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Genetic Algorithm based Optimization of Pulse Profile for MOPA based High Power Fiber Lasers

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ABSTRACT

Although the Master Oscillator Power-Amplifier (MOPA) based fiber laser has received much attention for laser marking process due to its large tunability of pulse duration (from 10ns to 1ms), repetition rate (100Hz to 500kHz), high peak power and extraordinary heat dissipating capability, the output pulse deformation due to the saturation effect of fiber amplifier is detrimental for many applications. We proposed and demonstrated that, by utilizing Genetic algorithm (GA) based optimization technique, the input pulse profile from the master oscillator (current-driven laser diode) could be conveniently optimized to achieve targeted output pulse shape according to real parameters' constraints. In this work, an Yb-doped high power fiber amplifier is considered and a 200ns square shaped pulse profile is the optimization target. Since the input pulse with longer leading edge and shorter trailing edge can compensate the saturation effect, linear, quadratic and cubic polynomial functions are used to describe the input pulse with limited number of unknowns (<5). Coefficients of the polynomial functions are the optimization objects. With reasonable cost and hardware limitations, the cubic input pulse with 4 coefficients is found to be the best as the output amplified pulse can achieve excellent flatness within the square shape. Considering the bandwidth constraint of practical electronics, we examined high-frequency component cut-off effect of input pulses and found that the optimized cubic input pulses with 300MHz bandwidth is still quite acceptable to satisfy the requirement for the amplified output pulse and it is feasible to establish such a pulse generator in real applications.

Keywords: MOPA, fiber laser, pulse shaping, genetic algorithm

1. INTRODUCTION

Master Oscillator Power-Amplifier (MOPA) fiber laser has received much attention as the laser source for laser marking process due to its large tunability of pulse duration (from 10ns to 1ms) and repetition rate (100Hz to 500kHz), high peak power (larger than 10kW) and extraordinary heat dissipating capability[1-4]. Faster repetition rates and greater control over pulse energy offers the advantage of both faster and finer processing and a far wider processing range. However, the deformation of output pulse shape (the leading edge of the pulse higher than the trailing edge) of MOPA fiber laser due to saturation effects of fiber amplifier (the leading edge depletes much more population inversion) is detrimental for many applications. It is well recognized that the flat waveform in time domain is important to suppress the heating effect, hence achieving better marking results such as deep black patterns, sharp contours and faster processing [2]. Therefore, pre-compensate of the pulse distortion in the MOPA is the most cost-effective way and the optimum input pulse shape is needed to obtain a flat pulse shape in time domain. Although optimizations of input pulse shape were investigated in Ref [5,6], it is sophisticated and impractical for

commercial use without considering real parameters. While genetic algorithm (GA) is a global search optimization method which is based on natural selection and genetic evolution, it enables us to get rid of complicated mathematic and physical model and focus on the analysis of input and output pulse shaper itself. In this paper, the optimized input pulse profile for targeted flat pulse shape is determined using Genetic Algorithm with the bandwidth constraint of input pulses taken into consideration. The investigation of this work is based on an Yb doped fiber amplifier (YDFA). The program used in the simulation consists of three modules: GA optimization module to optimize input pulse profile; Input Pulse Generation module to generate the required input pulse profile; and YDFA module to get the amplified output pulse according to the optimized input pulse profile [7-11].

2. SYSTEM CONFIGURATION AND THEORY OF GA

(1) Configuration of MOPA fiber laser

Fig. 1 illustrates our proposed MOPA fiber laser: the output electric pulse of arbitrary waveform generator (AWG) modulates the waveform of seed laser (LD); the output optical pulse of the seed laser is then amplified by the Yb doped high-power fiber amplifier. In the direct modulation of seed laser, we assume the input electric pulse shape is the same as the output optical pulse shape as the bandwidth of electric pulses is far less than the upper frequency limit of direct modulation of LD. This paper is focused on the optimization of input pulse profile to obtain the flat pulse shape from the fiber amplifier. [4]

Fig. 1. System Configuration

(2) Theory of GA

GA is a global search optimization method based on natural selection and genetic evolution. It applies binary encoding method to create chromosomes which consist of several bits (0 or 1) to represent different input pulses' parameters. Emulating evolution in the nature, GA could find the best solution among many possible solutions when appropriate population and parameters were selected. [6]

Optimization of input pulse profile is a multivariate problem. The parameters of input pulses are considered as operating variables and output power flatness is the optimization goal. After several following steps, the general GA could be connected to optimization problem of input pulse profile. The process of GA is demonstrated as follows. [8]

- A. Coding. As mentioned before, each chromosome or individual in population consists of M-bit binary codes which represent for the value of input pulses' parameters.
- B. Initialization. The initial population is determined randomly, which means each bit of population is 0 with half of probability or 1 with half of probability.
- C. Object-value function. This function is to change population into several decimal numbers called value of objects, which can reflect the strength or weakness of each individual. Here Object-value function stands for the function of fiber amplifier which can transfer input pulses into output pulses and obtain their power, namely

value of objects.

