Power Efficiency of Semiconductor Injection Lasers

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One of the advantages of semiconductor injection lasers is their potentially high power conversion efficiency. A device model and analysis of the power efficiency is presented and its dependence on the various device parameters such as length, mirror reflectivity, absorption coefficient and material conductivity is explained. Although the actual values of parameters used pertain to lasers fabricated from the AlGaAs system, the theoretical analysis is also relevant to semiconductor injection lasers of other atomic systems.

I. Introduction

Optimization of the overall efficiency of injection laser diodes is very important, especially for reliable long life optical space communication systems (Refs. 1, 2). This problem has been addressed by several authors, but their analyses contained various approximations and assumptions which are not always valid. In the treatment of Sommers (Ref. 3), the use of non-local rate equations is implied. This renders his results inaccurate in the region of low mirror reflectivities, which is the region where the efficiency is maximized in many cases. Whiteaway and Thompson (Ref. 4) take into account the spatial distribution of the light intensity along the laser cavity (Ref. 5). However, they assume that the laser operates very high above threshold, thus neglecting the spontaneous recombination of carriers. It can be shown that under some relevant physical conditions, the point of maximum efficiency is obtained when the laser is operated at current levels which are only a few times the threshold value.

This article treats the problem of efficiency optimization without the above assumptions except for neglecting the coupling of spontaneous emission into the lasing mode. This term can clearly be neglected in lasers not intended to operate at near threshold power levels. Other assumptions – also used in other works – are that the current injection is uniform along the laser and that thermal effects can be neglected because of low duty cycle operation.

In addition, several important constraints are included. From the results of previous work done on catastrophic mirror degradation in laser diodes (Refs. 6, 7), it is likely that the limiting parameter is the total photon density in the vicinity of the mirrors and not just the output light intensity. The effects of this constraint are described herein. There might also be other constraints on the laser operation besides that of the optical power. For example, the maximum current density can be a constraint, due to either thermal or reliability (Ref. 8) considerations. Another possibility is a constraint on the maximum available current from the primary power source, which can be imposed by overall system specifications. The effects of these constraints will also be considered.

Sections II and III of this report outline the derivation of the expressions for the output power and the power efficiency, respectively, of the laser diode. Section IV presents results of some numerical examples and a discussion. The results show that the different physical and geometrical parameters of the laser must be taken into account and be properly chosen in order to maximize efficiency.

II. Output Power from Laser Diodes

We start with the steady-state local rate equations describing the spatial evolution of the carrier and photon densities along the laser cavity (Ref. 5):

$$\frac{dS^+}{dZ} = [\Gamma g(N) - \alpha_0] S^+ \tag{1a}$$

$$\frac{dS^-}{dZ} = -[\Gamma g(N) - \alpha_0] S^- \tag{1b}$$

$$0 = \frac{J}{qd} - vg(N)\,[S^+ + S^-] - \frac{N}{\tau_s} \tag{2}$$

where S^+ and S^- are the forward and backward propagating photon densities, respectively, N is the carrier density, g is the gain coefficient, which is a function of N, Γ is the mode confinement factor, α_0 is the absorption coefficient, J is the current density injected into an active region with a thickness d, q is the electron charge, τ_s is the spontaneous carrier lifetime, v is the group velocity of the laser mode, and Z is the distance along the laser, with Z=0 at the mirror with the unit reflectivity.

The geometry of the laser is shown in Fig. 1. Its active region has a length L, width W and thickness d. It is assumed that one facet of the laser is coated so that its reflectivity is unity. The reflectivity of the other mirror is denoted by R. From symmetry considerations it is clear that the power efficiency of this laser is twice that of a laser of length $2L$ and with two mirrors of reflectivity R.

The expression for the gain g is taken as (Ref. 9)

$$g = \frac{A}{v}(N - N_{om}) \tag{3}$$

where A is the intrinsic gain constant of the laser material and N_{om} is the minimum carrier density needed for zero gain.

