

AUTOMATIC ADJUSTMENT OF A MICHELSON INTERFEROMETER USING GENETIC ALGORITHMS

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ABSTRACT

This paper describes the automatic adjustment of a Michelson interferometer using genetic algorithms (GA). A Michelson interferometer consists of optical components (such as mirrors, lens, and prisms) that must be physically positioned with micron-meter precision to obtain optimal performance. This, therefore, makes it very difficult to use interferometers outdoors for environmental measurements such as air pollution, as the optical components can become misaligned in transport.

In order to overcome this problem, we propose an automatic adjustment method using genetic algorithms to quickly achieve the optimal alignment of the optical components. We have also developed new compact mirror holders allowing the portable and on-site use of interferometers. The advantage of this system is shown in comparisons with conventional adjustment algorithms. A quick adjustment time of approximately three minutes has been achieved with the proposed interferometer, demonstrating the suitability of this system for on-site measurements.

1. INTRODUCTION

In recent years, advances in spectroscopic technology are making important contributions to the ultra-trace analysis of environmental pollutions such as dioxin and other air-pollutants. The Michelson interferometer [1] is widely used as an instrument for spectroscopic analysis, as well as for environmental pollution and ultra-trace analyses, as a component of Fourier-Transform Infrared spectroscopy (FTIR) [2]. Although it is commonly used within chemical laboratories for conventional analyses, recently there is an increasing demand for portable instruments for on-site analysis.

However, there are two major problems in using Michelson interferometers for on-site analysis. The first problem is that to achieve high-level analytic performance it is necessary to optimally align the component mirrors and prisms

with micron-meter precision. Conventional Michelson interferometers are usually set manually, and often include automatic dynamic alignment methods to compensate for small deviations in component positioning. However, this method is not capable of adjusting for the kind of large misalignments that occur during transportation to outdoor locations. This has made the on-site use of these interferometers, which are extremely sensitive to variations, impossible.

The second problem is that conventional interferometers are too bulky for on-site use. When aligning the components of an interferometer, it is necessary to adjust at least three alignment axes (such as the focus position, the rotation angle, and the tilt angle of a mirror). Because the alignment axes of the components are interdependent, however, achieving the optimal alignment for all components is extremely difficult. Using larger and heavier holders, which are less sensitive to discrepancies, is one way to avoid the problem of interdependency, although this creates a trade-off situation between the compactness desirable for on-site use and the ease of independent adjustment mechanisms.

In order to overcome these problems, we propose an automatic alignment method using genetic algorithms (GA) [4] for the Michelson interferometer, and introduce interdependent mirror holders for compactness. Specifically, our research shows that: (1) GA is more robust than a hill-climbing method for the automatic alignment of interferometers, (2) the proposed system can optimally adjust the mirrors quickly, and (3) alignment interdependency is not a problem for the compact mirror holders utilizing GA.

This paper is organized as follows: In section 2, we describe a conventional Michelson interferometer and its problems. Section 3 describes an interferometer system using GA developed to solve these problems, and section 4 outlines two conventional search methods. In section 5, data from experiments examining the performance of the developed system is presented. Finally, a summary of this study and its future prospects is given in section 6.

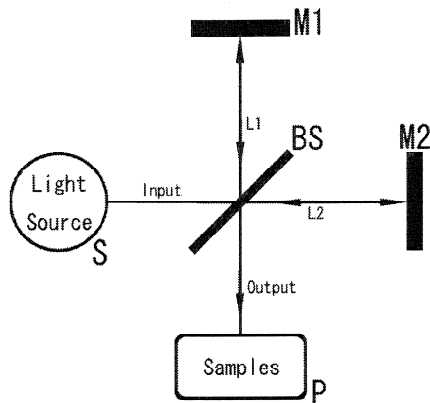


Figure 1: The Michelson Interferometer.

2. THE MICHELSON INTERFEROMETER AND ITS PROBLEMS

This section explains the structure of a conventional Michelson interferometer, its adjustment and related problems

2.1. The structure of a Michelson interferometer

The interferometer consists of a light source (S), a beam splitter (BS), a fixed mirror ($M1$) and a movable mirror ($M2$), as shown in Fig.1 [3]. $M1$ and $M2$ are usually flat mirrors. Emitted light from S is split at BS into reflection light and transmission light, which are directed towards $M1$ and $M2$, respectively. The lights are then reflected back towards BS , where they are combined and input to a sample (P). When the lights are combined, they form an interferogram, which can be utilized in quantitative and qualitative analyses.

