

The available pump power of the 7-channel LPM described above is barely enough to pump the NPRO laser. To characterize the performance of the proposed LPM we fabricated a larger fiber array with 37 channels and a lens array with 19 channels. Both the laser diodes and the fiber array are terminated with FC/PC connectors as in the 7-channel demo. However, due to the increased number of fibers, these fibers are connected on an FC/PC adapter array plate as shown in Figure 3.3-1. Fusion splices can be used to replace connectors to save space if desired.

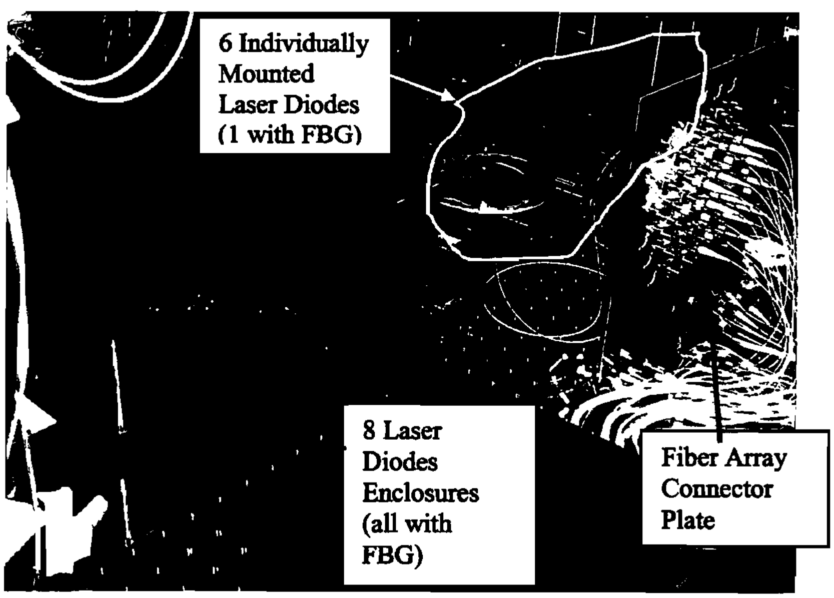


Figure 3.3-1 Fiber-pigtailed single mode laser diodes and fiber array connection plate of the breadboard demo.

We had 14 laser diodes available for this demo. 9 of them are commercial 100mW, 808nm, single-mode laser diodes with FBGs and 5 of them without FBGs. As in the 7-channel demo, the fiber array is mounted on an xyz stage and a pattern-matched diffractive micro lens array is aligned against the fiber array to collimate the fiber beams. Then the collimated fiber beams are focused into a multimode fiber, which is then connected to a fiber-coupled NPRO laser. The entire setup is shown in Figure 3.3-2.

