# Amplification in a Fiber Laser

Charles J. Koester and Elias Snitzer

Fiber lasers of neodymium-doped glass have been used on a pulsed basis to amplify 1.06-$\mu$ radiation. To prevent oscillation, the ends are polished at an angle such that reflected light is lost from the cavity. With the high inversion which can then be obtained, gains as large as $5 \times 10^4$ have been observed in a 1-m long fiber. The gain was measured as a function of pumping energy and as a function of time during the pumping pulse at which the amplification was determined.

## Introduction

In this experimental study the object has been to explore some of the parameters affecting gain in a fiber laser. Pulsed operation was used, and consequently one important parameter is the time during the pumping pulse at which the amplification is measured.

Laser amplification measurements have been carried out by a number of authors, using both gas and solid lasers. In ruby, Kisliuk and Boyle[1] reported power amplification of a factor of 2, and, more recently, Geusic and Scovil[2] reported gains as high as a factor of 1000. Gains in the original gas lasers were typically much lower,[3] but recently high gains have been observed at 3.39 $\mu$ in the He–Ne laser[4,5] and at 2.026 $\mu$ in the He–Xe laser.[6] In another approach, it has been shown that the use of a resonant cavity can provide high gain over narrow wavelength bands.[7]

In order to obtain both stable high gain and high bandwidth it is necessary to make the amplifier nonreciprocal, as pointed out by Geusic and Scovil.[2] They offered suggestions for reducing reflections of ruby end surfaces and for realizing a unidirectional traveling wave amplifier. Some preliminary amplification results with neodymium glass fiber lasers have been reported previously.[8]

## The Oscillation Condition in a Fiber Laser

In this section some simple expressions which are necessary for interpretation of the results are derived on a phenomenological basis. For the unpumped fiber laser let the loss per centimeter at the laser wavelength due to absorption and scattering be $\alpha$, i.e., the intensity $I$ decreases according to

$$I = I_0 e^{-\alpha x} \text{ (unpumped)}, \tag{1}$$

where $x$ is the distance along the fiber laser, $I_0$ the intensity at $x = 0$.

For the pumped laser let the gain per centimeter produced by the inverted ions be donated by $\beta$. Then the *net* gain (or loss) per centimeter is given by $\beta - \alpha$, and

$$I_p = I_0 e^{(\beta-\alpha)x} \text{ (pumped)}. \tag{2}$$

The situation is slightly complicated by the fact that in the experiments the total length $l_t$ of the fiber is somewhat greater than the length $l_p$ which is pumped. If we assume that $\beta$ is constant throughout the pumped length and that the absorption represented by $\alpha$ is not saturated at the light levels involved, then the gain is

$$G = I_p/I_0 = e^{\beta l_p - \alpha l_t}. \tag{3a}$$

Similarly, the intensity, $I_u$ received when the fiber is unpumped is given by

$$I_u/I_0 = e^{-\alpha l_t}. \tag{3b}$$

To measure gain it is, of course, necessary to compare the amplified signal with a reference. It would be difficult to measure with certainty the input signal to the fiber, i.e., the signal power which actually couples into the fiber laser. However, it is quite feasible to measure the signal which is transmitted through the fiber in its unpumped state. The ratio of signal obtained with fiber pumped [Eq. (3a)] to that obtained with the fiber unpumped [Eq. (3b)] is

$$I_p/I_u = e^{\beta l_p}. \tag{4}$$

This quantity is hereafter called the *gross* gain. It is the measured quantity in this experiment.

Let the reflectance of the fiber ends be $R$. If the net gain given by $I_p/I_0$ from Eq. (3a) is greater than $1/R$, then the gain per pass is greater than the loss per pass,

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and the fiber laser can oscillate. The threshold condition for oscillation is, therefore,

$$I_p/I_0 = e^{(\beta l_p - \alpha l_t)} = R^1. \tag{5}$$

If the laser oscillates, the inversion will be reduced, or at least prevented from increasing. Therefore, the limiting inversion is that which yields a gain coefficient $\beta$ given by Eq. (5). Thus, for a reflectance $R = 0.04$, a length of $l_p = l_t = 1$ m, and a loss coefficient $\alpha = 0.01$ cm$^{-1}$, the threshold value for $\beta$ is 0.042 cm$^{-1}$.

