Highly Efficient Nd:YAG Lasers for Free-Space Optical Communications

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The concept of a highly efficient Nd:YAG laser end-pumped by semiconductor lasers as a possible free-space optical communications source is discussed. Because this concept affords high pumping densities (thus high photon-to-photon conversion efficiencies), a long absorption length, and excellent mode-matching characteristics, it is estimated that electrical-to-optical efficiencies greater than 5% could be achieved. Several engineering aspects such as resonator size and configuration, pump collecting optics, and thermal effects are also discussed. Finally, possible methods for combining laser-diode pumps to achieve higher output powers are illustrated.

I. Introduction

The DSN is currently interested in optical communications as a means of increasing telemetry capabilities while reducing costs. Optical communication over interplanetary distances (10 AU or more) with transmitting apertures of practical diameters (i.e., on the order of 20 cm) requires approximately 1 W of optical power to achieve data rates on the order of several megabits per second (Ref. 1). One of the major obstacles to realizing such a system is the lack of an efficient single-mode source operating in the visible region of the electromagnetic spectrum with the required output power. Two candidates have been proposed for use as an optical source, the semiconductor laser and the Nd:YAG laser. While being relatively efficient, the semiconductor (e.g., GaAlAs) laser is primarily a low-power device, producing only about 20-mW, single-mode operation. Although arrays of individual laser diodes have produced output powers above 2 W (Ref. 2), a long-lived, high-power, communications-quality (i.e., single-lobed radiation pattern) device has yet to be realized. Nd:YAG (pumped by lamps), which emits light at the wavelength of 1.064 μm, has been operated continuous wave at power levels of well into the hundreds of watts regime, and up to several tens of watts of its second harmonic radiation (at 0.532 μm) have been produced. However, low efficiency – typically 0.1% in present day systems – is the main disadvantage of Nd:YAG lasers.

Much effort has been put into the development of a source that is a hybrid of these two lasers, namely the GaAlAs semiconductor laser-pumped Nd:YAG laser. In this arrangement, many GaAlAs laser diodes or diode arrays can be combined to optically pump the Nd:YAG laser medium. Moreover, the multimode operation of GaAlAs laser arrays is not a problem because they act only as a pump source, rather than a communications source, and hence their coherence, modal structure, and spectral purity are of lesser importance.

Figure 1 illustrates this laser with conventional side-pumping geometry. In this configuration, the diodes are placed along the length of the Nd:YAG rod and pump perpendicularly to the direction of propagation of the laser resonator mode. As more power is required, more diodes can be added along and around the laser rod. This hybrid laser, however, is only about 0.5% efficient, which is still too low for a deep-space optical transmitter (about 5% to 10% is necessary). The side-pumped geometries' large inefficiencies result from the small absorption length (only about 3 mm), relatively large pumped volume (so the pumping density is low), and the small cross section of the resonator mode (there are pumped regions of the rod where energy is wasted because of mode mismatch).

In this article, a highly efficient laser-diode-pumped Nd:YAG laser employing an end-pumped geometry is proposed. In this configuration, shown in Fig. 2, diode pump sources are placed at the ends of the Nd:YAG rod and, through the use of suitable optics, the pump light is collected and focused to a small spot (typically 50 to 100 μm) that matches the resonator mode. It is immediately apparent that this geometry rectifies virtually all the inefficiencies that plague the side-pumped scheme. First, the absorption length can be made as long as necessary to absorb practically all of the pump light. Second, the pump light can be focused to provide the intensities needed for efficient lasing. Finally, the beams can be adjusted to overlap for optimum mode matching.

This end-pumping concept has been demonstrated in the mid-1970s on miniature Nd-doped lasers end pumped by light emitting diodes and laser diodes for use as transmitters in optical fiber communications (Refs. 3 through 6). This work, however, was primarily concerned with achieving a low lasing threshold and not with efficient operation above threshold, as is the focus of this article.

In Section II, the various inefficiencies associated with laser operation needed to calculate the overall efficiency of this proposed device are identified and quantified. In Section III, some engineering aspects of this laser, such as the resonator, focusing elements, and temperature effects, are addressed, and, in Section IV, some possible pumping configurations are illustrated.

