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Evolvable Optical Systems and Their Applications

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Abstract. This paper describes evolvable optical systems and their applications developed at the National Institute of Advanced Industrial Science and Technology (AIST) in Japan. Three evolvable optical systems are described: (1) an evolvable fiber alignment system, (2) an evolvable interferometer system, and (3) an evolvable femtosecond laser system. As the micron-meter resolution alignment of optical components usually takes a long time, to overcome this time problem, we propose 3 systems that can automatically align the positioning of optical components by genetic algorithms in very short times compared to conventional systems. In the evolvable fiber alignment system, the positioning of a fiber can be aligned automatically according to 5 degrees of freedom (DOF) in three minutes. In the evolvable interferometer system, the optimal positioning of the plane mirrors is determined automatically. And, in the evolvable femto-second laser system, the positioning of laser components can be aligned automatically within thirty minutes; something which in conventional system would take technicians more than five days to achieve. Moreover, the automatic alignment system makes possible the compact implementation of optical systems.

1 Introduction

In recent years, the market for optical technology has been growing rapidly, particularly due to the advances in optical communication systems. In general, optical systems consist of many components, such as light sources, mirrors, lens, prisms, semiconductor elements, and optical fibers. In order to obtain the optimal performance from an optical system, it is necessary to align these optical components to the optimal position with micron-meter precision. Moreover, as shifts in the positioning of each component impacts on the alignment of the whole system, each component must be repeatedly adjusted until the optimal alignment is achieved. As the number of experienced technicians is extremely limited, these difficulties increase the manufacturing times and the costs of optical systems.

Although algorithms for automatic alignment have been devised, they are often not suitable for systems where the parameters to be set optimally are

numerous, where there are local optimum, and where the parameters are interdependent. In this paper, we propose methods of automatic alignment using genetic algorithms. These methods have the following four advantages.

1. Automatic adjustment for maintenance-free systems

The performance of an optical system is affected by the temperature and the stability of the environment in which it is used. However, variations in performance can be adjusted for automatically by our algorithms on-line. This means that the optical systems are maintenance-free, making them easy for non-experts to use.

2. Cost-reduction

Using less expensive mechanical parts in optical systems, unfortunately, often leads to longer adjustment times, because the precision of these components is usually inferior. However, as our algorithms provide a quick and flexible way of adjusting performance, it is possible to use less expensive mechanical parts in order to reduce the costs of the system.

3. Compact implementation

With automatic adjustment methods, it is possible to reduce the spaces between the components in an optical system, which are necessary when adjustments are made by technicians. Thus, it is possible to downsize optical systems.

4. Realization of on-site optical systems

Advantages 1. and 3. mentioned above also make the realization of on-site optical systems possible. Compact and maintenance-free systems open up new application areas, such as portable on-site environment measurement systems, which is something that has been impossible to date due to the difficulties of using high-performance lasers and spectrums outdoors.

This paper describes three optical systems using GA-based automatic alignment algorithms.

1. Evolvable Fiber Alignment System

The alignment of optical fibers according to five degrees of freedom can be completed within a few minutes, whereas it would take a human technician about half an hour.

2. Evolvable Interferometer

The adjustment of plane mirrors in an interferometer is difficult for non-experts. However, the automatic adjustment method eliminates this problem making it possible to use interferometers outdoors.

3. Evolvable Femto-Second Laser

It often takes five days for experienced technicians to adjust the physical positioning of femto-second laser components in order to achieve optimal performance. The GA-based adjustment can align the laser components automatically within 30 minutes.

2 Evolvable Fiber Alignment System

2.1 Background

With the growth in optical fiber communications, fiber alignment has become the focus of much industrial attention. This is a key production process because its efficiency greatly influences the overall production rates for the opto-electric products used in optical fiber communications. Fiber alignment is necessary when two optical fibers are connected, when an optical fiber is connected to a photo diode or a LED, and when an optical fiber is connected to an optical wave guide.