2.2. Conventional adjustment of a Michelson interferometer and its problems

In order to produce the interferograms that are used for spectroscopic analysis, the two lights must converge at the same point on the BS in a Michelson interferometer, which means that the positioning of $M1$ (its tilt, rotation and focusing, as shown in Fig.2) must be manually aligned with micron-meter precision. This kind of adjustment calls for expert technicians and the use of an automatic dynamic alignment system to compensate for fine discrepancies when making measurements.

In addition to problems with initial alignments, the conventional Michelson interferometer also has two problems relating to its use on-site.

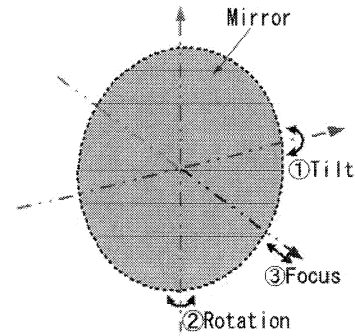


Figure 2: Mirror axes.

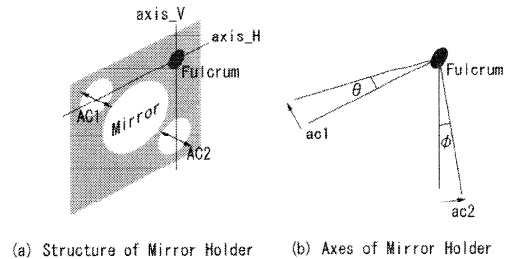


Figure 3: Independent axes of Conventional Mirror Holder.

1. Difficulty of adjusting for major misalignments

With the conventional automatic adjustment method used in Michelson interferometers, it is difficult to adjust for major misalignments of the mirrors due to transportation or temperature changes. This is because the feedback control for the adjustment method cannot function when the degree of misalignment is beyond a certain level, making conventional interferometers only suitable for use in controlled environments, such as chemical laboratories.

2. Obstacle to compactness

The structure of a conventional mirror holder is shown in Fig.3 (a) and (b). The holder has two independent mechanisms, $AC1$ and $AC2$ (such as micrometers or actuators), which adjust for rotation and tilt in two axes sharing a common fulcrum. A further mechanism for the stage is necessary to adjust the focusing position along the light axis. This kind of structural arrangement, however, represents a major obstacle when seeking to make mirror holders more compact.

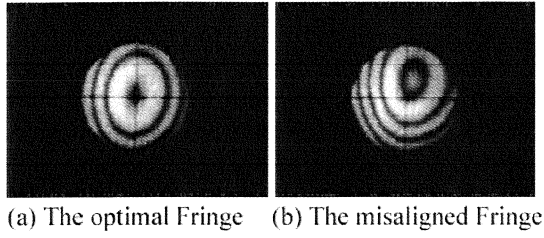


Figure 4: Interference Fringes.

3. ADJUSTMENT OF A MICHELSON INTERFEROMETER USING GA

In this section, we describe the developed automatic alignment of a Michelson interferometer using a GA, which is a stochastic search method capable of simultaneously assessing multiple solution candidates. When provided with a set, or population, of solution candidates, genetic operations that simulate evolutionary mechanisms operate on the set of candidates to evolve a better solution. The criterion by which the quality of a candidate solution is assessed is referred to as a fitness function. The design of the fitness function is crucial to the successful application of GA, for it determines the convergence ability, speed, and accuracy of the solution search.

In our study, each generation consists of four steps, (1) interferogram measurement, (2) fitness value calculation, (3) genetic operations, and (4) mirror control, which are repeated to achieve the optimal alignment of the interferometer. When measurements are taken during a generation cycle of the GA, which can be advantageous in some practical GA applications, there is a danger of measurement times determining the overall alignment time and creating difficulties for the application. Given that the primary objective of this study is to realize the on-site use of interferometers, and that fast GA processing is essential for this, priority has been placed on including a fast measurement system within the GA design. Emphasis has also been given to the design of the fitness function, so that even slight discrepancies will be adjusted for to achieve precise alignments. The Minimal Generation Gap (MGG) model [5] is introduced to the genetic operations, as this is excellent at maintaining diversity to avoid local solutions, while still converging on an optimal solution.

