EXTRACTION EFFICIENCY UNIFORMITY IN RARE GAS HALIDE LASERS

The dependence of the extraction efficiency on the temporal variations in the quenching rate, absorption, and upper level formation rate is analyzed for rare gas halide lasers. The influence of these effects on laser output irradiance uniformity is significant, and it is shown that the optimum laser design is obtained by a compromise between maximum extraction efficiency and output uniformity. The results are presented in a parametric manner for general applicability.

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Extraction efficiency uniformity in rare gas halide lasers

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Abstract. The dependence of the extraction efficiency on the temporal variations in the quenching rate, absorption, and upper level formation rate is analyzed for rare gas halide lasers. The influence of these effects on laser output irradiance uniformity is significant, and it is shown that the optimum laser design is obtained by a compromise between maximum extraction efficiency and output uniformity. The results are presented in a parametric manner for general applicability.

Subject terms: lasers; excimers; uniformity; extraction efficiency.


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1. INTRODUCTION
Output irradiance uniformity is a major factor in determining laser design suitability for applications such as Raman conversion\(^1,2\) or optical pumping. The temporal uniformity is sensitive to variations in the extraction efficiency caused by changes in quenching rates that occur during the pulse. These rate changes are due to temperature increases and halogen burn-up and can be significant for electron beam pumping with specific energy loadings on the order of 0.1 J/cm\(^2\). It is therefore important to examine the impact of these changes on the output uniformity. While a detailed discussion of the specific mechanisms that are responsible for temporal variations in the gain and absorption will be presented elsewhere\(^3\), the model developed here establishes the relationship between irradiance uniformity and medium kinetics. This enables one to determine an acceptable range for parametric variations once a design goal for irradiance uniformity is established. An example of the application of these results is provided for a KrF laser.

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2. MODEL
For a homogeneously broadened laser the output irradiance \(I_{\text{out}}\) is related to the extraction efficiency \(\eta\) by

\[
\eta = \frac{\beta_{\text{out}} R - A}{g_0 L R + Q},
\]

where \(\beta_{\text{out}} = I_{\text{out}}/L\) is the normalized output irradiance, \(g_0\) is the unsaturated gain, \(I_s\) is the saturation irradiance, \(L\) is the length of the gain medium, \(R\) is the terminal laser level removal rate, \(A\) is the Einstein A coefficient, and \(Q\) is the quenching rate. The one-dimensional flux transport model given by Rigrod\(^4\) results in the approximation

\[
\beta_{\text{out}} = \frac{(g_0 - \alpha_0)L + \ln r_0^2}{1 - (\alpha_0/\ln r_0)^2},
\]

where \(\alpha_0\) is the absorption coefficient and \(r\) is the reflectivity of the output coupler. Rigrod's model further identifies an optimum output coupling that maximizes both the output irradiance and power extraction efficiency when the other parameters are fixed. (The power extraction efficiency is defined\(^5\) as the ratio of the output intensity to the upper level pump rate.) Since the optimum output coupling is based on specific loss and unsaturated gain values, changes in the gain and absorption during the excitation pulse lead to nonoptimum resonator performance, accompanied by changes in efficiency and irradiance. In the following sections, the dependence of the extraction efficiency on these macroscopic laser parameters is established, and its relationship to the output irradiance uniformity is discussed. Schindler\(^6\) has shown that Rigrod's approximate solution to the flux transport equation is inaccurate for \(g_0L > 10\) when \(g_0/\alpha_0 > 1.5\), and
therefore the exact solutions are used to calculate the quantitative results in this paper. However, Rigrod’s approximation is used to derive the analytical expressions in the model. For the range of parameters relevant to this work, the difference between the two results is insignificant.

2.1. Dependence of extraction efficiency on pump rate

We begin by considering the extraction efficiency as a function of the pump rate \( P \), quenching rate, and absorption:

\[
\eta = \eta(Q, P, \alpha_0) ,
\]

where the dependence of \( \eta \) on the quenching rate and the upper level pumping rate comes from

\[
R_0 = \frac{R - A}{Q + A} R .
\]

with \( \sigma \) being the stimulated emission cross section. The variation in \( \eta \) is then

\[
\delta \eta = \frac{\partial \eta}{\partial Q} \delta Q + \frac{\partial \eta}{\partial \alpha_0} \delta \alpha_0 + \frac{\partial \eta}{\partial P} \delta P .
\]