Metallic wire connection is relatively easy because an electric current will flow as long as the two wires are in contact. The connection between two optical fibers, however, requires much greater precision, in the order of sub-micron-meters. Therefore, experienced technicians are needed for fiber alignment, but as such technicians are in limited supply, this causes a bottleneck in the mass production of opto-electric components for optical fiber communication. To overcome this, various algorithms for automatic alignment have been devised. However, existing automatic-alignment algorithms are only capable of aligning fibers according to three degree of freedom (DOF). Thus, the present authors have devised a new algorithm based on GAs that is capable of aligning fibers according to five or more DOF.

The advantages of the algorithm are summarized below:

1. Improvement in transmission efficiency

Unless two optical fibers are connected in an optimal way, there will be a reduction in transmission efficiency. However, as alignment is possible quickly and according to a greater DOF, there are no reductions in transmission efficiency.

2. Improvement in reliability

Automatic alignment reduces the numbers of tasks to be conducted by technicians, which leads to the improved reliability of products.

3. Improvement in production efficiency

The fiber alignment process is often a critical part in the entire production process, and so by reducing fiber-alignment times, production efficiency can be improved considerably.

4. Cost reductions

Less expensive opto-electric components are often inferior in terms of precision. However, variations from the desired specifications for each component can be compensated by using our alignment algorithm for greater DOF connections. This makes it possible to reduce the overall costs of a system.

The present authors have devised a fiber alignment algorithm for 5 DOF connections. Conventional alignment systems cannot achieve connections with 5 DOF because such precise fiber alignment is impossible given practical time constraints. However, our algorithm successfully carried out alignments for 4 different initial conditions in a few minutes. In the following subsections, the details of the alignment system and the algorithm are described.

2.2 Optical Fiber Alignment

Transmission loss due to non-optimal connections. Although metallic wire connections are very easy, optical fiber connections require extreme precision. This is because optical signals can only pass along the core of a fiber, which is only a few micron meters in diameter. Therefore, when connecting optical fibers, the cores of the two fibers must be aligned to face each other exactly with sub-micron-meter precision. In making such alignments, there are a number of factors that must be considered which can reduce transmission efficiency, such as shifts in the light axis, bending, and when core surfaces are not flush. To deal with these factors, alignment algorithms capable of greater DOF connections are required.

Automatic alignment system. Automatic alignment systems can shift slightly the light axes of the two optical fibers to minimize transmission loss. Once alignment is complete, the light axis is fixed by laser processing and a setting resin. Figure 1 shows the organization of the automatic alignment system. The system consists of a light source, alignment stages, a stage controller, a power meter to measure the light intensity, and a controlling PC. An alignment stage moves the tip of one optical fiber with micron-meter precision using step motors. The PC collects information from the power meter and feeds this back to the stage controller through a GP-IB interface in order to control the alignment stage. The control signals are generated by the PC where the automatic-alignment algorithm is executed.

Conventional automatic alignment algorithms. Alignment time depends completely on the performance of the automatic alignment system. Various algorithms are available on the market. For example, the alignment software sold by Suruga Seiki provides two search programs; a field search and a peak search program. The field search program is used when the two light axes are shifted greatly. Once this program has been executed, the peak search program is initiated. However, these programs have the following weakness; (1) local optimum,

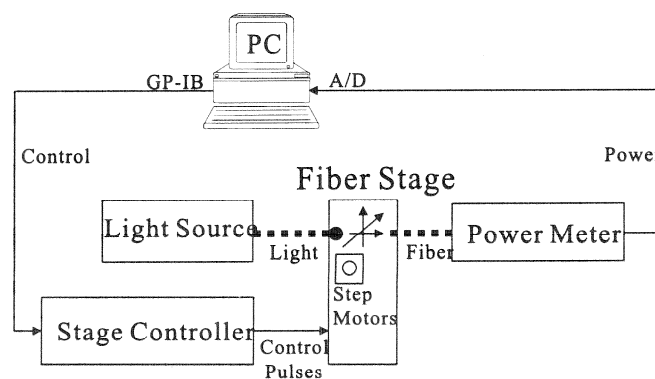


Fig. 1. An Automatic Fiber Alignment System

(2) problems with angle adjustments, and (3) noise-sensitivity. Due to these weaknesses, these software programs are not capable of alignments according to 5 DOF, have long alignment times, and result in large transmission losses.

