Broadband thin-film polarizer for 12 fs applications

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Abstract: A broadband non-dispersive thin-film polarizer for ultrafast applications is presented. The polarizer has a controllable flat-phase and a high extinction ratio of 23:1 in the working bandwidth from 680 nm to 900 nm. This bandwidth allows supporting laser pulses down to 12 fs. The unavoidable mechanical stress of the interference coating is completely compensated by a specially designed antireflection coating on the second side of the substrate, allowing the use of thin substrates.

OCIS codes: (310.4165) Multilayer design; (310.1620) Interference coatings; (310.5448) Polarization, other optical properties.

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1. Introduction

Broadband thin-film optical coatings are an indispensable tool to advance the progress in ultra-short laser science. The technology plays a key-role in the generation and manipulation of few-femtosecond pulses. By providing octave spanning bandwidths and superior dispersion control at the same time [1–3], it enables intra-cavity dispersion compensation in few-cycle lasers [4] and facilitates external, nonlinear pulse compression [5,6]. These concepts enabled substantial advancement in attosecond science [7,8], but higher pulse energies are desired for further progress. Therefore high power laser sources, such as regenerative amplifiers [9] and optical parametric amplifiers [10] are currently under development. This novel trend will require broadband thin-film polarizers for separation, combination and power adjustment of high-power laser beams.

Here, we report on design and production of a polarizer which allows manipulating and controlling the polarization of the transmitted and reflected light. The extinction ratio of our non-dispersive broadband polarizer is at least 23. To our knowledge, in combination with the unprecedented bandwidth of 220 nm this is the best result reported so far. To achieve the high bandwidth and good extinction ratio of the dielectric coating an angle of incidence (AOI) of 75° was chosen. In Section 2, we describe in detail the design and production of the polarizer. In Section 3, the results for transmission/reflection, GDD and flatness measurements are presented. In Section 4, we perform a pulse simulation to demonstrate that the coating has nearly zero dispersion, which introduces no distortion to the phase of the pulse. In addition, we compensated the unavoidable bending of the substrate caused by state of the art high-precision sputter deposition processes. The deposited layers have strong intrinsic stress. This mechanical stress bends the substrate and therefore the beam profile of a reflected and transmitted laser beam is distorted. The fused silica substrate had a diameter of 25.4 mm and a thickness of 3 mm. For our polarizer we compensated the bending by depositing a very thick anti reflective coating on the back side. The latter allowed us to deposit the coating on even thinner substrates, that helps to avoid the significant and unavoidable group velocity dispersion of substrates for transmitted beams.

After two bounces on such a polarizer the extinction ratio is >530, and four bounces yield an extinction ratio of >280.000 with a total reflection of the main beam of at least 74%.

Our polarizer provides the possibility to improve the polarization or to split s- and p-polarized femtosecond pulses. In combination with a rotatable half-wave plate the polarizer can be used as a variable attenuator that allows continuous power control of ultrashort pulses. A thin-film polarizer is also used in regenerative amplifiers [9]. The pulse circulating in the cavity is coupled out after a defined number of roundtrips by a polarizer, a quarter-wave plate and a Pockels cell. The combination of a polarizer and a Pockels cell can be used to interleave two pulse trains of two regenerative amplifiers used in a multi-kilowatt, joule-class picosecond laser setup [10].

2. Design and realization of the polarizer

A thin-film polarizer might be designed for the Brewster angle, which is about 56° for fused silica. At the Brewster angle the p-polarized light has no reflection from the surface and therefore 100% of it is transmitted through an uncoated substrate, while the s- component is still reflecting. The ratio of the transmitted p-polarized T_p and s-polarized light T_s gives the extinction ratio. A thin-film polarizer coating increases this extinction ratio. However a standard thin-film polarizer has a limited bandwidth. To increase the bandwidth of the coating, which doesn't introduce noticeable dispersion to an ultrashort pulse, the coating design must be optimized with sophisticated methods. Besides the coating design two more details are important for a large bandwidth. The angle of incidence is increased to 75°. And we chose two coating materials with a high contrast in refractive index. The materials are

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niobium pentoxide (Nb_2O_5, n = 2.37 at 500 nm) and silicon dioxide (SiO_2, n = 1.47 at 500 nm).

The commercial software OptiLayer (from OptiLayer GmbH, Germany) was used to design the multilayer coating. Gradual evolution and needle optimization were employed [11–13]. The polarizing coating on the front side has 74 layers with a total physical thickness of 12.7 µm (Fig. 1, left). The thickest layer is made of SiO_2 with 1.19 µm and the thinnest layer is of Nb_2O_5 with only 17.2 nm.

