Theoretical analysis of amplification performance of space-based lasers with different pump configurations

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We investigate a theoretical model to accurately predict the output performances of slab laser amplifiers, which is one of the key issues in the study of space-based lasers. The realistic absorbed pump energy density, which induces nonuniformity of stored energy density in the laser medium, is introduced into the model. Using this model, the amplification performances of two space-based laser amplifiers with different pump configurations are compared. The results indicate that the bounce-pumped amplifier (BPA) achieves much higher output energy and efficiency compared with the side-pumped amplifier (SPA); it is also more suitable for space-based lasers.

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A compact and robust single frequency laser source with high pulse energy and good beam quality is a critical element for a number of space-based lidar systems that can provide earth and planetary science measurements previously deemed unavailable[1]. Recently, diode-pumped zigzag slab laser in a master oscillator power amplifier (MOPA) configuration has served as the basis of many space-based lasers because of its high efficiency, compact structure, high stability, and good beam quality[1−3].

A unique set of requirements are demanded from laser designs since these are considered as sources of space-based lidar systems[4]. Of these, high efficiency is an important requirement because laser power consumption is often one of the highest in the overall system. The design of pump for the power amplifier is crucial in obtaining outstanding efficiency. Meanwhile, to reduce the development costs and risks, one practical option is to use laser model to predict accurately the various performance parameters of the lasers before the laser system is built and launched into space. This time- and money-saving approach is very useful in determining the efficiency of a potential space-based laser system.

This letter focuses on the output performances of space-based laser amplifiers. An expanded equation derived from the Frantz-Nodvik (F-N) equation[5] for predicting accurately the output energy and efficiency of zigzag slab laser amplifiers is investigated. In the derived equation, the realistic absorbed pump energy density, which induces the nonuniformity of stored energy density in the laser medium, is introduced. By using the expanded equation, we are able to compare the performances of two slab amplifiers with different pump configurations, namely, the bounce-pumped amplifier (BPA)[4] and the side-pumped amplifier (SPA), in terms of extracted energy and achievable efficiency.

Figure 1(a) shows a zigzag slab laser amplifier used as power amplifier by most space-based laser transmitters[1−4]. It is optically pumped on the total internal reflection (TIR) surfaces and conductively cooled on edge surfaces. To enable easier operation with a TEM_{00} Gaussian beam in the amplifier, the slab is commonly designed with a 1:1 aspect ratio (width/thickness of slab) which, as first modeled by Kane *et al.*[6], also has a large length to thickness aspect ratio. This design minimizes the transverse amplified spontaneous emission (ASE) and maximizes the gain for the signal along the length of the slab; more importantly, it can lower depolarization and thermal focusing compared with the laser rod[6,7].

An appropriate pump configuration is important in obtaining high efficiency. To date, there are two pump structures (Fig. 1) used for spaced-based zigzag slab amplifiers. Figure. 1(b) shows the traditional SPA, while Fig. 1(c) shows the new concept laser structure called BPA; in the latter, the pump diodes have gaps between them and are placed at the bounce points of the propagating beam in the TIR slab.

In general, the energy extracted from a laser medium is calculated by solving the rate equations. The F-N equation derived from these rate equations easily provides the

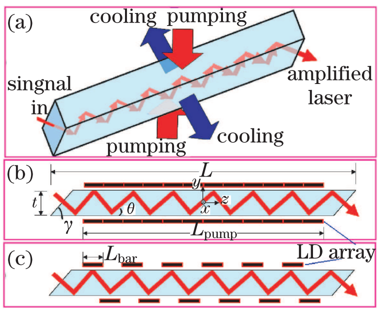

Fig. 1. (a) Diagram of zigzag slab laser amplifier; (b) side-pumped slab amplifier design. In this design, the origin of the coordinate system $(x, y, z) = (0, 0, 0)$ is at the geometric center of the slab, x is parallel to the width, y to the thickness, and z to the length of the slab; (c) diagram of the bounce-pumped slab amplifier design. LD: laser diode.