Automatic alignment with GA. Our alignment algorithm uses a GA called the Minimal Generation Gap (MGG) model [1]. The MGG model has two advantages; (1) it can maintain the diversity within a population, and (2) the convergence speed is fast. We also employ a local learning method in order to improve search efficiency.

Alignment is conducted in the following way. First, the positions of the light axes are coded as chromosomes, and then an initial population is generated. GA operations, such as selection, crossover, and mutations, are then carried out on the population and local learning is conducted. The fitness function is light intensity. With the GA-based alignment algorithm, the optimal positions for the light axes are obtained to minimize transmission loss.

2.3 GA-Based Automatic Alignment Experiments

Figure 2 shows an experimental system for automatic alignment. It consists of a light source, a power meter, a control PC, and the stage controller. Four experiments were conducted in which we prepared 4 different initial conditions by altering the light axes from the positions set by an experienced engineer. In each experiment, alignment was successfully completed in three minutes. The details of the experiments are described below.

Experimental conditions. The objective of the experiments was to align the tips of two optical fibers according to 5 DOF. The 5 DOF in fiber alignment correspond to the following 5 parameters; the coordinates in the X, Y, and Z planes, as well as the two angles of inclination in the X-Z and Y-Z planes for optical fiber which is moved, as shown in Figure 3. In the first three experiments,

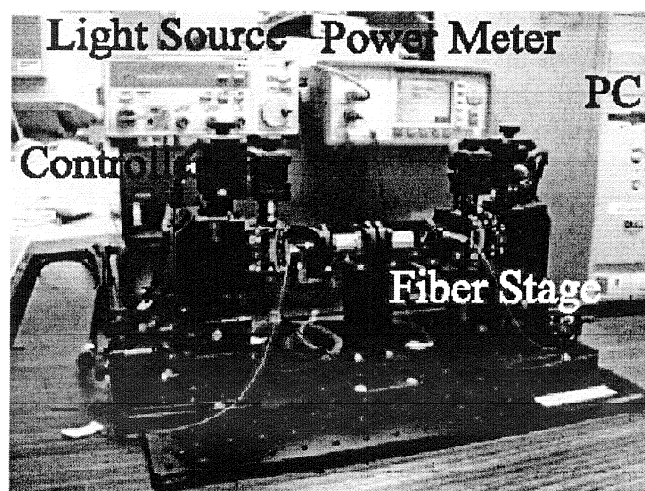


Fig. 2. The Fiber Alignment System Used for Development

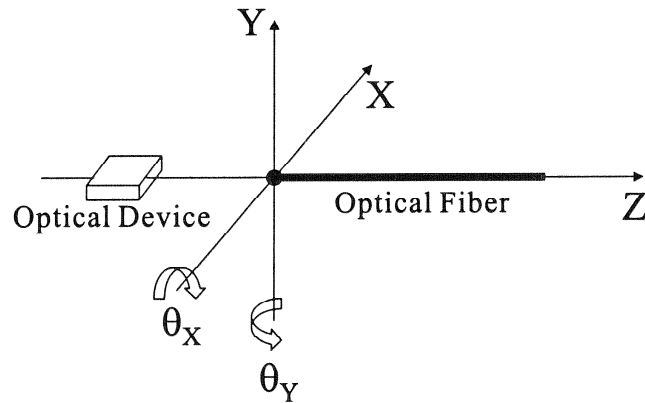


Fig. 3. Optical Axis

Table 1. Alignment Results for the Experiment 1

| Power(dBm) | Avg. | Max. | Min. | Std. |
|---------------|------|------|------|------|
| Conventional | 2.58 | 3.94 | 1.23 | 0.73 |
| GA without LL | 3.26 | 4.31 | 2.44 | 0.66 |
| GA | 4.41 | 4.73 | 3.85 | 0.27 |
| HC | 3.83 | 5.00 | 1.52 | 1.08 |

three of these parameters were altered, while two were changed in the fourth experiment.

In these experiments, the performance of our proposed method was compared to three other alignment algorithms. The first was a conventional alignment algorithm that is only capable of alignments according to 3 DOF. The second was a genetic algorithm that does not employ local learning, which is incorporated within our proposed method. The third was our GA method with local learning. The fourth method was a hill-climbing alignment algorithm. There were 10 trials in each experiment.

