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# Output characteristic of a gain guided, index anti-guided fiber amplifier under the condition of gain saturation

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**Abstract:** We numerically investigate the output characteristic of a gain guided, index anti-guided fiber amplifier with saturated gain. The result shows that there is an output power limitation depending on the inherent leakage loss of the fiber amplifier. But we find that the amplifier with the multimode condition can operate to get a high power output with keeping a good beam shape like a Gaussian beam.

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## 1. Introduction

A fiber laser guided by gain and having a negative index step from cladding to core was suggested by A. E. Siegman [1–3], and is now called a gain guided, index anti-guided (GG + IAG) optical fiber laser. Siegman suggested that GG + IAG fiber lasers could operate with very large single mode area and as a consequence emit high power with good beam quality. This was deduced by analyzing the spatial mode conditions of a GG + IAG fiber under the conditions of infinity fiber length, no cladding–air boundary and uniform gain distribution. Y. Chen *et al.* [4] reported that a GG + IAG fiber laser experimentally could operate in a single large area mode. But GG + IAG fibers unfortunately have an inherent leakage loss due to a negative index step from cladding to core. In general, losses inside the laser prevent the attainment of high output efficiency. If the losses become to couple to saturated gain, the power of a laser could be limited [5]. Thus it is important to understand the characteristics of the losses and the saturated gain inside the fiber to design an efficient laser. The loss of an index anti-guided (IAG) optical fiber has been well studied [6]. E. Marcetili *et al.* had studied the loss characteristic of a hollow fiber and derived the analytic formula for the losses of fiber

modes. The formula can give all the loss information of a GG + IAG fiber because the structure of an IAG optical fiber is the same as one of a hollow fiber with the hollow core filled with a lower index medium. But the effect of the saturated gain of a GG + IAG fiber laser on the output characteristic under the influence of the inherent leakage loss has not been studied to the best of our knowledge.

In this paper, we numerically investigate the effect of the saturated gain and leakage loss of a GG + IAG fiber on the amplifier output. This is performed by analyzing the output characteristic of a Gaussian beam amplified through the GG + IAG fiber amplifier with the saturated gain.

## 2. Numerical modeling

To model a GG + IAG fiber, we use the equation of the slowly varying envelope of the electric field ( $E$ ) of frequency ( $\omega$ ) satisfying the following equation in the paraxial approximation [7].

$$\frac{\partial E}{\partial z} = -j \frac{1}{2k} \nabla_{\perp}^2 E + j \frac{2\pi\omega}{cn} P_{NL} \quad (1)$$

where the wave number is given by  $k = n\omega/c$ , with  $n$  the linear refractive index of the medium,  $\nabla_{\perp}^2$  is the transverse Laplacian and  $P_{NL}$  is the nonlinear polarization which come from the laser gain [8]. To solve Eq. (1), we use a scalar beam propagation method.

We set most of the physical constants for modeling the GG + IAG fiber to the same as those used in Y. Chen *et al.*'s [4]. The fiber length is 12 cm, the index of cladding is 1.5734 and the index difference ( $\Delta n$ ) of cladding to the core is  $-0.0045$ . A Gaussian beam is utilized as an input to propagate inside fiber and its wave length in vacuum ( $\lambda_0$ ) is 1052 nm. To investigate a pure GG + IAG fiber, we assume that the cladding-air boundary is surrounded by an absorber in order to remove the interference effect of a reflected beam from a cladding-air boundary and a beam guided inside a core [9].

To understand the propagation characteristic of a Gaussian beam inside a GG + IAG fiber, we decompose the Gaussian input field in terms of the fiber modes of  $EH_{1m}$  by a Bessel-Fourier series [10].

$$E_{input}(r) = \sum_{m=1}^{\infty} A_{1m} EH_{1m}(r). \quad (2)$$

The expansion coefficient  $A_{1m}$  gives the information of the coupling ratio of each waveguide mode to the Gaussian mode. To get the coefficient  $A_{1m}$ , we assume that the beam waist of the Gaussian beam is at the front end of a fiber. Figure 1 shows the mode amplitudes of the main excited modes as a function of the ratio of the Gaussian beam waist ( $w$ ) to the fiber core radius ( $a$ ).

