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Starting designs for broadband chirped mirrors

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Abstract. The chirped mirror (CM) is one of the key elements in ultrafast optics. We investigate a problem of a CM designing. The series of starting designs for broadband CM are reported. The appropriate starting design can significantly simplify a problem of design searching, and improved a performance of a final solution. The acceptable performance of CM was achieved by optimization one of the proposed starting design. The achieved design has comparable performance in comparison with the best design which was realized up to now.

Keywords: ultrafast optics, chirped mirrors.

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1. Introduction

In recent decades, femtosecond lasers were significantly developed [1-3]. One of the key elements in femtosecond laser systems is a chirped mirror (CM). One has to control both the reflectivity and group delay dispersion (GDD) (the second deviation of the phase in a frequency domain). Since invention of CM mirrors in 1994 [4], 14 years has already passed. In previous years, CM performance was considerably improved: the wavelength bandwidth – increased, the GDD comes closer to desired values [5-11]. As usually, in thin film optics, to solve such an inverse problem one employed mathematics optimization algorithms to find one of local minima, because analytical solution of this problem is impossible [12-16]. Unfortunately, the local minima are often insufficient solution. Most of modern optimization algorithms cannot jump from one local minimum to another. To overcome this problem, the starting design has to be changed and the optimization procedure has to be launched again. Due to complication of CM designing, the modern computer to optimize one of the starting designs needs from tens of minutes to several hours. Therefore, a proper starting design may save hours, and what is more important allows us to find a design, which has better performance. In this paper, being based on performances of symmetrical and classical multilayer structures, we demonstrate a way in which one can obtain an appropriate design. The different designs were considered. The most valuable of them are reported. One of the designs was optimized with a modern algorithm to demonstrate efficiency of our approach.

2. The calculation of spectral characteristics of multilayer structures

In the case, when basic parameters of multilayer structure are known (q is the number of layers, n_r - refractive index, k_r – extinction, d_r – thickness for each layer, and k_m – substrate optical constants, n_0 and k_0 – optical constants of external media, θ_0 – angle of incidence), we calculate the spectra of reflection, transmittance, phase changes both for reflection and transmission, and, respectively, the group delay, group delay dispersion can be calculated. Using the matrix method [17], we can write:

The reflection is

$$R = \left(\frac{\eta_0 B - C}{\eta_0 B + C}\right)\left(\frac{\eta_0 B - C}{\eta_0 B + C}\right)^*, \qquad (1)$$

the phase change is

$$\text{tg } \phi = \frac{\text{Im}\left[\eta_0\left(CB^* - BC^*\right)\right]}{\left(\eta_0^2 BB^* - CC^*\right)}. \qquad (2)$$

Where the characteristic matrix of the assembly is

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left(\prod_{r=1}^{q} \begin{bmatrix} \cos\delta_r & (i\sin\delta_r)/\eta_r \\ i\eta_r \sin\delta_r & \cos\delta_r \end{bmatrix}\right)\begin{bmatrix} 1 \\ \eta_m \end{bmatrix}, \qquad (3)$$

the phase thickness of the layer r is

$$\delta_r = \frac{2\pi N_r d_r \cos\theta_r}{\lambda}, \qquad (4)$$

the layer admittances are

$\eta_r = \chi_{vac} N_r \cos\theta_r$ for TE waves or
$\eta_r = \chi_{vac} N_r / \cos\theta_r$ for TM waves, (5)

$\eta_m = \chi_{vac} N_m \cos\theta_m$ for TE waves or
$\eta_m = \chi_{vac} N_m / \cos\theta_m$ for TM waves, (6)

where λ is the wavelength, $N_r = n_r - ik_r$, χ_{vac} = $2.6544\cdot10^{-3}$ S – vacuum admittance, η_0 and η_m – external and substrate admittances, respectively.

The values of θ_r can be found from Snell's law

$$N_0 \sin\theta_0 = N_r \sin\theta_r = N_m \sin\theta_m . \quad (7)$$

The group delay is

$$GD = -\frac{d\phi}{d\omega} = \frac{\lambda^2}{2\pi c}\cdot\frac{d\phi}{d\lambda}, \quad (8)$$

where ϕ is given in the equation (2), c = $3\cdot10^8$ m/s is the speed of light.

