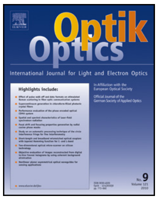
Optik 125 (2014) 5618–5621

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo



Design of multilayer high-dispersion mirrors using multi-swarm optimization method

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ARTICLE INFO

Article history:
Received 19 October 2013
Accepted 16 May 2014

Keywords:
Thin film filters
Particle swarm optimization
Multi-swarm optimization
Dispersive mirror

ABSTRACT

Design of high-dispersion mirrors (HDMs) using a proposed multi-swarm optimization method is reported. We design HDMs for Yb:YAG disk oscillator at 1030 nm and ultrashort pulse Cr:YAG laser at 1550 nm. The results show that the optimum group delay dispersion and reflectance can be obtained with optimal number of layers. The proposed optimization method has a fast convergence rate and powerful global search ability and can be utilized effectively for the design of a variety of optical thin film filters.

1. Introduction

Optical multilayer filters and coating are very important elements in optics and photonics. There are many optical functional devices that operate based on these elements. Thin film elements with special spectral amplitude and phase properties including reflection-induced phase retarders and dispersion compensators have found important role in femtosecond lasers and optical communications [1]. In ultrashort pulse laser technology, the main limitation of generating short pulses is pulse broadening due to dispersion of gain-generating materials like Ti-sapphire [2]. These laser systems generate pulses with high energy and broad bandwidth that can be compressed by employing proper dispersion compensation elements and techniques. Generation and compression of ultrashort pulses has been a basic research area in optics and laser physics. Various elements like grating compressor, prism, pulse shaper utilizing an adaptive light modulator and compressor with dispersive mirror (DM) can be used for this purpose [3]. Comparison of these four devices shows that the prism and grating compressor have a limited bandwidth and adaptive pulse shaper increases the complexity of optical system and limits the maximum of pulse energy. In contrast, DM can have broad spectral band, does not limit the output pulse energy, and has a compact structure. These properties make them a good choice for dispersion compensation. Dispersive mirrors usually provide high level of group delay dispersion (GDD) (higher than 1000 fs^2) in a relatively narrow wavelength band, however, their counterpart that is chirped mirrors (CM) can operate in wider bands. DMs and CMs are now the key elements for laser systems with ultrashort pulses such as Ti:sapphire at 800 nm and Yb:YAG at 1030 nm. Recently, mode-locked laser systems have been investigated for operation over the infrared optical communication band at 1300 and 1500 nm like Cr:YAG laser with tunable outputs adjustable between 1350 and 1550 nm [4].

Design of a multilayer thin film structure with desired spectral amplitude and phase properties is usually a relatively difficult task. In particular, design of a DM for exact dispersion compensation over a particular spectral range (specially for ultrashort pulse laser systems) is a huge challenge [5–8]. In this regard, optimization techniques for thin film filters are being developed. It is clear that faster algorithms can reduce computer run time from days to hours. Finding thin film filters with less number of layers is a very important issue directly related to the technical limitations of mirror fabrication processes. Also, reducing the number of layers decreases the probability of error associated with the layer deposition process. During the last 18 years, different algorithms like genetic algorithm (GA), needle optimization method and the others have been used in designing dispersive and chirped mirrors [9,10]. One of the evolutionary algorithms that have had a few applications in thin film filter optimization is particle swarm optimization (PSO).

In this paper a multi-swarm optimization technique based on PSO is proposed to design two high dispersive mirrors for femtosecond chirped pulse amplifiers and oscillators (Yb:YAG disk oscillator at 1030 nm and ultrashort pulse Cr:YAG laser at 1550 nm). In these designs, the desired reflectance (R) and GDD are considered to be

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http://dx.doi.org/10.1016/j.ijleo.2014.07.043

>0.99 and −2200 fs^2, respectively, and are optimized concurrently using the proposed optimization technique.

2. Optimization/design method

As mentioned, finding a robust method with optimal solution in designing dispersive mirrors can be very difficult. Methods such as needle optimization and gradual evolution have had relative successes in this field [9,10]. Regarding the literature, PSO algorithm is rarely employed in optimization of thin film structures especially in case of simultaneous amplitude and phase response optimization. In [9], by combining a time-domain method and needle optimization and introduction of a new fitness function, a DM has been designed. Also in [10], by using a combination of the needle optimization and the gradual evolution algorithms, high-dispersive mirrors (HDMs) for chirped-pulse amplifiers and oscillators have been realized. In [11], memetic algorithm, i.e., a kind of improved genetic algorithm, was introduced to optimize chirped mirrors. One of the studies that has used PSO algorithm in designing DMs was reported by Luo and colleagues in 2010 [12] and the other one has been reported by Baedi and colleagues [13]. The noticeable issue in these articles is that the number of layers is fixed. In addition, in the second report, PSO is utilized only for amplitude optimization (reflectance and transmittance). In the aforementioned article, three methods of GA, PSO and flip-flop are compared and it is concluded that the PSO method has better convergence rate. Therefore, by firstly considering PSO as a powerful optimization method for designing optical thin film filters especially DMs and CMs, and secondly, since it has been little focus on the number of layers as an optimization parameter in using PSO method, we propose a multi-swarm optimization technique based on PSO to design thin film filters.