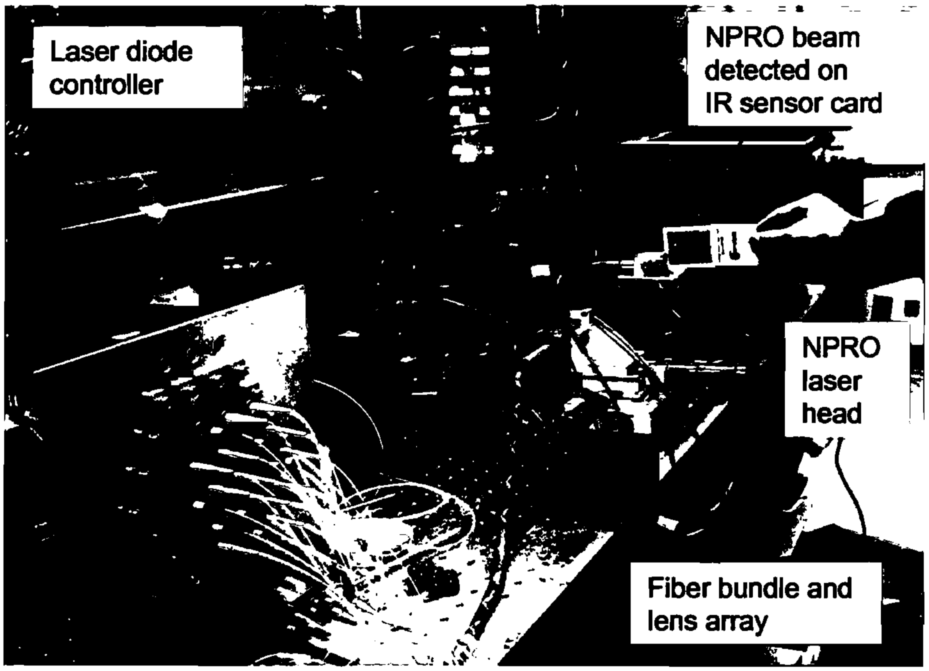


Figure 3.3-2 19 channel single mode laser diode beam combiner connected to pump an NPRO laser head.

The fiber-coupled NPRO laser head used in this demo was developed earlier for SIM as shown in Figure 3.3-3. It passed thermal vacuum and random vibration tests required for SIM brass-board development. The pump beam fiber was fixed to the laser head by laser welding to enhance the reliability of the fiber attachment.

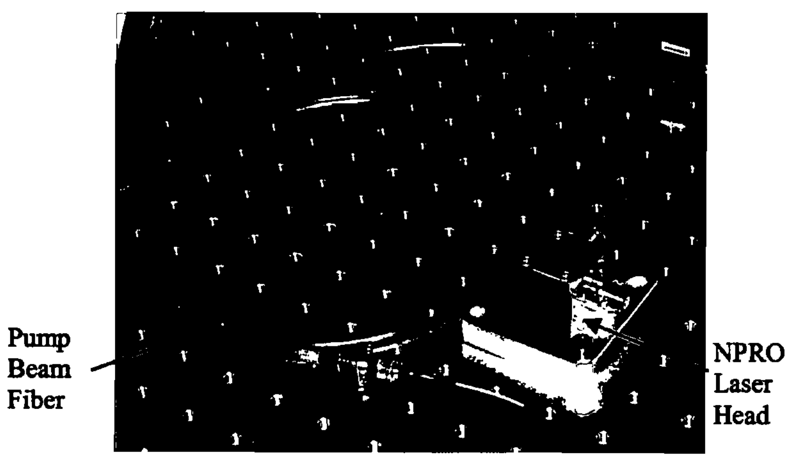
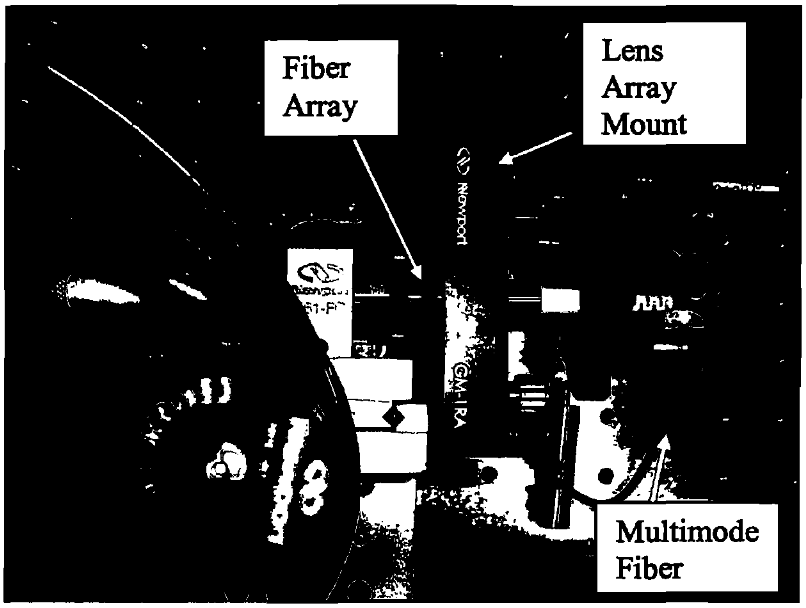