The reflectance, $R_1$ and $R_2$, of the two ends may be dissimilar, in which case the threshold oscillation condition becomes

$$e^{\beta l_p - \alpha l_t} = (R_1 R_2)^{-\frac{1}{2}}. \tag{6}$$

The right-hand side of Eq. (6), therefore, represents the maximum gain which can be obtained:

$$G_{\max} = (R_1 R_2)^{-\frac{1}{2}}. \tag{7}$$

For completeness, it should be noted that in the preceding discussion the gain $G$ is that obtained in a single pass. For a reciprocal amplifier with feedback, Geusic and Scovil[2] have shown that the observed gain $\bar{G}$ can be expressed as

$$\bar{G} = \frac{(1 - R)^2 G}{1 - G^2 R^2}. \tag{8}$$

In obtaining this expression it was assumed that the bandwidth of the radiation is larger than that of the cavity. This was necessary so that the gain $\bar{G}$ could be obtained by averaging over a range of wavelengths large compared to the separation between resonant modes in the cavity. This assumption is certainly justified for a fiber laser of length 1 m, in which the separation between axial modes would be

$$\Delta\lambda = \frac{\lambda^2}{2nl} = \frac{1}{3} \times 10^{-2}\ \text{Å},$$

where $\lambda = 1\ n$ is the wavelength, $n = 1.5$ is the index of refraction, and $l = 1$ m is the length of the fiber. The bandwidth of the signal light is the order of 70 Å.

## Experimental Procedure

1-m fibers were fabricated by cladding a neodymium glass core with a lower index clear glass.[9] Typical diameters were 10 $\mu$ for the core and 0.75 mm to 1.5 mm for the cladding. The assembly was wound hot into the form of a helix (Fig. 1) for convenient pumping with a flashtube. The fiber ends were brought outside the pumping enclosure to facilitate the input and output coupling.

The signal to be amplified was provided by a neodymium glass laser rod as shown in Fig. 2. The particular rod used had a very reproducible damped relaxation oscillation, a definite convenience for making measurements. It was not necessary to focus the signal laser light onto the end of the fiber. A sufficient signal was picked up with the simple coupling arrangement shown in Fig. 2. The phototube monitored the signal laser output.

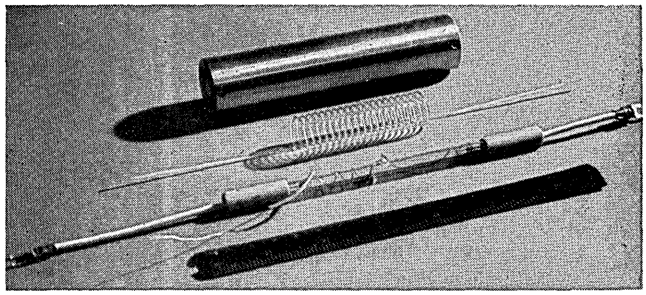

Fig. 1. Coiled fiber laser. From the top the components are: cavity, fiber laser, flashtube, and 18 cm scale

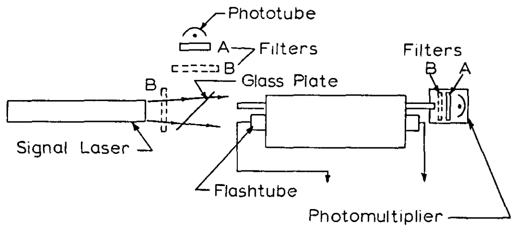


Fig. 2. Experimental setup for measuring amplification. Signal laser: 6.35-mm diam core, 9.5-mm diam cladding, 30.5-cm long. Filters, A, in front of the phototube pass only the 1.06-$\mu$ laser radiation. Filters, B, partially absorb at 1.06 to keep the signal within the linear range.

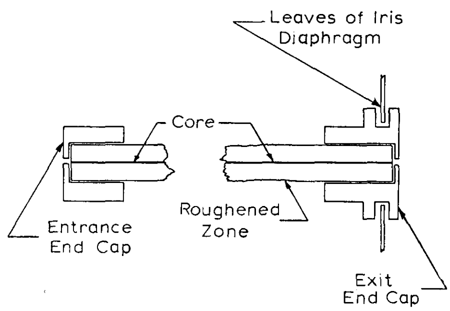


Fig. 3. Arrangement of end caps on fiber lasers. The iris diaphragm is mounted on the front of the photomultiplier housing, and together with the exit end cap it provides a light trap.