II. Efficiency

To accurately estimate the overall efficiency of such a device, all factors that give rise to energy loss must be identified. First, there is the quantum efficiency, η_q, which is the ratio of the lasing photon energy to the pumping photon energy. The quantum efficiency represents the maximum theoretical limit for laser efficiency. Next, η_0, the operating efficiency, includes the resonator losses and conversion efficiency of pump photons into lasing photons. The mode-matching efficiency, η_m, is the fraction of the pumped cross-section area that lies within the oscillating mode volume. The fraction of light incident at the laser rod end that is absorbed in the gain medium (assuming all of the laser diode light falls within the pump absorption bands) is designated η_{abs}, while η_i and η_c describe the interface and pump light coupling efficiencies respectively. Finally η_{LD} is the electrical-to-optical laser-diode efficiency. In the following sections, these factors will be discussed in greater detail.

A. Operation Efficiency (η_0)

The efficiency with which pump photons are converted to lasing photons can be calculated as a function of input pump power, cavity loss, and beam radius. We start with the steady-state rate equations describing the spatial evolution of the inversion and photon energy densities:

$$\frac{dS^+}{dz} = [\beta N - \alpha]\, S^+ \tag{1a}$$

$$\frac{dS^-}{dz} = [\beta N - \alpha]\, S^- \tag{1b}$$

$$0 = R_p - \frac{N}{\tau_s} - \nu\beta N\, [S^+ + S^-] \tag{2}$$

where S^+ and S^- are the forward and backward propagating photon energy densities respectively (J/cm^3), N is the inversion energy density (J/cm^3), α is the loss coefficient per unit length of material (cm^{-1}), β is the stimulated emission coefficient ($\beta = \sigma/h\nu_l$ where σ is the stimulated emission cross section (cm^2)), τ_s is the spontaneous emission lifetime (s), ν is the group velocity of the wave in the medium, and R_p is the pumping power density (W/cm^3). Any radial dependence is included in the mode matching efficiency η_m and so is neglected here.

These equations can be solved numerically (Ref. 7) to find the output power efficiency as a function of the mirror reflectivity for various input power intensities. Figure 3 illustrates that for an input intensity of 10 kW/cm^2, the photon-to-photon conversion efficiency exceeds 90% (where a single pass loss of 1% and σ given by Ref. 8 were assumed). Figure 3 shows efficiency as a function of output mirror reflectivity for various input power intensities, and Fig. 4 relates efficiency to input power for various modal radii.

Another factor considered is that due to the absorption of pump light along the rod (i.e., as R_p is a function of z), with the most basic case being the exponential decay of a single-ended pump. This problem has been analyzed (Ref. 9), and for the pump intensities and emission cross sections relevant to our application, it was found to be of no consequence.

It is well known that high pumping densities result in more efficient laser operation. By focusing the light of the diode pump, high pumping densities can be created even with low levels of pump power.

B. Mode Matching Efficiency (η_m)

For the efficient use of pump light for stimulated emission, the pump light must fall within the Gaussian mode of the resonator and not be wasted as spontaneous emission. Because the pump beam cross section may be elliptical and not circular, and because the gain along the laser rod is nonuniform, laser efficiency varies with pump and laser mode parameters in a complex way. In their analysis, Hall et al. (Ref. 10) showed that efficiency is maximized for the matched mode case: i.e., $R_0 \cong W_0$, where R_0 and W_0 are the pump- and laser-mode Gaussian beam waist radii respectively. Although their analysis did not take into account high-gain operation, nonuniform gain distribution, or the divergent nature of Gaussian beams, $R_0 \cong W_0$ is still a good design starting point. Further analysis and experimentation are being conducted to determine exact conditions for optimum performance.

C. Absorption Efficiency (η_{abs})

Figure 5 shows the absorption spectrum of a 1-cm sample of 1% Nd^{+3} in YAG and the corresponding emission spectrum of the laser diode pump source. It can be seen from this figure that the laser diode source spectrum falls well within the main Nd:YAG pump band centered at 807 nm. As illustrated, the Nd:YAG absorption spectrum is fine structured, so experimentation is needed to determine how precisely the laser diode spectrum needs to be controlled. From Fig. 5 one can calculate the length of the YAG rod needed to absorb virtually all of the pump light. For example, a 1- to 2-cm-long crystal will absorb over 90% of the incident pump light.