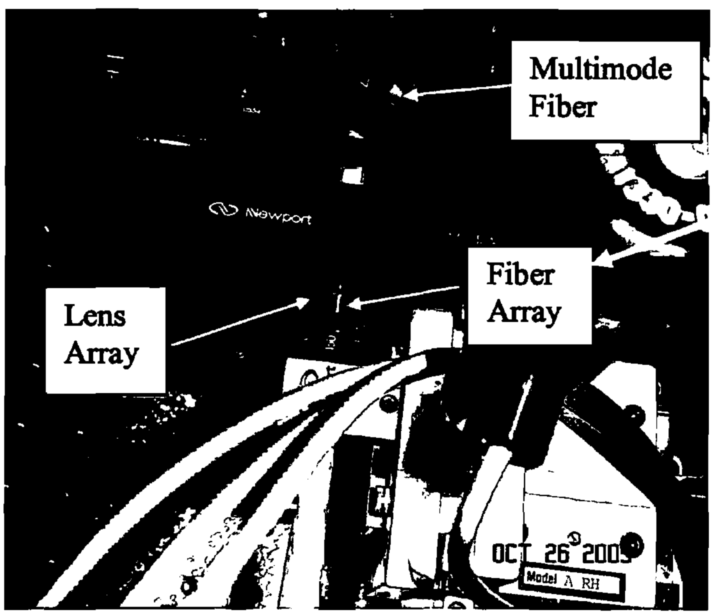
Figure 3.3-3 Fiber-coupled NPRO laser head developed at JPL

A close up of the fiber array and lens array mounted on alignment stages is shown in Figure 3.3-4 (a) and the pattern of the lens array when illuminated by the fiber beams is shown in Figure 3.3-2 (b).

(a)



(b)



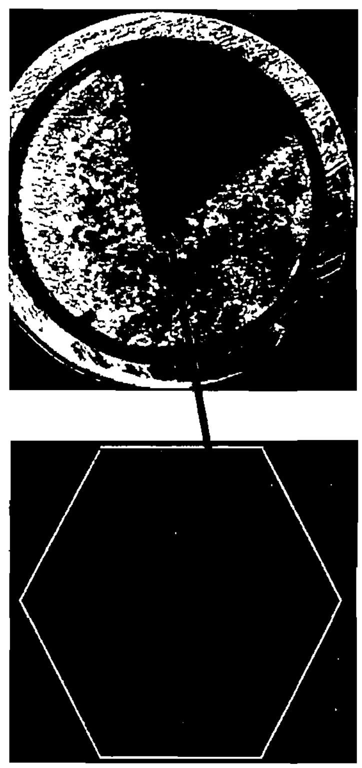


Figure 3.3-4 (a) Side view of fiber array, lens array, multimode fiber assembly; (b) Front view of fiber array, lens array, multimode fiber assembly and the closeup images of the fiber array.

Figure 3.3-5 shows the fiber beams on the lens array and Figure 3.3-6 shows the beam profile of the combined beam spot. The beam spot size is approximately 60μm and is smaller than the 100μm core diameter of the output fiber.

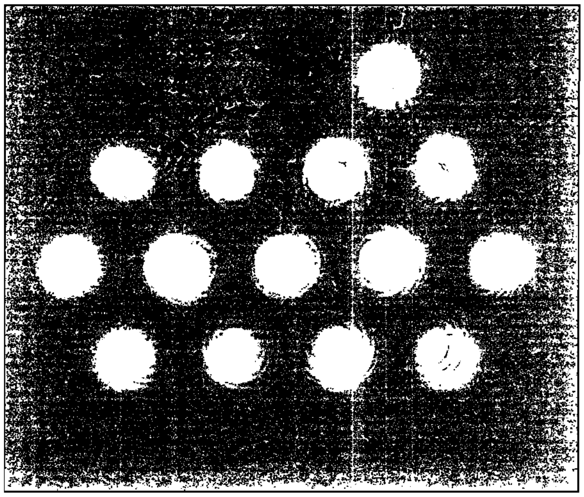


Figure 3.3-5 Fiber array beams (14 total) aligned with the diffractive lens array.