For small changes in the independent variables, Eq. (5) can be linearized (\( \Delta^2 \) and higher terms dropped), giving

\[
\Delta \eta = \frac{\partial \eta}{\partial Q} \Delta Q + \frac{\partial \eta}{\partial \alpha_0} \Delta \alpha_0 + \frac{\partial \eta}{\partial P} \Delta P .
\]

The fractional change in \( \eta \) can then be obtained from Eqs. (1) through (6):

\[
\Delta \eta = \left[ \frac{Q(R - A)}{(Q + A)(Q + R)} - \frac{g_0 L}{(g_0 - \alpha_0) L + \ln r^{\gamma} Q + A} \right] \Delta Q
\]

\[
+ \left\{ \frac{-g_0 L}{[\ln r^{\gamma} \alpha_0 L - 1][\ln r^{\gamma} \alpha_0 L + (\gamma - 1)]} \right\} \Delta \alpha_0
\]

\[
+ \left[ \frac{\alpha_0 L - \ln r^{\gamma} L}{\ln r^{\gamma} L + (g_0 - \alpha_0) L} \right] \Delta P .
\]

where \( \gamma = g_0/\alpha_0 \). As a representative case, a 2 m e-beam-pumped XeCl laser might have the following values: \( g_0 L = 5 \), \( \alpha_0 L = 0.5 \), \( \gamma = 10 \), \( r = 0.115 \), \( Q = 10^8 \) s\(^{-1} \), \( A = 9 \times 10^7 \) s\(^{-1} \), and \( R = 9 \times 10^8 \) s\(^{-1} \). Equation (7) then is

\[
\Delta \eta = -0.34 \frac{\Delta Q}{Q} - 0.46 \frac{\Delta \alpha_0}{\alpha_0} + 0.46 \frac{\Delta P}{P} .
\]

For a maximum acceptable \( \Delta \eta/\eta \), two to three times this uniformity in the spatial and temporal variation of \( Q, \alpha_0 \), or \( P \) could be tolerated. Similarly, the fractional change in the normalized output irradiance \( \beta_{out} \) is

\[
\Delta \beta_{out} = -1.33 \frac{\Delta Q}{Q} + 0.59 \frac{\Delta \alpha_0}{\alpha_0} + 1.46 \frac{\Delta P}{P} .
\]

While it is desirable to design a laser for optimum extraction efficiency, it has been noted that as \( g_0 \) and \( \alpha_0 \) change during the pulse, laser operation will proceed in a nonoptimized cavity. In Fig. 1 curves of constant extraction efficiency are shown for a cavity in which the output coupling is optimized at a design point \( (\eta_0 = 0.47) \). The curves were obtained by evaluating Schindler’s transcendental equation for the cavity flux for the case where \( R >> (A + Q) \), and in general they are closely approximated by the Rigrod model. The extraction efficiency for each curve is referenced to the optimum efficiency at the design point \( (\eta_0 = 0.47) \) with the output reflectivity set at \( r = 0.115 \). These curves provide a contour map, indicating the direction in which the operational extraction efficiency changes for a given change in \( \alpha_0 L \) and \( g_0 L \). The infinite gain limit of the constant \( \eta \) curves is determined by the absorption and \( r \), and since in this limit the reflectivity is far off optimum, the efficiency is less than 1.
2.3. Irradiance uniformity

As was mentioned in discussing Eq. (9), the normalized output irradiance is more sensitive to changes in gain than is the extraction efficiency. The saturation irradiance is constant only if the quenching rates are constant, in which case $\Delta \beta_{\text{sat}} = \Delta \beta_{\text{sat}}^0$. If quenching of the upper level is not constant,

$$\frac{\Delta I_{\text{out}}}{I_{\text{out}}} = \frac{\Delta I}{I} + \frac{\Delta \beta_{\text{sat}}}{\beta_{\text{sat}}} \quad (12)$$

The variation in output irradiance about the design point is shown graphically in Fig. 3. Note that for this figure, as well as for Figs. 1 and 2, the range of variation in $g_{\text{out}}L$ and $\alpha_{\text{out}}L$ shown in the curves is greater than can be justified by the linearization approximation. However, it can be clearly seen that small changes in the gain and absorption produce even greater changes in the output irradiance than in the extraction efficiency. At the design point the output irradiance is 2.34.

