Principles of Increasing the Output Power of a Fiber Laser

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Abstract— **In the paper we present research on how to increase the output power of a fiber laser. A fiber laser is a laser in which the active gain medium or the laser medium is an optical fiber usually doped with rare-earth elements such as erbium, ytterbium, and neodymium. The paper discusses the history of fiber lasers and the advantages fiber lasers present over bulk lasers. Theory on layout of a fiber laser, how a fiber laser operates and increasing the output power is covered in the paper. The steps followed to increase the output power is discussed, including the experimental results obtained. The focus of the paper is on increasing the output power of a fiber laser by changing and optimizing the pump source, length of amplifier and output coupling ratio of the fiber laser.**

Index terms - Erbium doped fiber laser

I. Introduction

Research on optical fiber-based lasers began after the famous proposal of the optical maser by Schawlow and Townes [1] in 1958 and the first demonstration of the laser effect by Maiman [2] in 1960. Snitzer proposed, in January 1961 [3], to use an optical fiber as the gain medium and resonant cavity, which he demonstrated experimentally later that year using a neodymium-doped barium crown glass fiber [4].

The glasses made at that time had large intrinsic losses (about 4 dB/m). The first silica-based fiber lasers were realised by Stone et al [5] [6] in the early 1970s. These fiber lasers showed good promise for fiber-optic telecommunications applications [7].

A breakthrough in the optical fiber fabrication process allowed the incorporation of rare-earth ions in the core, leading to the fabrication of the first singlemode fiber lasers [8].

The singlemode fiber lasers, in a linear or ring cavity, emitted a few milliwatts of output power around 1.08 - 1.09 μm. These fiber lasers opened the doors to using other rare-earth-doped ions for fiber lasers and amplifiers. The erbium ion attracted most of the interest for fiber-optic telecommunications, due to the radiative transition around 1.55 μm corresponding to the lowest loss transmission window in silica fiber. Silica fiber is the standard fiber used for telecommunicational applications. The erbium ion in silica can be made into a very potent gain medium once put in fiber form. The guided-wave approach has many advantages over a bulk gain medium such as [9]:

- High pump intensity: Since glass fiber cores can be made only a few microns in diameter, the small mode field diameter of the waveguided pump light yields a much higher pump intensity in a fiber laser than in a bulk device, and therefore a reduced lasing threshold;
- Laser emission and pump light waveguiding: The excellent mode overlap between the laser emission and pump light and the guaranteed parallelism between the two light beams allows efficient laser operation;
- Independence of pump spot size and gain medium length: This added degree of freedom allows the doping density to be kept sufficiently low to avoid unwanted ionion interactions like cooperative up-conversion. Having the possibility to use an arbitrarily long gain medium allows for weak pump absorption lines to be used to excite the lasing transition. This can be of practical importance if that weak pump band were to coincide with the wavelength of commercially available diode lasers;
- Compact gain medium: In fiber form, the gain medium can be arbitrarily long, yet compact. High quality silica fiber can be coiled to small bend radii (about 10 mm) and can be packaged in many different ways;
- Heat dissipation: The small diameter of the fiber allows for good heat dissipation, thus greatly reducing the occurrence of heat-related problems like thermal lensing, thermal gradient-induced stresses and reduced fluorescence at high temperature;
- Beam quality: A single mode optical fiber will provide a diffraction limited beam up to very high output powers; and
- Robustness: An all-fiber laser cavity is much more robust to mechanical perturbations than a free-space laser; once every component is spliced, there is no need for further optical alignment.

In the telecommunication sector sending information over a long distance is difficult, because of the losses occuring inside the fiber. One solution is to use a fiber laser as an optical source and increase the output power of the fiber laser, increasing the strength of the signal and leading to more information being sent. The fiber laser is also used as a source for optical fiber sensors. Certain fiber sensors, such as Raman fiber sensors, need higher pump energy; the higher pump energy from the fiber laser can increase the sensitifity of the Raman sensor [10] [11].