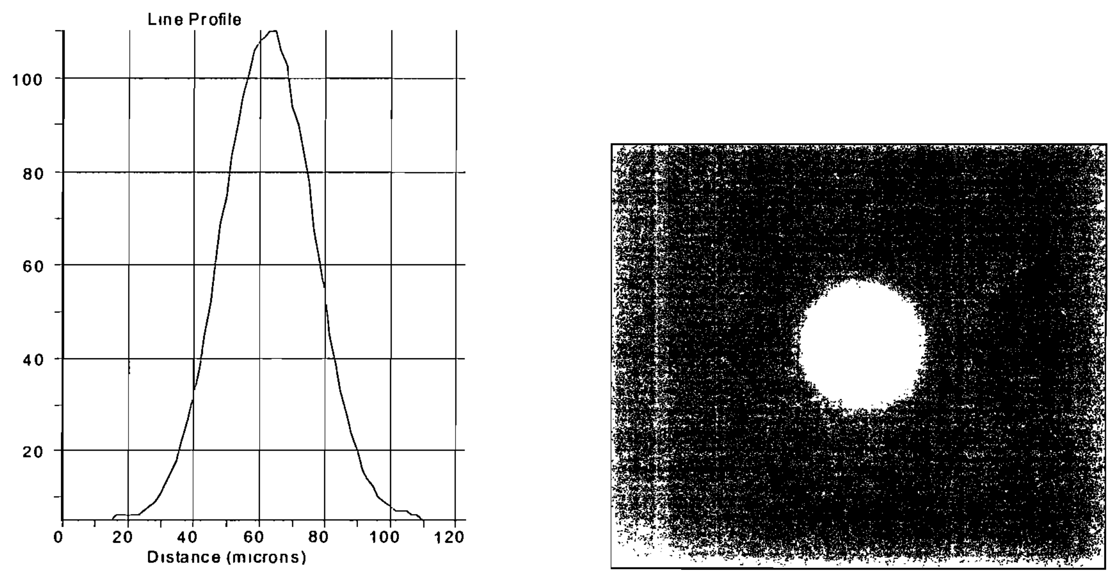


Figure 3.3-6 Beam profile of combined beam spot (scale not matched to scanned profile).

The theoretical beam spot size is the magnification of the fiber collimating and focusing optical system times the mode field diameter of the single mode fiber and is estimated to be approximately 40μm, which smaller than the measured spot size of 60 μm. The combined beam spot size can be further improved by better matching the lens array to the fiber array and the individual focal lengths to the converging lengths of the diffractive lens array. Nevertheless, because the output fiber has a much larger core diameter than the beam spot size, improving the spot size will not improve the coupling efficiency significantly. In the 19-Channel demo, the output beam was focused to a fiber patch cord with a 105 μm core diameter 0.15NA to match the fiber attached to the NPRO laser head.

The end to end optical efficiency of the 19-fiber combiner is listed in Table 1. The overall efficiency includes Fresnel reflection losses at the lens array and connector losses at the fiber array connection plate, which can be as large as 1 dB in some cases. In the flight unit, the connectors can be replaced with fusion splices and the lens array can be AR coated to further improve the efficiency.