When each excited mode propagates through an IAG fiber, the modes strike the wall of the core which results to an outgoing refracted wavelet from the core. The outgoing wavelet becomes to induce the inherent loss of an IAG fiber which depends on a fiber mode. The attenuation coefficients ( $2\alpha_{1m}$ ) of the modes in an IAG fiber are given as in Ref. 6,

$$2\alpha_{1m} = \left( \frac{u_{1m}}{2\pi n} \right)^2 \frac{\lambda_0^2}{a^3} \frac{v^2 + 1}{(v^2 - 1)^{1/2}}$$

$$\approx \left( \frac{u_{1m}}{\pi} \right)^2 \frac{\lambda_0^2}{a^3} \frac{1}{(2n)^{3/2} \sqrt{-\Delta n}}, \quad (3)$$

where  $v$  is the ratio of the cladding index to the core index and  $u_{1m}$  is the  $m$ th root of the Bessel's function of the zeroth order,  $J_0(u_{1m}) = 0$ . The second equation of Eq. (3) is an

approximated form when the index difference of the cladding and core index is very small. The approximated form is the same as the threshold gain to guide a fiber mode inside a GG + IAG fiber [3]. That means that the amplification through a GG + IAG fiber can be achieved after overcoming the inherent loss induced by the refraction at the boundary of the core and cladding of a GG + IAG fiber.

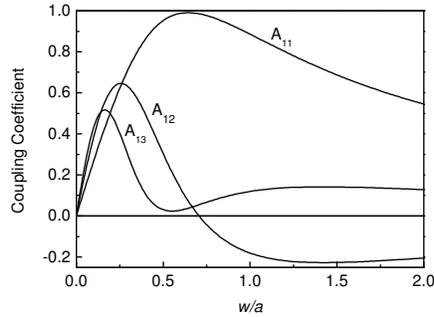


Fig. 1. Expansion coefficients of a Gaussian beam for the  $\text{EH}_{1m}$  as a function of  $w/a$ .

To reduce the coupling of adjacent modes when the lowest mode ( $\text{EH}_{11}$ ) propagates through an IAG fiber, we choose the input beam size at which the most adjacent mode ( $\text{EH}_{12}$ ) disappears. The coefficient  $A_{12}$  of Eq. (2) is zero at  $w/a = 0.706$  as shown in Fig. 1. Hence the input beam diameter of  $70.6 \mu\text{m}$  should be chosen to reduce the intensity oscillation inside the core by the coupling of  $\text{EH}_{11}$  and  $\text{EH}_{12}$  mode when the beam propagates through the fiber with the core size of  $100 \mu\text{m}$ . Figure 2 shows the intensity distribution on the core axis along a fiber axis ( $z$ ).

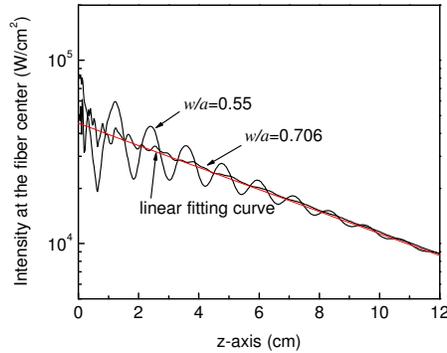


Fig. 2. Intensity distribution on the fiber core axis for the case of  $55\text{-}\mu\text{m}$  and  $70.6\text{-}\mu\text{m}$  input beam size.

The graph with a logarithmic scale shows that the curve linearly decays outside of the transient regime. That means that the intensity exponentially decreases by a leakage loss when a beam propagates through the fiber. After linear fitting of this data, we calculate a loss coefficient of  $0.1382/\text{cm}$ . The calculated loss coefficient is almost the same as the value,  $0.1387/\text{cm}$ , obtained from Eq. (3). The input beam with  $70.6\text{-}\mu\text{m}$  diameter monotonically decays without a strong oscillation because  $\text{EH}_{12}$  mode is removed, while the beam with  $55\text{-}\mu\text{m}$  diameter decays with an oscillation. The  $55\text{-}\mu\text{m}$  beam size corresponds to the size for  $w/a = 0.55$  at which the expansion coefficient ( $A_{13}$ ) for  $\text{EH}_{13}$  has a minimum value. Hence the oscillation for  $55\text{-}\mu\text{m}$  beam comes from only the coupling of  $\text{EH}_{11}$  and  $\text{EH}_{12}$  mode. The period

of the calculated oscillation is 1.2 cm. The same results can also be obtained from the analytic function for the phase constant [6]. The comparison of the numerical result to the one obtained from the analytic function shows that our numerical model is correct.