The group delay dispersion is

$$GDD = -\frac{d^2\phi}{d\omega^2} = -\frac{\lambda^2}{(2\pi c)^2}\cdot\left(\lambda^2\frac{d^2\phi}{d\lambda^2} + 2\lambda\frac{d\phi}{d\lambda}\right) \quad (9)$$

3. The starting designs - results and discussions

To investigate the influence of layer thickness changes in CM, it was chosen a starting multilayer structure (SMS) with the high reflection (as high as 99.7 %) within the wavelength range 600 to 1200 nm. This wavelength range is equivalent to one optical octave. The SMS consist of three multilayer mirrors based on symmetrical periods, and its structures looks as shown below:

$$S(0.5H_0L_00.5H_0)^{15}(0.5H_1L_10.5H_1)^{15}(0.5H_2L_20.5H_2)^{15}S_0 , \quad (10)$$

where S_0 is the fused silica substrate (refractive index n_S = 1.4656 at the wavelength λ_0 = 1100 nm) and S is an external medium (air, n_0 = 1.0); H_0, H_1, H_2 and L_0, L_1, L_2 – the niobium oxide layers (Nb_2O_5, n_H = 2.2393 at the wavelength λ_0 = 1100 nm) and the silica dioxide layers (SiO_2, n_L = 1.4656 at wavelength λ_0 = 1100 nm), respectively. At simulation, the optical constants of magnetron sputtering thin films were used [5]. The optical thicknesses of layers are equal:

$$n_{H_0} d_{H_0} = n_{L_0} d_{L_0} = 0.77273\, n_{H_1} d_{H_1} = 0.77273\, n_{L_1} d_{L_1} = 0.59091\, n_{H_2} d_{H_2} = 0.59091\, n_{L_2} d_{L_2} = \lambda_0/4 = 275\text{ nm}. \quad (11)$$

The reflectivity and GD of these structures are shown in Fig. 1. Three wavelength ranges with different GD characteristics versus the wavelength are crearly defined at 780 and 1000 nm. The sharp picks in GD were obtained at passing ranges at the edge of a high reflection ranges and strong ripples are observed in various wavelength ranges. These spectral ranges are superposed with high reflection bands of each single mirror; its structures are determined in the expression (10).

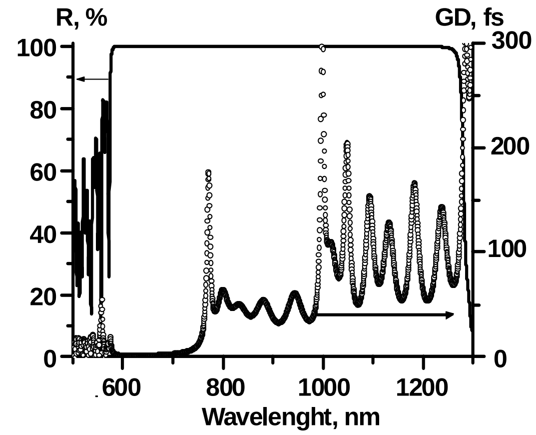

Fig. 1. Reflectivity and GD of multilayer structure $S(0.5H_0L_00.5H_0)^{15}(0.5H_1L_10.5H_1)^{15}(0.5H_2L_20.5H_2)^{15}S_0$.

The structure (10) has 91 layers, as selection of internal layers on the symmetrical periods is symbolical. How does thickness changes influence on the GD and is it possible to obtain a smooth-linear wavelength dependence of GD by monotonous? To answer, the reflectivity and GD characteristics for about 100 different structures were investigated. They consist of alternating of 91 Nb_2O_5 and SiO_2 layers. We conclude that GD is strong oscillating function inside of high reflection bands, when optical thicknesses monotonous are increased or decreased. In case of mismatch of external media and the last layer, GD oscillations can be reduced. Shown in Fig. 2 are GD characteristics of the multilayer structure with linear changes of optical thicknesses.