We postulate a solution to Eq. (1) in the form

$$S^{\pm}(Z) = \frac{B}{A\tau_S} e^{\pm[u(Z) - \alpha Z]} \tag{4}$$

where α, the total effective loss coefficient, is given by

$$\alpha = \alpha_0 + \frac{\Gamma A\, N_{om}}{v} . \tag{5}$$

B is a constant, to be determined as described below, and $u(Z)$ is a function which contains the "slow" Z-dependence of $S^{\pm}(Z)$. From Eqs. (1a), (3) and (4) it is easily found that

$$\frac{du}{dZ} = \frac{\Gamma A}{v} N(Z) . \tag{6}$$

Substitution of Eqs. (3) and (4) into Eq. (2) yields the following expression for the carrier density:

$$\frac{N(Z)}{N_{om}} = 1 + \frac{\frac{J}{J_{om}} - 1}{1 + 2B\cosh\,[u(Z) - \alpha Z]} \tag{7a}$$

where

$$J_{om} = \frac{qd\,N_{om}}{\tau_s} \tag{7b}$$

is the current density required to establish the carrier density needed for intrinsic transparency N_{om}.

Substitution of Eq. (7) in Eq. (6), and the application of the boundary conditions $S^+(0) = S^-(0)$ and $S^-(L) = RS^+(L)$ in Eq. (4) yields the following equation for $u(Z)$:

$$\frac{du}{dZ} = G\left(1 + \frac{\frac{J}{J_{om}} - 1}{1 + 2B\cosh\,(u(Z) - \alpha Z)}\right) \tag{8a}$$

$$u(0) = 0 \tag{8b}$$

$$u(L) = \alpha L + \ln\frac{1}{\sqrt{R}} \tag{8c}$$

with

$$G = \frac{\Gamma A N_{om}}{v} . \tag{8d}$$

Equation (8) is solved numerically. Then, given the value of $u(Z)$ the total photon density in the laser cavity can be found from

$$S_t(Z) = S^+(Z) + S^-(Z) = \frac{2B}{A\tau_S}\cosh\,[u(Z) - \alpha Z] \tag{9}$$

The maximum photon density is at the mirror with the reflectivity R. From Eqs. (4), (8b) and (8c) we find that it is given by

$$S_{max} = S^+(L) + S^-(L) = \frac{B}{A\tau_S}\frac{1+R}{\sqrt{R}} . \tag{10}$$

Similarly, the net photon density that is emitted from the laser is given by

$$S_{out} = S^{+}(L) - S^{-}(L) = \frac{B}{A\tau_S} \frac{1-R}{\sqrt{R}} \tag{11}$$

The optical power emitted from the laser is then given by

$$P_{out} = v \cdot (q\,Eg) \cdot S_{out} \cdot W \cdot \frac{d}{\Gamma} \tag{12}$$

where it has been assumed that the energy of an emitted photon approximately corresponds to the bandgap Eg of the material.

The qualitative behavior of the photon densities, $S^{+}(Z)$ and $S^{-}(Z)$, as well as the electron density $N(Z)$ are depicted in Fig. 2.

III. Power Efficiency of the Laser Diode

The first step is to find the constant B which scales the amplitudes of the photon waves (Eq. 4). It is determined from either Eq. (10) (for a maximum photon density constraint) or from Eq. (12) (for a maximum output intensity constraint). The next step involves the numerical solution of Eq. (8a) with the boundary conditions of Eqs. (8b) and (8c). The solution of Eq. (8a) yields the needed value of J.

The electrical power invested in the laser is given by

$$P_{elect.} = J \cdot W \cdot L\,(Eg + \rho J) \tag{13}$$

The first term in Eq. (13) is the electrical power spent at the junction itself (it is assumed that under the injection conditions occurring in laser diodes, the voltage across the junction roughly equals the bandgap), and the second term corresponds to power losses in resistive layers with resistivity of $\rho(\Omega-\mathrm{cm}^2)$ which are in series with the junction current path.

