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Optimization of MOPA for YD-DC Fiber Laser

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Abstract Power scalability of fiber lasers, today, is from few mW to several kW in CW operation and tens of kW in pulsed operation. The wide range of power is possible due to various configurations of the fiber laser system. One such configuration is Master Oscillator Power Amplifier (MOPA), the topic of interest of our paper. We explain the design aspects of MOPA and discuss optimization methodology for MOPA based fiber lasers. We propose optimization, under co-directional pumping, of pump laser, seed laser and the fiber length. We have focused on the state of art technologies considering Ytterbium doped double clad single mode Nufern fiber.

Keywords: *fiber laser, optimization, MOPA, MOFA, YD-DC*

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1. Introduction

Fiber lasers have been known since early 1970s. They are a class of solid state lasers, often considered the next generation to the rod and disk structures [1]. The major advantage with fiber lasers over rod and disk lasers is ‘efficient heat dissipation’. The flexible structure and ease of access made fiber lasers special interest in telecommunication networks. With the evolving fiber technologies, fiber lasers have seen a great leap and are now available from few mW to as high as several kW. IPG Photonics, the world’s leading photonics company, has recently reported a 100kW fiber laser. NASA has also demonstrated a high power missile using Fiber Laser technology. Further, high beam quality, ease of delivery and high power feasibility [2] made fiber lasers readily accepted in material processing, Aerospace industry and spectroscopy. Most of these applications require high power lasers. One approach to achieve the high powers is the Master Oscillator Power Amplifier approach.

Master Oscillator Power Amplifier (MOPA) is the most popular technique for high power lasers. It consists of two parts: master oscillator (MO) and amplifier (PA). The MO produces a coherent beam, and an optical amplifier is used to increase the power of the beam, preserving its main properties. This concept was first proposed by ‘High Power Laser Energy Research Facility’ [3].

The MO of MOPA is usually a low efficient laser and need not have high power. The PA is gain medium which amplifies the ‘seed’ power and also improves the beam quality. In case of fiber lasers, an active fiber acts as PA. Due to this, the term MOPA is often re-defined as MOFA (Master Oscillator ‘Fiber’ Amplifier). An active fiber is a fiber doped with rare earth (RE) elements. Since double clad (DC) fiber is proved to be better than single clad fibers, DC fibers are of more demand today [4]. In a DC fiber laser, the pump is fed into the inner cladding and laser is extracted from the core of the fiber. Emphasis was initially on Erbium doped fibers, because of their application in telecommunication systems but gradually Ytterbium received great attention because of their high power capability. The high power feasibility of Yb is due to its interesting spectral properties [5,6] and long metastable lifetime (1 ms). Further, the advantages of Yb are: a.) No excited state emission (ESA) and b.) Quasi-three level energy band structure.

Any MOPA works on the principle of coherent combination. Several texts explain the working of Fiber lasers and MOPA [7,8]. The working of MOPA can be understood in 3 steps:

i). Pump absorption & RE ion excitation
ii).De-excitation of RE ions
iii).Stimulated emission

When the pump laser is fed to the fiber, the pump power is absorbed by the RE ions doped within. This causes the RE ions to be excited to higher energy levels, which later de-excite emitting at different wavelength. The absorption & emission wavelengths are controlled by the absorption-emission cross-sections of the fiber. Usually, fibers are chosen such having maximum absorption at pump and maximum emission at laser wavelengths. This is the reason to choose 976nm and 1070nm prominent absorption and emission wavelengths in Yb doped fiber lasers [9].

During de-excitation, the photons collide with the photons from the seed laser and coherent transfer of energy takes place, resulting in stimulated emission. As a result, we get laser at same wavelength as the seed laser source. Other wavelengths may also be present due to spontaneous emission in the fiber. These wavelengths together contribute to an interesting phenomenon termed as ‘Amplifier Spontaneous Emission’ (ASE), usually of lower orders of magnitude. However, lasers have also been demonstrated and also commercially available based on ASE.