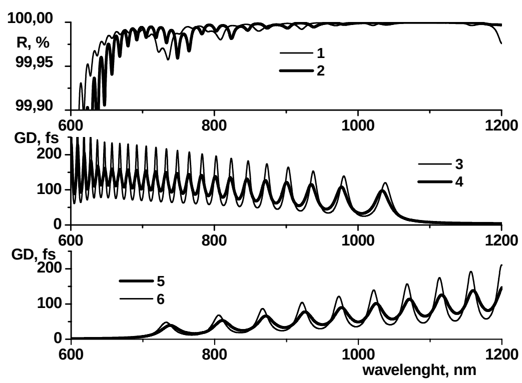

Fig. 2. Reflectivity (1, 2) and GD (3-6) of 91-layer structures with alternating Nb_2O_5 and SiO_2 layers (first and final layers are Nb_2O_5) on the fused silica substrate. Optical thicknesses are increased from $0.5\lambda_0/4$ to $1.15\lambda_0/4$, beginning from substrate (3, 4) and external media (5, 6). External media: air (3, 6), fused silica (4, 5).

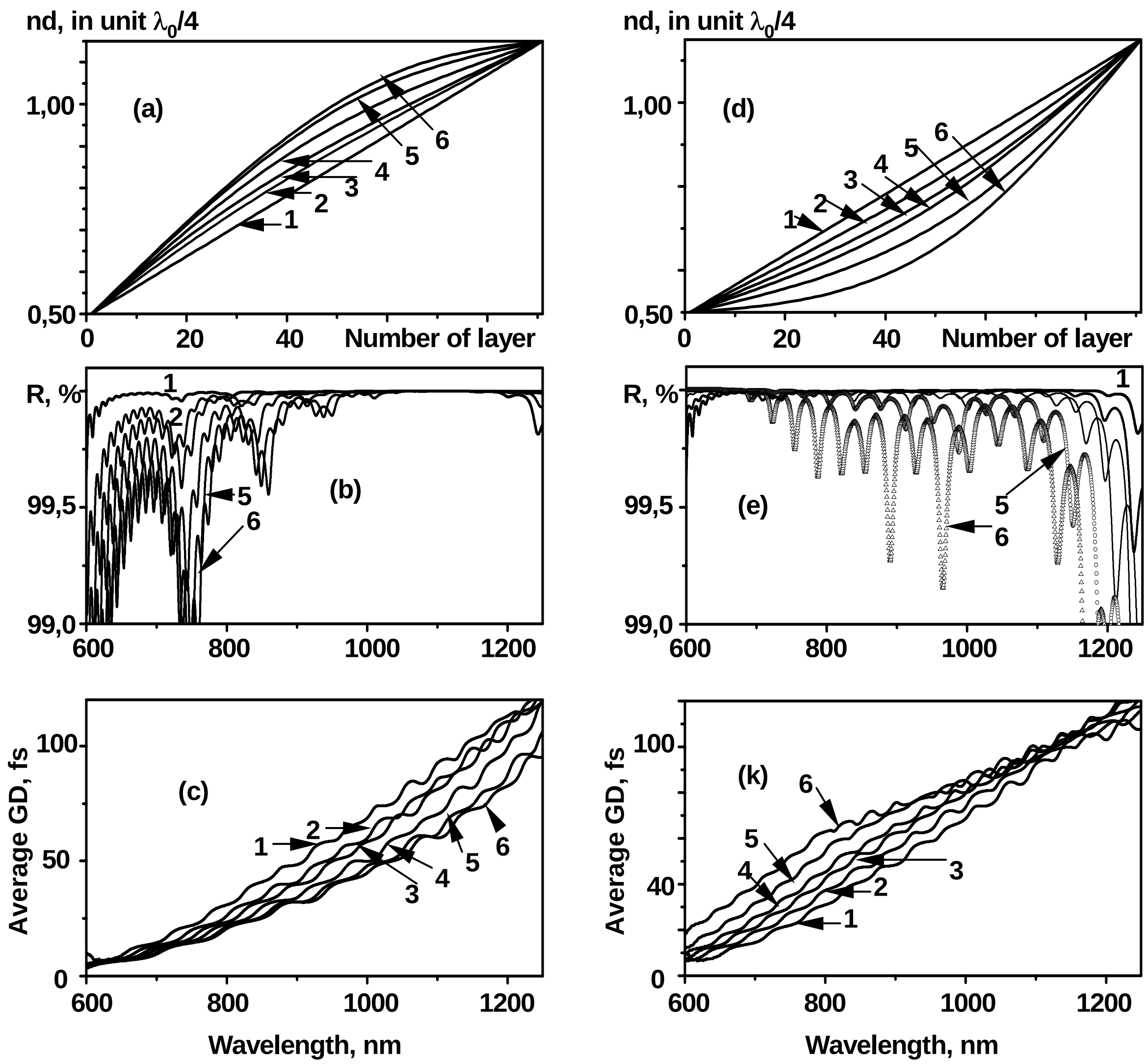

Fig. 3. The optical thicknesses of layers (a, d), reflectivity (b, e) and GD (c, k) of 91-layer structures with alternating Nb_2O_5 and SiO_2 layers.

Curves 4 and 5 in Fig. 2 correspond to structures on the fused silica substrate with external media of fused silica. In this case, in the structure significant mismatch with external media is observed, in contrast to the case when external media is air (curves 3 and 6). It is known that oscillations can be reduced by utilizing the complementary pair approach [6]. The average group delay is important characteristic, namely, this characteristic determines the total GD of the complementary pair of CM. So, to choose optimal initial optimization approximation, the structure with a similar average GD are required. To create CM with a negative group delay dispersion (GDD), it is necessary for GD to behave linearly. In the most modern laser schemes, the negative GDD is used to compress ultrashort pulses. Simulation results of optical properties for some structures with different dependences of optical thicknesses versus the layer number are shown in Fig. 3. In the wavelength domain, the linear thickness change provides us nearly a linear average GD (see Fig. 3). When a thickness change is decreased with the number of layers (layer number are counted from media of incidence), then an average GD is increased. And vice versa.

The structure, which has the GDD value closed to –80 fs^2, was chosen to be optimum. By uncomplicated homemade software the optimization procedure was performed. As target for optimization procedure, we used the reflectivity value as high as 100 % and the main value of GDD –80 fs^2. CM with –80 fs^2 GDD is often used in femtosecond laser systems to compensate the second order of dispersion. The designs before and after optimization are shown in Fig. 4. After the optimization procedure, GDD oscillations were significantly reduced. This design consists of 86 layers, what is less than respective starting design. This design has an optical

