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Air-gap silicon nitride chirped mirror for few-cycle pulse compression

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We propose new design solution for broadband chirped mirrors. It consists in application of silicon nitride with air-gap interlayers. This proposal is the first application of silicon nitride to a chirped mirror, to the best of our knowledge. The proposed material combination allows to realize CMs supplying bandwidth from ultraviolet to near infrared. Using this idea we have made design of silicon nitride - air-gap chirped mirror for compression of few-cycles laser pulses in the near-infrared. Our CM provides high reflectivity and good dispersion properties in the wavelength range 400-1200 nm. Time domain analysis shows that designed CM allows to operate on few-cycles laser pulses.

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1. Introduction

Chirped mirrors (CMs) have been widely used for dispersion control in ultrafast optics; CMs are typically intended for use in intracavity dispersion compensation in femtosecond solid state lasers. Therefore, they are designed in the near-infrared wavelength range, where the Ti:Sapphire laser crystal has fluorescence. The typical bandwidth of CMs bounded at 400 nm of the spectral bandwidth supports the generation of sub-10-fs pulses [1]. However, recent applications of CMs, such as those operating on few-cycle pulses, require a broader bandwidth and more precise dispersion control [2; 3].

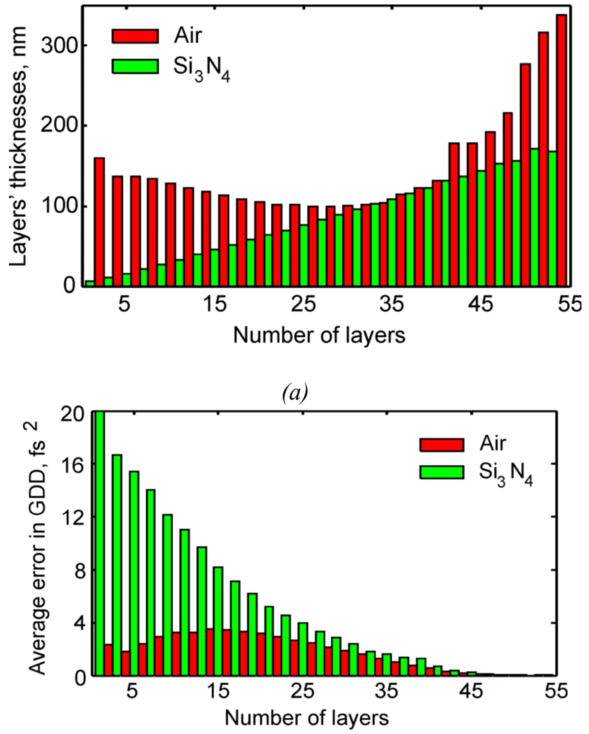
Titanium dioxide TiO_2 and silicon dioxide SiO_2 are commonly used for the fabrication of CMs in the wavelength range around 800 nm, owing to high refractive index contrast. However, TiO_2 does not support a broader bandwidth due to sizeable absorption below 500 nm; hence, new materials and design approaches are proposed [2, 3]. We have discussed the application of silicon nitride Si_3N_4 in the design of ultrabroadband CMs [4].

In this letter we propose new design solution consisting of the application of Si_3N_4 as an alternative high-index material to TiO_2, which combines with air-gap interlayers to form low-index layers. Note that Si_3N_4 has low absorption and a continuous refractive index in a wide spectral range [5], though Si_3N_4 has a smaller refractive index than TiO_2 (2.0 and 2.5 at 800 nm, respectively). Other proposed materials have the same problem. Since the contrast of refractive indices is important in achieving broadband reflection, air is a favorable solution for increasing the contrast due to its refractive index smaller than that of SiO_2. CMs based on the combination of Si_3N_4 and air-gap interlayers are capable of providing a bandwidth covering the range over the ultraviolet-visible-near infrared frequencies. Dispersion control inside this bandwidth is only limited by two factors pertaining to CM performance. First, the phase ripples rise with bandwidth expansion, requiring more complex and efficient methods for their suppression. Second, is increasing the number of layers in the CM design required to provide as wide bandwidth of high reflection as possible. However a progress in fabrication technologies allows to rise the complexity of CM design.