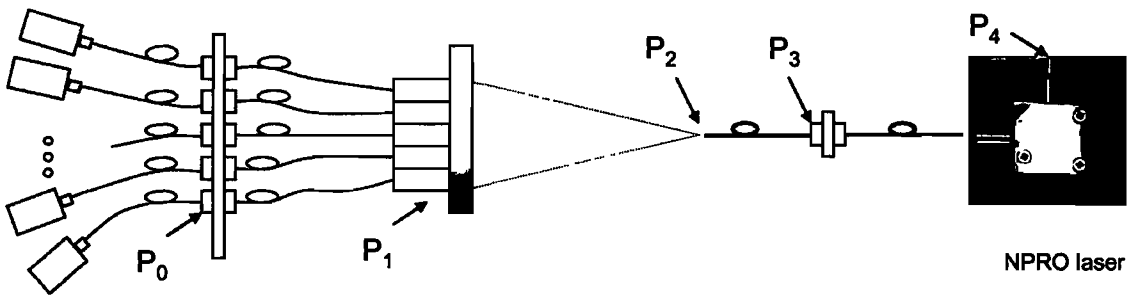


Figure 3.3-7 Locations of power measurement of the single-mode LPM demonstration.

Table 1 Efficiency of the single mode laser diode beam combiner. (See Figure 3.3-7 for definition of symbols)

Fiber #	Bias (mA)	T (°C)	P_0 (mW)	P_1 (mW)	P_2 (mW)	P_3 (mW)	P_1/P_0	P_2/P_1	P_3/P_2	P_3/P_0	P_3/P_1	P_4/P_3	P_4/P_0	P_4/P_1	P_4/P_0
29	250	32	119	102	89.3	67.4	0.857	0.875	0.755	0.566	0.661				
30	230	45	104	92.5	84.4	72.1	0.889	0.912	0.854	0.693	0.779				
31	230	32	110	63.9	57.4	52.5	0.581	0.898	0.915	0.477	0.822				
32	230	45	114	91.6	80.9	71.4	0.804	0.883	0.883	0.626	0.779				
36	250	32	110	85.3	75.6	57.8	0.775	0.886	0.765	0.525	0.678				
37	250	32	125	98.5	85.4	74.9	0.788	0.867	0.877	0.599	0.760				
39	250	32	108	103	90.7	77.4	0.954	0.881	0.853	0.717	0.751				
44	250	32	104	88.1	78.7	66.1	0.847	0.893	0.840	0.636	0.750				
22	250	32	84	73.8	62.5	48.4	0.879	0.847	0.774	0.576	0.656				
23	250	32	120	116	94.6	82.6	0.967	0.816	0.873	0.688	0.712				
24	250	32	120	90.8	81.4	71.7	0.757	0.896	0.881	0.598	0.790				
25	250	32	119	109	95	79.1	0.916	0.872	0.833	0.665	0.726				
14	230	35	104	98.1	84.2	60.5	0.943	0.858	0.719	0.582	0.617				
15	230	45	93	75.1	66.1	53.2	0.808	0.880	0.805	0.572	0.708				
Calculated total power or average ratio from individual measured diode powers			1534	1288	1126	935.1	0.839	0.875	0.830	0.610	0.726	0.253	0.154	0.184	0.154
Measured total power or ratios when all diodes on				1280	1120	939		0.875	0.838		0.734	0.252		0.185	

The NPRO 1319nm laser beam power vs the 808nm pump power was measured and plotted in Figure 3.3-8, showing a linear relationship between the two powers. The pump power threshold of the NPRO laser is approximately 260mW. From extrapolation, to obtain 300mW of NPRO power as needed for SIM requires slightly more than 1.1 watt of total power at P_3. The P_4/P_3 efficiency was found consistent with that of a single fiber-pigtailed multimode laser diode LPM.

All laser diodes packages used in this demo have built-in TECs to control the temperatures of the laser diodes. The temperature of all laser diodes with FBGs were set at around 32C, while the temperatures of those laser diodes that did not have FBGs were set at temperatures so that the output wavelengths were optimized to pump the NPRO laser.

Nominally, this wavelength is approximately 808.4nm. In future development, all laser diodes can be equipped with FGBs, without TECs, and compactly grouped together on a common circuit board and heat sink.