In fiber lasers, the pump and laser signal variations along the length of a DC single mode fiber with forward pumping, neglecting the contribution of ASE, can be analytically represented by [10]:

$$\frac{N_2(z)}{N} = \frac{\dfrac{\Gamma_p \sigma_{ap}[P_p(z)]}{h\upsilon_p A} + \dfrac{\Gamma_s \sigma_{as}[P_s(z)]}{h\upsilon_s A}}{\dfrac{\Gamma_p \begin{pmatrix} \sigma_{ap} \\ +\sigma_{ep} \end{pmatrix} [P_p(z)]}{h\upsilon_p A} + \dfrac{\Gamma_s \left(\begin{pmatrix} \sigma_{as} \\ +\sigma_{es} \end{pmatrix} \right) [P_s(z)]}{h\upsilon_s A} + \dfrac{1}{\tau}} \quad (1)$$

$$\frac{dP_p(z)}{dz} = \Gamma_p \begin{bmatrix} (\sigma_{ap} + \sigma_{ep}) N_2(z) \\ -\sigma_{ap} N \end{bmatrix} P_p(z) - \alpha_p P_p(z) \quad (2)$$

$$\frac{dP_s(z)}{dz} = \Gamma_s \begin{bmatrix} (\sigma_{as} + \sigma_{es}) N_2(z) \\ -\sigma_{as} N \end{bmatrix} P_s(z) - \alpha_s P_s(z) \quad (3)$$

It can be inferred that for a given fiber (having MOPA configuration), the output laser power depends on 3 major parameters:

i) Pump signal power
ii) Fiber length
iii) Seed signal.

Though MOPA is very common approach and widely used today, very little has been discussed on the optimization of the MOPA. Especially in fiber based MOPA, a variety of demonstrations have been shown across the world but none claimed them as ‘optimized’. A lot of research is still being carried out to enhance the fiber laser power but most of the work is limited to the fiber geometry and novel fibers such as Photonic crystal fiber [11], helical core fiber [12] etc [13]. Very little has been done on the power capabilities of YD-DC fibers, although few works state the power limitations of the systems and non linear effects suppression.

In the following section, we explain the optimization of the parameters of MOPA for the state of art technologies. This is very essential and beneficial from practical point of view than trying to develop new technologies for achieving efficient laser systems. The state of art values for various parameters in equations (1)-(3) are given in Table 1.

Table 1. Fiber, Pump and Signal Parameters

Parameter	Value
λ_p	976 nm
λ_s	1070 nm
τ	0.84 ms
α_p	0.003 m^{-1}
α_s	0.005 m^{-1}
A	5e-11 m^{-2}
Γ_p	0.0012
Γ_s	0.825
N	7.72e25 m^{-3}
σ_{ap}	2.5e-24 m^2
σ_{as}	4.5e-27 m^2
e_p	2.44e-25 m^2
e_s	3.6e-26 m^2
h	6.63e-34 J.s
L	15 m

2. Optimization of MOP(F)A parameters

2.1. Pump Signal

Pump signal is the important parameter for the MOPA. It can be considered as the maximum output power (100% efficiency) that can be extracted from the fiber. The role of the pump in fiber laser systems is to excite the RE ions doped in the fiber. The pump laser power is absorbed by the RE ions which populate the higher energy levels. It is interesting to note that in MOPA, population inversion is not the mandatory condition for laser action to occur. The excited ions further de-excite emitting photons. More the pump signal more is the absorption and hence more will be excitation-de-excitation process. But pump power cannot be increased indefinitely. There is a limit to the increase in pump imposed by two factors: doping concentration and damage threshold of fiber. If the doping concentration is low, even by pumping high power the amount of absorption will be less and more fractions will be left unabsorbed in the fiber. If the doping concentration is high, more excitation can occur by high power pump. However, at some stage the fiber will be damaged as it is made of silica material. Thus, the pump power should be chosen well below the damage threshold of the fiber. The pump dependent output power for a double clad YD fiber is given by:

$$P_{out}^{pump} = \eta_{laser} I_{pump} (\pi b^2)(\pi . NA^2) \quad (4)$$

Another limitation to the pump power is given by the brightness of the pump diodes. If the pump brightness is less than a threshold value, the output power is governed by (1) else it is governed by:

$$P_{out}^{dam} = I_{dam} \pi (\Gamma_s a)^2 \quad (5)$$

The pump threshold can be calculated using the relation:

$$I_{pump}^{Th} = \frac{\Gamma^2 I_{damage}}{\eta_{laser} R_{cl-co} (\pi . NA^2)} \quad (6)$$

Where η_{laser} is the optical-optical conversion efficiency; η_{heat} is the fraction of the pump light converting to heat; *G* is the power gain in dB of fiber lasers; *L* is the length of the active fiber; *a* and *b* are the core and inner-cladding radius of the DC active fiber, respectively; *NA* is the numerical aperture of the cladding of the active fiber; Γ_s is the ratio of the mode field radius to the core radius; λ_s is the signal/lasing wavelength; I_{pump} represents the brightness of pump light in (W/μm^2 /steradian); I_{dam} is the upper limitation intensity that cannot induce the damage to the fiber; R_{cl-co} (= b^2/a^2) is the ratio of square of the diameter of cladding to that of core of the fiber.