The aim of the project is to increase the output power of a fiber laser; using standard telecommunicational erbium doped fiber and changing the parameters of the fiber laser, such as the power of the pump source, the length of the fiber and the output coupling ratio and also scaling the output power of the fiber laser by combining the fiber laser with a erbium doped pre-amplifier.

The aim of the paper is to discuss the increase in the output power of a fiber laser, using standard telecommunicational erbium doped fiber, by changing the parameters of the fiber laser, such as the power of the pump source, the length of the fiber and the output coupling ratio. The paper includes the experimental results achieved from the fiber laser setup.

II. THEORY

To understand how to increase the output power of a fiber laser, it is necessary to understand what a fiber laser consists of and how a fiber laser operates. A fiber laser, as illustrated by Figure 1, consists of the following components:

- The pump source;
- The amplifier; and
- The cavity (formed by two mirrors, as shown in Fig 1.)

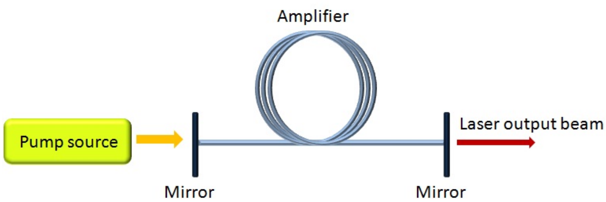

Fig. 1. Illustration of a basic fiber laser

The pump source pumps light into the cavity. The fiber laser cavity is constructed by mirrors on the fiber ends. The mirrors, which are shown in Figure 1 reflect energy back into the amplifier, which assist in the operation of the fiber laser. The amplifier is an optical fiber consisting of a core surrounded by a cladding layer, the core can guide energy by total internal reflection. Both the pump and laser radiation are guided in the erbium fiber. This complete integration of the laser process leads to the inherent compactness and long-term stability of fiber lasers, because no components are necessary in a long free-space cavity.

The amplifier, which is the amount of amplification of energy, is usually defined by the ratio of input to output optical power. To achieve high amplification, one has to store enough light in the amplifier using the pump source efficiently. Fiber lengths of several tens of metres are possible because of the low intrinsic losses of rare-earth-doped fibers. Therefore, the decisive product in order to achieve high amplification can be orders of magnitude higher in fibres than in other bulk solid-state lasers. This leads to very efficient operation of fiber laser systems with very high amplification and low pump threshold values [12].

A. How a fiber laser operates

Absorption, spontaneous emission and stimulated emission are the driving processes for the operation of any laser. Absorption is the phenomenon where energy from a source is absorbed and stored for a certain amount of time.

The pump source pumps light at the pump wavelength into the cavity. This light is absorbed by the ions of the amplifier. The ions move from a “ground” energy state to a “higher” energy state. At the higher energy state the ions emit the absorbed light in the form of photons. The photons are emitted at the laser wavelength. The phenonmenon of the ions emitting the absorbed energy is known as spontaneous emission.

The emitted photons move through the amplifier. There are two mirrors; one mirror, closest to the pump source, is transperant to the pump wavelength and is 100% reflective at the lasing wavelength; the other, situated at the end of the amplifier, is 80 - 99% reflective at the lasing wavelength. The mirrors reflect some of the emitted photons back into the amplifier. The reflected photons stimulate the ions in the higher energy state to emit even more photons as illustrated in Figure 2. This phenomenon is known as stimulated emission. The lasing effect produced in a fiber laser is due to the stimulated emission phenomenon.

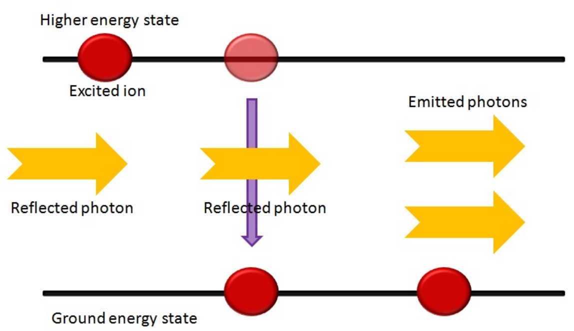

Fig. 2. Illustration of stimulated emission

B. Increasing the output power

There are a few ways to increase the output power of a fiber laser, such as changing and combining pump sources, using different fibers like, double cladding or photonic crystal fibers, using pre-amplifier systems or changing from continuous wave (CW) to pulsed wave signals. Our focus though is to increase the output power of the fiber laser by increasing the pump source, changing the length of the amplifier and changing the output coupling ratio.