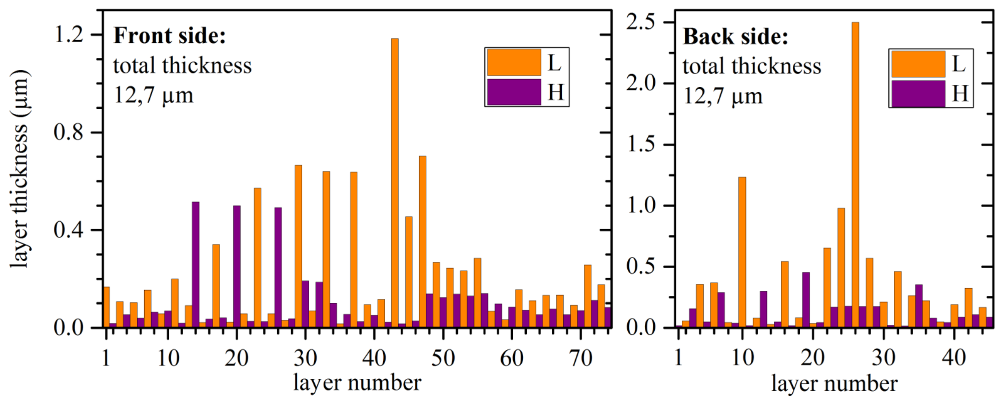

Fig. 1. Physical layer thicknesses for the polarizing coating on the front side (left) and the stress compensating antireflection coating on the back side (right).

The antireflection coating for the back side of the substrate (Fig. 1, right) has 45 layers. To compensate the mechanical stress of the front side coating, the total thickness of the antireflection coating was designed to be the same as of the front side coating [14]. Also the ratio of Nb_2O_5 and SiO_2 was chosen to be about the same, since the two materials have different stress tensors.

Magnetron sputtering was used for coating deposition because it produces high quality layers with high precision of the layer thicknesses. Well calibrated time monitoring combined with an optical broad band monitoring system for in situ transmission measurements was used to control the layer thickness. The model of the magnetron sputtering coating plant was Helios by Leybold Optics (Bühler AG, Switzerland).

3. Characterization of the polarizer

The polarization dependent transmission measurements (Fig. 2) for an angle of incidence of 75° was performed using a Lambda 950 spectrophotometer from PerkinElmer Corporation. A Glan-Thompson polarizer was used to select s- and p-polarized light. For light detection of wavelengths below 860nm a Photomultiplier tube and a slit of 2 nm was used. For wavelengths above that wavelength, a lead sulfide (PbS) photoconductive detector and a slit of 10nm was selected. The light for the detector was collected by an integrating sphere, which is mandatory in order to get precise results for non-normal incidence measurements. This kind of light detection is insensitive to beam displacements caused by the substrate. A standard detector suffers from the inhomogeneous sensitivity of the active area. To compensate the residual inhomogeneity of the integrating sphere, two measurements for each polarization were conducted and then averaged: one at AOI = + 75° and another with AOI = −75°. The measurement is in good agreement with the theoretical coating design. The measured transmittance for s-polarization T_s is less than 4% and for p-polarisation T_p more than 93%, on average. Therefore, the extinction ratio T_p/T_s is about 23:1.

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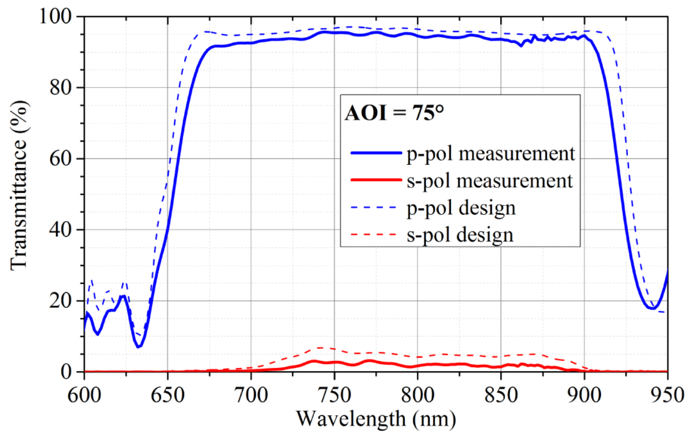

Fig. 2. Absolute transmission measurements at AOI = 75° (solid). Calculated Design including the Anti reflective coating on the back side (dashed).