Very recently, a special fiber structure has been proposed, which can withstand very high powers but no satisfactory results have been obtained. Besides the damage threshold, there is another factor that greatly affects the performance of fiber lasers: Thermal effects [14]. Care should be taken to avoid these losses also.

2.2. Fiber Length

Once the pump power is optimized the next focus is on the length of the fiber. In fiber lasers, an active fiber acts as an amplifying medium. Long amplifying medium can be expected to result in more output power but it is not the case! In case of conventional lasers, the length of the amplifying medium (cavity) is limited by pump threshold and saturation condition. However, in case of MOPA, no population inversion occurs and thus same approach cannot be used. The consideration here should on the excited state density [$N_2(z)$] of the fiber.

The pump energy traverses through the fiber with nearly an exponential decay (Beer's law). The attenuation of pump is due to the absorption by the RE ions in the fiber. At a certain stage, the available pump power will be very less such that the excited state density will be low. This results in less power density of the emitted laser radiation. We still observe the laser but its contribution will be very little. This length beyond which the emitted laser power is small can be termed as "optimum length". However, very long lengths result in lower thresholds for Stimulated Raman Scattering (SRS) and Stimulated Brillion Scattering (SBS) [15]. In such cases, care should be taken to eliminate these effects in the system.

Measuring the excited state density can be tedious but pump power variation can be accurately obtained. Thus, the same principle can be explained in terms of pump power (since excited state density is directly proportional to pump power). This can be better done using graphical analysis than mathematical approach. It is interesting to note that for a given fiber, the attenuation is almost same for all pump powers. This is because the attenuation constant depends only on the absorption-emission cross-sections of the fiber. For high power MOPA, with the absorption-emission cross sections chosen as suggested earlier, the Eq (2) can be simplified as:

$$\frac{dP_p(z)}{dz} = -\Gamma_p\left[\sigma_{ap}\mathrm{N} + \alpha_p\right]\mathrm{P}_p(z) \tag{7}$$

Clearly, it is evident that the pump power varies exponentially along the fiber. The attenuation co-efficient is mainly dependent on the doping concentration. The optimum point can be chosen where the pump reduces to about less than 10% of input.

2.3. Seed Signal

The primary role of seed laser is to provide stimulating photons for laser beam generation. These photons get multiplied as they propagate through the fiber. So, if the seed power is chosen such that the photon density at the input end is greater than or equal to the excited state density, maximum laser power can be obtained at the output. Thus, having a low power seed (photon density=$N_2(0)$) can itself be sufficient for generating desired output power.

However, using very low seed for a desired output means the fiber has very high gain. But, the gain of the amplifier is limited by the Amplified Spontaneous Emission (ASE). ASE is an inherent phenomenon of the amplifier which reduces the output power. In order to suppress ASE, the amplifier should have ~ 40dB gain [16]. This is the maximum gain for lossless (ideal) operation. By using high power seed we can even have very small gain. The upper limit of the seed can be chosen based on the damage threshold of the fiber besides other non-linear effects- SRS and SBS. Since the fiber is chosen with low absorption at laser wavelength, having high power seed means high unabsorbed power density in the core of the fiber; this easily damages the fiber. It was earlier proposed in [17] that high power stable operation can be obtained with just having a 10dB gain. Thus, seed should be optimized accordingly.

3. Results

Equations (1)-(3) are solved using simple iterative algorithm using MatLab with parameter values in Table 1 and results are shown in Figure 1-Figure 4. The model is validated with the results of [18] and the observations are in agreement. The model can be applied to any MOPA based system to obtain the optimized parameters

4. Discussion

Figure 1, Figure 2, Figure 3 are used for the optimization of length of the fiber. We obtained 15m as the optimum length since the Normalized excited state density is very small beyond this point. The corresponding pump is about 3W (~9% input). We also observe that the signal strength growth rate is very small around this point and the gain is almost constant. Figure 2 is a clear indication that the gain is not a linear function of length but varies exponentially. This has been confirmed by several earlier works also [19].