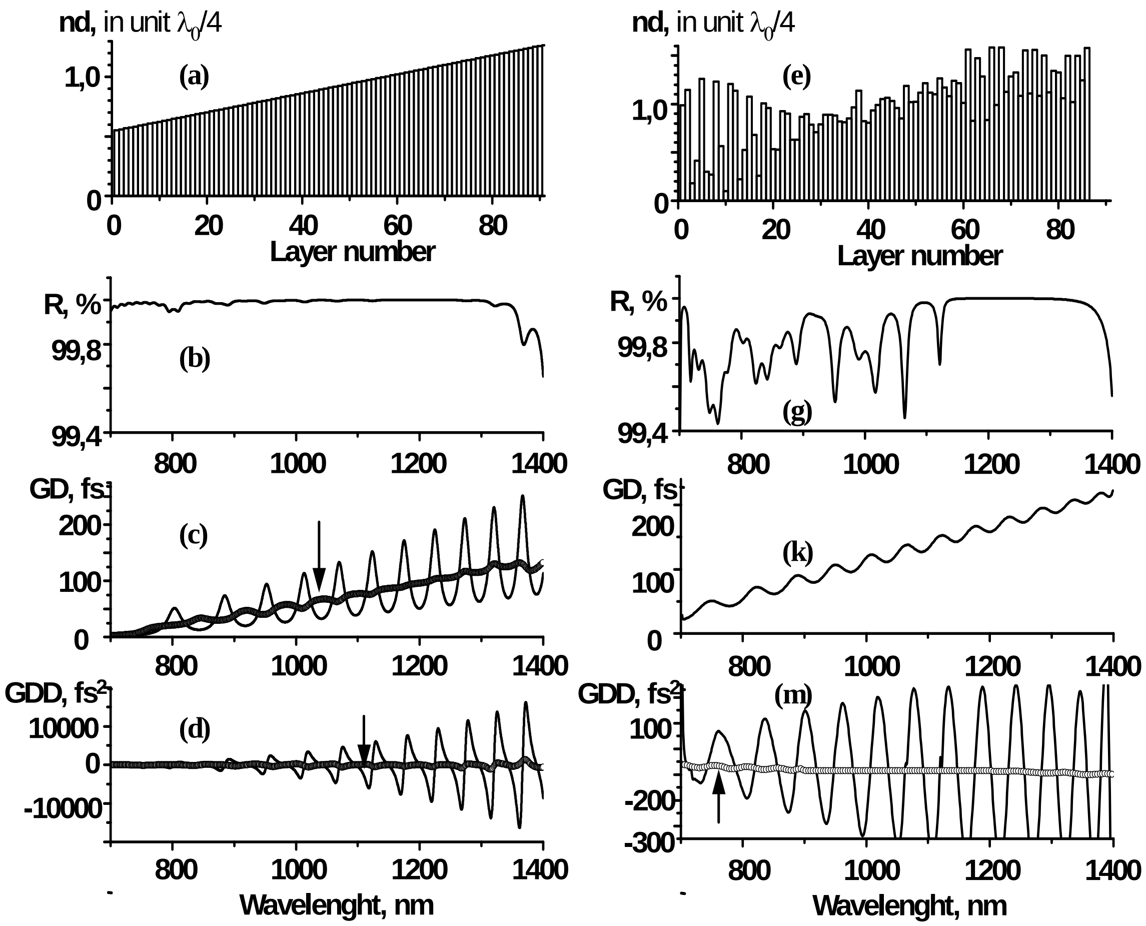

Fig. 4. Multilayer structures (a, e), reflectivity (b, g), GD (e, k) and GDD (d, m) of the starting design (a, b, c, d) and optimized one (e, g, k, m). Arrows show the average values of GD (c) and GDD (d, m).

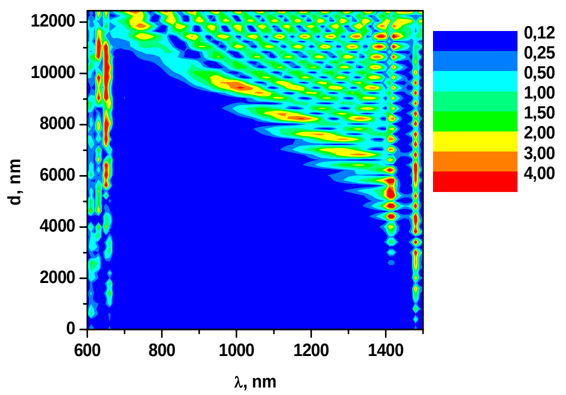

Fig. 5. Penetration of electric field through the multilayer structure of optimized CM. Parameters of CM are shown in Fig. 4. Light comes from the top of the figure. The electric field intensity is shown in the inset. *d* is the physical layer thickness, and λ is the wavelength.

performance comparable with the design reported [5]. Shown in Fig. 5 is penetration of electric field through the multilayer structure of the optimized CM. Parameters of this CM are shown in Fig. 4. Fig. 5 shows how the chirped mirror operates. The electric field components at 1400 nm penetrate much deeper into the multilayer structure than the components at 700 nm. This means that the longwave components become delayed relatively to the shortwave ones. Fig. 5 gives an additional hint for optimizing the design: the longwave components must penetrate almost down to the first layer on the substrate. If this is not the case in the design, several layers must be removed. In the opposite case, viz. when longwave components penetrate through the entire multilayer structure including the substrate, several layers must be added. This only applies to mirrors with a negative dispersion.

4. Conclusion

The proposed design can be successfully used as the starting one for CM manufacturing. Keep it in mind that

CM designing is challenging and important optical problem. Additionally, the designing procedure for one-octave CM (700-1400 nm) can take hours when using the modern computer equips Pentium 4 Xeon 3 GHz. Therefore, for standardization of the way for CM designing we proposed procedure and series of designs that can be utilized as the starting ones. At the same time, a proper starting design significantly accelerates designing the complicated CM and provides complicated solution even after minor-local optimization.

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