An Evolvable Laser System for Generating Femtosecond Pulses

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Abstract

This paper describes an evolvable laser system that can generate femtosecond optical pulses. Laser systems must be aligned precisely, because the light has to travel many times within a laser cavity before returning to the focus point with μm resolution. This is particularly true of the high-peak power involved in femtosecond pulse lasers, which the distorting nonlinear lens effects should also be considered. It, therefore, typically takes about a week to manually align a femtosecond laser, where the optimal condition must be determined empirically. In order to overcome this problem, we propose and demonstrate an evolvable laser system that can adjust the positioning of the laser cavity components (e.g. the mirrors and prisms) by genetic algorithms, which incorporate a special local learning method. In an initial experiment, an output power was obtained which is 2.3 times higher than the power achieved with a manual alignment set in our laboratory. This laser system has three advantages, namely; (1) higher output power, (2) automatic and reliable adjustment and (3) compactness, all of which are important prerequisites for femtosecond laser technologies to become a widely-used industrial technology.

1 Introduction

Laser systems, invented in the 1960s [Maiman, 1960] [Siegman, 1986], have been applied to various fields such as semiconductor lithography [Moreau, 1988], optical communication [Yairv, 1996], and sampling measurement methods [Valdmanis, 1990]. During the last decade, the development of femtosecond lasers, based on Kerr-lens mode-locking techniques, has progressed rapidly and many commercial products are now available. Ultra-short optical pulses in femtosecond region ($\sim 10^{-15}$ sec.) are essential for the development of ultra-fast optical communication and measurements methods [Kamiya et al., 1999].

However, the Kerr-lens mode-locking technique used in femtosecond pulse lasers requires precise positioning of the focusing mirrors within the laser cavity, femtosecond lasers are difficult to align, which makes them less attractive for industrial use. For example, even a 10μm discrepancy in a focusing mirror will prevent an optical resonation with 1.0W pumping power from forming. It, therefore, typically takes about a week to manually align a femtosecond laser. Moreover, because nonlinear lens effects must be considered when high-peak power is involved in the laser cavity, optimal alignment is dependent on the pumping power level used and a system must be re-aligned if a different pumping power is used.

In order to overcome these difficulties, we propose an Evolable Laser System (ELS) for femtosecond lasers, which can adjust the positioning of the laser cavity components (e.g. the mirrors and prisms) by genetic algorithms (GAs). This laser system has three advantages:

1. Higher Power
   When the ELS starts up or the pumping power is changed, the GA can be executed to optimize the laser power.
2. Automatic and Reliable Adjustment
   As the GA is capable of adjusting the system automatically and reliably, manual adjustment is not required with the ELS. Moreover, because the need for manual adjustment is eliminated, the risk of human eyes being damaged while making such alignments is also effectively removed.
3. Compactness
   Conventional laser systems requiring manual adjustment tend to be rather large, as there must be sufficient space to allow human hands to make the physical adjustments. However, by virtue of the incorporated automatic adjustment mechanisms, the ELS can be made much smaller, even mak-

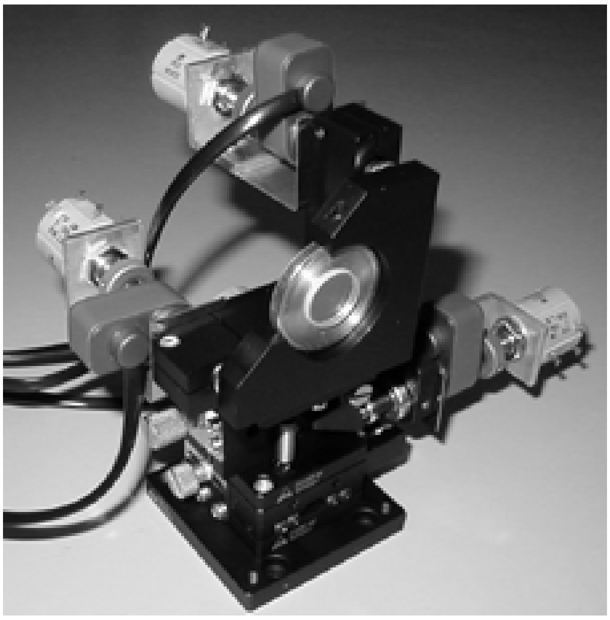

Figure 3: Photograph of the Mirror Holder Incorporated with Three Picomotors and Potentiometers

ing the development of portable femtosecond laser systems feasible in the future.