Experimental Results. We show only the result of the first experiment in Table 1. Figure 4 shows how the optical fiber tips converged in the experiment. Although only the result of the first experiment is shown, the best average performances in all four experiments were attained by the proposed automatic alignment method.

3 Evolvable Interferometer

3.1 Background

Advances in spectrum technology are making important contributions to the analysis of substances that cause environmental pollution. There is an increasing demand to be able to carry out spectrum analysis rapidly *on-site*. However, because the instruments used for spectrum analysis are very large, and performance is greatly influenced by environmental conditions, the on-site use of spectrum-analysis instruments has been virtually impossible. If portable spectrum-analysis

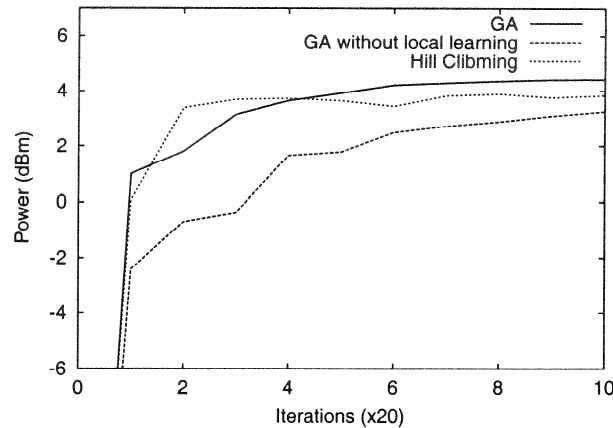


Fig. 4. Power versus Iterations for Experiment 1

instruments were developed, they would greatly accelerate the development of surveillance and analysis technology for environmental pollutants.

The challenge in developing portable instruments is to realize the automatic adjustment of the optical components of spectrum analysis instruments. Most analysis instruments consist of optical components that must be physically positioned with micron-meter precision for optimal performance. If such instruments are used on-site outdoors, then the optical components have to be re-adjusted every time an instrument is moved, but this kind of adjustment usually requires experienced technicians. Therefore, automatic adjustment methods for optical components are essential in order to realize portable spectrum-analysis instruments. We have developed an evolvable interferometer, which is used in Fourier-transform Infrared Spectroscopy (FTIR). FTIR performance is heavily dependent on the performance of the internal interferometer. The evolvable interferometer is a version of a Michelson interferometer, involving mirrors, that requires automatic adjustment in order to realize portable FTIRs.

The advantages of the evolvable interferometer are as follows:

1. Portable FTIR

When the FTIR is used outdoors, variations from the optimal positions for the optical components can be adjusted on the spot.

2. Compact FTIR

The automatic adjustment of the interferometer does not require the large spaces needed by engineers when manually adjusting interferometers. This makes it possible to downsizing the FTIR considerably.

3. Greater versatility for environmental measurements

With an automatic adjustment method, it is possible to employ optical components that are more suitable to the environment. For example, users can exchange prisms according to the target.

After outlining the Michelson interferometer, the evolvable interferometer is described in detail.

The Michelson Interferometer. The Michelson interferometer consists of a light source(S), a beam splitter (BS), a fixed mirror (M1), and a movable mirror(M2), and a testing chamber (P), as shown in Figure 5. The BS splits the light from S into two beams sending them towards M1 and M2. These beams are reflected back by these mirrors towards BS that then synthesizes them to send out a single beam in the direction of P. The synthesized beam, called an inter-ferogram, is used to analyze substances by the FTIR. In order to obtain an optimal inter-ferogram, the movable mirror, M2, has to be adjusted to the right position with micron-meter precision. As interferometer performance is influenced by the temperature and transportation, it is very difficult to implement portable FTIR without automatic adjustment.

Evolvable Interferometer. We have realized an automatic adjustment system for interferometers. Figure 6 shows the overall organization of the system. The system automatically adjusts the position and the inclination of the movable mirror in the interferometer. This adjustment can be conducted according to 3 DOF. The 3 DOF here are the position of the mirror, its angle of inclination, and its angle of rotation. In Figure 6, the PC reads the light intensity from a detection board and the genetic algorithm on the PC determines the three mirror parameters. The genetic algorithm employs the MGG model.