D. Interface Efficiency (η_i)

To achieve sufficient feedback, the gain medium in a laser must be placed between two mirrors of high reflectivity. The high reflectivity is usually obtained by coating the mirrors with a multilayer dielectric coating. Since the pump light must pass through this coating (or interface) to pump the medium, it is important that the coating be highly reflective at the lasing wavelength yet highly transmissive at the pump wavelength. By using properly designed dielectric coatings, one can produce a mirror that reflects 99.8% of the light at 1.06 μm, yet transmits over 95% of the pump light at 0.810 μm (A. Zook, Z.C.R. Optical Coating Company, private communication).

E. Coupling Efficiency (η_c)

For the device to operate efficiently, the pump light must be collected and focused onto the gain medium efficiently. The focusing system must be small, have a short working distance, and have a minimum number of optical components to ensure high throughput and less sensitivity to motion (displacements). Figure 6 shows how collection efficiency varies with the f number of the collecting lens for standard laser diodes. Systems with over 90% efficiency (collection and transmission) are available commercially.

F. Total Optical Conversion Efficiency

The total optical conversion efficiency can now be calculated by simply taking the product of all the subsystem efficiencies previously mentioned:

$$
\begin{aligned}
\text{quantum efficiency: } & \eta_q = 76.7\% \\
\text{operation efficiency: } & \eta_0 \gtrsim 90\% \\
\text{mode matching efficiency: } & \eta_m \approx 100\% \\
\text{absorption efficiency: } & \eta_{abs} \gtrsim 90\% \\
\text{interface efficiency: } & \eta_i \gtrsim 95\% \\
\text{collection efficiency: } & \eta_c \gtrsim 90\%
\end{aligned}
$$

$$\therefore \eta_{opt} = \eta_q \, \eta_0 \, \eta_m \, \eta_{abs} \, \eta_i \, \eta_c \geqslant 50\%$$

The laser is therefore expected to convert over half of the pump power into laser light at the Nd:YAG fundamental wavelength.

G. Overall Electrical Efficiency

The total overall electrical-to-optical efficiency is just the optical efficiency η_{opt} times the power efficiency of the laser diode pump source, η_{LD}. For commercially available diode lasers, η_{LD} is 10% or more, so overall efficiencies of up to and greater than about 5% can be expected. This value is over 10 times better than the efficiency of previous side-pumped lasers. It is also to be noted that laser diode efficiency becomes the limiting factor for highly efficient operation. Since over 35% overall efficiency has already been achieved in laboratory devices (Ref. 11), the total efficiency is expected to go up as laser diode technology matures.

III. Engineering Aspects

Although this proposed device seems very promising in terms of highly efficient operation, questions regarding its feasibility from an engineering standpoint need to be answered. In this section, some of the pertinent engineering aspects are discussed.

A. Resonator

To achieve the small spot sizes necessary for efficient operation, the dimensions of a simple (i.e., 2-mirror) and stable resonator must be small. For example, the confocal resonator, the most stable, requires mirrors with radii of curvature of 5 cm and a separation of 5 cm to achieve beam waist radii of approximately 50 μm. This is advantageous in that it reduces the overall size of the optical transceiver package – a prime consideration in space optical communications systems development.

B. Focusing Subsystem

The focusing subsystem needs to have an f number smaller than 1 to efficiently collect and deliver the pump light (see Fig. 6). Since only on-axis performance is required, commercially available aspheric lenses with f numbers as low as 0.6 can be used for this purpose. A working distance (i.e., the distance from the optics to the focal plane) of 1 to 2 cm is required. For a given working distance, there is a minimum diameter that the incident beam possess in order to be focused to the desired size. For Gaussian beams, the minimum focused spot size is given by:

$$2W_0 = \frac{1.27\,\lambda f}{d} \tag{3}$$

where W_0 is the radius of the focused spot, d is the diameter of the incident beam, f is the focal length of the lens, and λ is the wavelength. Hence, for $W_0 = 50\ \mu$m and $f = 2$ cm, d equals 0.02 cm. What this shows is that extremely small optics can be used to collect and deliver the pump light, thus keeping the overall size and weight of the laser small.