As this approach can be applied to a wide variety of laser systems, femtosecond laser technology can become a more widely-used industrial technology.

The ELS developed in this study has 10 picomotors that determine the positioning of the mirrors genetically. Each picomotor can adjust the x-position, yaw and pitch of a mirror with a resolution of μm. Manual adjustment with picomotors is very difficult because the light has to travel many times within a laser cavity before returning to the focus point with μm resolution. In an initial experiment, an output power was obtained that is 2.3 times higher than the power achieved with a manually alignment made in our laboratory.

This paper is organized as follows: In section 2, an overview of the ELS is given. Section 3 describes the developed ELS in detail, and section 4 presents the results of performance experiments. In section 5, the advantages of the ELS are discussed, as well as future work, before a summary section.

2 Overview of the Evolvable Laser System

This section provides an overview of the proposed system. Details of the laser cavity and the genetic learning are discussed in the section 3.

Figure 1 is a schematic representation of the evolvable laser system, and Figure 2 is a photograph of the developed system. YVO_4 green laser is used in the system as the pumping beam (input to the laser system), which enters at IN in Figure 1. Four focusing mirrors M3–M6, which form an optical resonator, output the laser light from OUT. The positioning of these four mirrors can be adjusted subtly to correct for positioning errors, which can greatly reduce output performance. This adjustment involves ten picomotors in total (the picomotor is a piezo that turns a screw [Newfocus]). For example, the mirror holder for M3 incorporates three picomotors, which alter the positioning of the mirror (Figure 3).

The screw positions of the picomotors are determined by the motor controller in Figure 1. Their absolute positions can be set by downloading a binary string to the controller. We call this string the control bits. In the genetic learning, the control bits are regarded as GA chromosomes. GAs are robust search algorithms which use multiple chromosomes and apply natural selection-like operations in seeking improved solutions [Holland, 1975]. The GA identifies the optimal control bits for the evolvable laser system. The goal of this evolution is to obtain the maximum power level for the laser pulse from the laser cavity.

Every chromosome is downloaded into the controller. A fitness value is calculated by observing the laser outputs. The positioning of the mirrors is varied to improve the performance of the laser system.

3 Configurations of the Evolvable Laser System

This section describes the evolvable laser system in detail.

3.1 Cavity Configuration

The layout of the cavity is shown in Figure 4. The cavity is a standard Ti:sapphire laser [Spence, 1991]. The main cavity consists of four mirrors, M3 to M6, and the 20-mm-long Brewster-angled Ti:sapphire gain medium placed at the center of the cavity. This z-cavity configuration is essential for femtosecond laser systems.

The pumping laser is a diode-pumped frequency-doubled YVO_4 laser. The wavelength is 530 nm and noise is less than 0.5% of the output power. The pumping beam is focused into the Ti:sapphire gain medium by means of the plane mirrors M1, M2, M5, M6, and the concave mirrors M3 and M4. The output power of the laser from mirror M6 is measured by a power meter. A plane coupler before the power meter has a transmission of approximately 2.0%.