3. NUMERICAL EXAMPLE AND IMPLICATIONS FOR LASER DESIGN

To demonstrate the application of the model developed in the previous section, we consider an e-beam-pumped KrF laser excited by a 500 ns pulse in an Ar/Kr/F* mixture, pumped with a specific energy loading of 0.1 J/cm$^2$. The change in the gain comes primarily from two phenomena that independently affect the quenching rates. The first is the gas heating, which affects the rate coefficients, and the second is the fluorine depletion, which both increases the electron density and hence the electron quenching rate, and reduces the halogen quenching rate. Using published values for the temperature dependence of the attachment rate coefficient, the attachment rate coefficient, and the electron quenching rate, and the halogen quenching rate, combined with the dependence of the fluorine depletion rate on the pump rate, one can obtain the details of this calculation will be presented elsewhere. The magnitude of the temperature-induced changes depends on the argon density, while the initial fluorine density determines the influence of fluorine depletion. A range of conditions can therefore be identified under which these changes are minimized.

With a fixed ratio of [F$_2$]:[Ar] = 1.7 $\times$ 10$^{-3}$, $\Delta g_{\text{out}}L/g_{\text{out}}L$ is 0.10 at 1.5 amagat argon and 0.20 at 2 amagat. These argon densities keep the variation in $g_{\text{out}}$ low, and for both densities the change represents the gain increasing from its initial value. The absorption change during the pulse is due primarily to fluorine depletion since the other major absorbers (F* and KrF*) do not undergo significant density changes. The decrease in net absorption, $\Delta \alpha_{\text{out}}/\alpha_{\text{out}}L$, is a little over 0.1 for both argon densities considered. From Fig. 1 it can be seen that under these conditions the fractional change in the extraction efficiency is 0.10 and 0.15, while Fig. 3 shows that the change in the normalized output irradiance is 0.2 and 0.35 for the 1.5 amagat and 2 amagat mixtures, respectively.

While these changes are significant, shorter pulse lengths and lower [F$_2$]:[Ar] ratios give rise to even larger nonuniformities. The sensitivity of the output irradiance to changes in the gain and absorption shown in Fig. 3 indicates that some care must be taken to consider irradiance uniformity when designing a laser around a given operating point. This is especially true for lasers where the internal flux is large since temporal increases in output irradiance can exceed the threshold for optical damage to the...
nonuniformities arising from all possible sources, but within the Equation (11) is obtained directly from Rigrod's model for short pulse systems are more severe.

the diode closure time, but kinetics-driven nonuniformities in the pumped device designed by AVCO for Raman conversion* provided much more uniform output. Short pulse operation can be restricted in magnitude by the picture frame effect can lead to unloaded gain regions and variations. It would be useful to compare the nonuniformities within the active volume, additional output nonuniformities will result if the optical elements are large. The key to optimizing laser performance for irradiance uniformity (assuming uniform energy deposition) is in selecting the resonator design point in such a manner as to minimize the effects of anticipated \( g_0 \) and \( \alpha_0 \) changes. In general, this will require selecting an output coupling that is higher than optimum so that the improved uniformity is obtained by compromising the magnitude of the output irradiance. One must therefore consider trading off extraction efficiency magnitude for extraction efficiency uniformity, or equivalently, output energy for output uniformity.

4. CONCLUSIONS
For the 500 ns e-beam-pumped KrF laser described, the magnitude of the normalized output irradiance uniformity will lie in the 20% to 35% range. This might be unacceptable for a nonlinear Raman conversion process, for example, but lasers designed for other applications may have much larger tolerances for variations. It would be useful to compare the nonuniformities obtained from the kinetics considerations in this work with temporal and spatial nonuniformities expected from phenomena such as nonuniform e-beam deposition and transverse amplified spontaneous emission (ASE). E-beam-pumped excimer lasers vary greatly in size and used intensity, however, and the nonuniformities inherent in demonstrated designs can cover an extremely wide range. For example, the large "Scale-Up" excimer laser designed by AVCO* displayed temporal variations in e-beam current that were typically 300% over 2 ms, although an e-beam-pumped device designed by AVCO for Raman conversion* provided much more uniform output. Short pulse operation can avoid temporal e-beam current variations by staying well below the diode closure time, but kinetics-driven nonuniformities in short pulse systems are more severe.