The power efficiency η is simply found by

$$\eta = \frac{P_{out}}{P_{elect.}} \tag{14}$$

where P_{out} and $P_{elect.}$ are given by Eqs. (12) and (13), respectively. It should also be noted that the efficiency obtained in Eq. (14) is actually normalized to the internal efficiency η_i of the laser (Ref. 10). At room temperatures η_i approximately equals 0.8.

IV. Numerical Examples and Discussion

Numerical calculations for several cases were carried out. The values of the parameters chosen were $Eg = 1.4$ V, $v = 8.7 \cdot 10^7$ m-sec^{-1} (corresponding to an index of refraction of 3.6), $A = 1.6 \cdot 10^{-6}$ cm^3-sec^{-1}, $N_{om} = 7.5 \cdot 10^{17}$ cm^{-3}, $\tau_s = 3 \cdot 10^{-9}$ sec, $\Gamma = 0.2$, $d = 0.1$ μm and $W = 5$ μm. The efficiency was calculated as a function of the laser length for several values of mirror reflectivity ($R = 0.8, 0.5, 0.32, 0.1, 10^{-2}, 10^{-3}, 10^{-4}$), absorption coefficient ($\alpha_0 = 0, 10, 20$ cm^{-1}), laser material resistivity ($\rho = 0, 10^{-4}, 8 \cdot 10^{-4}$ Ω-cm^2) and maximum output power intensity ($I_{max} = 10^6, 10^7$ W-cm^{-2}).

A typical result is shown in Fig. 3. In this example $\alpha = 10$ cm^{-1}, $\rho = 10^{-4}$ Ω-cm^2 and $I_{max} = 10^6$ W-cm^{-2}. With these parameters, the maximum available efficiency is about 46% and it is achieved for a 125-μm-long laser with a mirror reflectivity of 0.32. The laser operates at about four times the threshold current. The total power emitted by the laser depends on the cross-sectional dimensions of its active region.

In Fig. 4(a) and 4(b) we see the impact of constraints on the current density and current, respectively. We see that unless operation at $J \gtrsim 5$ kA/cm^2 (Fig. 4(a)) or $I \gtrsim 25$ mA is allowed, the maximum available efficiency cannot be obtained.

The maximum available efficiency depends heavily on the various laser parameters, as is shown in Fig. 5. It is clear that the efficiency improves as α_0 and ρ decrease. It is also important to note that as we are operating the laser at higher output power levels its efficiency decreases since the optical power is proportional to the current density J, but the electrical power wasted at the resistive layers in the laser material is proportional to J^2.

For lasers operating at high output power levels the optimum efficiency is obtained at low values of mirror reflectivity ($10^{-1} \lesssim R \lesssim 10^{-4}$). As the operating power level is decreased, however, the optimum efficiency is obtained at higher values of mirror reflectivity. This trend becomes more pronounced as α_0 and ρ decrease. Also as the power levels are decreased, the laser operates at current densities which are closer and closer to the threshold value. It can also be shown that as the mirror reflectivity becomes smaller, it takes longer lasers to obtain the optimum efficiency (Fig. 6).

It is interesting to note what happens in the idealized case of $\rho = 0\ \Omega\text{-cm}^2$. When $\rho = 0\ \Omega\text{-cm}^2$ the efficiency is always maximized as the laser length approaches zero. This shows the importance of including ohmic losses in the analysis in spite of the fact that they are not related to the intrinsic operation of the laser.

As a final remark we will touch on the subject of the difference between the constraints on maximum output intensity or maximum photon (energy) density. For low values of mirror reflectivity there is no significant difference between the two cases because most of the energy is contained in the outward going wave. However, as the mirror reflectivity is increased, more energy is contained in the reflected wave. If the constraint is on the overall photon density it implies that we can extract less power from the laser, a fact that reduces the efficiency of the laser.

V. Conclusions

Analysis of a model of semiconductor injection lasers has been carried out in terms of the basic parameters relevant to efficient device operations (i.e., device length, mirror reflectivity, absorption coefficient and material conductivity). Not surprisingly it has been found that the efficiency is improved as the optical absorption coefficient and the resistivity of the laser material are reduced. The next step is to specify either the maximum output intensity or the maximum photon density of the laser; these parameters are constrained by reliability considerations. When all these are determined, there will exist a unique value of laser length and laser reflectivity which will optimize the laser efficiency for each application. It is important to note that all the device parameters must be adequately designed in order to optimize its overall power efficiency.