amplified output energy for a straight-through optical path in a laser medium. Eggleston *et al.* extended the F-N equation[8] to zigzag slabs possessing regions with and without standing waves (Fig. 2). The stored energy, which is unextracted by the laser beam, plays no role in the kinetics of amplification. Therefore, considering only the extraction from atoms that are in the beam path, and using trigonometric principles (Fig. 2(c)) that deduce the factor of $f(2-f)$, the output pulse energy of the single-pass zigzag slab amplifier can be described as[8]

$$E_{\text{out}} = F_{\text{sat}} A_{\text{act}} \cos\theta \times f(2-f) \times \ln\Big\{1 + [\exp(E_{\text{in}}/(A_{\text{act}} F_{\text{sat}} \cos\theta f(2-f))) - 1] \exp[E_{\text{st}}/(A_s F_{\text{sat}} \cos\theta)]\Big\}, \quad (1)$$

where E_{out} is the output energy, F_{sat} is the saturation fluence, E_{in} is the input energy, A_{act} is the cross-sectional area of the propagating laser beam, A_{s} is the cross-sectional area of the slab, $f = l_{\text{s}}/l_{\text{b}}$ is the fill factor (l_{s} is the overlap region length and l_{b} is the bounce period), and θ is the complementary angle to the angle of incidence at the TIR surface. The total stored energy E_{st} in the slab is expressed as

$$E_{\text{st}} = hv_{\text{e}} \iiint_{V_0} n \text{d}V, \quad (2)$$

where hv_{e} is the photon energy, n is the population inversion density, and V_0 is the pump region in the laser medium.

The derivation of Eq. (1) implies a uniform stored energy density in the slab, which means n is a constant in the pump region of the slab; thus, the factor $f(2-f)$ is obtained easily by trigonometric principles[8]. Unfortunately, it is impossible to obtain uniform stored energy density in the slab because of the nonuniformity of the absorbed pump energy in practical laser systems. In order to predict accurately the output performances of slab laser amplifiers, especially for BPA which definitely

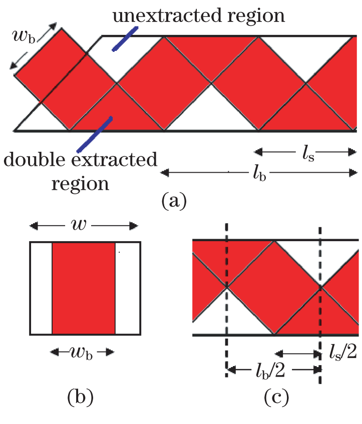

Fig. 2. (a) Geometry of the partially filled slab for a single-pass slab amplifier. The distance between the two parallel lines indicating the beam path represents the diameter of the laser beam w_{b}. (b) Active cross section of the slab has a width of w_{b} and a thickness of t, while the cross-section area of the slab is $A_{\text{s}} = wt$. (c) The simplest position of plane for deriving the relation between pulse energy and photon flux.

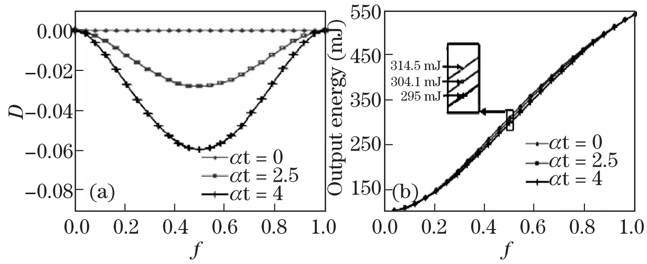

Fig. 3. (a) Difference factor D as a function of f for $\alpha t = 0$,2.5, and 4; (b) predicated extracted energy for a single pass of the laser amplifier by the original and the modified F-N equation, respectively, as a function of f. $E_{\text{in}} = 100$ mJ, $F_{\text{sat}} = 210$ mJ/cm^2, $L_{\text{pump}} = 120$ mm, $E_{\text{st}} = 720$ mJ, and $\theta = 45°$.

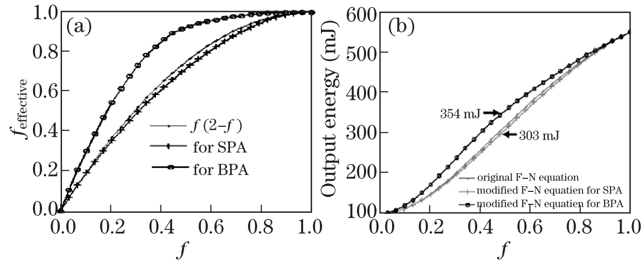

Fig. 4. (a) Effective fill factor as a function of f; (b) predicted output energy of the zigzag slab laser amplifier as a function of f, $E_{\text{in}} = 100$ mJ, $F_{\text{sat}} = 210$ mJ/cm^2, $L_{\text{pump}} = 120$ mm, $E_{\text{st}} = 720$ mJ, $\theta = 45°$, and $L_{\text{bar}} = 10$ mm.