The output power is greatly affected by discrepancies between the actual and ideal positioning of the mir-

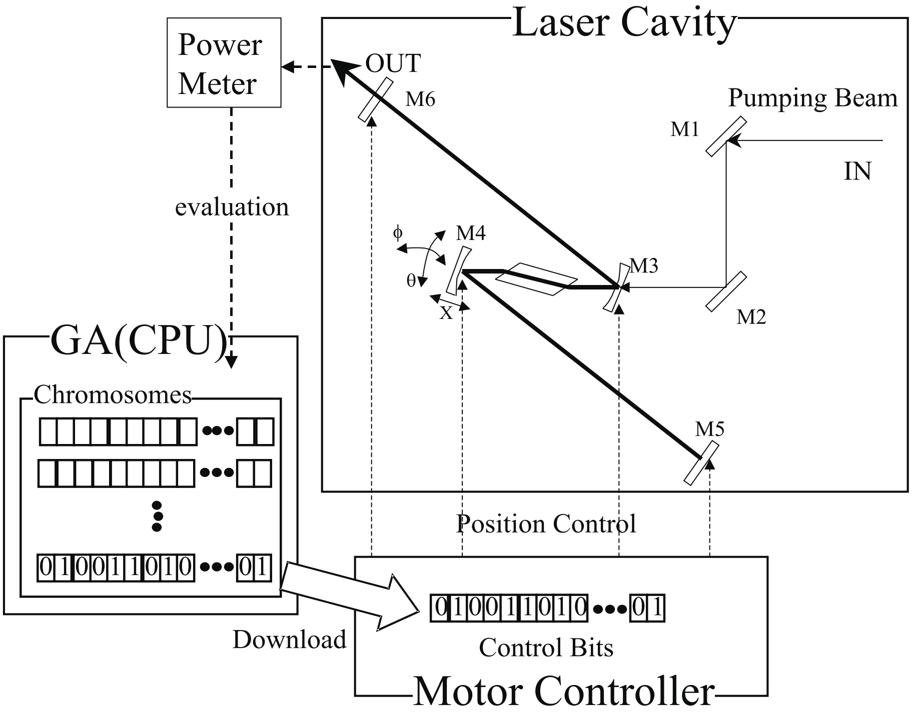

Figure 1: Schematic Representation of the Evolvable Laser System

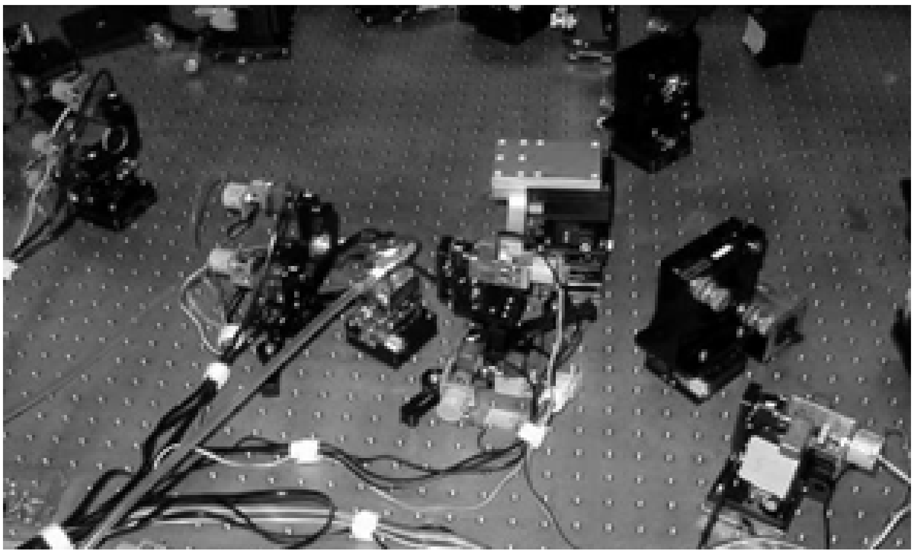

Figure 2: Photograph of the Developed Evolvable Laser System

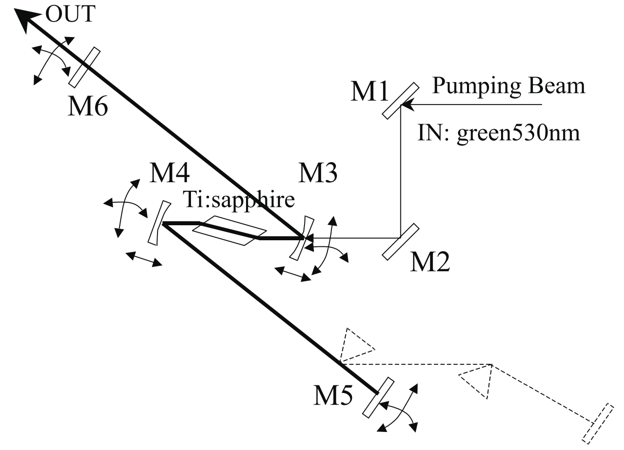

Figure 4: Cavity Configuration for the Ti:sapphire Laser

rors M3–M6. For example, even a 10μm discrepancy in the focusing mirror M4 can prevent an optical resonation with 1.0W pumping power from forming. In order to correct for such discrepancies, the mirrors in conventional femtosecond laser systems can be aligned manually by subtly moving adjustment screws.

However, it is very difficult to align the positioning of the mirrors, because adjusting one mirror will affect the alignment with the other mirrors. Thus, alignment sometimes takes a week, even for skilled hands. Moreover, because nonlinear lens effects must be considered when high-peak power is involved in the laser cavity, optimal alignment is dependent on the pumping power level used and a system must be re-aligned if a different pumping power is used.

In order to overcome these difficulty, we propose the evolvable laser system, which has ten picomotors for automatic adjustment, which is determined by genetic learning. The yaws and pitches of mirrors M5 and M6 can be adjusted with two picomotos, and the x-positions, yaws and pitches of mirrors M3 and M4 can be adjusted with three picomotors. With the aid of potentiometers, the absolute screw positions of the picomotors can be specified by downloading a bit string to the controller. By treating the bit strings as GA chromosomes, the proposed system can adjust the positioning of the mirrors. A detailed description of the adjustments using GAs is given below.

3.2 Genetic Learning

The laser system has 10 parameters in total for the genetic learning. These parameters represent the absolute screw positions; two relate to the x-positions (X_3, X_4), 4 to the pitches $(P_3, \cdots, P_6)$, and 4 to the yaws $(Y_3, \cdots, Y_6)$. A chromosome in the GA consists of 10 floating value genes (i.e., X_3, X_4, $P_3, \cdots, P_6$, $Y_3, \cdots, Y_6$).