2. Proposed structure of the chirped mirror

In this letter, we present the design of an Si_3N_4-air-gap chirped mirror with 54 layers. This design has shown good reflective and dispersion properties in the wavelength range from 400 to 1200 nm. Moreover, subsequent analysis of the pulse compression shows that designed CM provides required dispersion compensation and pulse reconstruction. The simplest way to produce a CM is based on the linear modulation of a local Bragg wavelength (a Bragg mirror has a constant Bragg wavelength over the stack). However, such a simple design has a serious drawback; ripples of the reflection phase have the potential to distort the pulse shape and can even destroy pulse formation in the laser cavity. There have been proposed numerous methods to avoid this imperfection. Here, to eliminate the impedance mismatch we applied a double-chirped technique [1] to the structural design, which is realized via the modulation of the local Bragg wavelength and the thickness of the high-index layers (i.e., double chirp). But this method does not provide complete suppression of the phase ripples, so additional conjugate gradient method was then applied for numerical optimization.

Results of these procedures are shown in Fig. 1a), where the layer thickness profiles are depicted. Note that the first few layers close to the surface of the structure are rather thin; special care is required in the fabrication of these layers. Fig. 1b) presents the sensitivity of the mirror design to errors in layer thickness. To estimate this sensitivity, we calculated the average deviation of the group delay dispersion (GDD) from its theoretical value. In this way, the thickness variation of each layer was chosen to be 0.5 nm.



(a)

(b)

Fig. 1. Air-gap-Si_3N_4 CM design consisting of 54 layers. a) Layers thicknesses of designed CM. b) The average deviation (average error) of GDD from its theoretical value; the thickness variation of each layer is 0.5 nm.

In addition, from Fig. 1 (a) and (b) we can see that GDD reacts strongest to layer thickness variation of the thin layers of Si_3N_4 at the front of a CM, and deviations can be observed in some layers, with values ranging as high as 4-7 fs^2 from the prescribed dispersion value. Thus, it could be confirmed that the designed CM has moderate sensitivity to errors in layer thicknesses. Further methods of potentially decreasing the sensitivity of a CM design to thickness errors are desensitization procedures [6], in conjunction with other ways of controlling layer thickness during the growth process.

3. Numerical results and discussion

Spectral characteristics of the designed CM were calculated using a well-known transfer matrix method, traditionally used in the calculation of multilayer optical coatings. The calculated reflectance, group delay (GD), and GDD of the designed CM are shown in Fig. 2. The mirror's bandwidth covers the wavelength range from 400 to 1200 nm, supporting a reflectivity of over 98% in this range. The amplitude of GDD oscillations is about 80 fs^2, with a GDD value of about -17 fs^2 at 800 nm. In order to estimate the capability of the developed CM design, we performed an analysis of the pulse compression in the time domain [7; 8]. A sapphire crystal 2.0 mm in length was selected as the dispersion source; this is close to one pass in the cavity of a femtosecond laser intended for the generation of extremely short pulses.

This sapphire crystal produces a GDD value of 115 fs^2 at 800 nm. In order to compensate for such dispersion, eight reflections from the designed CM were used. The duration of the initial transform-limited Gaussian pulse was set at 5 fs (two periods of electrical field at 800 nm). This pulse was broadened after launching into the sapphire crystal. Subsequent pulse compression from the eight CM time reflections was calculated, resulting in the formation of the compressed pulse. Fig. 3 shows the waveforms of all mentioned pulses.

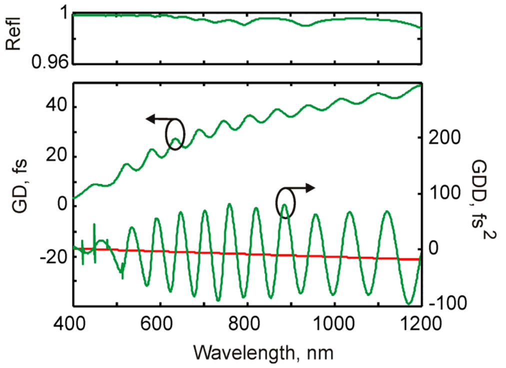


Fig. 2. Group delay and group delay dispersion of designed CM (green lines). Red line demonstrates approximating GDD line (undistorted). Top insertion shows reflectance of designed CM.