It is not practical to present quantitative estimates of the nonuniformities arising from all possible sources, but within the context of the present calculations (which allow one to "fine-tune" a laser that has already been designed for output uniformity) we examine several excimer laser designs in which output uniformity is a consideration. The direct relationship between pumping uniformity and variations in the output flux were established in Sec. 2, but the most obvious source of pump non-uniformity is the variation in temporal and spatial energy deposition of the e-beam. Optical beam quality measurements using a Mach-Zender interferometer have been shown\(^1\)\(^3\) to provide direct information on the spatial variation of the e-beam deposition profile through a determination of the transient refractive index. The XeF laser in Ref. 14 produced a peak phase shift of 8 rad over 2 m and a variation in line pair production rate of 4% over a 5 cm aperture. A much improved 1 m XeF laser designed for high beam quality was recently reported\(^5\) to produce near-diffraction-limited output with a Strehl ratio of 0.76 throughout a 500 ns pulse. Modeling of a large scale KrF laser\(^6\) for laser fusion indicates that with two-sided pumping, diode impedance collapse requires a tradeoff between spatial and temporal e-beam energy deposition uniformity. For example, the spatial deposition uniformity can be maintained within 10% across a 1 m aperture, but under these conditions the temporal variation in pump rate during a 1 ms pulse exceeds 40%.

Another major contribution to spatial nonuniformity, particularly for large aperture devices, is the transverse ASE.\(^7\)\(^8\) For apertures of several centimeters this effect is negligible, but beyond 50 cm the transverse ASE flux becomes an important factor in determining output uniformity. This comes about due to the nonuniform flux profile, which is largest at the aperture edge and causes nonuniform gain across the aperture. For a 3 m long by 1 m square-aperture KrF laser with a \( g_0 \) of 0.04/cm, the transverse ASE nonuniformity\(^6\) will be 20%. Nonuniformities can also result from the extraction dynamics of the unstable resonator. This occurs since a fraction of the laser volume sees only one pass of the extracting flux while other parts of the volume see two or more. This "picture frame" effect leads to spatial nonuniformities on the order of 20%. A related phenomenon arises from the competition between the intracavity coherent flux and longitudinal ASE. This competition is affected by the resonator output coupling because a large longitudinal ASE flux can develop if the coherent flux fails to saturate the gain. Since the spatial variation of the intracavity flux resulting from the picture frame effect can lead to unloaded gain regions within the active volume, additional output nonuniformities will arise.

In conclusion, it has been shown that small changes in the gain and absorption may lead to substantial changes in the laser output irradiance. Changes in the kinetics rates and species densities that occur during the excitation pulse are a result of gas heating and halogen donor removal, and these variations may cause unacceptable changes in output irradiance in a poorly designed rare gas halide laser. The temporal irradiance nonuniformities will occur even though the pumping is both temporally and spatially uniform and can be restricted in magnitude by suitable selection of gas mixture, total pressure, and pulse length.

5. APPENDIX: OPTIMUM EXTRACTION EFFICIENCY
Equation (11) is obtained directly from Rigrod's model for volumetric extraction efficiency, but the optimum local extraction efficiency for an infinitesimal slab of gain medium in a single pass amplifier\(^6\) is given by the same expression. This is

\[ \text{(11)} \]

\[ \alpha_0 = 0.2. \]

\[ \beta_0 = 2.341s. \]

\[ \text{Fig. 3. Curves of constant normalized output irradiance indexed to the normalized output irradiance at the design point of Fig. 1 (} \beta_0 = 2.341s). \text{ Constant } \beta \beta_0 \text{ curves are shown for } \Delta(\beta/\beta_0) = 0.1 \text{ but labeled for } \Delta(\beta/\beta_0) = 0.2. \]

*M J Boness, private communication

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contrary to what one might expect since the optimum extraction efficiency for the finite length gain medium should differ from that for the infinitesimal slab due to the axial $(z)$ dependence of the intracavity flux. This section is directed toward demonstrating that the equivalence of the calculated optimum extraction efficiency for the two gain lengths is a direct consequence of the average gain approximation in the Rigrod model and as such puts a limitation on the application of Eq. (11) to an actual laser. The Rigrod solution for the lossy traveling wave resonator is then lead to approximating the solution to that for the infinitesimal slab due to the axial irradiance. This section is directed toward demonstrating that for the infinitesimal slab due to the axial irradiance. Equation (13) is appropriate when ground state dissociation is rapid. For the infinitesimal gain slab the optimum extracting flux $\beta_{\text{max}}$ can be found directly by differentiating Eq. (13) with respect to $\beta$ and setting the derivative equal to zero. This gives

$$\beta_{\text{max}} = \gamma^2 - 1 ,$$

from which Eq. (11) follows since

$$\eta_{\text{local}} = \frac{1}{g_0} \frac{d\beta}{dz}.$$

The finite length optimum irradiance can be found by integrating Eq. (13),

$$\beta + \Delta \beta = \int_{0}^{\Delta z} \frac{d\beta}{1 + \beta} = \int_{0}^{\Delta z} (g_0 - \alpha_0 - \alpha_0 \beta) dz,$$

where $\Delta \beta$ is the increase in the irradiance for a single pass through the gain medium and $\Delta z$ is the gain length, to obtain

$$\Delta \beta + \ln \left(1 + \frac{\Delta \beta}{\beta}\right) = (g_0 - \alpha_0) \Delta z - \int_{0}^{\Delta z} \alpha_0 \beta dz .$$