It is not altogether clear whether or not the pump beam needs to be anamorphically transformed from its elliptical shape at the laser diode source to the circular beam of the resonator mode. The analysis of Hall (Ref. 12) seems to indicate that pump profile shape does not matter much as long as all of the pump light falls within the resonator mode area. There is a problem with applying this analysis because it does not take into account the divergent nature of Gaussian beams. Further experiments and analysis are being conducted to determine the required pump beam manipulation. Even so, to accomplish this requires only the addition of a cylindrical lens.

C. Temperature Effects

As noted earlier, efficient laser operation of Nd:YAG requires pump intensities on the order of 10 kW/cm^2. With such high optical intensities, thermo-optical effects must be taken into account. Thermo-optical distortions of a laser beam arise because of temperature-induced changes in the index of refraction. The major effects include thermal lensing, spherical and higher-order aberrations, and thermal depolarization. The main process by which the material heats up is through the nonradiative electronic transitions that take place from the pump band to the upper laser level and from the lower laser level to the ground state. These transitions are illustrated in Fig. 7.

Since the pump beam is Gaussian, the material will be heated in a nonuniform manner. If we assume that the heat flows mainly in the radial direction (i.e., neglecting laser-rod edge effects), the heat conduction equation can be replaced by the one-dimensional heat equation in radial coordinates

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} + \frac{q_0}{k}\exp\frac{-r^2}{R_0^2} = 0 \tag{4}$$

where the source term contains the Gaussian heat profile. In Eq. (4), q_0 is the thermal power density on axis ($q_0 = P_a/\pi R_0^2 l$), R_0 is the pump beam waist, l is the length of the material, k is the coefficient of thermal conductivity, and P_a is the fraction of pump power that goes into heating the material ($P_a = P_{abs}(1 - \eta_q)$). The complete analysis of this problem is quite involved and will be published later. This heat transfer equation has been solved for local beam heating in nonlinear crystals (Refs. 13 and 14), and we can use these results to estimate the magnitude of the relevant thermal effects.

We now consider the thermal loading effects on the operation of a 1-W Nd:YAG laser utilizing the end pumping concept. From the efficiency estimates in Section II, we see that approximately 2 W of optical pump power are required to produce 1 W of Nd:YAG radiation. From this we calculate the power absorbed to be $P_{abs} = P_{out}/\eta_0\,\eta_m\,\eta_q \cong 1.4$ W. Of this, the fraction $P_a = P_{abs}(1 - \eta_q) \cong 0.3$ W goes into heating the rod. If we assume this power is absorbed uniformly along a 1-cm rod (in reality the absorption is nonuniform: for estimation purposes, the uniform approximation will suffice), then the thermal load is well below the 115-W/cm fracture limit for Nd:YAG. In addition, the power focused onto the end of the laser rod ($P_{abs} = 1.4$ W) to achieve the necessary 10 kW/cm^2 pumping intensity for efficient operation is more than a factor of 3 below the optical damage threshold of Nd:YAG and even further below the coating damage threshold at the rod facet.

The first thermo-optical effect we consider is thermal lensing. This occurs when radial temperature gradients produce stress-induced distortion in the laser material such that the cylindrical laser rod takes on the form of a thick lens. Preliminary calculations indicate that the focal length of any lensing that occurs will be longer than the length of the laser resonators under consideration. This result is important because it shows that stable laser resonators with small mode dimensions can be configured with the appropriate choice of mirrors.

Another thermo-optical distortion that can be quite debilitating, especially in situations where a polarized laser output is required, is stress-induced birefringence. This has the effect of introducing a birefringence into the crystal that tends to depolarize the beam. If we assume uniform pumping over a volume bounded by the pump beam waist R_0, and if we assume that the resonator mode waist radius W_0 equals R_0, then we can estimate the loss due to stress-induced birefringence by the fraction of the light rejected when an analyzer is placed in the path of the depolarized beam. This loss is given by (Ref. 15).

$$L_{depol} = 1/4 \left(1 + \frac{16}{C^2 P_a^2}\right)^{-1} \tag{5}$$

where C is a material constant (C = 8.1 × 10^{-2} W^{-1} for Nd:YAG). If we use the value of P_a = 0.3 W in our example, then we calculate $L_{depol} \cong 10^{-5}$, which is an insignificant amount. Further analysis is being conducted to compute these values more accurately.