Several precautions were found to be necessary. First, with such a large cladding to core diameter ratio, it was necessary to control the input light so that it entered only the core and the area immediately surrounding the core. This was done by placing a mask with a 0.1-mm hole over the entrance end of the fiber. Placing a similar mask over the other end of the fiber further reduced the stray signal light and light from the pump, which otherwise would travel through the cladding to reach the detector. As shown in Fig. 3, it was also necessary to provide a light trap so that stray light did not reach the photomultiplier.

Second, a necessary precaution was to destroy the light guide effect in the cladding, to eliminate the last traces of stray signal and flashtube light. One way of accomplishing this was to roughen the surface of the cladding for a length of 3 or 4 cm between the pumping cavity and the detector.

Third, it was essential to keep the light level reaching the photomultiplier low enough so that the PM did not saturate. For the Dumont K1430 tube at 1200 V, saturation effects were noticed above about 0.5-mA anode current. This situation was later improved by adding appropriate capacitors to the voltage dividing resistor string.

Finally, in order to avoid saturation of the fiber laser amplifier it was necessary to keep the input signal level within limits. The saturation level was determined experimentally by noting the signal level at which the output did not reproduce the input faithfully. The input signal was kept below this value by appropriate filters.

The flashtubes for the rod and fiber were energized by separate power supplies. A continuously variable time delay could be introduced between the trigger pulses to the two flashtubes. Thus the signal laser could be made to oscillate at any desired time during the pumping cycle of the fiber laser.

Outputs from the phototube and photomultiplier were displayed and photographed on a dual-beam oscilloscope. Typical traces are shown in Fig. 4. In Fig. 4(a), the upper trace shows the amplified signal with a relaxation oscillation of approximately 500 kc/sec superposed on the spontaneous emission curve. The amplified signal was measured not from the base line, but from the spontaneous emission curve to the peaks of the high-frequency spikes. In most cases where amplification was obtained it was necessary to insert absorbing filters as shown at B in Fig. 2, in order to keep the signal within the limits listed above.

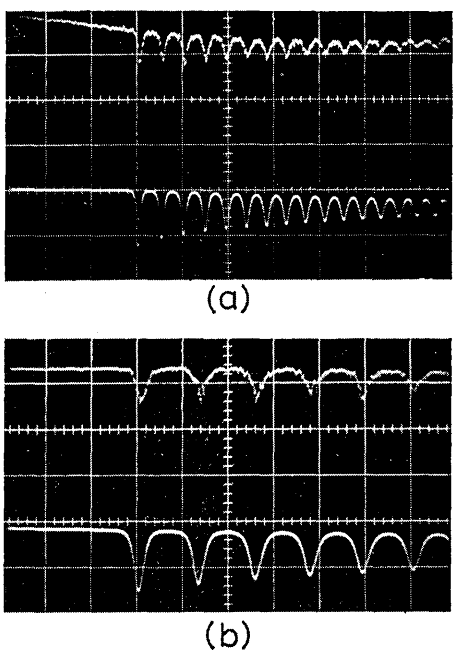


Fig. 4. Oscilloscope traces showing fiber laser amplification. Time increases to the right, and the signal is negative. Upper trace: fiber laser output as detected by photomultiplier. Lower trace: monitor of laser rod output. Fiber laser pump energy (a) 220 J; (b) 0. Sweep speed, μsec/cm: (a) 5; (b) 2. Oscilloscope vertical sensitivity, v/cm: (a) 0.02; (b) 0.005. Transmittance of filters between rod and fiber: (a) 0.023; (b) 1.0. Transmittance of filters between fiber and PM: (a) 0.00195; (b) 1.0. Calculated gross gain: 85,000. For fiber data, see Fig. 9.

## Amplification Obtained with Normal Fiber Ends

Fiber lasers were fabricated as shown in Fig. 1, with the ends polished normal to the fiber axis. Figure 5 illustrates the increase in signal output as the pumping of the fiber laser amplifier was increased.

