

matched to the fiber-optic NA, so no further slow-axis beam shaping is needed.

In this beam combiner (see figure), the laser-diode outputs are collimated by aspherical lenses, then half-wave plates and polarizing beam splitters are used to combine the four collimated beams into two beams. Spatial combination of the two beams and coupling into the optical fiber is effected by use of anamorphic prisms, mirrors, and a focusing lens. The anamorphic prisms are critical elements in the NA-matching scheme, in that they reduce

the fast-axis beam width to 1/6 of its original value. Inasmuch as no slow-axis beam shaping is needed, the collimating and focusing lenses are matched for 1:1 imaging. Because these lenses are well corrected for infinite conjugates, the combiner offers diffraction-limited performance along both the fast and slow axes.

*This work was done by Paul Gelsinger and Duncan Liu of Caltech for NASA's Jet Propulsion Laboratory.*

*In accordance with Public Law 96-517, the contractor has elected to retain title to this*

*invention. Inquiries concerning rights for its commercial use should be addressed to:*

*Innovative Technology Assets Management  
JPL*

*Mail Stop 202-233  
4800 Oak Grove Drive  
Pasadena, CA 91109-8099  
(818) 354-2240*

*E-mail: iaoffice@jpl.nasa.gov  
Refer to NPO-43783, volume and number of this NASA Tech Briefs issue, and the page number.*

## Spatial Combining of Laser-Diode Beams for Pumping an NPRO

Multiple multimode beams are efficiently combined into one optical fiber.

NASA's Jet Propulsion Laboratory, Pasadena, California

A free-space optical beam combiner now undergoing development makes it possible to use the outputs of multiple multimode laser diodes to pump a neodymium-doped yttrium aluminum garnet (Nd:YAG) non-planar ring oscillator (NPRO) laser while ensuring that the laser operates at only a single desired frequency. This optical beam combiner serves the same purpose as does the one described in "Diffractive Combiner of Single-Mode Pump Laser-Diode Beams" (NPO-42411), NASA Tech Briefs, Vol. 31, No. 5 (May 2007), page 16a. Although the principles of design and operation of the present and prior beam combiners are not identical, they are so closely related that it is necessary to devote the next four paragraphs to reiteration of a substantial portion of the cited prior article in order to give meaning to a description of the present beam combiner.

Heretofore, a Nd:YAG NPRO like the present one has been pumped by a single multimode laser-diode beam delivered via an optical fiber. It would be desirable to use multiple pump laser diodes to increase reliability beyond that obtainable from a single pump laser diode. However, as explained below, simplistically coupling multiple multimode laser-diode beams through a fiber-optic combiner would entail a significant reduction in coupling efficiency, and lasing would occur at one or more other frequencies in addition to the single desired frequency.

Figure 1 schematically illustrates the principle of operation of a laser-diode-pumped Nd:YAG NPRO. The laser beam path is confined in a Nd:YAG crystal by means of total internal reflections on

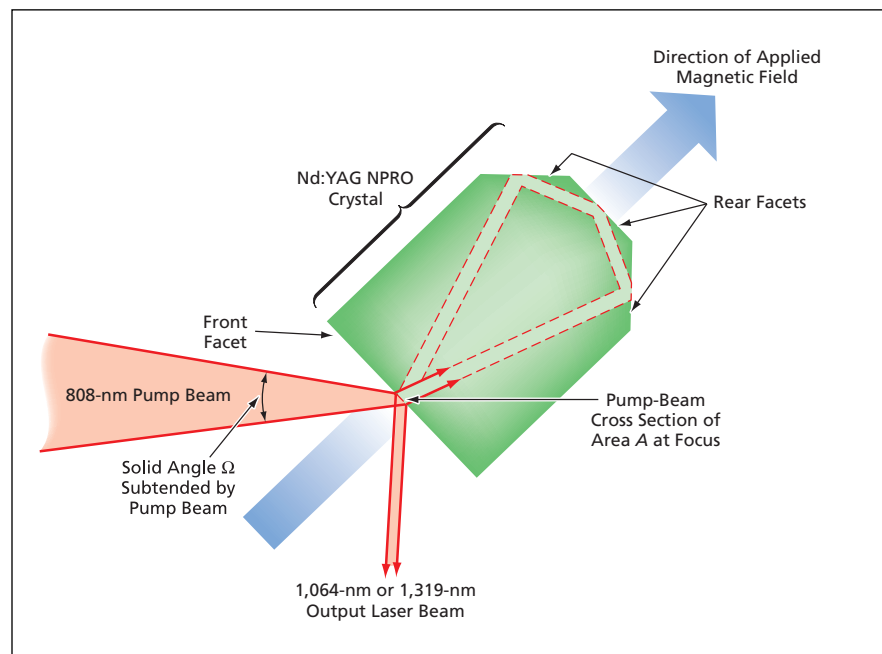


Figure 1. A Pump Beam of Solid Angle  $\Omega$  has a cross section of area  $A$  at incidence upon the front facet of a Nd:YAG NPRO laser crystal.

the three back facets and an optical coating on the front facet. The wavelength of the pump beam — 808 nm — is the wavelength most strongly absorbed by the Nd:YAG crystal. The crystal can lase at a wavelength of either 1,064 nm or 1,319 nm — which one depending on the optical coating on the front facet.

In order to restrict lasing to a single frequency, it is necessary to confine the pump beam within the region occupied by the  $TEM_{00}$  mode of the NPRO laser beam near the front facet inside the crystal. In practice, this means that the pump beam must be focused to within a given solid angle ( $\Omega$ ) and area ( $A$ ). [If a given

pump beam has a larger  $A$  or larger  $\Omega$  but its  $A\Omega$  is equal to or less than the maximum  $A\Omega$  for single-frequency lasing in the crystal, then an imaging lens can be used to trade  $A$  against  $\Omega$  so that both  $A$  and  $\Omega$  are equal to or smaller than the maximum values for single-frequency lasing. It is possible to do this because it is a basic principle of optics that  $A\Omega$  is preserved in imaging by a lens.]