References

1. Katz, J., "High Power Semiconductor Lasers for Deep Space Communications," *TDA Progress Report 42-63*, Jet Propulsion Laboratory, Pasadena, Calif., pp. 40-50, June 15, 1981.
2. Katz, J., and Lesh, J. R., "Optical Communication for Deep Space Missions Using Integrated Semiconductor Injection Lasers," Technical Report (in preparation), Jet Propulsion Laboratory, Pasadena, Calif.
3. Sommers, H. S., Jr., "Theoretical Maximum of the Power Efficiency of a Pulsed Injection Laser with a Fabri-Perot Cavity," *Solid-State Electron., 11*, pp. 909-916, 1968.
4. Whiteaway, J. E. A., and Thompson, G. H. B., "Optimization of Power Efficiency of (GaAl)As Injection Lasers Operating at High Power Levels," *IEEE J. Solid-State Electron. Dev., 1*, pp. 81-88, 1977.
5. Hasuo, S., and Ohmi, T., "Spatial Distribution of the Light Intensity in the Injection Lasers," *Jpn. J. Appl. Phys., 13*, pp. 1429-1434, 1974.
6. Yonezu, H., et al., "High Optical Power Density Emission from a 'Window-Stripe' AlGuAs Double-Heterostructure Laser," *Appl. Phys. Lett., 34*, pp. 637-639, 1979.
7. Henry, C. H., et al., "Catastrophic Damage of $Al_x Ga_{1-x}As$ Double-Heterostructure Laser Material," *J. Appl. Phys., 50*, pp. 3721-3732, 1979.
8. Ettenberg, M., and Kressel, H., "The Reliability of (AlGa)As CW Laser Diodes," *IEEE J. Quant. Electron., QE-16*, pp. 186-196, 1980.
9. Kressel, H., and Butler, J. K., *Semiconductor Lasers and Heterostructure LEDs*, Academic Press, New York (1977).
10. Yariv, A., *Quantum Electronics*, Ch 10.7, Wiley 1975.