- D. Fitness function. Fitness function calculates the variances of power of output pulses resulted from A. Variance can reflect the flatness of output power. The smaller variance is, the more flat output pulse displays. If the output pulse is an ideal square waveform, the variance of output power is 0. In order to simplify the next step, I want to achieve a high value of fitness standing for a small variance. So fitness is written as:

$$F_i = \max(U V_i) - V_i \quad (1)$$

Where i is the index of individuals in population and F_i and V_i are the fitness and variance of individuals separately.

- E. Selection function. Here roulette wheel selection has been employed. The higher fitness values result in the higher probability of being selected into the next generation. The probability could be expressed as:

$$P_i = F_i / \sum_{j=1}^N F_j \quad (2)$$

Where i is the index of individuals in population and F_i is the fitness of individuals.

Crossover and mutation function. Crossover exchanges pieces of chromosomes, namely pieces of binary bits, between two individuals. The function of crossover is to reproduce better individuals which possess higher fitness, achieving the presupposed goal, optimum input pulse profile. Mutation reverses random bits of chromosomes, for example, 0 to 1, 1 to 0. It can bring some new genes and solutions to population.

3. PROGRAM AND PARAMETERS OF SIMULATION

Fig. 2 shows the flow chart of program. GA module initializes the parameters of input pulses randomly and passes them to Input Pulse Generation module; the Input Pulse Generation module generates input pulses based on the parameters set in GA; the Fiber Amplifier module amplify the input pulses; then GA module analyzes all the pulses output from the Fiber Amplifier module, selects the better pulse out and initialize parameters in next loop using the retained pulse. The program can also illustrate using objectvalue function of output pulses in GA, which can be seen in Fig. 3.

Fig. 2. Flow chart of program.

(1) Program

A. GA

In GA, one iteration loop is also called one generation, and the assembly of input pulses' parameters is the population. Based on the theory of GA mentioned in Section 2, the population will be encoded and initialized, then judged by objectvalue and fitness functions. Next, the population is going to be operated by three operators:

selection, crossover and mutation. The population applied with three operators will be the parents of next generation. After several generations, the population tends to convergence. [9]

B. Input Pulse Generation

Since the convergence of GA is poor when optimizing more than 5 parameters simultaneously, the input pulse described by square pulse sequences is not desirable. Consider input pulse with longer leading edge and shorter trailing edge can compensate the saturation effect, linear, quadratic and cubic polynomial functions can be used to describe the input pulse with limited number of unknowns(<5).

Consider the waveforms generated by AWG have an upper bandwidth limit due to the performance of AWG, we construct several ideal filters to limit the bandwidth of input pulses, the filter is construct using frequency-domain analysis method [10], and the upper cutoff frequency is in the range of 100-400MHz.

C. Fiber Amplifier

The Yb doped fiber amplifier is describe by the rate equation and power propagation equations, and solved iteratively using the Runge-Kutta algorithm. The output pulse is stabilized after 10 input pulse cycles.

(2) Parameters of Simulation

A. GA

The key parameters used in GA module are given in Table. 1 [11], where Popsiz is the size of population and relates with the variety of population and genes; Chromlength is the Length of chromosome and proportional to the accuracy of the result; Iteration is the iteration cycle of the GA module and the convergence must be achieved before the iteration ends; Pc is the probability of crossover and should choose carefully to avoid get a divergent or local maximum result; Pm is the probability of mutation, and should avoid too high to result in divergence of the result.

B. Input Pulse Generation

The key parameter in Input Pulse Generation module is upper limit frequency of filters (filterlim, in the range of 100MHz to 400MHz), which need to be optimized in order to realize with common PCB.

C. Fiber Amplifier

The optimization of input pulse profile is based on the Yb doped fiber amplifier, and the key parameters of the Fiber Amplifier module are given in Table. 2 [7]. This paper is focused on the optimization of input pulse profile, but the GA optimization method can also use in other rare earth doped fiber amplifier and the fiber amplifier parameters optimization. The pump of the amplifier in this paper is CW laser, and pulsed pump can also be realized with this program.

Fig. 3. Tree flow chart of GA. Input Pulse Generation module and Fiber Amplifier module could be regarded as object-value function calculating the power of output pulses in GA.

4. SIMULATION RESULTS AND DISCUSSIONS

The optimization of input pulse will be presented and discussed in the following paragraphs: we first use the input pulse without bandwidth constraint and then consider the bandwidth constraint due to upper limit frequency of AWG in the simulation. Linear input pulse, quadratic input pulse and cubic input pulse profile are optimized for both situations.

