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OPTIMIZATION OF PARASITIC ISOLATORS IN LASER FUSION SYSTEMS*

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Abstract

The results of model calculations for the optimization of the efficiency of high-gain amplifier systems stabilized by saturable absorbers are described. It is shown that the isolator performance can be characterized by a convenient figure of merit.

The selective use of nonlinear saturable absorbers distributed throughout a high-gain amplifier chain has proven to be an effective means of controlling undesired parasitic oscillations in CO_2 fusion lasers. Much work has been reported on the characterization of these absorbers and their deployment in existing laser facilities. In this paper, we discuss the extension of these specific techniques to more general advanced laser systems and develop a useful figure of merit to describe the performance of this class of parasitic isolators in specific laser geometries.

Isolator Modeling

The transmission, T(I), of a nonlinear saturable absorber is a function of the incident laser power (energy). At a given intensity (fluence) level, an effective absorption coefficient can be defined by

$$\alpha(I) = (\ell n\, T(I))/\ell \qquad (1)$$

for a material of length ℓ irradiated by a laser intensity I. If the small-signal loss coefficient is denoted by α_0, then a figure of merit (FOM) for the saturable absorber can be defined by

$$\mathrm{FOM} = \alpha_0/\alpha \geq 1 \qquad (2)$$

With these definitions we can express energy absorbed by a given material as

$$I_{abs} = I_0 - I_t = I_0 - (I_0 e^{-\alpha\ell})$$

$$I_{abs} = I_0\,(1 - e^{-\alpha\ell})$$

and in the high field limit and using (2) we find

$$I_{abs} = \frac{\alpha_0\ell}{\mathrm{FOM}}\, I_0 \qquad (3)$$

In all applications of saturable absorbers to the stabilization of high gain laser fusion systems, one attempts to optimize the overall performance of the laser/isolator system by minimizing the laser energy absorbed by the isolator. As can be seen above, minimization of I_{abs} implies the maximization of the FOM of the saturable absorber. It is this observation that provides a partial motivation for the FOM as defined in equation (3).

The functional dependence of the FOM on input intensity is related to the physical parameters of the saturable absorber. To illustrate the usefulness of this definition of a FOM, consider the case of an intense beam of light propagating through a homogeneously broadened saturable absorber whose characteristic recovery time is short compared to the length of the interacting laser pulse (a Rigrod-type absorber). Under these conditions the incremental change of intensity of the incident pulse in a distance dz in the absorber can be written as

$$\frac{dI}{dz} = -\frac{\alpha_0}{1 + I/I_s} - \alpha_{NS} I \qquad (4)$$

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where α_o is small-signal loss coefficient, I_s is the saturation intensity for the absorber, α_{NS} is the nonsaturable loss coefficient for the absorber and I is the local laser intensity. In the limit of high intensities, $I >> I_s$ this can be solved for an input fluence I_o to give for the FOM,

$$\text{FOM} = \frac{\alpha_o \ell}{\ell n(I/I_o)} = \frac{\alpha_o \ell}{\ell n \left[\frac{\alpha_o}{\alpha_{NS}} \frac{I_s}{I_o} \left(e^{-\alpha_{NS} \ell} - 1 \right) + e^{-\alpha_{NS} \ell} \right]} \qquad (5)$$

In the high field limit we find several special cases. For $\alpha_{NS}=0$, the FOM = I_o/I_s and the energy absorbed by the isolator, is given by

$$I_{abs}(\alpha_{NS}=0) = \alpha_o \ell I_s \qquad (6)$$

and is a constant, independent of input intensity. For $\alpha_{NS} \neq 0$, we find FOM = α_o/α_{NS}, limited to a maximum value which depends on the parameters of the material. In this limit the energy absorbed by the isolator is given by

$$I_{abs}(\alpha_{NS} \neq 0) = \alpha_{NS} \ell \times I_o \qquad (7)$$

and increases in direct proportion to the input intensity.