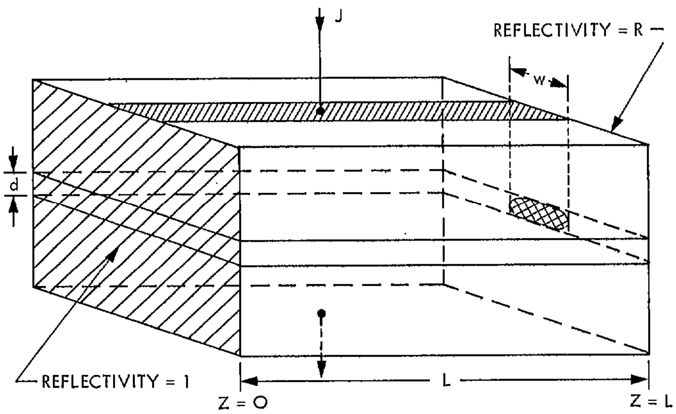

Fig. 1. Schematic drawing of a semiconductor injection laser

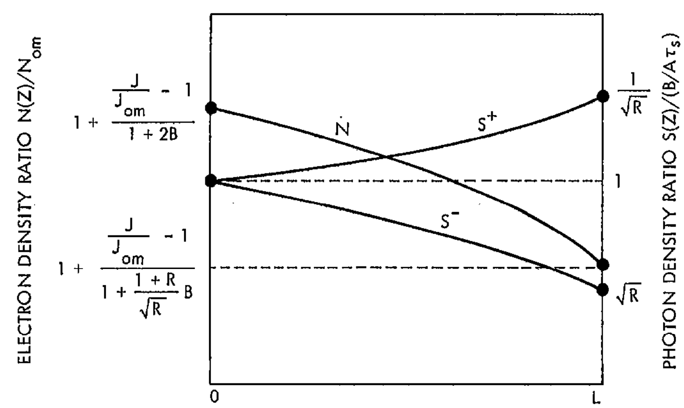

Fig. 2. Spatial distribution of photon and electron densities along the laser

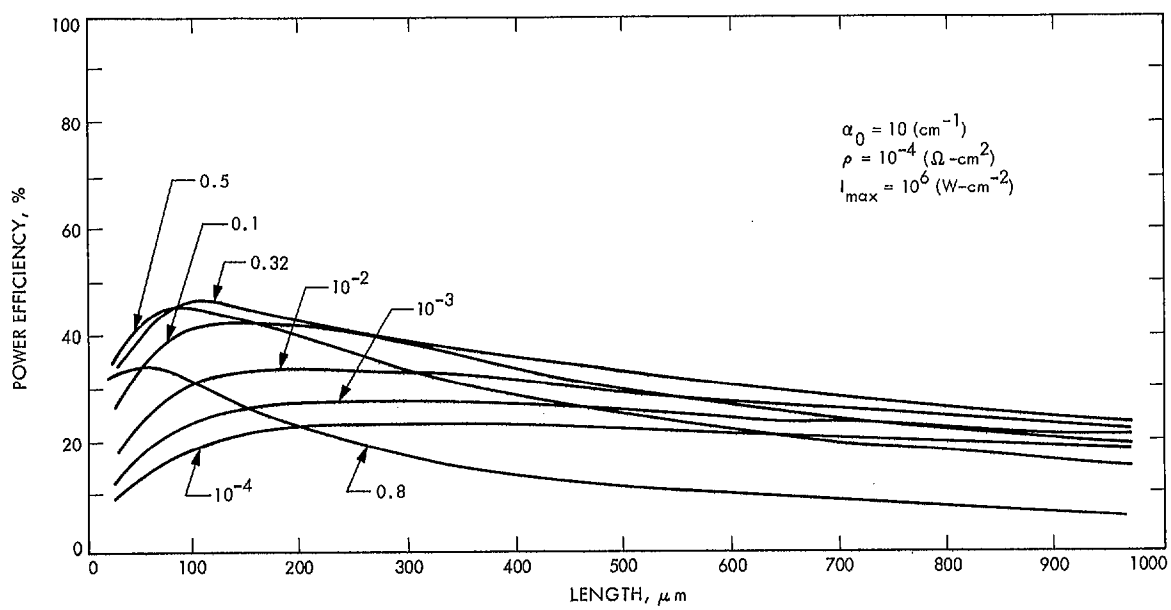

Fig. 3. An example of the dependence of the laser efficiency on the laser length, with the mirror reflectivity as a parameter