Amplification data were then obtained as described above, and the results are shown in Fig. 6. In each case, the measurement was made at or near the time at which maximum amplification was obtained. As

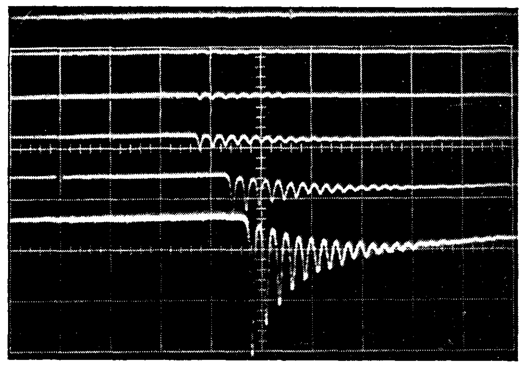

Fig. 5. Amplification at several pumping levels. Each trace represents the signal out of the fiber laser amplifier. Starting from the top, the pumping levels were 0, 5 J, 10 J, 15 J, 20 J, and 25 J. The input signal and oscilloscope sensitivity were the same in each case. For fiber data, see Fig. 6.

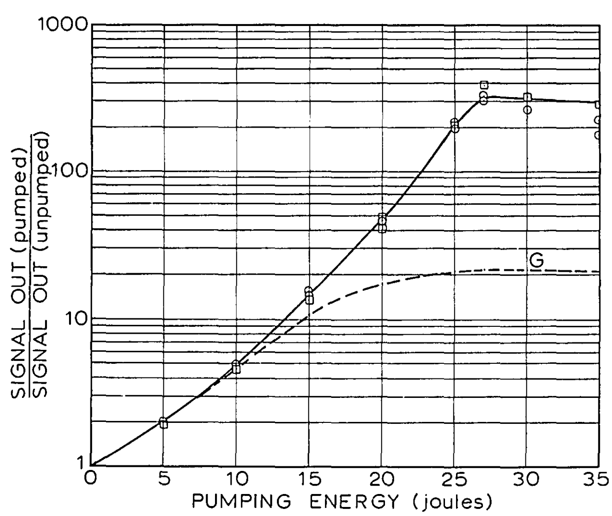


Fig. 6. Amplification as a function of pumping energy. Fiber data: 25-μ core diameter, 1.5-mm cladding diameter, core glass contained 6.3 wt% $Nd_2O_3$ in a barium crown base, core index 1.531, cladding index 1.51. Pumped length 110 cm, total length 119 cm. In the case of 30 J and 35 J pumping, amplification was measured just before the fiber oscillated. The solid curve represents the measured ratio of $I_p/I_u$. The dashed curve represents the calculated single pass gain $G$.

shown in Fig. 6, the amplification increased with pumping energy up to the level at which oscillation occurred, which in this case was 27 J into a GE FT 91/L flashtube. Greater pumping energy did not increase the amplification.

Since the fiber laser in this case was of the resonant type, the gain per pass $G$ must be calculated from the observed gain $\bar{G}$ by Eq. (8).* For this calculation it was assumed that the reflectance is the same as that at normal incidence from an infinite interface between indices 1.531 and 1.0, namely, $R = 0.044$. The results are shown as the dashed line in Fig. 6.

The principal conclusion to be drawn from Fig. 6 is that for a fiber laser (or any laser) with normal ends, the gain ($G$ or $\bar{G}$) approaches a limit as pumping is increased. This limit is set by the oscillation threshold. In order to obtain higher gains, it is necessary to reduce or eliminate entirely the feedback which produces oscillation.

## Methods of Eliminating Feedback

Several methods for reducing reflections from the fiber laser ends have been considered. Low-reflection coatings would help, but it is difficult to obtain less than about 0.1% to 1% reflectance over a range of angles of incidence such as are present at the end of a fiber. Another possibility is to contact the end of the fiber to an effectively infinite medium of the same index of refraction as the core. An immersion oil was used and was effective in raising the threshold for oscillation. However, practical difficulties were encountered in combining the immersion effect with the end cap, which was necessary to reduce stray light in amplification measurements.

A simple, effective method for essentially eliminating end reflection is shown in Fig. 7. The end face is polished at an angle $\theta$ which is large enough that reflected light is not contained in the core by total internal reflection. This constitutes the lower limit for $\theta$. In order to get light out of the end of the fiber there is an upper limit on $\theta$, namely, the angle at which the light in the core would be totally internally reflected at the end surface. The calculation of these two limits on $\theta$ is as follows.