For the general case of intermediate values of I_o, equation (4) must be numerically integrated in space and time for the figure of merit. Figure 1 shows a typical calculation for a Rigrod absorber with homogeneously and inhomogeneously broadened absorption and no nonsaturable loss ($\alpha_{NS}=0$). As can be seen the broadening mechanism has a profound effect on the efficiency of the saturable absorber performance. For homogeneously broadened absorbers, FOMs in excess of 50 are easily obtained for input fluences of $10^2 \times I_s$ while FOM $\sim$ 10 are achievable for inhomogeneously broadened absorbers. The figure also shows that variation of the value of $\alpha_o \ell$ from 3 to 9 has only a minor effect on the dependence of the FOM with input intensity. This independence of the FOM on the small-signal loss is only true for the case of $\alpha_{NS}=0$. Figure 2 shows an example of the more general case where $\alpha_{NS} \neq 0$. In Fig. 2 the FOM is calculated for a Frantz-Nodvik absorber (absorber recovery times long compared to the laser pulse duration). Here, for high fluences we see the limiting behavior described previously by (7).

Isolator Performance

For use in a broadband CO_2 laser fusion system a parasitic isolator must have the proper spectral absorption characteristics to provide loss for all of the laser wave lengths having excess gain. In addition the isolator must efficiently saturate, as described above, so that is use does not represent an unacceptable energy loss to the output going laser beam. Many materials have been shown to possess saturable absorptions in the ir. Several characteristic materials are listed in Table 1 along with comments regarding their usefulness.

TABLE I

Saturable Absorber FOMs

Material	Bandwidth	I_o(1ns)	FOM
SF_6	20 cm^{-1}	200 mJ/cm^2	23
Mix 907	9 μm + 10 μm	200 mJ/cm^2	12
Ge	9 - 11 μm	200 MW/cm^2	5
CO_2 (Hot)	9 - 11 μm	500 MW/cm^2	40
$KCl:ReO_4^-$	1 cm^{-1}	500 MW/cm^2	30

The FOMs range from 5 for the inhomogeneously broadened Ge, through 10 - 20 for the multiphoton absorber SF_6 to approaching 50 for the two-level homogeneously broadened CO_2 and KCl doped with ReO_4^-. Practical considerations against heating CO_2 to

450°C in large cells and poor spectral match of the currently available doped alkali halides dictate the use of mixtures of polyatomic gases as typified by mixture 907 which contains SF_6 plus a variety of other florinated hydrocarbons.* Figure 3 shows a typical measured FOM curve for mixture 907 for a variety of small signal loss lengths ranging from 2 to 6. The laser produced a 1.7-ns pulse which was tuned to the P(20), 10 μm line for this measurement. As can be seen the FOM tends to a limiting value of 12 implying that $\alpha_{NS} = 0.08\ \alpha_o$. This value is consistent with the known nonsaturable losses due to the other components in the mixture, including the multiphoton absorption of the SF_6 itself which accounts for about 1/3 of the nonsaturable loss. Thus for practical isolators currently available, FOMs of 12 can be expected.

Systems Applications

The optimization of an isolated laser fusion system requires the consideration of the detailed architecture of the system to determine the proper staging of the isolator. In general isolators with large FOMs are best placed nearer the output end of the system, while less efficient isolators are best placed further up the amplifier chain toward the front end. To illustrate this behavior consider the system shown in the insert of Fig. 4. A laser amplifier is operated in single pass at the saturation limit. In order to stabilize the system against unwanted parasitic oscillations, a saturable absorber is placed at the output of the amplifier and the loss in the absorber is adjusted so that the amplifier small-signal gain is numerically equal to the absorber loss. This is isolation at zero gain. Under these conditions we have

$$g_oL_1 - \alpha_{SS}L_2 = 0 \qquad (8)$$

where g_oL_1 is the amplifier gain length ($G = e^{g_oL}$) and $\alpha_{SS}L_2$ is the isolator loss length. If E_s is saturation fluence for the amplifier then the output of the amplifier in the absence of any isolator is