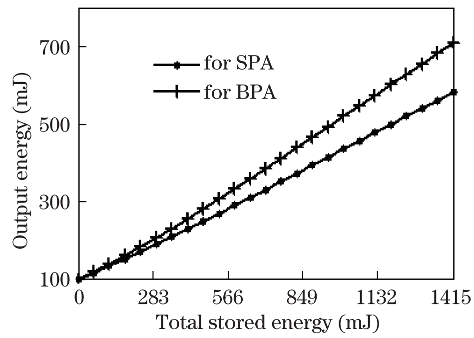

Fig. 5. Predicted output energy as a function of the total stored energy in the slab with $E_{\text{in}} = 100$ mJ, $F_{\text{sat}} = 210$ mJ/cm^2, $L_{\text{pump}} = 120$ mm, $\alpha t = 3.1$, $f = 0.5$, $\theta = 45°$, and $L_{\text{bar}} = 10$ mm.

leads to low uniform stored energy density in the slab, Eq. (1) should be modified.

For an amplifier, the stored energy in the region of the slab, where the propagating laser beam passes through, plays a role in the kinetics of amplification. For the reason, the available stored energy in the active cross-section of the slab (Fig. 2(b)) is defined as[7]

$$E_{\text{avail}} = E_{\text{st}} A_{\text{act}}/A_{\text{s}} = hv_{\text{e}} \iiint_{V_0} n(x,y,z,t) \text{d}x\text{d}y\text{d}z A_{\text{act}}/A_{\text{s}}. \quad (3)$$

The maximum extractable energy $E_{\text{extracted}}$, for a zigzag optical path is given by

$$E_{\text{extracted}} = E_{\text{avail}} f_{\text{effective}}, \quad (4)$$

where $f_{\text{effective}}$, which is defined as the effective fill factor, is written as

$$f_{\rm effective} = E_{\rm extracted}/E_{\rm avail} = \iiint_{V_{\rm beam}} n(x,y,z,t){\rm d}x{\rm d}y{\rm d}z \Big/ \iiint_{V_0} n(x,y,z,t){\rm d}x{\rm d}y{\rm d}z, \tag{5}$$

where $V_{\rm beam}$ is the region of the slab which the propagating laser beam passes through.

Generally, we have $n(x,y,z,t) \propto \rho_{\rm absorb}(x,y,z,t)$, where $\rho_{\rm absorb}(x,y,z,t)$ is the absorbed pump energy density in the slab. By substituting it into Eq. (5), we obtain

$$f_{\rm effective} = \iiint_{V_{\rm beam}} \rho_{\rm absorb}(x,y,z,t){\rm d}x{\rm d}y{\rm d}z \Big/ \iiint_{V_0} \rho_{\rm absorb}(x,y,z,t){\rm d}x{\rm d}y{\rm d}z, \tag{6}$$

and the modified equation is presented as

$$E_{\rm out} = F_{\rm sat}A_{\rm active}\cos\theta f_{\rm effective} \times \ln\left\{1 + \left[\exp\left(\frac{E_{\rm in}}{A_{\rm active}F_{\rm sat}\cos\theta f_{\rm effective}}\right) - 1\right]\exp\left[\frac{E_{\rm st}}{A_{\rm s}F_{\rm sat}\cos\theta}\right]\right\}. \tag{7}$$

If the ideal case is present where the absorbed pump energy density is uniform in the slab medium, Eq. (6) then becomes:

$$f_{\rm effective} = V_{\rm beam}/V_0. \tag{8}$$

Using simple trigonometric principles in accordance with the process used by Eggleston *et al.*, $f_{\rm effective}$ is reduced to $f(2-f)$, and Eq. (7) becomes equivalent to Eq. (1).

In using Eq. (7) to evaluate the performances of SPA and BPA, we consider a 130×10×10 (mm) Nd:YAG slab with the apex angle of 45° on both ends as the space-based amplifier. The extracting laser beam is nearly normal to the tip face shown in Fig. 1 with the coordinate system as indicated.

For SPA, more pump light is absorbed near the pump light entrance surfaces of the slab than near the center. This nonuniform pump light absorption leads to nonuniformity of stored energy along the thickness of the slab.

For simplicity, we consider the pump light to be a uniform plane wave. As a function of the position in the thickness of the slab, the absorbed pump energy density is given by[9]

$$\rho_{\rm absorb} = \frac{\alpha E_{\rm pump}}{wl}\exp(-\alpha t/2)\cosh(\alpha y), \tag{9}$$

where $E_{\rm pump}$ is the total pump energy incident on the slab, $\alpha = \sigma_{\rm eff} n_{\rm d}$ is the pump absorption coefficient, $n_{\rm d}$ is the dopant concentration, $\sigma_{\rm eff}$ is the effective absorption cross section, w and l are the width and length of the slab, respectively.