IV. Pumping Configurations

In all the analyses presented thus far, we have neglected the problem of concentrating the diode pump power to produce sufficient laser output power. The area into which the laser diodes themselves must be packed to ensure proper mode matching over the length of the rod is governed by conservation of brightness: $A_1 \Omega_1 = A_2 \Omega_2$, where A_1 and A_2 are the object and image source areas respectively, and Ω_1 and Ω_2 are the divergent and convergent solid angles respectively. Since the diode pump source is anamorphic, the packing requirements for directions perpendicular to the junction are different than those for directions parallel to the junction. As was mentioned in Section II, the relationship between pump beam and laser-mode size is quite complicated, but estimates based on conservation of brightness seem to indicate that pump diodes must be placed within 100 μm for efficient operation. Further analysis is needed to resolve this point. An alternative to simple stacking, which has been used in pumping very short Nd^{+3} lasers, is fiber-optical pump coupling. In this scheme, the pump light is transmitted from the diodes to the gain medium through multimode fibers as shown in Fig. 8. Such fiber couplers have been built with only 1.5-dB insertion loss (Ref. 16).

Since the single pass gain of the laser is the integral of the gain per unit length, several laser rods can be cascaded together so that the packing requirement goes down by a factor of $1/N$ compared to a simple double-ended pump (N is the number of rods, assuming each rod can be pumped from both ends, cascaded together). This novel concept is illustrated in Fig. 9. A traveling wave laser consisting of four laser rods pumped by eight sources of 200 mW each produces 1.6 W of pump power, and, from Section II, 800 mW of output power at 1.06 μm. Unidirectional power flow in this ring cavity can be insured in several ways, for example by an InGaAlAsP laser operating at 1.06 μm acting as an injection locking device. The scale in Fig. 9 is drawn to show that it is possible to achieve high output powers in very small packages.

Although none of the devices described in this section have been built yet, they illustrate that efficient lasers producing approximately 1 W could be built today using off-the-shelf technology with the end-pumping concept. Furthermore, extensive industry efforts are now being invested in developing high-power laser diode arrays for pumping second harmonic Nd:YAG lasers, so that an order of magnitude increase in the available pump power from a single array can probably be expected in the near future.

V. Conclusions

In this article, a highly efficient Nd:YAG laser end-pumped by GaAlAs lasers has been proposed. The overall efficiency of such a device was estimated by evaluating the efficiency of each component, and the optical-to-optical efficiency η_{opt} was found to exceed 50%. Next, engineering aspects such as resonator design and coupling optics were discussed and the degradation of the device operation due to thermo-optical effects was calculated and found to be minimal. Finally, several ways for combining and arraying pump sources to increase power output were presented. It was concluded that output power levels close to the goal of 1 W could be achieved with existing technology, with the prospect of increased power virtually assured. An experimental program is now underway to demonstrate key concepts with the goal of developing such a high-efficiency device.

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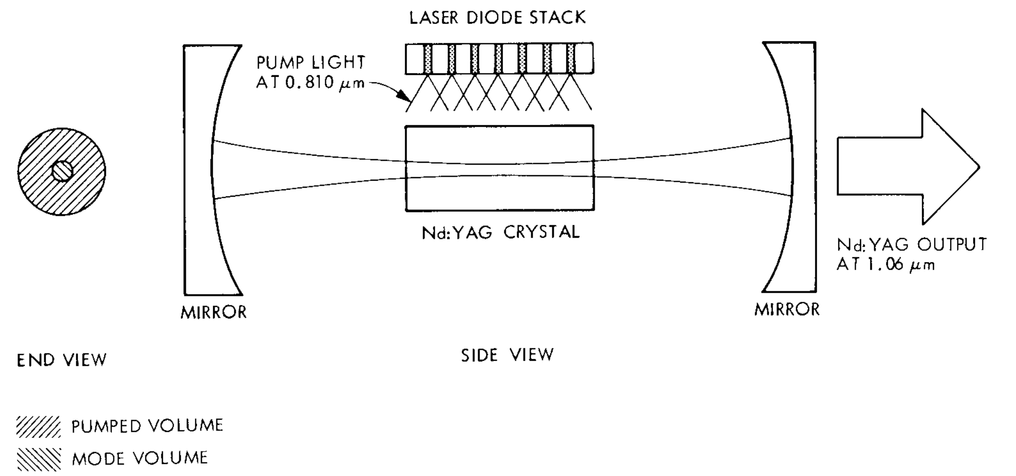

Fig. 1. Semiconductor-laser-diode-pumped Nd:YAG with side pumping geometry; end view illustrates mode mismatch.