The dispersion measurement was made using a homebuilt white light interferometer [15]. It is a Michelson interferometer with a white light source. One arm has a motorized translation stage to change the path length. In the other arm the sample is placed. The interference signal of the two overlapped beams is measured by a spectrometer. Due to the short coherence length of the light source, the location of the interferograms for each wavelength depending on the path length can be determined. This directly yields the group delay (GD). The derivative in frequency space yields the group delay dispersion (GDD) shown in Fig. 3. The measurement shows excellent agreement with the theoretical data. The GDD of the reflected s-polarized pulse is nearly zero for the whole bandwidth. Therefore, the temporal profile of a reflected pulse is almost unchanged. The AR coating itself has also zero GDD but the dispersion of the 3mm thick fused silica substrate leads to the non-zero GDD in the measurement. This dispersion cannot be compensated by the transmissive antireflection coating but it can be compensated by dispersive mirrors with negative dispersion [2].

The surface flatness of the polarizer was measured using a homemade Fizeau-interferometer. We measured the uncoated substrate, the substrate with one coating, and with two coatings. The flatnesses of the uncoated substrate and that of a substrate with two coatings were λ/10 each, meaning that the stress was successfully compensated [14].

With the data from the coating design a simulation for the temporal profile of a Gaussian pulse of 11 fs (FWHM) centered at 780 nm was made (Fig. 4). One can see that the reflected and the transmitted pulses are almost unchanged. There is no pulse broadening and no satellite pulse generation. Only a small drop in intensity is observed due to the coating design. For the transmitted pulse the dispersion of the fused silica substrate was not taken into account to show the capability of the coating.

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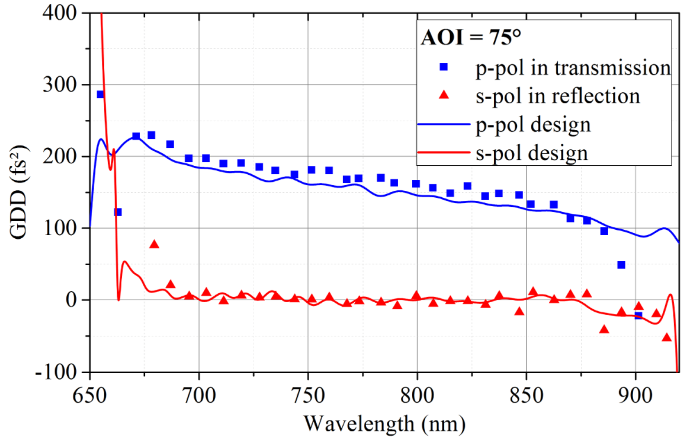

Fig. 3. GDD measurement at AOI = 75° (symbols). The calculated design includes the dispersion of the substrate with a thickness of 3 mm and the antireflection coating (solid).

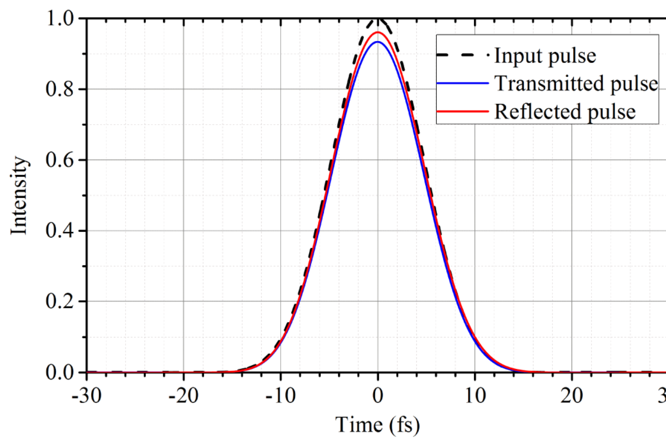

Fig. 4. Simulations for the interaction of a Gaussian pulse with duration of 11.1 fs with the polarizer-coating. The shapes of the reflected and transmitted pulses is not changed by the coating. The dispersion of the substrate was not included to demonstrate the capability of the coating.

4. Conclusion

We designed, produced and characterized a non-dispersive broadband polarizer with an unprecedented bandwidth which supports sub-12 fs pulses. The stress of the coating and the resulting deformation of the substrate are compensated by a special antireflection coating on the second side of the substrate, keeping the beam-profile unchanged for both the reflected and the transmitted pulses. Also the backside-coating doesn't introduce additional dispersion. This polarizer paves the way for applications where few-femtosecond pulses are separated, combined or attenuated.

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