In this section, we outline the acceleration of interferogram measurement, which is an important feature of our GA design, as well as describing the design of the fitness function, the genetic operations and finally the development of a compact mirror holder with a dependent adjustment structure for fine control by utilizing a GA.

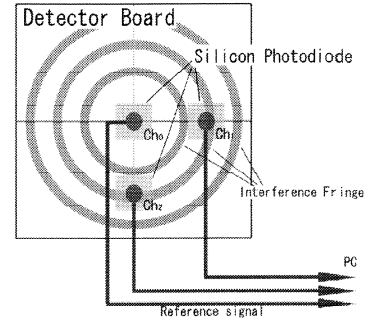


Figure 5: Developed Detector Board for Fitness.

3.1. Measurement acceleration

The usual method of evaluating an interferogram is by taking an interference fringe, often in the form of a CCD camera image, and calculating the deviation from an optimal pattern by image processing a method that requires at least some milliseconds of processing. We have attempted to accelerate the evaluation process by designing a specialized board for interferogram measurement, which has the following design features and structure.

When an interferometer is correctly aligned, the center of a fringe is in the light path and the fringe forms a clear pattern of concentric circles, as shown in Fig.4 (a). In contrast, when the components are misaligned, the center will deviate from the light path and the pattern will be distorted, as in Fig.4 (b).

We have developed a method of measuring 3 points on a fringe image, by locating 3 silicon photo-detectors on a special board, positioned at the center (Ch_0), on the horizontal axis (Ch_1) and on the vertical axis (Ch_2) as shown in fig.5. By calculating fitness values based on the light intensities at the 3 detectors, it is possible to accelerate GA processing.

3.2. Fitness calculation

The fitness function has been designed to achieve the following 3 objectives.

1. Reduce the light intensity at the center of the interference fringe.
2. Align the center with the light path.
3. Include even slight differences for light intensities in fitness calculations.

This function is formulated as:

$$Fitness = \frac{\alpha}{Ch_0} - \beta \log(1 + |Ch_1 - Ch_2|) \quad (1)$$

where, Ch_0 , Ch_1 and Ch_2 represent the outputs from the photo-detectors (shown in Fig.5), and α and β are constants.

The first term in Eq.1 achieves the first objective of reducing the light intensity at the center, Ch_0 . The second term reflects the second objective of reducing any differences in the intensities at Ch_1 and Ch_2 . The third objective is realized by using Ch_0 as a denominator in the first term and by logarithmic conversion of the differences between Ch_1 and Ch_2 in the second term, so that even slight differences, which are otherwise lost as noise, are accentuated.

3.3. Genetic Algorithms (GA)

Fig.6 shows a flowchart of the proposed automatic adjustment method using GA.

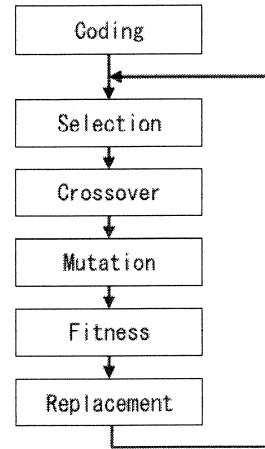


Figure 6: Flowchart of Alignment based on GA.

1. GA chromosome coding

A chromosome consists of 3 genes, which correspond to the positions of the 3 actuators (utilizing the piezo effect) that adjust the positioning of the fixed mirror, $M1$. The initial values for these genes are randomly assigned values between $-L$ to $+L$, where L represents the range of the actuators. A population of chromosomes will have N_p individuals.

2. Selection

Two individuals, referred to as parents (A and B), are selected at random from a set of chromosomes, and undergo genetic operations.

3. Crossover

Crossover is an operation that produces two children, A' and B' , from the selected parents, A and B . The operation used in this application is uniform crossover, where A' and B' are created from A and B and where the genes in A and B are exchanged with a probability P_c .

4. Mutation

Each child, A' and B' , undergoes mutation whereby its genes are partially altered. The mutation used here is a normally distributed random-number type of mutation [6] that creates new genes, X'_j ($j = 1, 2$ or 3), from the genes X_j according to the following formula

$$X'_j = X_j + \sigma N(0, 1) \quad (2)$$

where, $N(0, 1)$ denotes a normally distributed random number with a mean of 0 and a standard deviation of 1. σ is a constant and the probability of mutation is P_m .