(1) Results without bandwidth constraint

A. Optimum linear input pulse

Linear input pulse can be depicted with the follow function

$$y = ax + b \quad (3)$$

Table. 1. Parameters of GA

Parameter	Value
Popsiz	20
Chromlength	10
Iteration	10
Pc	0.7
Pm	0.01

Table. 2. Parameters of Fiber Amplifier

Parameter	Physical Meanings	Value
L	Length of fiber	13.3m
Freq	Repetition rate of input signal pulses	50kHz
T_Sig	Pulse duration	200e-9s

NO	Density of reverse population	$1e25m^{-3}$
Aco	Core area of double-clad fiber	$7.85e-11m^2$
P_Input_L	Forward DC pump	5W
P_Input_R	Backward DC pump	0W
lambda_p	Wavelength of pump beam	976e-9m
lambda_s	Wavelength of signal beam	1060e-9m
sigma_sa	Absorbing section of signal beam	$6.09e-27m^2$
sigma_se	Emitting section of signal beam	$3.33e-25m^2$
sigma_pa	Absorbing section of pump beam	$4.47e-24m^2$
sigma_pe	Emitting section of pump beam	$4.28e-24m^2$

Where y is the power of the input pulse and the unit is watt. The optimum parameter obtained from GA optimization is $a=0.1445$, $b=0.0559$, $x=[0,1]$, while the profile of optimum linear input pulse and correspondent output pulse can be seen in Fig. 4. Fig. 4 (c) shows the maximum and minimum power of the output pulse amplified from the optimum linear input pulse is 340.0222W and 274.5239W respectively. The output pulse is apparently not flat in the time domain and the difference of maximum and minimum power (65W) is larger than the tolerance in laser marking.

Fig. 4. (a) The function of optimum linear input pulse. (b) Shape of linear input pulse. (c) Corresponding output pulse.

B. Optimum quadratic input pulse

Quadratic input pulse can be depicted with the follow function

$$y = ax^2 + bx + c \quad (4)$$

Where y is the power of the input pulse and the unit is watt. The optimum parameter obtained from GA optimization is $a=0.0473$, $b=0.0563$, $c=0.1123$, $x=[0,2]$, while the profile of optimum quadratic input pulse and correspondent output pulse can be seen in Fig. 5.

Fig. 5 (c) shows the maximum and minimum power of the output pulse amplified from the optimum linear input pulse is 332.1842W and 319.3136W respectively. The output pulse is apparently more flat in the time domain compare to Fig. 4 (c) and the difference of maximum and minimum power (12.8706W) satisfies the requirement in laser marking.

C. Optimum cubic input pulse

Cubic input pulse can be depicted with the follow function

$$y = ax^3 + bx^2 + cx + d \quad (5)$$

Fig. 5. (a) The function of optimum quadratic input pulse. (b) Shape of quadratic input pulse. (c) Corresponding output pulse.

Where y is the power of the input pulse and the unit is watt. The optimum parameter obtained from GA optimization is $a=0.0032$, $b=0.0076$, $c=0.0493$, $d=0.1070$, $x=[0,3]$, while the profile of optimum cubic input pulse and correspondent output pulse can be seen in Fig. 6. Fig. 6 (c) shows the maximum and minimum power of the output pulse amplified from the optimum linear input pulse is 325.7926W and 324.7930W respectively. The output pulse is very flat in the time domain and the difference of maximum and minimum power ($<1W$). The output square pulse will improve the marking result undoubtedly.

Fig. 6. (a) The function of optimum cubicbb input pulse. (b) Shape of cubic input pulse. (c) Corresponding output pulse.

(2) Results with bandwidth constraint

From the above simulation result, we can see that the output pulse is much more flat and square with the optimum cubic input pulses amplified by the amplifier, thus the cubic input pulse is chosen for the following simulations. Considering the periodicity of input pulses, 10 consecutively identical cubic pulses are used to analyze the input pulse in frequency domain. Fig. 7 shows the frequency components of input pulses mentioned above. It can be seen that most energy of the pulse exist in the frequency components below 40MHz, but high-frequency components could not be neglected since it cannot be generated by AWG. In the simulation, we use virtual filters to cutoff high-frequency component of input pulses. The upper limit frequency of filter (filterlim) in the simulation is 100MHz, 200MHz, 300MHz and 400MHz, respectively. Fig. 8~11 shows the simulation results with filterlim=100MHz, 200MHz, 300MHz, 400MHz, respectively.

Fig. 7. Amplitude of frequency components of cubic input pulses in 10 periods. Most of energy accumulates below 40MHz, but high-frequency components still could not be neglected.

Fig. 8. (a) Cubic input pulse after 100M filtering. (b) Corresponding output pulse

Fig. 9. (a) Cubic input pulse after 200M filtering. (b) Corresponding output pulse

Fig. 10. (a) Cubic input pulse after 300M filtering. (b) Corresponding output pulse

Fig. 11. (a) Cubic input pulse after 400M filtering. (b) Corresponding output pulse

5. CONCLUSIONS

The pulse distortion of MOPA fiber lasers is detrimental in many applications. In order to solve the pulse distortion caused by saturation effect and get the flat pulse output from MOPA fiber lasers, optimization of the input pulse using GA is proposed in this paper. Linear, quadratic and cubic polynomial functions are used to represent the input pulse. Cubic input pulse is found to be the best to achieve most flat and square output one. Considering the bandwidth constraint of practical electronics, the cubic input pulses with less than 300MHz bandwidth is still eligible to satisfy 200ns pulse-width square-shaped output with negligible fluctuations.

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