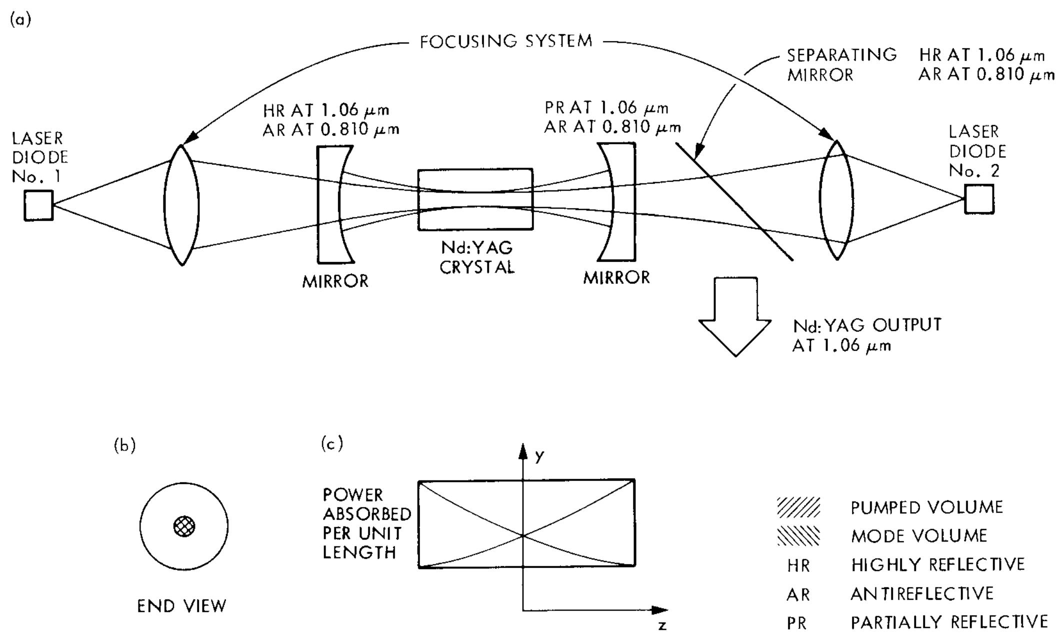

Fig. 2. Semiconductor-laser-pumped Nd:YAG: (a) end-pumping geometry; (b) end view of mode matching properties; (c) side view of nonuniform pumping along length of rod.

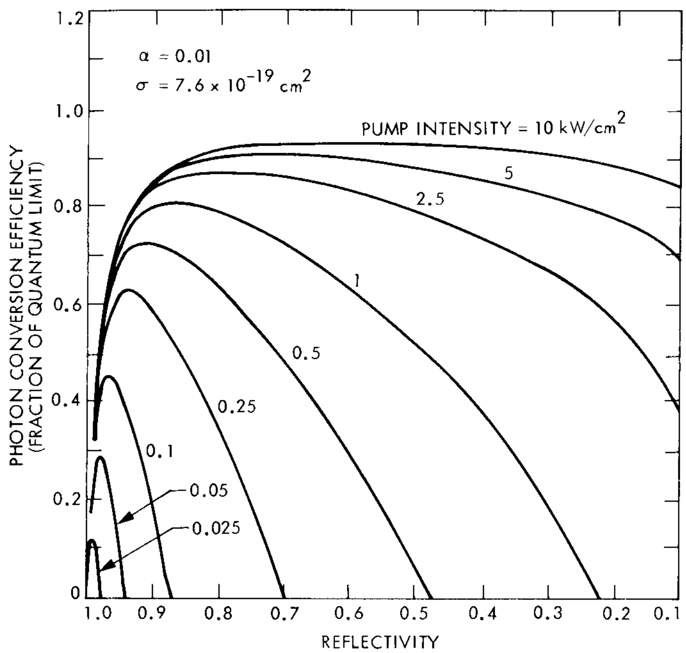

Fig. 3. Calculated values of semiconductor-laser-pumped Nd:YAG efficiency as a function of mirror reflectivity for several values of input pump intensity (for the case of perfect mode matching).