$$E_{stored} = E_s\ g_oL_1 + E_{in}$$

and with isolator

$$E_{out} = (E_s\ g_oL_1 + E_{in})\ e^{-\alpha_{SS}L_2}$$

and using (2) we can calculate an effective amplifier effiency,

$$E_{out}/E_{stored} = e^{-\alpha_oL_2/FOM} \qquad (9)$$

For constant efficiency α_oL_2/FOM = constant and higher gain amplifiers required increasingly more efficient isolators. Figure 4 shows a graphical representation of equation 9. The laser efficiency (E_{out}/E_{stored}) is plotted for various values of the figure of merit (α_{SS}/α_{LS}) for different values of the amplifier gain length g_oL, ranging from 3 to 9. Practical CO_2 lasers run at g_oL's of 6 - 9. As can be seen for efficiencies of 90% or greater, FOMs between 25 and 100 are required. For more optimal staging with multipass lasers the required FOMs can be reduced to 10 - 20 by proper design.

Conclusion

In this paper we have introduced the concept of the figure of merit (FOM) for a saturable absorber defined as FOM = $\alpha_o/\alpha(I)$ and have described the results of several specific FOM calculations. The currently available saturable absorbers were reviewed and shown to have useful FOMs of ~ 12. Finally some simple system calculations were described indicating the requirements of FOMs in the range of 20 for efficient performance.

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*907 is a mixture of SF_6, C_4F_8, FC-115, FC-152A, FC-1112A, FC-12 and FC-1113 in the by volume proportions of 0.82%, 2.27%, 6.64%, 9.09%, 13.63%, 25.0% and 42.6% respectively.

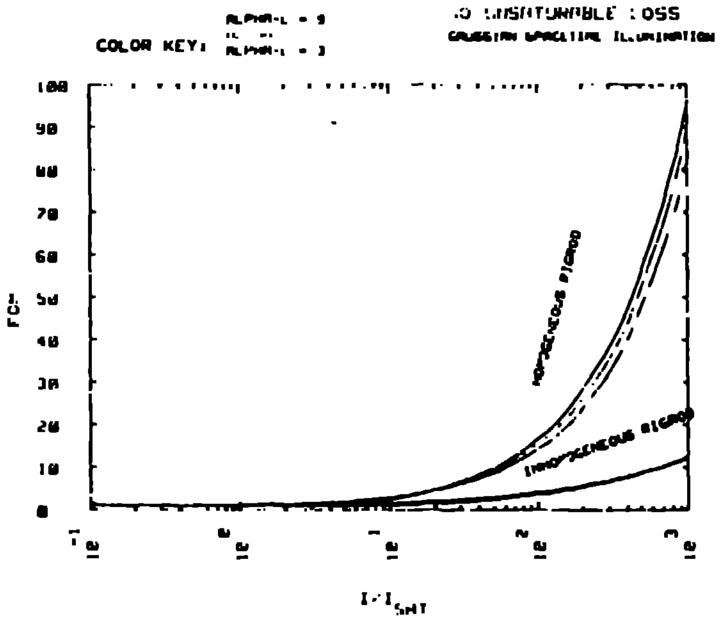

Figure 1. Model calculations of the FOM of a Rigrod absorber for a homogeneously and inhomogeneously broadened absorber. Calculations for $\alpha_0 L$ of 3, 6, and 9 are shown.