Multiple chromosomes are prepared as a population for the GAs. By repetitive application of the GA operations to the population, a configuration that gives a higher output power emerges from a search space of potential solutions.

3.3 Genetic Operations

The laser output can be measured in terms of either the output power, the pulse-width or the spectrum. Although all three criteria are important, in the present system the fitness function is based on power meter readings. Chromosomes with higher fitness values are reproduced according to the tournament selection rule. The tournament size is 2. By using an elitist strategy, the chromosome with the best fitness value is always reproduced.

After reproduction, child chromosomes are generated using single-point crossover with a probability of P_c. After crossover, every chromosome undergoes one Gaussian mutation, which adds a random value $N(0, \sigma)$ to each gene. $N(0, \sigma)$ denotes a normally distributed one-dimensional random number with a mean of zero and a standard deviation of σ.

To accelerate the genetic learning, we have adopt a special local-learning method, which utilizes measurements of the output power taken while the screw positions are being reconfigured according to a newly downloaded control bits. Because it takes more than 10 seconds for the picomotors to reconfigure the positioning of the mirrors, laser output can be repeatedly measured more than 20 times to provide evaluations intermediate configuration positions. The local-learning method compares the fitness function values for these intermediate configurations, and replaces current chromosome with the chromosome representing the screw positions that gave the local maximum output power value, which leads to an improvement in search efficiency.

4 Experimental Results

In this section, we present experimental results for the evolvable laser system, as well as experimental results for a hill-climbing method for comparison.