An increase in the power of the pump source will lead to more light being absorbed by the amplifier, thus increasing spontaneous and stimulated emission. The increase in stimulated emission leads to an increase in the output power of the fiber laser.

Changing the length of the amplifier influences the amount of light absorbed in the amplifier. When the length of the amplifier is short the saturation point is reached faster, due to the small amount of light absorbed. When the length of the amplifier is long the saturation point is reached in a longer time, thus more light can be absorbed. Its inefficient to increase the pump power when the saturation point of the amplifier is reached, because all the light from the pump source is already absorbed in the amplifier.

Changing the output coupling ratio, influences the amount of light fed back into the setup and coupled to the output. The output power will be low, when the output coupling ratio is high, because the amount of light coupled back into the fiber laser is to low to assist in stimulated emission. Thus it is important to determine the correct parameters for the pump source, length of amplifier and output coupling ratio to achieve a higher output power.

III. Methodology

Increasing the output power of a fiber laser will be done by optimizing the parameters such as the pump source, the length of amplifier and the output coupling ratio. First we determine the setup of the fiber laser and then build the fiber laser setup experimentally.

A. Fiber laser setup

Figure 3 illustrates the setup of the fiber laser used. The setup consists of the following components:

- The pump source - diode laser emitting at 980 nm;
- The amplifier - Erbium doped fiber;
- The cavity
  - The wavelength division multiplexer (WDM)
  - The circulator;
  - Erbium doped fiber;
  - The mirror - Fiber bragg grating; and
  - The output coupler

The pump source pumps light at 980 nm to the amplifier, via the WDM. The WDM has the capability to combine signals of different wavelengths, in the fiber laser setup, the WDM combines the pump source light at 980 nm with the light at the lasing wavelength of 1550 nm. The amplifier absorbs the light from the pump source, which excites the ions to move to the higher energy state.

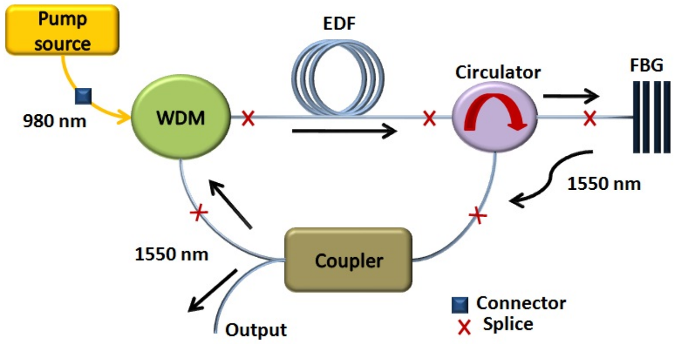

Fig. 3. Layout of the erbium doped fiber laser (EDFL)

The output light from the amplifier is send through the circulator to the fiber bragg grating. The circulator acts as an isolator, light can only go in one direction from the amplifier to the fiber bragg grating. Light reflected form the fiber bragg grating (FBG) can only go to the coupler. The light reflected by the FBG is coupled to the output and the rest is fed back into the amplifier via the WDM to assist the stimulated emission. The output is connected to an optical spectrum analyzer and power meter to measure the output power and spectrum of the fiber laser.

B. Experimental implementation

The fiber laser setup, illustrated in Figure 3 was experimentally constructed in the laboratory. All the components were spliced together to reduce the losses, which occur from the connectors. A reduction in the losses causes the output power to improve. The steps followed to implement the fiber laser are:

- The first step was to determine the coupling ratio for the fiber laser;
- The second step was to determine the range of length of the amplifier;
- The third step was to splice all the components together; and
- The final step was to take measurements of the output of the fiber laser.