4 Evolvable Femtosecond Laser system

4.1 Background

Laser systems, invented in the 1960s [2] [3], have been applied to various fields, such as semiconductor lithography [4], optical communications [5], and sampling

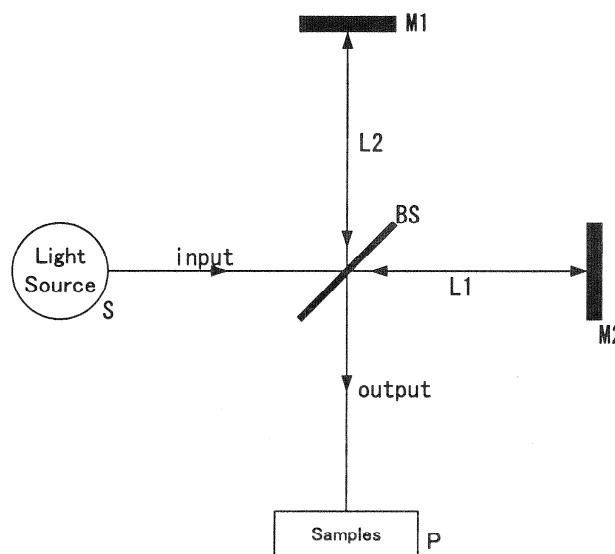


Fig. 5. The Michelson Interferometer

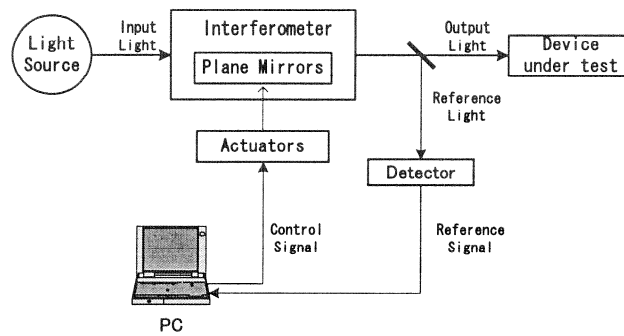


Fig. 6. An Automatic Adjustment System for the Interferometer

measurement methods [6]. 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.

However, as 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 $10\mu\text{m}$ discrepancy in a focusing mirror will prevent an optical resonance with 1.0W pumping power from forming. It, therefore, typically takes about a week to manually align a femtosecond laser.

In order to overcome these difficulties, we propose an Evolvable 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 making 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 manual alignment made in our laboratory.

4.2 Overview of the Evolvable Laser System

This section provides an overview of the proposed system. Figure 7 is a schematic representation of the evolvable laser system, and Figure 8 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 the point marked IN in Figure 7. Four focusing mirrors, M3–M6, which form an optical resonator, output the laser light from the point marked 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 [7]).

The screw positions of the picomotors are determined by the motor controller in Figure 7. 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 [8]. 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.