In the experiments, the pumping power was set to 3.0W. The initial positioning of the screws was according to the standard alignment procedure used in our laboratory, which was the same for all the experiments. The adjustment range for each parameter was restricted to within 32μm of the initial position.

4.1 Adjustment with the Genetic Learning

We used a GA population of 50 individuals. The

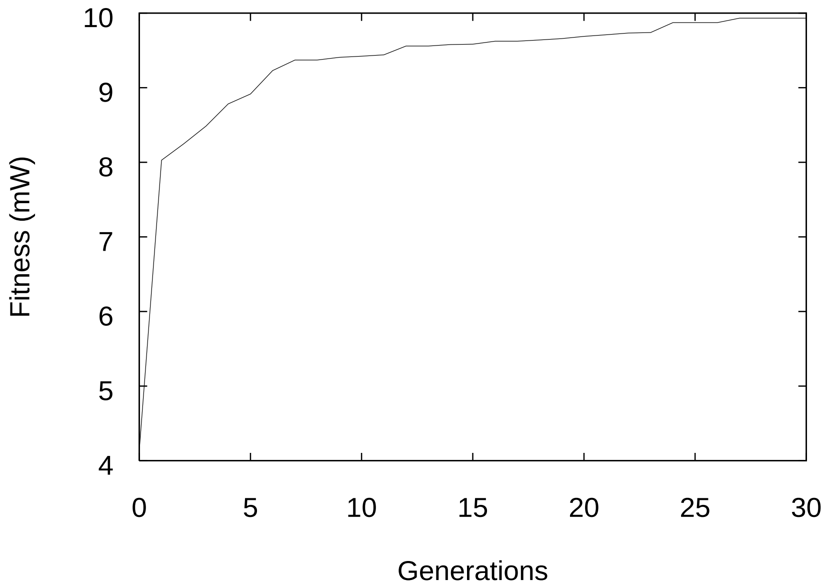

Figure 5: Adjustment Results with the Genetic Learning (Average of 4 independent runs)

crossover rate P_c was 0.5 and σ in the Gaussian mutation was 3.2μm. A run terminated after the 30th generation.

Figure 5 shows the fitness values for the best-of-generation individual. This curve was obtained by averaging the results of 4 independent runs. As can be seen, the fitness rises from 4.37mW to 9.96mW. (The best fitness values after the final generation in the 4 runs were 10.38mW, 9.67mW, 9.78mW and 10.01mW.) That is, the GA adjustment obtained an output power that is 2.28 times higher than that achieved with the standard manual alignment used in our lab.

Table 1: Final Results of the Hill Climbing Methods

50 trials	output power
Start	4.14mW
Average	6.01mW
Maximum	6.79mW
Minimum	5.38mW
Std. Dev.	0.288

4.2 Adjustment with the Hill Climbing Method

The adopted hill-climbing method adjusted the laser system as follows:

1. Generate a random permutation of 10 parameters (X_3,X_4, $P_3, \cdots, P_6$, $Y_3, \cdots, Y_6$).
2. Optimize the output power sequentially by varying the only one parameter within the permitted range on the basis of the permutation.
3. Repeat 1. and 2. N times (i.e. total optimized parameters = N $\times$ 10)

Figure 6 shows the averaged adjustment results of 50 trials with $N = 3$ which used different random seeds. The permitted range for each parameter was same as the range in the GA experiments. The measured output power is plotted against the number of optimized parameters.

As can be seen in the figure, the laser output was adjusted to rise from 4.14mW to 6.01mW. However, the output power sometimes fell as the number of optimized parameters increased. This was due to errors in the power meter and in the positioning control by the potentiometers. These results clearly show that the laser cavity of a laser system must be precisely aligned. Tab. 1 gives the final results of the adjustments. This table indicates that the search space for this problem has many local optima.

Comparing the results from the two experiments, the power output was 1.66 times higher with the GA than with the hill-climbing method. This shows the effectiveness of the GA in avoiding the local optima in the search space.