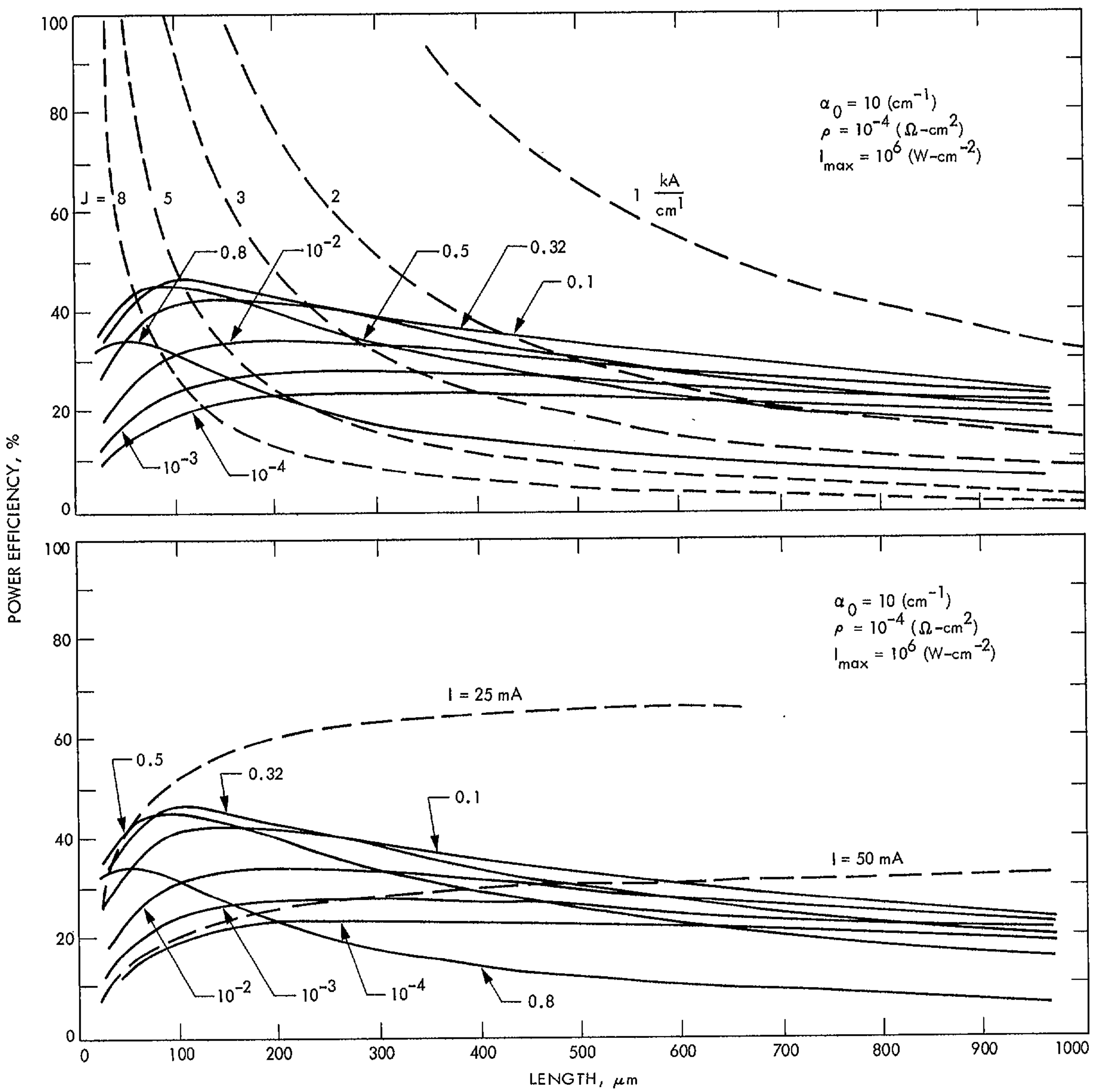

Fig. 4. Same as Fig. 3, but with dashed lines showing constraints of (a) current density and (b) current