Due to the concetration of the erbium fiber used, it was determined that the length of the amplifier will range from 0.5 m to 2.5 m in increments of 0.5 m. The coupling ratio of the fiber laser was determined by Figure 4, which is presented in the Laser Engineering book [13]. As can be seen from Figure 4, the most effective coupling is present at 0.2 output coupling, which was used in the experimental setup of the fiber laser. It can be seen from the figure by increasing the output coupling, the output power decreases. This is due to the amount of light fed back to the amplifier reduces, thus reducing the stimulated emission in the amplifier. The reduction in stimulated emission leads to a lower output power. Using a lower output coupling is more beneficial, due to more light being fed back to the amplifier and thus increasing the stimulated emission.

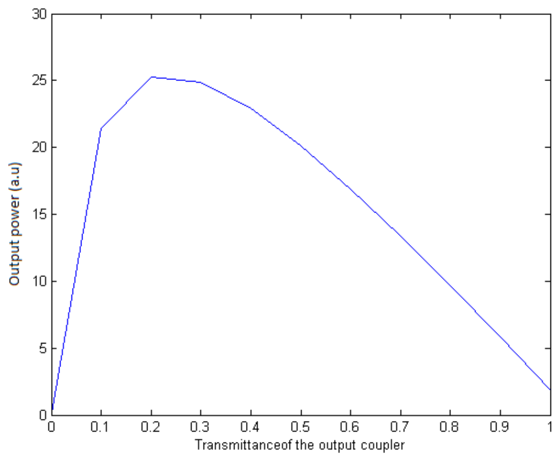

Fig. 4. Output power as a function of the transmittance of the output coupling

The experimental method used was the following:

- The amplifier length was chosen in the range of 0.5 m to 2.5 m;
- The pump power was then increased from 0 mW to 100 mW, in increments of 5 mW; and
- The output power was measured via the power meter.

One of the goals of this experiment is to determine the threshold point for the fiber laser at each different length of amplifier. The threshold of the laser is the amount of power necessary to start the fiber laser's operation. Figure 5 illustrates the threshold of the fiber laser. The blue line (low output) shows the output power before the threshold is overcome and the red line (large output) shows the output power after the threshold is overcome.

IV. Results and Discussion

This section covers the results obtained from the implementation of the fiber laser and discusses the influence of changing each of the parameters.

Figure 6 illustrates the output power of the fiber laser, using different lengths of amplifier. Increasing the pump power leads to an increase in the output power as shown by Figure 6. The pump absorption of the EDF was as high as 20 dB/m, thus it was decided to use short lengths of amplifiers.

The efficiency of the fiber laser is low, as can be seen from the above table, but this is a common result due to the absorption capabilities of the erbium doped fiber. The highest threshold of the fiber laser was measured at 21.8 mW at a length of 2.5 m.

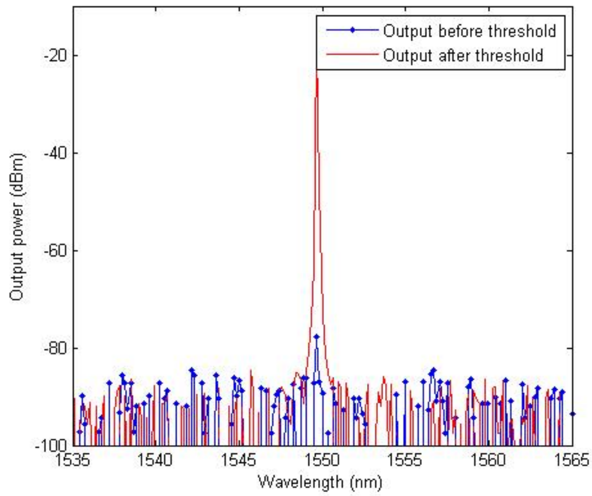

Fig. 5. The threshold of the fiber laser

Length of amplifier (m)	Output power (mW)
0.5	6.291
1	6.726
1.5	6.55
2	5.212
2.5	3.969