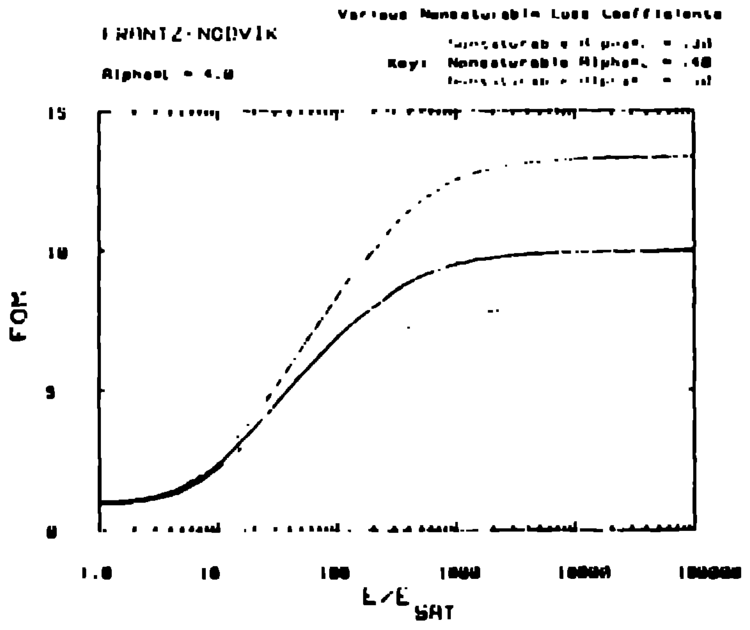

Figure 2. Model calculations for a Frantz-Nodvik absorber [illegible] nonsaturable loss and $\alpha_0 L$ = 4. A nonsaturable loss of 0.35 represents the practical case of Mix 907.

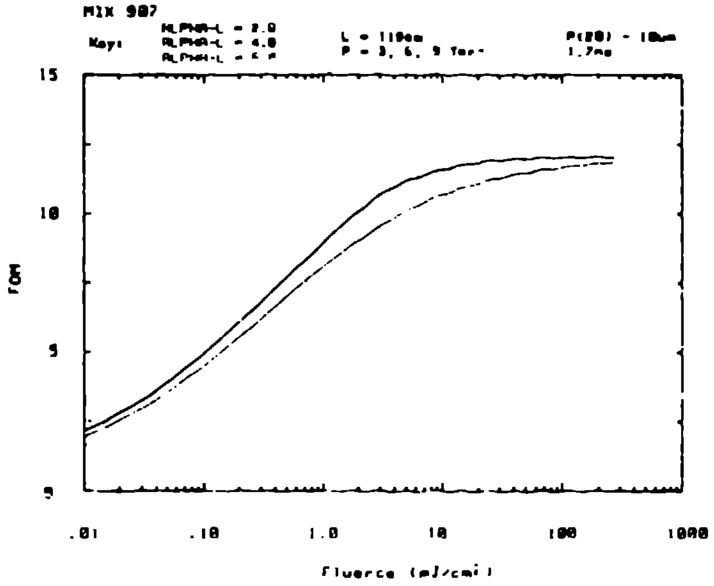

Figure 3. The measured FOM of gas Mix 907 for small-signal loss lengths of 2, 4, and 6 at P(20) - 10 μm with 1.7 ns pulses of Gaussian space time radiation. Maximum FOM is 12.

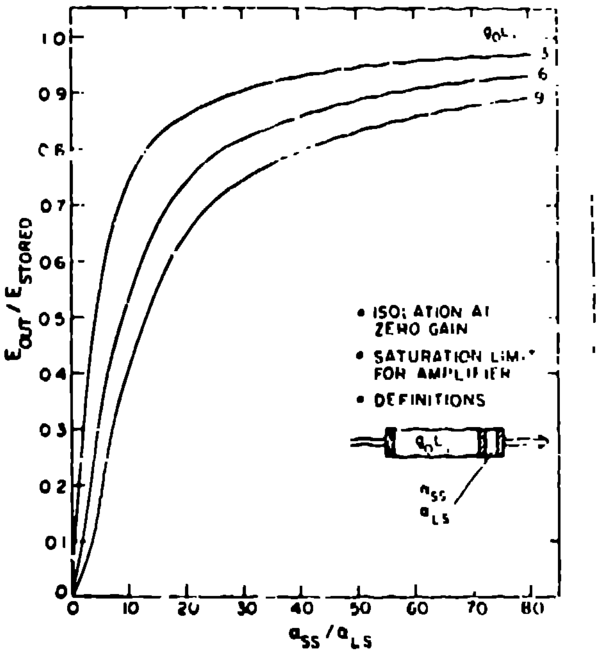

Figure 4. Single pass amplifier efficiency for isolation of zero gain for various amplifier gain lengths (3, 6, [illegible] is located at output of amplifier.