5. Fitness

Fitness has three steps: (1) Moving three actuators of a mirror holder according to new chromosome, (2) Measuring interference fringe, and (3) Fitness calculation using Eq.1. In each generation, these steps are run twice each new two chromosomes (A' and B').

6. Replacement

After completing fitness calculations for A' and B' , a replacement operation replaces the parents A and B with the two individuals that have the highest fitness values among A , B , A' and B' . Although the MGG model cited in the references replaces the individual with the highest value and one of the remaining chromosomes, for simplicity, we take the two individuals with the highest values for replacement.

By repeating this cycle of operations, the fitness value will be maximized and the optimal positioning for the mirror will emerge. The GA terminates after calculating a fitness function G times.

3.4. Compact mirror holder

Because of the staging used with conventional mirror holders for independent adjustment, it is difficult to make them more compact. We have designed a new holder that eliminates the need for staging, making it more compact. The new holder incorporates 3 adjusting mechanisms ($AC4$, $AC5$ and $AC6$) that are capable of moving simultaneously, as shown Fig.7 (a) and (b). The structure of this holder consists of 3 adjustment parameters which are interdependent and control for rotation, tilt and focusing position.

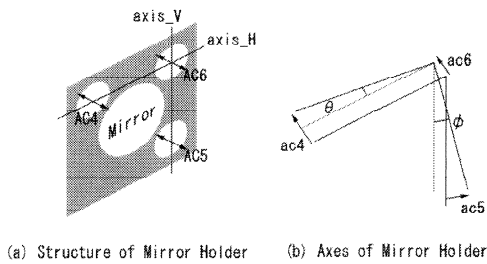


Figure 7: Interdependent axes of new Mirror Holder.

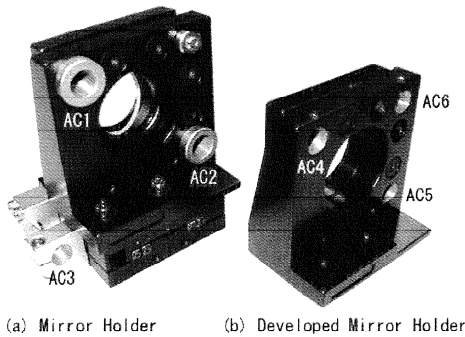


Figure 8: Photograph of the Mirror Holders.

Although it is not possible to align mirror holders of this kind of complexity either manually or by conventional automatic adjustment mechanisms, by employing GA to search for the optimum values for these interdependent parameters, we are able to realize a new compact mirror holder.

Fig.8 shows both the conventional mirror holder (a) and the new holder (b). With 3 adjustment mechanisms integrated within the frame, the new holder is more compact because it does not require a conventional staging.

4. HILL-CLIMBING SEARCH METHODS

In this section, we briefly describe 2 kinds of search methods, Hill Climbing (HC) and Random Start Point Hill Climbing (RSHC), which we have used as comparisons for our GA-based alignment method.

HC is the simplest search method, and can serve as a good comparison for assessing the effectiveness of GA as a multiple solution search approach. However, because the results of HC are greatly dependent on its starting position, it is somewhat difficult to make direct comparisons with GA, which involve randomly-generated initial populations,

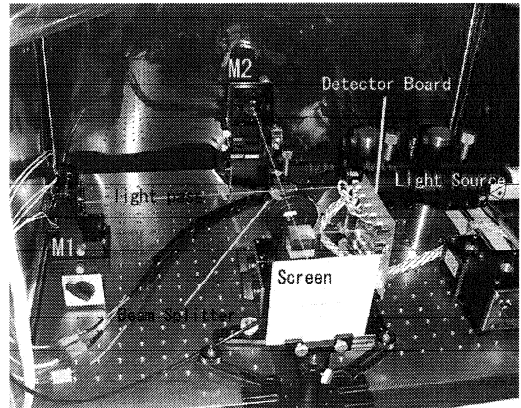


Figure 9: Photograph of the Developed Michelson Interferometer.

so in our comparisons, we have also used RSHC, which is more similar to GA in having a randomly-generated starting point.