TABLE I

The output power with the change in length of amplifier

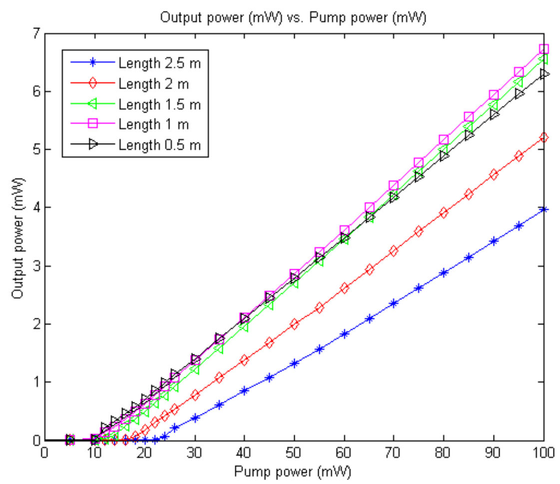

Fig. 6. The output power (mW) versus the pump power (mW)

The 2.5 m and the 2 m amplifier sections have lower output powers compared to the 1.5 m, 1 m and 0.5 m amplifier sections, due to all the pump energy being absorbed in the first 1.5 m of amplifier, thus the rest of the section of amplifier, doesn't absorb more pump light but absorbs part of the light at the laser wavelength leading to a lower emission of light from the fiber laser.

The higher output powers achieved by the 1.5 m, 1 m and 0.5 m, is due to the pump power absorbed more efficiently, it leads to more light being emitted and a higher output power being reached.

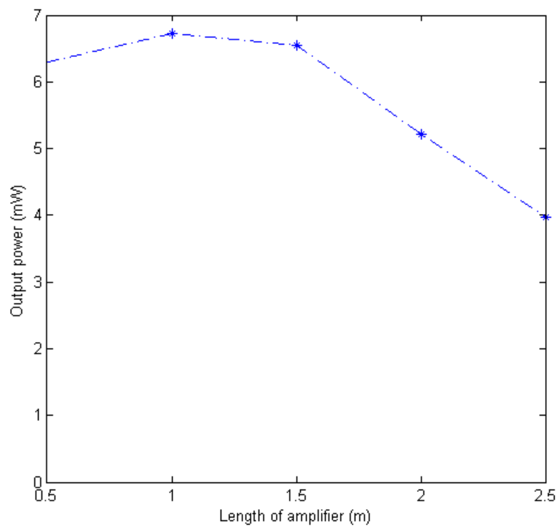

Fig. 7. The output power (mW) versus the length of the amplifier (m)

Figure 7 illustrates the change in output power of the laser with the change in length of the amplifier at a pump power of 100 mW.

The decrease in the output power with an increase in the length of the amplifier is due to the absorption of light at the laser wavelength when the fiber is longer that 1 meter. Increasing the length of the amplifier beyond this point will lead to a waste in the use of the amplifier and a lower output power.

V. Future Work

This section covers the future work for increasing the output power of the fiber laser. The proposed option for increasing the output power of the fiber laser is to connect a pre-amplifier to the fiber laser setup.

There are factors to be considered for the design of the pre-amplifier:

- The configuration to be used;
- The length of the amplifier; and
- The erbium fiber to be used;

The focus of the pre-amplifer is to increase the output of the fiber laser.

VI. Conlusion

This paper focusses on presenting experimental results for increasing the output power of a fiber laser by changing the pump power, length of amplifier and output coupling ratio.

The output power of the fiber laser does increase with an increase in pump power, after the threshold of the amplifier has been overcome. It was determined that the output coupling ratio should be 0.2 and the length of the amplifier should be 1 m long.

We conclude the output power of the fiber laser was successfully increased with an increase in the pump power, the change in length of amplifier and output coupling ratio and an output power of 6.726 mW was reached using a pump power of 100 mW. The efficiency of the fiber laser may seem low, but this is a common result using erbium doped fiber. The next step is to combine a pre-amplifier to the fiber laser setup to increase the output power.

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