The limiting numerical aperture of meridional rays in a core of index $n_1$, surrounded by a cladding of index $n_2$ is given by

$$\text{N.A.} = n_1 \sin\phi_{\max} = \sqrt{n_1^2 - n_2^2}.$$

If the angle $\theta$ is made equal to $\phi_{\max}$, then the steepest meridional ray is reflected directly back on itself. But all other meridional rays are reflected at angles greater than $\phi_{\max}$, and are, therefore, lost. See Fig. 8(a).

If the extreme meridional ray is not to be totally internally reflected the following inequality must hold: $n_1 \sin(\theta + \phi_{\max}) < 1$. See Fig. 8(b). Therefore, reasonable limits on $\theta$ are:

$$\cos^{-1}\frac{n_2}{n_1} < \theta < \sin^{-1}\overline{\frac{1}{n_1}} - \cos^{-1}\frac{n_2}{n_1}. \tag{9}$$

For example, with $n_1 = 1.5230$ and $n_2 = 1.5082$ the limits are $8.0° < \theta < 33°$. Fibers having these indices were polished at an angle $\theta = 10°$.

Although the beveled end eliminates reflection of meridional rays, there will still be some skew rays which can reflect from the end and remain within the N.A. of the fiber. Also, for fiber diameters comparable to the wavelength, edge effects at the core-cladding interface can give a significant reflection back into the fiber. For these reasons, the above analysis is only approximate. However, it is found experimentally that beveling the fiber end is usually effective in reducing feedback. For example, one fiber had an oscillation threshold of 40 J into an FT 91/L flashtube for $\theta = 0$ on both ends. After one end was repolished so that $\theta = 10°$, oscillation was not obtained even at 370 J, the maximum energy rating of the flashtube. In some other cases, larger bevel angles were required to eliminate oscillation.

It should be noted that use of an immersion liquid at the beveled end would allow larger bevel angles to be used before total internal reflection would occur. This would be a significant advantage for fibers with a high ratio of core index to cladding index.

## Amplification Obtained with Beveled Fiber Ends

A 1-m long fiber with 10-$\mu$ diameter laser glass core, and bevel of $\theta = 10°$ polished on one end was tested. The gross gain $e^{\beta l_p}$ is plotted in Fig. 9 as a function of time during the pumping pulse. The scatter of the experimental points is due in part to slight variations in

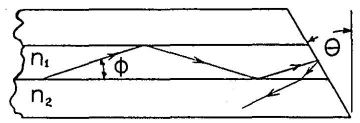


Fig. 7. Method for eliminating end reflection.

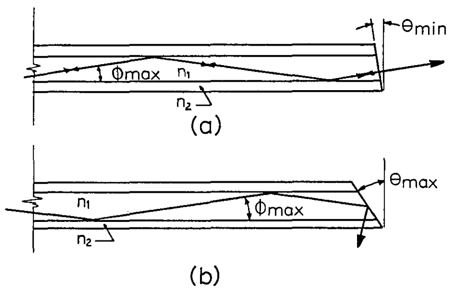


Fig. 8. Limits on bevel angle. In (a) the extreme meridional ray is reflected back on itself. All other meridional rays are, therefore, reflected at angles such that they do not undergo total internal reflection at the core-cladding interface. In (b) the extreme meridional ray is totally internally reflected at the end surface. If the angle $\theta$ is made larger than this value, more of the useful rays will be totally reflected and thereby lost for purposes of amplification.

* See the Appendix for a further discussion of this point.