The  $A\Omega$  of a commercial multimode 808-nm laser diode of the type used heretofore is not axisymmetric; instead, it is elliptically distributed about the optical axis and, hence, does not match the circular distribution of a multimode

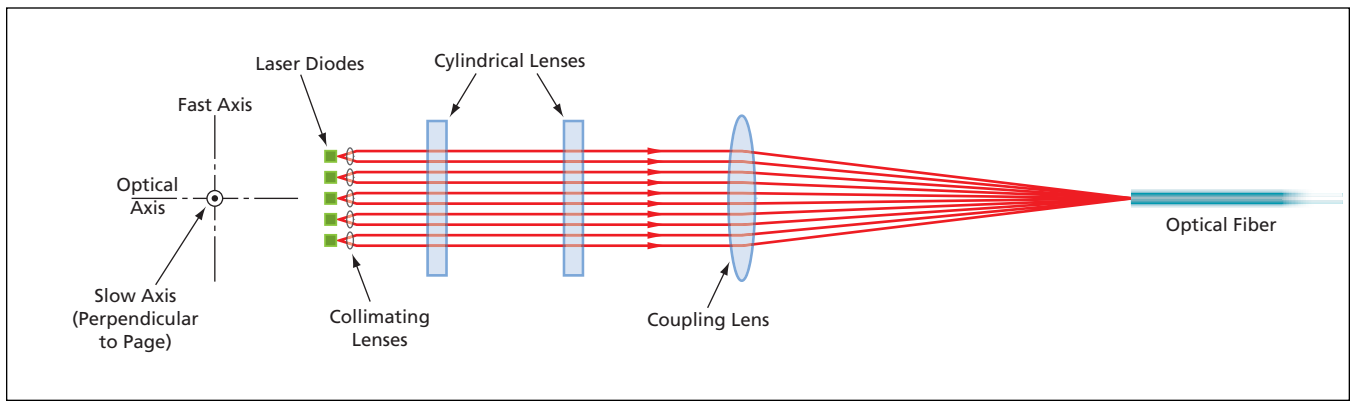


Figure 2. **Beams From Laser Diodes** stacked along the fast axis are focused onto the input face of an optical fiber by use of a combination of small collimating lenses and a larger lens here denoted the coupling lens. The cylindrical lenses cancel the magnifying effect of the collimating and coupling lenses in the slow-axis plane. This is a simplified and partly schematic view. In practice, it is necessary to position the laser diodes in a more complex layout and to use folding mirrors or prisms to direct beams along the optical axis of the coupling lens.

fiber of the type used heretofore to deliver a pump beam. As a result of this mismatch,  $A\Omega$  for the pump beam emerging from the output end of the fiber is increased, typically to near the maximum single-frequency-lasing value in at least one of the planes containing the principal axes of the elliptical distribution. Consequently, it is difficult or impossible to maintain single-frequency lasing when combining the beams from two or more multimode laser diodes.

This concludes the reiteration of information from the cited prior article.

For a typical commercial 808-nm laser diode of the type upon which the design of the present beam combiner is based, the axes of the elliptical distribution are defined as follows: The far-field distribution of output optical power density is characterized by (1) a single-mode beam in a meridional plane containing an axis, perpendicular to the optical axis, that is customarily denoted the “fast” axis; and (2) a narrower multimode beam in the orthogonal meridional plane, wherein the axis perpendicular to the optical axis is customarily denoted the “slow.” The value

of  $A\Omega$  in the fast-axis plane is only about 1/50 of that of the  $A\Omega$  value associated with the combination of diameter (105  $\mu\text{m}$ ) and numerical aperture, NA, (0.15) of the optical fiber used to deliver the pump beam. Hence, it is possible to stack multiple laser diodes along the fast axis and couple their outputs into the same optical fiber, as shown in Figure 2.

To minimize coupling loss, one must ensure that the NA ( $\approx 0.3$ ) of the combined laser-diode beams is less than the NA of the fiber. This amounts to a requirement to reduce the fast-axis NA of the beam from  $\approx 0.3$  to a value  $< 0.15/N$  (where  $N$  is the number of laser-diode beams to be combined) and translates to a requirement to reduce the fast-axis divergence by use of a magnification factor of at least  $0.3/(0.15/N) = 2N$ . For example, a prototype to demonstrate this beam-combiner concept was designed using  $N = 5$ , for which required magnification factor is  $> 10$ . In practice, to allow for alignment errors, a magnification factor of 19 was chosen for the prototype.

The  $A\Omega$  of the laser-diode beam in the slow-axis plane is 1/1.3 as large as that of

the fiber. This  $A\Omega$  is small enough to enable efficient coupling of light into the optical fiber, but too large for combining of beams in the slow-axis plane. Therefore, a pair of cylindrical lenses is used to cancel the slow-axis-plane magnification introduced by the non-cylindrical lenses used to effect magnification in the fast-axis plane.

*This work was done by Paul Gelsinger, Duncan Liu, Jerry Mulder, and Francisco Aguayo of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).*

*In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to:*

*Innovative Technology Assets Management  
JPL*

*Mail Stop 202-233  
4800 Oak Grove Drive  
Pasadena, CA 91109-8099  
(818) 354-2240*

*E-mail: iaoffice@jpl.nasa.gov*

*Refer to NPO-43782, volume and number of this NASA Tech Briefs issue, and the page number.*