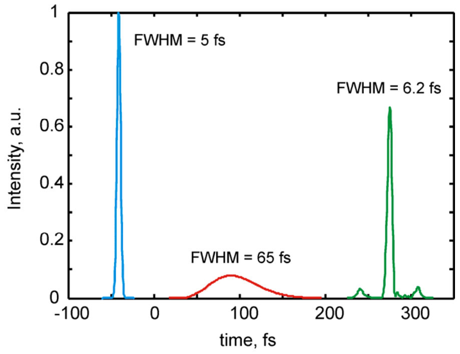


Fig. 3. Waveforms of initial transform-limited, broadened incident, and compressed reflected pulses.

Comparing the pulse shapes shows that compression with CM is rather strong but incomplete. The shape of the reflected pulse is close to a Gaussian one. However, its amplitude is smaller as compared to the initial transform-limited pulse arising from weak satellite pulses on both sides of the main pulse. This negative effect results from residual GD oscillations in the designed CM [9]. Thus, absolute pulse reconstruction requires more effective suppression of phase ripples in the design of the air-gap-Si_3N_4 CM. This problem can be eliminated using more complex global optimization algorithms or performing sophisticated CM designs, such as using a pair of CMs with spectrally-shifted dispersion ripples [10]. However, in spite of having a non-ideal reconstructed waveform, the quality of the compressed pulse is high. Figure 4 shows the Polarization Gate FROG trace calculated for the compressed pulse shown in Fig. 3. The FROG trace has an elliptical shape very similar to that demonstrated by a transform-limited pulse; there is no slope, suggesting that chirp is almost completely compensated for.

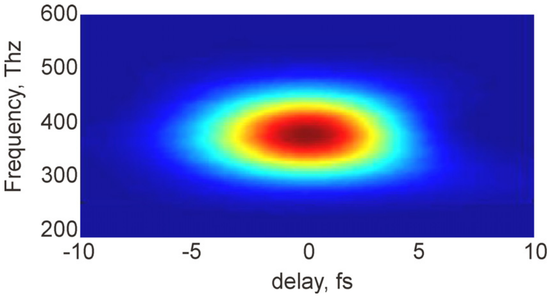


Fig. 4. Calculated PG FROG trace of compressed pulse shown in Fig. 3.

Fabrication of air-gap structures is possible using either vertical or lateral geometry. Vertical fabrication can be realized via the deep reactive ion etching of a bulk sample over a mask. 2D photonic crystals and DBRs for edge emitting lasers are fabricated in such a way, though various thicknesses and depths of semiconductor layers consisting of such DBRs have also been reported [11; 12; 13] depending on the laser structure and grating order required. Lateral implementation of air-gap structures allows for the creation of much thinner layers as it is possible to take advantage of different deposition techniques. In this case, a multilayer structure with sub-10 nm layers could be grown, with subsequent etching of the sacrificial layers used to create the air-gap structures. The mechanical stability of such structures is realized using supporting layers and constructions [14]. Therefore, this implies that air-gap-Si_3N_4 CMs are likely to find applications as ultrabroadband devices for dispersion compensation.

4. Conclusions

To conclude, we have proposed new design solution for the creation of ultrabroadband chirped mirrors capable of operating on few-cycle laser pulses. This proposal is based on application of Si_3N_4 with air-gap interlayers, and provides a potential CM bandwidth covering the range from ultraviolet to near infrared. Our concept has been illustrated through the optimized single-mirror design of air-gap-Si_3N_4 CM that provides high reflectivity and good dispersion properties in the wavelength range 400-1200 nm. The subsequent time-domain analysis of the pulse compression using the designed CM shows that our mirror provides good reconstruction for 5 fs, giving a pulse of 6.2 fs FWHM after eight bounces. This waveform analysis is supported by the calculated polarization gate FROG trace, which shows a good quality resultant pulse and virtually full chirp elimination, though it should be noted that the presented design solution can be further developed and improved.

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