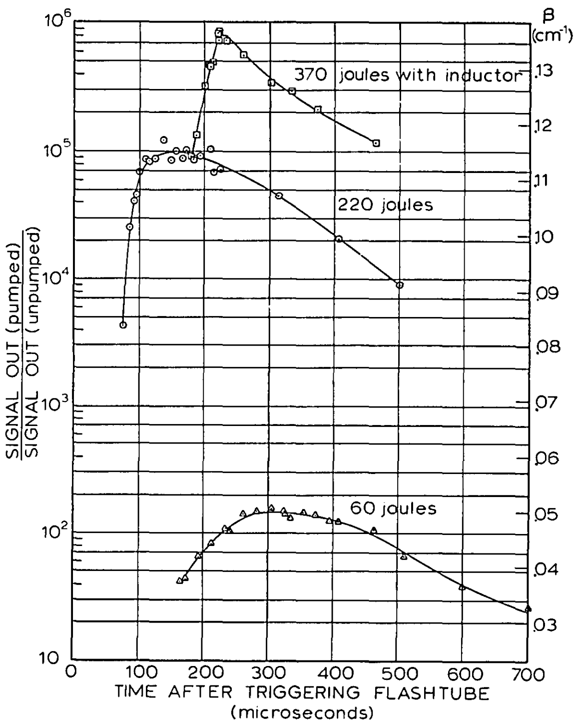


Fig. 9. Gross amplification, $e^{\beta l_p}$, in a fiber laser. Length 1 m, core diameter 10 $\mu$, 2.5% $Nd^{3+}$ in a barium crown glass. Bevel angle, $\theta = 10°$, on one end. Pump power was supplied by a 7.6-cm straight flashtube (GE FT 91/L). For pumping at 370 J it was necessary to use an inductance in series with the power supply. This accounts for the fact that the peak amplification occurs at a later time than for 220-J pump energy.

pumping energy to the fiber laser. Another source of error is the time jitter of the flashtube discharge relative to the trigger pulse.

The gain per centimeter $\beta$ is given along the right side of Fig. 9. It should be restated at this point that the net gain is to be calculated using Eq. (3a), where the loss per centimeter, $\alpha$, is also taken into account. Recently developed glasses have loss coefficients of 0.001 $cm^{-1}$ which give a value of 0.878 for $e^{-\alpha l_t}$ with $l_t = 124$ cm. The glass used as core material in this study was one of the first laser glasses developed and had the relatively high loss coefficient of $\alpha = 0.022$ $cm^{-1}$. Therefore, assuming that the loss in a fiber is the same as that in bulk glass, for a length of $l_t = 124$ cm the value of $e^{-\alpha l_t}$ is $^1/_{15}$. The maximum gross gain observed was $8 \times 10^5$. This yields a net gain of about $5.3 \times 10^4$.

As shown in Fig. 4(a), the noise associated with the fiber laser is principally a slowly varying light level consisting of radiation from spontaneous emission. Therefore, in some applications, such as communications and ranging, the bulk of the noise could be filtered out electrically after the signal has been detected.

## Conclusions

Substantial gain has been observed in a 1-m long fiber laser. As expected, the gain is a strong function of the pump power and of the time during the pulse at which the gain is measured. Oscillation of the amplifier has been prevented by beveling one end of the fiber laser, thereby effectively eliminating feedback and allowing a higher inversion to be obtained.

Fiber laser fabrication techniques were developed by W. P. Bazinet, Jr., and C. Yates. Design of test equipment and testing of fiber lasers was done by C. W. Ask. Valuable assistance with electronic equipment was provided by R. Lavallee and A. Battista.

## Appendix

Strictly speaking, we do not measure $\bar{G}$. The measured gross gain $I_p/I_u$ is related to $\bar{G}$ as follows:

$$\frac{I_p}{I_u} = \frac{\bar{G}}{e^{-\alpha l_t}}. \tag{A1}$$

Therefore, in principle, it is necessary to know the loss coefficient $\alpha$ before $\bar{G}$ and $G$ can be calculated. For the fiber used for Fig. 5, the measured loss coefficient for bulk glass at 1.06 $\mu$ was 0 ($\pm 0.0025$) $cm^{-1}$. Taking the two extreme values for $\alpha$, the calculated values for $G$ were:

| $\alpha$ | $G$ (27 J pumping) |
|---|---|
| 0 | 22.0 |
| 0.0025 $cm^{-1}$ | 21.8. |

It is fortunate that the calculated value of $G$ is insensitive to the loss coefficient $\alpha$. For the data shown in Fig. 6, the nominal value $\alpha = 0.001$ $cm^{-1}$ was used.

In calculating losses the length $l$ used was the axial length of the fiber. The justification is that even the highest angle meridional ray in a fiber of N.A. = 0.25 such as was used in these studies travels only about 1.5% farther than an axial ray.

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