### 3. Results and discussion

To investigate the effect of gain saturation on a GG + IAG fiber amplifier, we use the following nonlinear polarization for a homogeneous gain medium [8].

$$P_{NL} = j \frac{1}{4\pi k} \frac{g_0 E}{1 + I / I_{sat}}, \quad (4)$$

where  $g_0$  is a small signal gain coefficient,  $I$  is the intensity inside a fiber core and  $I_{sat}$  is the saturation intensity of a laser gain medium. The intensity ( $I_{sat}$ ) for an Nd doped glass is in the range of  $1.4$  to  $1.9 \times 10^4$  W/cm<sup>2</sup> [11]. We set the value of  $I_{sat}$  to  $1.4 \times 10^4$  W/cm<sup>2</sup>. We use the fiber parameters used in Fig. 1 to get the intensity distribution along the core axis, and use the input beam with 70.6- $\mu$ m diameter to reduce the coupling effect between EH<sub>11</sub> and EH<sub>12</sub> modes. We set the small signal gain coefficient of an amplifier to be same as the inherent leakage loss (0.138/cm) of the given fiber for EH<sub>11</sub> mode. The results show that the threshold gain to overcome the inherent loss depends on the incident beam power as shown in Fig. 3.

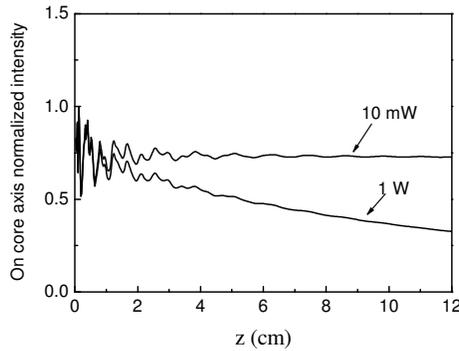


Fig. 3. Normalized intensity distribution on the core axis of the fiber with  $g_0 = 0.138/\text{cm}$  at the input power of 10 mW and 1 W.

The Fig. 3 shows that the intensity of the beam launched with the high input power decreases as the beam propagates through a GG + IAG fiber amplifier. That means that the amplifier to be operated in a high power needs the gain much larger than the EH<sub>11</sub> threshold to overcome the leakage loss. It can be understood as the gain reduction by the gain saturation effect described in Eq. (4). In order to investigate a gain saturation effect, we use a long fiber with the same core size used in Fig. 2. Figure 4 shows that to get the gain of over 1, a small signal coefficient should be much larger than the gain threshold of EH<sub>11</sub> mode. And the curves of Fig. 4 show that the output intensity has the saturated value which depends on a small signal gain coefficient. After the intensity saturation, the beam propagates through the fiber axis without changing the beam shape and with no amplification as shown in Fig. 5. The numerical result of Fig. 5 show that the saturated output beam profile is almost like a Gaussian beam shape. The Gaussian fitted curves for the output profiles of a GG + IAG fiber are shown in Fig. 6. All the calculated beam diameters of fitting curves for several small signal gain coefficients have same values of 75.4  $\mu$ m.

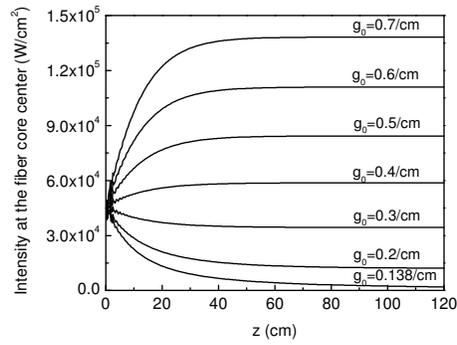


Fig. 4. Intensity distribution on the fiber core axis for the incident beam of 1-W power.

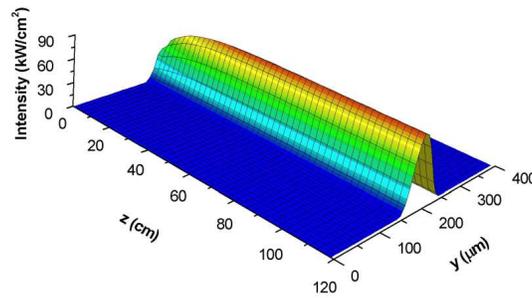


Fig. 5. Amplified beam profile along the fiber axis with  $g_0 = 0.5/cm$  for the incident beam of 1-W power.