Defining the average irradiance as

$$\bar{\beta} = \frac{\int_{0}^{\Delta z} \beta(z) dz}{\Delta z} ,$$

Eq. (17) becomes

$$\Delta \beta + \ln \left(1 + \frac{\Delta \beta}{\beta}\right) = (g_0 - \alpha_0) \Delta z - \int_{0}^{\Delta z} \alpha_0 \beta dz .$$

To obtain an analytical solution to Eq. (13), Rigrod defines the average gain $\bar{g}$ as

$$\bar{g} = \frac{g_0}{1 + \beta} - \alpha_0 ,$$

and approximates the solution to $\beta(z)$ as

$$\beta(z) = \beta_{\text{max}} \exp(\bar{g} \Delta z) ,$$

where $\beta_{\text{max}}$ is the irradiance at $z = 0$. Equations (18) and (21) then lead to

$$\ln \left(1 + \frac{\Delta \beta}{\beta}\right) = \frac{\Delta \beta}{\beta} .$$

with $1 + \Delta \beta/\beta = \exp(\bar{g} \Delta z)$ and $\beta = \beta_{\text{max}}$. Rewriting Eq. (19), one obtains

$$\frac{\Delta \beta}{\Delta z} = \frac{1}{\beta_0} \frac{1}{1 + \beta} \bar{g} .$$

Maximizing $\Delta \beta/\Delta z$ with respect to $\bar{g}$ produces the equivalent of Eq. (14) for $\bar{g}$, and since $\eta_{\text{opt}} = \Delta \beta (g_0 \Delta z)^{-1}$, $\eta_{\text{opt}}$ for the finite length laser is also given by Eq. (11).

The impact of the average gain approximation can be clearly resolved by defining the average extraction efficiency as

$$\eta_{\text{local}} = \frac{1}{g_0} \frac{d\bar{g}}{dz} ,$$

Comparison of Eq. (24) with Eq. (15) shows that the Rigrod model calculates the analog of the thin slab local efficiency for an extracting flux intensity equal to $\beta$ and medium saturated amplification factor $\bar{g}$. While the medium as modeled does not approximate a thin slab $[\ln(1 + \Delta \beta/\beta) \neq \Delta \beta/\beta]$, it is important to note that only the $\bar{g}$ approximation requires small axial variations in the cavity flux.

In the context of the previous analysis, it can be shown that the fit to Eq. (11) obtained by Chernin$^6$ for the extraction efficiency in a confocal unstable resonator results from the range of cavity parameters he selected. Based on reasonable expectations for rare gas halide lasers, $g_0 \Lambda$ was kept below 10. This kept the intracavity flux variations low and the average gain approximation therefore applied. In such an instance the optimum volumetric extraction efficiency will be given by Eq. (11).

Near the optimum flux, the thin slab extraction efficiency is insensitive to small changes in the interior irradiance associated with flux propagation through the cavity. An expression relating the change in extraction efficiency to the interior irradiance can be obtained from Eqs. (13) and (15):

$$\eta_{\text{local}} = \frac{\bar{g}}{1 + \beta} - \gamma .$$

Combining this with Eqs. (11) and (14) gives

$$\frac{\Delta \eta}{\eta_{\text{opt}}} = \frac{(1 - \omega)^2}{1 - \omega(1 - \gamma)} ,$$

where $\beta = \omega \beta_{\text{max}}$ and $\Delta \eta = \eta_{\text{opt}} - \eta$. For $\gamma = 10$, a 20% change in $\beta (\omega = 0.8)$ produces only a 1% change in $\eta$, while a 50% change in $\beta$ causes $\eta$ to decrease by 12%.
6. REFERENCES


9. R. A. Scheps received his Ph.D. from the University of Chicago in chemical physics and received his BS degree from the University of California at Berkeley. He has been actively involved in laser research since 1973 and has published numerous papers in this field and presented his results at major conferences. After completing his graduate studies, Dr. Scheps was awarded a postdoctoral fellowship at the Joint Institute for Laboratory Astrophysics in Boulder, Colo. He has held several senior positions in corporate laser research before joining the Naval Ocean Systems Center. He has been involved in the management of the XeCl laser submarine communications program and also heads an active experimental research program in diode-pumped solid-state lasers.