From Figure 3, it is evident that population inversion is not necessary to achieve laser. This is an interesting aspect and the exclusive property of MOPA. Fig 4 indicates that seed signal adds linearly to the laser generated within the fiber. The linearity is due to the suppression of ASE in the fiber. This also proves that the seed signal follows the generated laser signal.

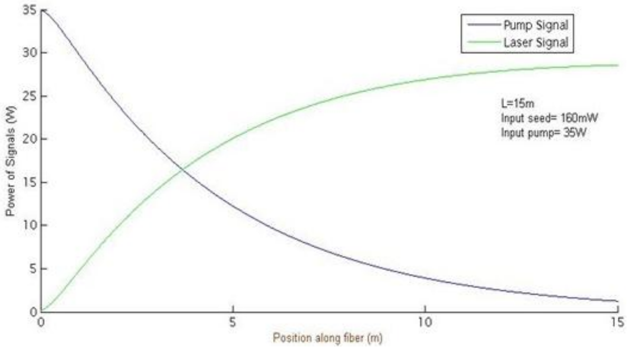

Figure 1. Variation of Pump, Laser signals along the length of fiber

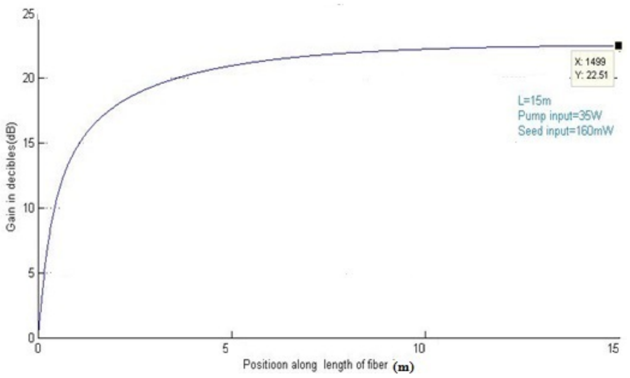

Figure 2. Gain build up along the length of fiber

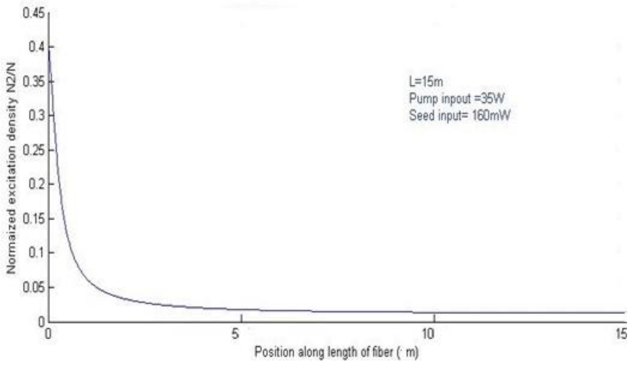

Figure 3. Variation of excited state population density along the length of fiber

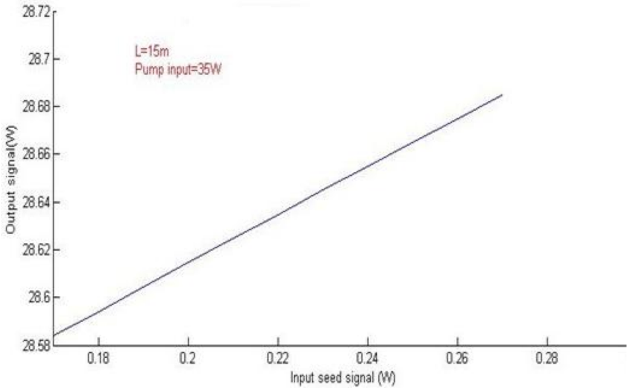

Figure 4. Output laser power for various powers of seed signal

Although several MOPA based experiments have been done, hardly a few of them can be called ‘optimized’; hence experimental validation with previous works is difficult. However, using the proposed model, one can carry out an experiment and compare the results. This can be treated as the future scope of this paper.

5. Conclusion

We presented the optimization of MOPA parameters for Fiber lasers considering the state of art technology. Optimization method is proposed for the fiber length, seed laser power. The pump power is proposed to be optimized based on the desired output laser power, considering the brightness of the pump laser and the damage limitations of the fiber. Simulations results are presented for YD-DC Single Mode Nufern fiber.

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