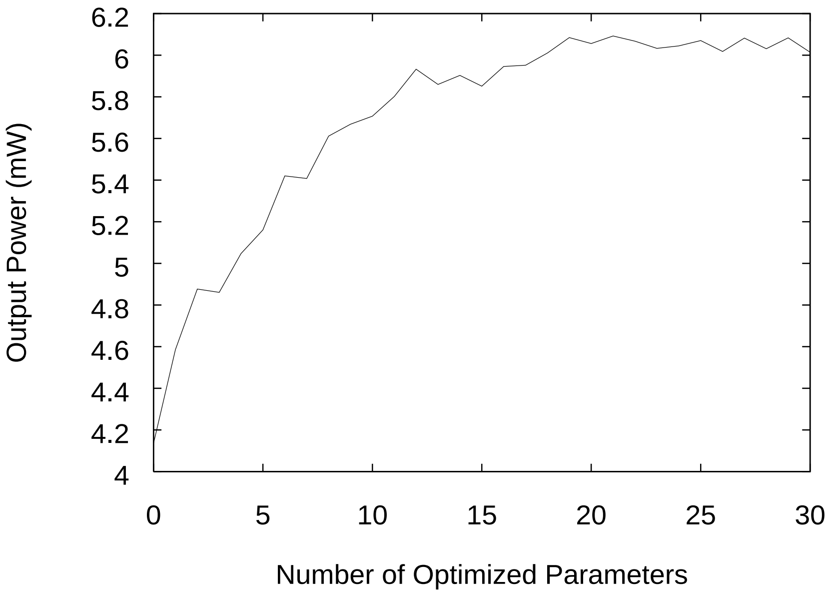

Figure 6: Adjustment Results with the Hill Climbing Methods (Average of 50 independent runs)

5 Discussion

This section discusses the advantages and the future work on the proposed system.

5.1 Advantages of the Proposed System

As described in the introduction, the proposed system has three main advantages from an industrial point of view. In addition to these advantages, the system also merit from a scientific point of view.

In the research field of femtosecond lasers, when new methods or systems are proposed, they are evaluated after thorough alignment by skilled hands and reported in journals or proceedings. However, a problem with this approach is that it is difficult to judge whether proposed laser systems are reliable and effective due to the the difficulties in reproducing the same precise alignment of a laser cavity elsewhere.

Our proposed method can resolve this problem as the genetic algorithm aligns the system automatically and reliably. This makes it easy to double-check new findings. Such an approach to femtosecond lasers research is essential given the non-linearity characteristics associated with high-peak power in the laser cavity.

5.2 Future Work

When aligning femtosecond-pulse laser systems for industrial use, laser output should also be considered in terms of pulse-width and spectrum, as well as output power. However, it has been shown empirically that an optimal alignment for maximum power is not the same as the optimal alignment for the pulse width, where short-width pulses are desirable. In future work, we will incorporate within the calculation of the fitness function some tradeoff compromise between these three conflicting ideals.

Although the proposed method in this paper is an off-line adjustment method, higher levels of precision in the alignment of laser systems could be achieved if the adjustment could be conducted on-line, allowing the system to be adjusted in line with fluctuations in the pumping power. Moreover, on-line adjustment mechanisms could also compensate for drops in performance due to environmental shocks to or temperature changes in the laser cavity. However, fine-tuning algorithms will need to be developed in order to realize on-line adjustment.

6 Conclusions

In this paper, we have proposed and demonstrated an evolvable laser system for generating femtosecond pulses, which can correct discrepancies in the positioning of laser cavity components by genetic algorithms. Even if the pumping power for the laser system is changed, the system can reconfigure the laser cavity to an optimal alignment. This laser system has three advantages, namely; (1) higher power, (2) automatic and reliable adjustment and (3) compactness. These advantages represent a breakthrough in opening the way for femtosecond laser technology to become a widely-used industrial technology. Under secured industrial cooperation, a compact ELS is currently being designed, and is scheduled to be manufactured in the fourth quarter of 2000. Experiments with different pumping power levels are also currently being conducted.

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