Substituting Eq. (9) into Eq. (6), we obtain

$$f_{\rm effective} = \frac{E_{\rm avail}^{\rm extracted}}{E_{\rm avail}} \tag{10}$$

$$= f - \frac{[1-\exp(\alpha t f)]\cdot\{\exp[\alpha t(1-f)]-1\}}{[\exp(\alpha t)-1]\cdot\alpha t}, \tag{11}$$

and define the difference factor as

$$D = f_{\rm m} - f(2-f) \tag{12}$$

$$= f^2 - f - \frac{[1-\exp(\alpha t f)]\cdot\{\exp(\alpha t(1-f))-1\}}{[\exp(\alpha t)-1]\cdot\alpha t}. \tag{13}$$

Figure 3(a) represents D as a function of f for $\alpha t = 0$, 2.5, and 4, illustrating that the shape of D depends only on f, while the magnitude depends on αt. D approaches 0 as f approaches either 0 or 1, and there is a valley of D in the regime of intermediate fill ($f = 0.5$), where D decreases as αt increases. According to Eq. (7), this is an indication that the extracted energies of SPA decreases, as shown in Fig. 3(b).

Similarly, we obtain $f_{\rm effective}$ for BPA through

$$f_{\rm effective} = \begin{cases} \dfrac{2\left[\alpha t f - 2\exp\left(-\dfrac{\alpha t}{2}\right)\sinh(\alpha t f) - \exp(\alpha t f)\right]}{\alpha t\{\exp[1-\exp(\alpha t)]\}}, & 0 \le f \le 0.5 \\ \dfrac{\alpha t - \alpha t(1-2f)\exp(-\alpha t) - 2\exp(-\alpha t f) + 2\exp(-\alpha t)}{\alpha t\{\exp[1-\exp(\alpha t)]\}}, & 0.5 \le f \le 1 \end{cases}. \tag{14}$$

Figure 4(a) shows the plot of $f_{\rm effective}$ for SPA as a function of f derived through a comparison with $f_{\rm effective}$ for BPA. In addition, $f_{\rm effective}$ for BPA is larger than both $f_{\rm effective}$ for SPA and $f(2-f)$, except in the case where f=0 or 1, which will lead to larger value errors in the predictions with Eqs. (7) and (1). As shown in Fig. 4(b), the modification of Eq. (1) is necessary, and Eq. (7) becomes more applicable to predict the output performances of realistic laser systems with different pump configurations.

With Eq. (7), we can predict the output performances of BPA and SPA. In Fig. 5, the predicted output energy is proportional to the total stored energy in the slab for both BPA and SPA. The maximum output energies of 703 and 565 mJ for 1.4-J total stored energy in the slab with corresponding extracted efficiency ratios (or the ratios of extracted energy to total stored energy) of 43.1% and 33.2% are obtained for BPA and SPA, respectively. Obviously, we can obtain these with the same stored energy in the slab, where higher output energy and efficiency for BPA can be obtained compared with SPA.

In conclusion, we have investigated an expanded equation derived from the F-N equation to accurately predict the output performances of zigzag slab laser amplifiers. In this proposed method, the realistic absorbed pump energy density, which induces the nonuniformity of stored energy density in the laser medium, is introduced. Using the equation, we compare the amplification performances of BPA and SPA, and find that BPA is more suitable for space-based lasers because of its higher efficiency.

References

1. F. E. Hovis, J. Edelman, T. Schum, J. Rudd, and K. Andes, Proc. SPIE **6871,** 68710E (2008).
2. J. Luttmanna, K. Nicklausa, V. Morascha, S. Fua, M. Höfera, M. Trauba, H. D. Hoffmanna, R. Treichelb, C. Wührerc, and P. Zellerc, Proc. SPIE **6871,** 687109 (2008).
3. A. W. Yu, S. X. Li, G. B. Shaw, A. Seas, M. A. Stephen, E. Troupaki, A. Vasilyev, L. Ramos-Izquierdo, A. Lukemier, W. Mamakos, A. Melak, J. Guzek, and A. Rosanova, Proc. SPIE **7193,** 719305 (2009).
4. F. E. Hovis, N. Martin, and R. Burnham, Proc. SPIE **5798,** 101 (2005).
5. L. M. Frantz and J. S. Nodvik, J. Appl. Phys. **34,** 2346 (1963).
6. T. J. Kane, J. M. Eggleston, and R. L. Byer, IEEE J. Quantum Electron. **1,** 1195 (1985).
7. A. K. Sridharan, S. Saraf, and R. L. Byer, Appl. Opt. **46,** 7552 (2007).
8. J. M. Eggleston, L. M. Frantz, and H. Injeyan, IEEE J. Quantum Electron. **25,** 1855 (1989).
9. T. Rutherford, W. M. Tulloch, E. K. Gustafson, and R. L. Byer, IEEE J. Quantum Electron. **36,** 205 (2000).