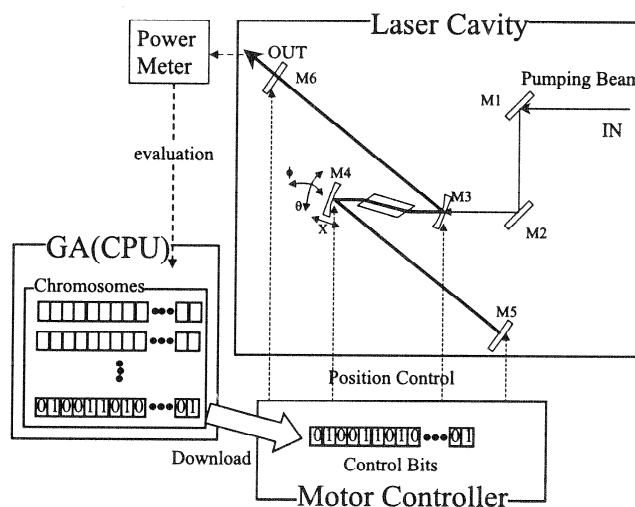


Fig. 7. Schematic Representation of the Evolvable Laser System

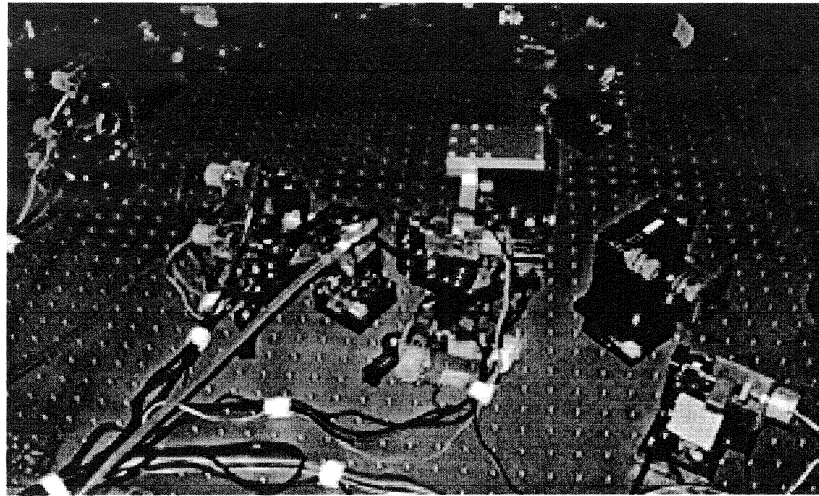


Fig. 8. Photograph of the Developed Evolvable Laser System

4.3 Configurations of the Evolvable Laser System

This section describes the evolvable laser system in detail.

The layout of the cavity is shown in Figure 9. The cavity is a standard Ti:sapphire laser [9]. 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 YVO₄ 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 the plane mirrors M1, M2, M5, M6, and the concave mirrors M3 and M4. The output power of

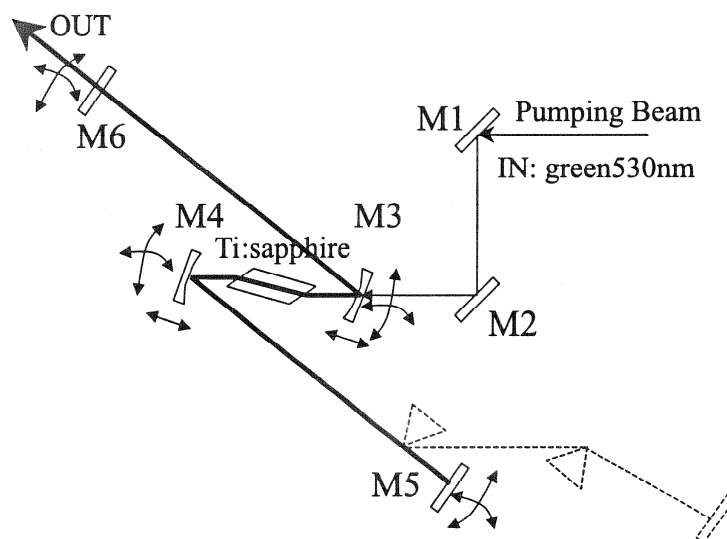


Fig. 9. Cavity Configuration for the Ti:sapphire Laser

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 mirrors M3–M6. For example, even a 10 μ m discrepancy in the focusing mirror M4 can prevent an optical resonance 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.

In order to overcome the problems of positioning and non-linear lens effects, 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 picomotors, 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. In tests, automatic adjustment was successfully completed within 30 minutes. Currently, we are also developing a very compact ELS for industrial usage.

5 Conclusion

This paper has described three evolvable optical systems;(1) an evolavable fiber alignment system, (2) an evolvable interferometer system, and (3) an evolvable femtosecond laser system. The advantage common to all these systems is the inclusion of GA in order to automatically execute the micron-meter precision alignment of optical components, such as mirrors and prisms, very quickly and very efficiently. This opens up the possibility of developing new optical instruments that can be used on-site outside for the analysis of environmental pollutants. Although the fitness function for the GA used in the present three systems was light intensity, other fitness functions are possible which would make automatic alignment even more stable and faster. The present systems are simply early examples of how mechanical evolution can be utilized in a wide variety of industrial applications in the future.

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