PSO is an optimization method that is based on population with probabilistic behavior. Also, this algorithm is in the class of evolutionary algorithms, like GA algorithm. This algorithm has found applications in many areas of engineering and optics [14,15]. PSO was introduced in 1995 by Kennedy and Eberhart for the first time [16]. After that, a variety of techniques based on this algorithm have been introduced [14]. In this method, there are a number of particles in the swarm. Each particle is considered as a point in an N-dimensional search space. The position of each particle in the swarm is represented by an N-parameter vector given by $X_m = \{x_{1m}, x_{2m}, \ldots, x_{Nm}\}$. In this expression, m is an integer and shows the position of the particle in the swarm. Each particle adjusts its movement according to its own experience as well as the experience of other particles. Like all evolutionary optimization techniques, PSO uses fitness (merit) functions to numerically evaluate the quality of the particles. The algorithm initiates by randomly locating particles moving with random velocities. Velocity is the rate of a particle's position change and is represented by $V_m = \{v_{1m}, v_{2m}, \ldots, v_{Nm}\}$. The modification of the particle's position in $(k+1)$th iteration in the standard PSO (also sometimes known as adaptive PSO (APSO)) can be modeled as [14]:

$$\begin{aligned} V_m^{k+1} &= wV_m^k + c_1 rand_1()(P_m - X_m^k) + c_2 rand_2()(G - X_m^k), \\ X_m^{k+1} &= X_m^k + V_m^k \end{aligned} \tag{1}$$

In the above equations, V_m^k is the velocity of mth particle in kth iteration, w indicates inertia weight function (linearly drops from 0.7 to 0.4 during the optimization process), c_1 and c_2 are local and global acceleration functions, $rand()$ represents a uniformly distributed random number between 0 and 1, P_m is the best position of the mth particle in its search history and G is the best position ever found in the swarm's history [14,15].

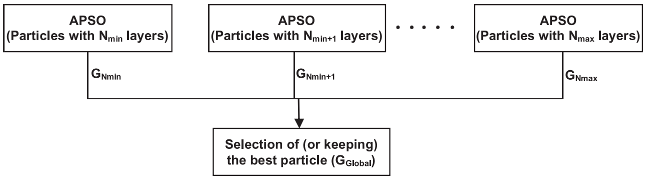

Fig. 1. Diagram showing the basics of the proposed MSO method.

The main optimization parameters of thin films are the number of layers, thicknesses, refractive indices and extinction coefficients of incidence and substrate media and the individual layers. Note that there are economic and technical restrictions on the number of layers which are the cost of the multilayer filter production and the probability of random error grows with increasing number of layers. Therefore, it is very useful to find optimum designs with fewer layers. In our mirror design problem, instead of fixing the number of layers (like previous reports [12] and [13]), the maximum and minimum allowed number of layers is assumed constant and hence more degrees of freedom are provided. One of the concerns in using PSO in practice is to keep the moving particle inside the specified search space by applying appropriate boundary conditions. To do that, we use the method of absorbing walls [14].

We employ multi-swarm optimization (MSO) method to design dispersive mirrors in this paper with considering number of layers as an optimization parameter. It is assumed that the optimal filter has number of layers in range of 35–65. In this multi-swarm optimization method, there are number of swarms each corresponding to a layer number. To further explain, we generate first swarm consisting of particles with $N_{\min}$ layers (minimum number of layers), second swarm with $N_{\min+1}$ layers and so on until the last swarm with $N_{\max}$ layers (maximum number of layers). In our design, each swarm includes 30 particles and the velocity of particles in each swarm has been updated independently using Eq. (1). After running PSO algorithm and obtaining the best particle for each swarm (G_{Ni}), the best overall particle is selected and saved (G_{Global}). The optimization process is ended if the maximum allowed iteration is reached or the desirable fitness function value is obtained. Fig. 1 schematically illustrates the concept of the proposed MSO.

The fitness function of the MSO optimization is similar to the one proposed in [12] which is defined as:

$$\begin{aligned} FF = {} & \sum_{\lambda} W_R(\lambda) \left[\frac{R(\lambda) - R_{target}(\lambda)}{R(\lambda)} \right]^4 \\ & + \sum_{\lambda} W_{GDD}(\lambda) \left[\frac{GDD(\lambda) - GDD_{target}(\lambda)}{GDD(\lambda)} \right]^2 \end{aligned} \tag{2}$$

where λ is the wavelength, R (GDD) and R_{target} (GDD_{target}) are calculated and desirable reflectances (GDDs), respectively. W_R and W_{GDD} are the optimization weighting functions.

3. Results and discussion

Two designs are presented in this section. In the first part, we design a HDM in the spectral range of 1022–1038 nm with application in Yb:YAG disk oscillator. Yb:YAG laser is a tunable laser with tuning range of 680–1100 nm. It is one of the most useful media for high-power diode-pumped solid state lasers. In our design, desired reflectance is as high as possible (>99%) and GDD = −2200 fs^2 (similar to the one in [10]). We developed Matlab codes both for analysis and optimization of the proposed multilayer thin film structures. Fig. 2 shows the spectral reflectance and GDD of the designed HDM which has 49 layers obtained for 50 iterations. In addition to reflectance and GDD graphs, the best merit function value has