5. ADJUSTMENT EXPERIMENTS

5.1. Experiment system

The experiments were conducted with the automatically adjusted Michelson interferometer system shown in Fig.9, 10, which consists of a light source, an interferometer, 3 detectors (on the detector board), a controlling PC, an actuator controller, 3 actuators (integrated into the frame of *M1*) and mirror holders.

The light source is a He-Ne gas laser with a wavelength of 633nm made by JDS Uniphase. The detectors are silicon photo-diodes, TSL252 Texas Instruments, with a noise level of 0.001Vrms. The optical components for the interferometer were made by SIGMA KOKI CO. and the 3 piezo-actuators were made by Tokin. The actuator controller is an EAP-15013 by Echo Electronics.

Two kinds of adjustment experiments were conducted using the system: (1) with a conventional mirror holder and (2) with the developed compact mirror holder. Comparison experiments were conducted where adjustments were made either by HC, RSHC or by GA for two experimental settings; using either (1) a conventional mirror holder or (2) the developed compact mirror holder. In each experiment, the initial position of *M1* was roughly set by a technician.

The search parameters in these experiments were $N_p = 10$, $L = 1094steps$, $P_c = 0.5$, $P_m = 0.5$, $\sigma = 20steps$, $\alpha = 20$, $\beta = -15$ and $G = 610$, which were determined through preliminary experiments. In comparing the three search methods, the best trial out of N_p trials was used for

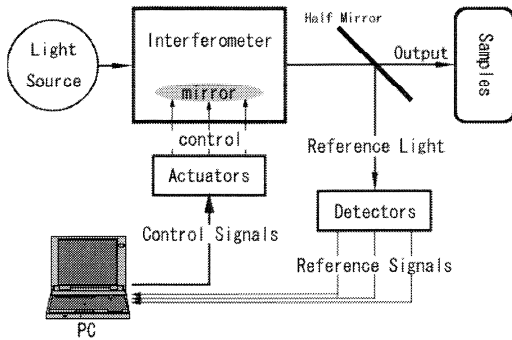


Figure 10: The Developed Michelson Interferometer System.

the HC and RSHC methods, in order to equate for the GA population size. In this way, the number of fitness calculations was the same for all three methods.

5.2. Experiment 1, using conventional mirror holder

The results of Experiment 1 are presented in Table 2, which shows that the GA yielded the best performance. The differences between HC and GA demonstrates the effectiveness of the multiple solution search approach, which was undisturbed by noise. Clearly, the poor results for HC in comparison to the GA and RSHC indicate how dependent this method is on its starting point.

Fig.11 shows how adjustment proceeded for the various methods. The poorer performance for HC suggests that this method has problems with avoiding local minimum and is greatly dependent on its starting position. Search methods that can avoid existing local minimums are likely to be more effective for interferometer alignment. Looking at the GA performance after 2 minutes (about 420 iterations), clearly this is superior to the other two methods.

Table 1: Alignment Results for the Experiment 1.

Fitness	AVE	MAX	MIN	STD
GA	7.46	7.89	6.80	0.30
Hill Climbing	5.23	6.80	3.16	1.42
RSHC	6.88	7.77	5.09	0.79

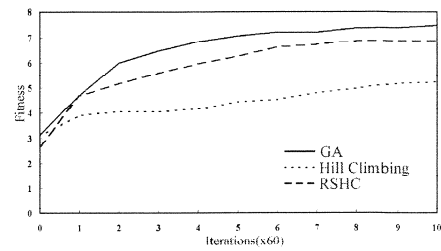


Figure 11: Fitness Versus Iterations for the Experiment 1.

5.3. Experiment 2, using the developed compact mirror holder

Table 2 and Fig.12 show the average adjustment performance for 10 trials. Despite the greater difficulties in adjusting for the interdependent structure of this holder, the GA performed extremely well. This shows that it is possible to make mirror holders more compact with our proposed GA-based adjustment method. In comparison with the other two methods, the deviation was less, indicating that GA is not influenced by noise.

Fig.12 shows that the convergence performances for HC and RSHC were much lower than in Experiment 1. This reflects the difficulties these two methods had due to the interdependent structure of this holder. Fig.12 presents fringe images: (a) is before alignment in Experiment 2, with (b) showing the results of the GA, (c) the results of HC, and (d) the results of RSHC. This figure shows that only the GA was able to satisfy the two objectives of (1) reducing light intensity at the center and (2) of aligning the center with the light path, whereas RSHC could only satisfy objective (1) and HC could satisfy neither. These results demonstrate that GA functions well, and that the fitness calculation, discussed in Section 3.2, is well design to achieve its objectives.