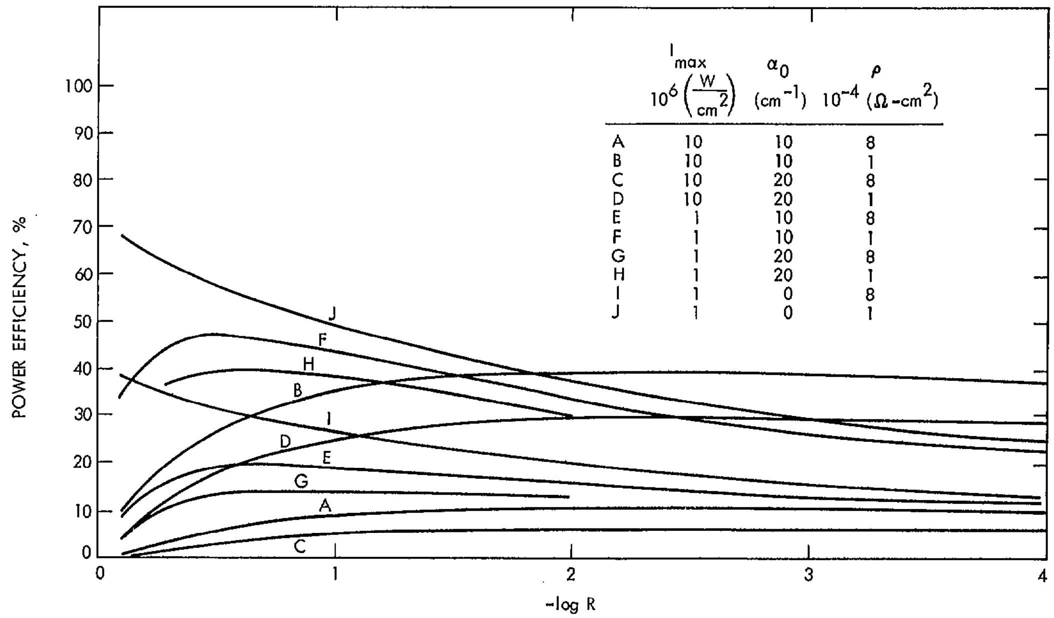

Fig. 5. Dependence of the maximum available efficiency as a function of the mirror reflectivity, with α_0, ρ and I_{max} as parameters

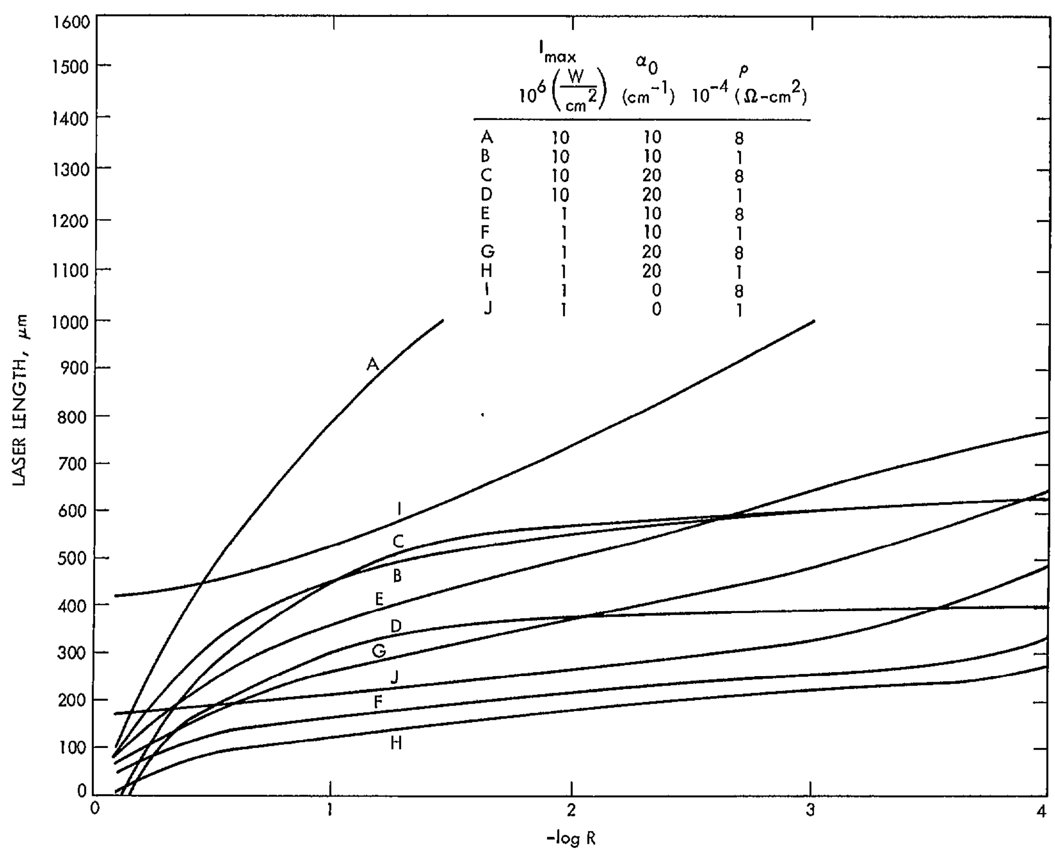

Fig. 6. Laser lengths at which the maximum efficiency is obtained (parameters are the same as in Fig. 5)