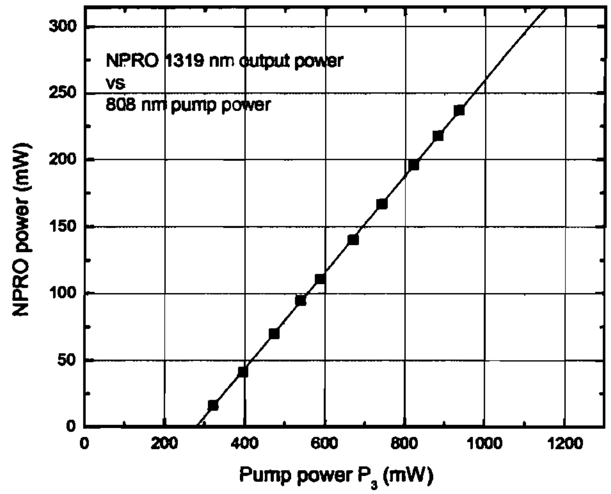


Figure 3.3-8 NPRO power vs Pump power.

3.4 Scalability

The number of laser diodes of a single-mode laser diode beam combiner is scalable. The important parameters to be considered for beam combining are the emitting dimensions and divergence angles of the laser diode as listed in Table 2, from which we can calculate the beam width divergence product (or one-dimensional Entendu) for both laser diodes.

Table 2 Beam Width Divergence product of multimode and single mode 808nm laser diodes (LD)

	Beam Width (μm)	Beam Divergence (deg)	Beam Width Divergence Product	Ratio of pump limit/ Beam Width Div Prod	Maximum number of diodes that can be combined	Max. total combined power (based on 100% combining efficiency)
2W Multimode LD – slow axis	~100	12	1200	2 : 1	~150	300 watt
2W Multimode LD – fast axis	~1	32	32	75 : 1		
150mW Single mode LD – slow axis	~3	9	27	89 : 1	~7000	1000 watt
150mW Single mode LD – fast axis	~1	30	30	80 : 1		
2W 105μm 0.15NA fiber-coupled LD	105	17	1790	4 : 3	~ 2	4 watt
100mW single mode fiber-coupled LD	5	14	70	34 : 1	~ 1000	150 watt

As shown in Table 2 the single mode laser diode method has the highest total combined power in either bare laser diode combiners or fiber-coupled combiners. Although the required NPRO pump power is only 1 to 2 watts, a higher total maximum power means a longer lifetime of the laser diodes can be achieved by running them at a lower power.

3.5 Reliability

The random failure rate of a commercial 808nm single mode laser diode is approximately 1000 FITs. Based on a reliability calculation program that we developed, approximately 19 laser diodes are needed to meet a reliability requirement of 99.7% over 5 years with a 2:1 margin when the pump laser diodes are operated simultaneously at de-rated power level and 5 °C and the output power of the NPRO laser is maintained at approximately 300mW. The time to wear-out or lifetime of each laser diode of most commercially available single mode laser diodes is only 10,000 hours or 1.14 years at room temperature and full designed power. By lowering the temperature and the power of the laser diode, they can be increased to meet the mission lifetime for SIM. The activation energy and power acceleration exponent used for estimating the reliability and lifetime of the LPM are assumed to be 0.4 eV and 2, respectively, and are deemed to be conservative for the 808nm laser diodes we used.

4. SUMMARY AND CONCLUSIONS

We reported the concept and a breadboard implementation of a single-mode laser diode combiner laser pump module for efficient and reliable optical pumping of a fiber-coupled, Nd:YAG NPRO laser designed for the SIM space mission. The key components of this module include FBG wavelength stabilized single mode laser diodes, a closely packed fiber array, a micro-lens array, and a multimode optical fiber. The reliability simulation shows that using 19 laser diodes and de-rated power and operation temperature, the laser pump module can have a reliability of 99.7% over 5 years. The reliability of the reported laser pump module is further improved by using laser diodes without TECs due to the FBG wavelength stabilizer. We demonstrated a 240mW NPRO laser output as pumped with 14 single mode laser diodes. The reported LPM is scalable to provide 10s of watts of pump power in practice.

5. ACKNOWLEDGMENT

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