6. CONCLUSIONS

In this paper, we have described a method for the automatic adjustment of Michelson interferometers using a GA and a compact mirror holder, which has been newly developed for automatic adjustment.

Table 2: Alignment Results for the Experiment 2.

Fitness	AVE	MAX	MIN	STD
GA	7.24	7.41	6.87	0.17
Hill Climbing	3.09	4.59	2.45	0.73
RSHC	6.47	6.92	5.81	0.34

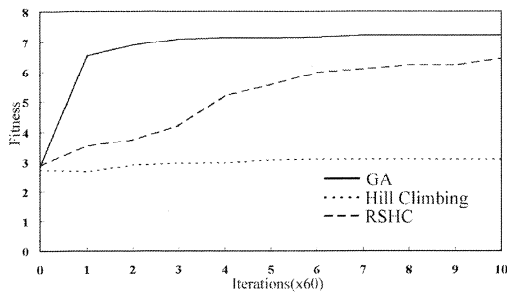


Figure 12: Fitness Versus Iterations for the Experiment 2.

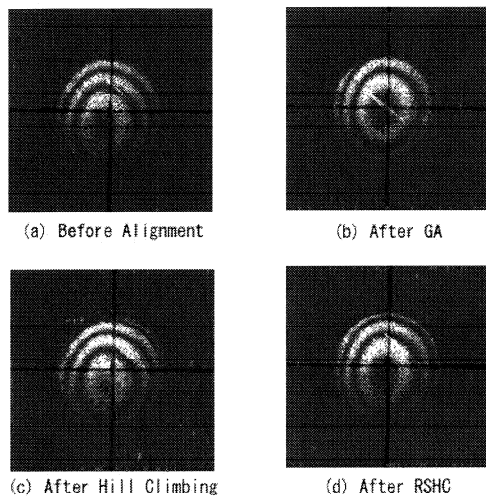


Figure 13: Interference Fringes for the Experiment 2.

With the proposed method, we have been able to realize an automatically-adjustable Michelson interferometer system, which is capable of adjusting for the large misalignments that might arise at setting and previously had to be adjusted for by technicians, in a practical time of approximately 3 minutes in our experiments. Comparison with two other methods of HC and RSHC confirmed the effectiveness of the GA-based method. This method should make it possible to realize the on-site use of ultra-trace analysis instruments, for which demand has been increasing recently.

One area for future investigation is the evaluation of this system in more realistic environments, such as being used as spectroscopic analyzers for Fourier-transform infrared spectroscopy, in terms of GA parameters. Another area to examine is the use of different crossover methods in order to accelerate even further alignment times.

The alignment method discussed here in terms of its

application in adjusting Michelson interferometers also has great potential for other optical systems, such as femto-second laser systems [7] and fiber alignment systems.

Challenging the notion that conventional system should be solid, heavy and immobile in order to avoid the need for readjustment, our adjustment method represents a new way of designing optical systems that can be characterized by their flexibility, lightness and portability.

7. REFERENCES

- [1] A. A. Michelson, *Philos. Mag.*, 31 (5), 256 (1981)
- [2] P. R. Griffiths: "Chemical Infrared Fourier Transform Spectroscopy", John Wiley & Sons (1975)
- [3] R. J. Bell: "Introductory Fourier Transform Spectroscopy", Academic Press, New York (1972)
- [4] D. E. Goldberg: "Genetic algorithms in search, optimization", and machine learning, Addison Wesley (1989)
- [5] H. Satoh, M. Yamamura, and S. Kobayashi: "Minimal Generation Gap Model for GAs Considering Both Exploration and Exploitation", *proc. 4th International Conference on Soft Computing (IIZUKA96)*, pp. 494-497 (1997)
- [6] H. P. Schwefel: "Evolution and Optimum Seeking", John Wiley & Sons (1995)
- [7] M. Murakawa, T. Itatani, Y. Kasai, H. Kikkawa, and T. Higuchi: "An Evolvable Laser System for Generating Femtosecond Pulses", *Proc. the Genetic and Evolutionary Computation Conference (GECCO2000)*, pp. 636-642 (2000)