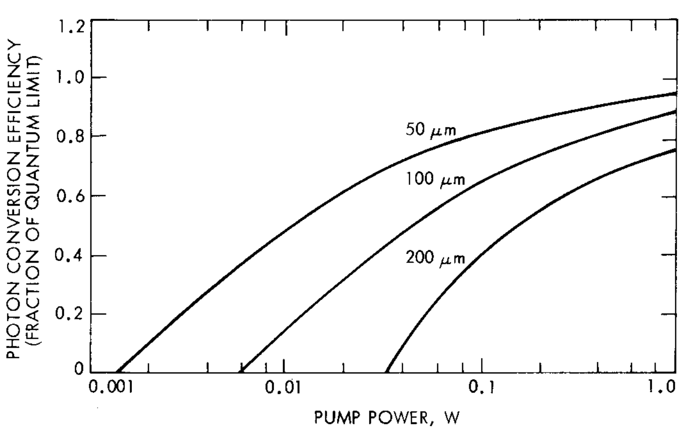

Fig. 4. Semiconductor-laser-pumped Nd:YAG: end-pumped configuration. Calculated efficiency as a function of input pump power for several values of minimum pump beam radii.

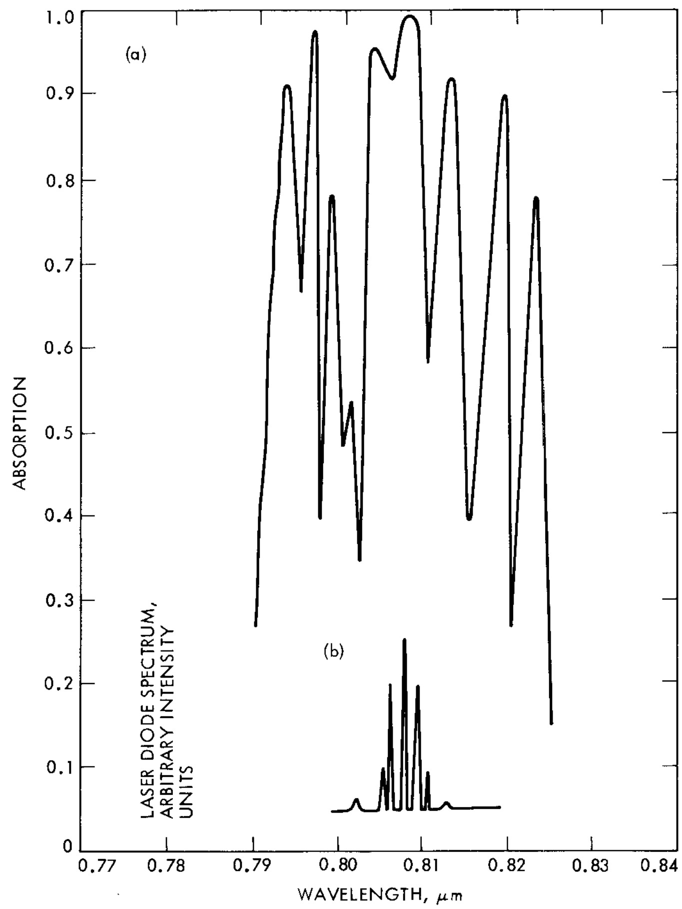

Fig. 5. Spectral properties of diode-pumped Nd:YAG: (a) 0.81-μm absorbtion band in a 1-cm sample of 1% Nd:YAG; (b) emission spectrum of semiconductor laser pump array.