We numerically find that the output profile is almost like a Gaussian beam as shown in Fig. 6 under the conditions of our numerical modeling. The profile is almost not changed when a small signal gain coefficient increases to  $0.9/cm$  which is much larger than  $0.351/cm$  of the gain threshold for  $LP_{11}$  mode [3]. That means that the output of the fiber amplifier with the gain of the multimode gain threshold can have a good spatial profile.

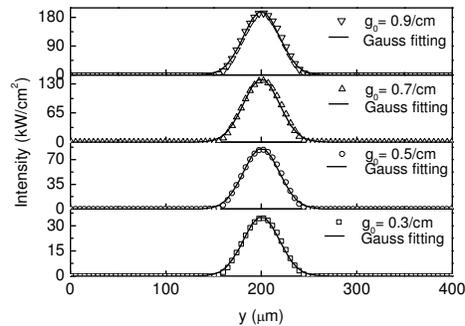


Fig. 6. Output beam profile at the end surface of a 120-cm long fiber for the incident beam of 1-W power.

The behavior of the propagating beam with the gain saturation as shown in Fig. 5 can be understood with the help of a simple amplification equation for a Gaussian beam [5]. In the

equation, we set the absorption coefficient to be  $\alpha_{11}$  of the lowest mode. The amplification equation is the following.

$$\frac{dP(z)}{dz} = \left( \frac{\pi w^2}{2} \right) g_0 I_{sat} \ln \left[ 1 + \frac{2P(z)}{\pi w^2 I_{sat}} \right] - \left( \frac{u_{11}}{\pi} \right)^2 \frac{\lambda_0^2}{a^3} \frac{1}{(2n)^{3/2} \sqrt{-\Delta n}} P(z), \quad (5)$$

where  $P(z)$  is the total power inside a GG + IAG fiber core. For a long fiber, the derivative of  $P(z)$  approaches to zero when  $z$  becomes to be sufficiently large. That means that there is the maximum available power ( $P_{max}$ ) existing inside the fiber core at which the gain effect balances with the loss effect of a GG + IAG fiber. We calculate the maximum output power ( $P_{max}$ ) and the effective fiber length to get 90% of  $P_{max}$  as varying the core radius with the help of Eq. (5). The results are shown in Fig. 7.

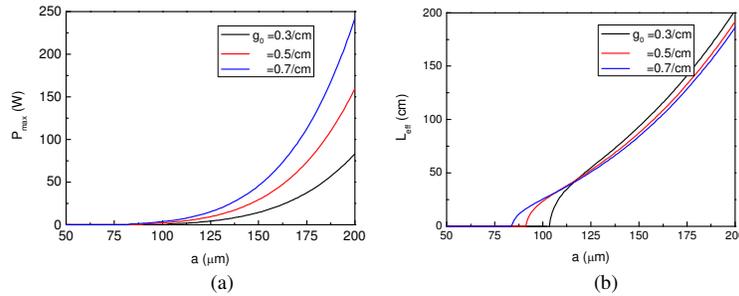


Fig. 7. (a) Maximum output power ( $P_{max}$ ) and (b) the effective fiber length to get 90% of  $P_{max}$  as varying the core radius.

Figure 7 show that the power ( $P_{max}$ ) rapidly increases as increasing the gain coefficient ( $g_0$ ) and the core radius ( $a$ ). But the effective fiber length ( $L_{eff}$ ) weakly depends on the gain coefficient while  $L_{eff}$  increases as increasing the core radius. The numerical results of Fig. 7 show that the fiber with 100  $\mu\text{m}$  could not get a high power over 100 W under the condition of our fiber model. But we can get a high power from GG + IAG fiber when the inherent leakage loss is reduced by increasing the core radius. Although the increase of the core radius means that an amplifier may operate in a multi-mode, we can presume that the output profile should be like a Gaussian shape as shown in Fig. 6.

#### 4. Conclusions

We numerically investigated the output characteristic of a GG + IAG fiber amplifier when the amplifier gain is saturated. The results showed that the gain threshold formula derived by Siegman is equal to the attenuation coefficient of IAG fiber. We found that in order to get the amplifier gain of over 1, the gain coefficient should be much larger than the threshold of the lowest mode due to gain saturation. When the gain coefficient is at near the threshold of the lowest fiber mode, we could get only a low power from a GG + IAG fiber amplifier. But we could get a high power from the amplifier when the gain coefficient set to be in the threshold of a high mode. We found that the output profile could be like a Gaussian shape regardless of the mode condition of a GG + IAG fiber under the conditions of our numerical modeling.

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