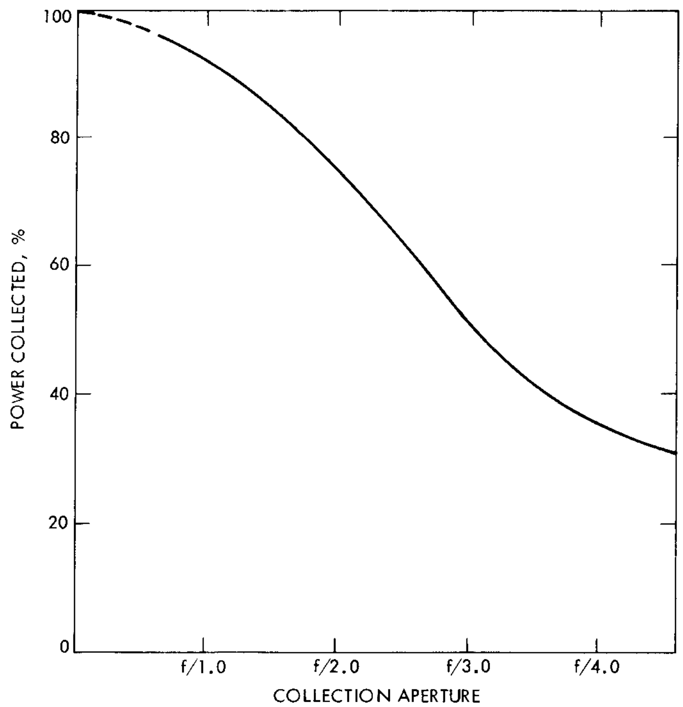

Fig. 6. Power collection efficiency for standard semiconductor lasers

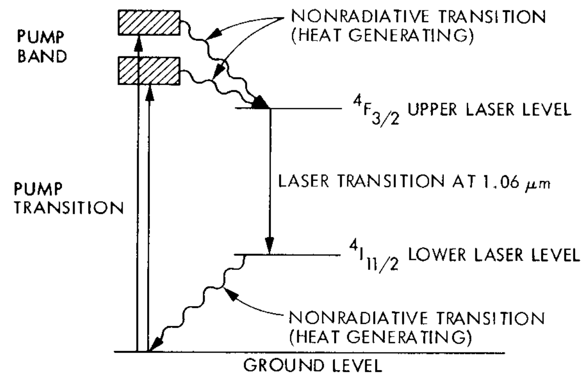

Fig. 7. Energy diagram of four-level laser operation and heat generation process in Nd:YAG

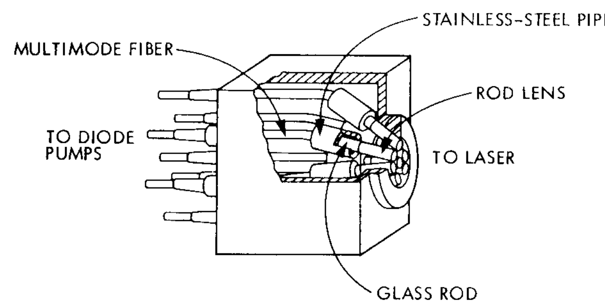

Fig. 8. Optical pump fiber coupler (after Ref. 16)

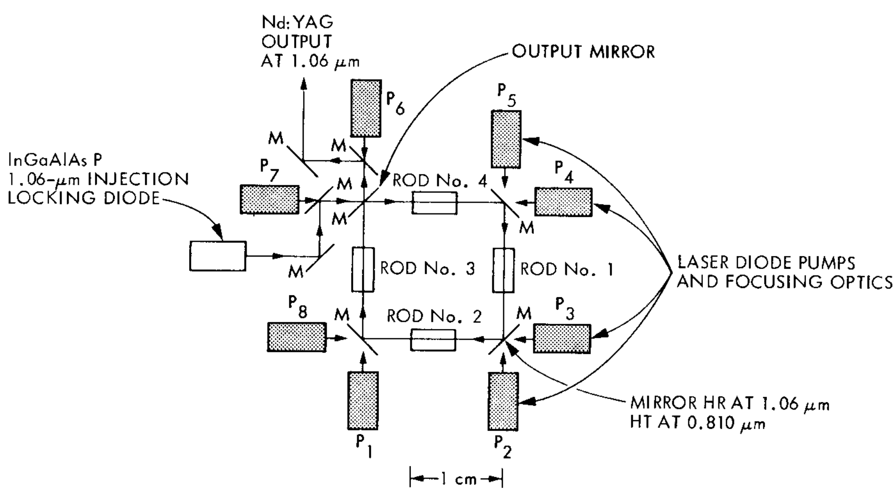

Fig. 9. Schematic of unidirectional Nd:YAG ring laser comprised of four Nd:YAG rods pumped by eight sources