All-reflective, highly accurate polarization rotator for high-power short-pulse laser systems

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Abstract: We present the setup of a polarization rotating device and its adaption for high-power short-pulse laser systems. Compared to conventional halfwave plates, the all-reflective principle using three zero-phase shift mirrors provides a higher accuracy and a higher damage threshold. Since plan-parallel plates, e.g. these halfwave plates, generate postpulses, which could lead to the generation of prepulses during the subsequent laser chain, the presented device avoids parasitic pulses and is therefore the preferable alternative for high-contrast applications. Moreover the device is easily scalable for large beam diameters and its spectral reflectivity can be adjusted by an appropriate mirror coating to be well suited for ultra-short laser pulses.

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References and links

1. D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," Opt. Commun. **55,** 447–449 (1985).
2. M. C. Kaluza, J. Schreiber, M. I. K. Santala, G. D. Tsakiris, K. Eidmann, J. Meyer-ter-Vehn, and K. J. Witte, "Influence of the laser prepulse on proton acceleration in thin-foil experiments," Phys. Rev. Lett. **93,** 045003 (2004).
3. S. P. D. Mangles, A. G. R. Thomas, M. C. Kaluza, O. Lundh, F. Lindau, A. Persson, Z. Najmudin, C. -G. Wahlström, C. D. Murphy, C. Kamperidis, K. L. Lancaster, E. Divall, and K. Krushelnick, "Effect of laser contrast ratio on electron beam stability in laser wakefield acceleration experiments," Plasma Phys. Control. Fusion **48,** B83–B90 (2006).
4. A. Henig, D. Kiefer, K. Markey, D. C. Gautier, K. A. Flippo, S. Letzring, R. P. Johnson, T. Shimada, L. Yin, B. J. Albright, K. J. Bowers, J. C. Fernández, S. G. Rykovanov, H. -C. Wu, M. Zepf, D. Jung, V. Kh. Liechtenstein, J. Schreiber, D. Habs, and B. M. Hegelich, "Radiation-pressure acceleration of ion beams driven by circularly polarized laser pulses," Phys. Rev. Lett. **103,** 045003 (2009).
5. N. V. Didenko, A. V. Konyashchenko, A. P. Lutsenko, and S. Yu. Tenyakov, "Contrast degradation in a chirped-pulse amplifier due to generation of prepulses by postpulses," Opt. Express **16,** 3178–3190 (2008).
6. M. Hornung, R. Bödefeld, M. Siebold, A. Kessler, M. Schnepp, R. Wachs, A. Sävert, S. Podleska, S. Keppler, J. Hein, and M. C. Kaluza, "Temporal pulse control of a multi-10-TW diode-pumped Yb:Glass laser," Appl. Phys. B **101,** 93–102 (2010).
7. S. Keppler, R. Bödefeld, M. Hornung, A. Sävert, J. Hein, and M. C. Kaluza, "Prepulse suppression in a multi-10-TW diode-pumped Yb:glass laser," Appl. Phys. B **104,** 11–16 (2011).
8. C. E. Greninger, "Reflective device for polarization rotation" Appl. Opt. **27,** 774–776 (1988).

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10. according to supplier data (*LAYERTEC GmbH*)

1. Introduction

State of the art high-power short-pulse laser systems are mainly based on the principle of chirped pulse amplification (CPA) [1]. An oscillator pulse is stretched, amplified and recompressed to high peak powers which can be focused to intensities in excess of $10^{21}\,\mathrm{W/cm^2}$. Since most components in such high-power systems are polarization sensitive, e.g. dielectric mirrors and gratings, a well-defined state of the polarization is required. Furthermore, it is often necessary to change the polarization of the laser pulses within the system in a controlled manner. For this purpose, halfwave plates (HWPs) are commonly used. However, due to the ongoing development of such high-power laser systems to generate shorter and more energetic pulses HWPs soon reach their limits. The low laser induced damage threshold prohibits the application for compressed, and therefore ultra-short, high-power laser pulses. Furthermore, the residual dispersion of the laser pulse as well as the wavelength dependency of the polarization rotation, which eventually leads to a narrowing of the bandwidth, impede the use of HWPs for few-cycle pulses. Finally the scalability proves to be challenging regarding the ratio of diameter and thickness. HWPs with a diameter larger than 100 mm are not state of the art.

Using high-power laser systems in high-intensity laser-matter experiments, the temporal intensity contrast (TIC) is also an important parameter. Here, the TIC, $\eta(t)$, is defined as the ratio between the pre- or postpulse intensity $I(t)$ at the time t before ($t<0$) or after ($t>0$) the arrival of the main pulse at $t=0$, which reaches the peak intensity I_0, i.e., $\eta(t)=I(t)/I_0$. Prepulses on nanosecond (ns) and picosencond (ps) timescales as well as pedestals introduced by amplified spontaneous emission (ASE) in the laser amplifiers can dramatically affect the target properties due to ionization and preheating [2, 3, 4]. Hence, the TIC for prepulses needs to be as small as possible if preheating needs to be avoided.

2. Generation of prepulses by postpulses

In order to achieve the best possible TIC at $t<0$ it is also important to eliminate postpulse sources. Postpulses do not influence laser-matter experiments in a direct way. However, when the streched pulse duration in a CPA system is longer by several orders of magnitude than the time difference between main and postpulse, the two streched pulses considerably overlap in time. The frequency chirp and the delay between the two pulses lead to spectral interference. This sinusoidal modulation of the spectra is equivalent to a sinusoidal intensity modulation within the temporal shape of the stretched main pulse. Due to the intensity dependence of the B-Integral [5] accumulated by the main laser pulse in the subsequent optical elements of the laser chain, the intensity modulation can again cause a sinusoidal modulation in the spectral phase of the stretched main pulse. By recompression, a prepulse is generated from a postpulse at an identical time difference *before* the main pulse [5]. The energy of the generated prepulse, E_{pre}, for a Gaussian shaped near field profile depends on the energy of the postpulse, E_{post}, and the B-Integral, B, of the pulse accumulated in the following amplifier chain [5]:

$$E_{\mathrm{pre}} = \frac{1}{3\sqrt{3}} B^2 E_{\mathrm{post}}. \tag{1}$$

Plan-parallel plates (PPs) used in the laser system equipped with an anti-reflection (AR) coating up to a residual reflectivity of typically 0.6 % per surface generate a postpulse by a double reflection of the transmitted pulse at the two surfaces. This leads to a postpulse with a TIC of $\eta(t)=4\times10^{-5}$ at a time t determined by $t=2d\,n_{\mathrm{PP}}/\mathrm{c}$, with the thickness d and the

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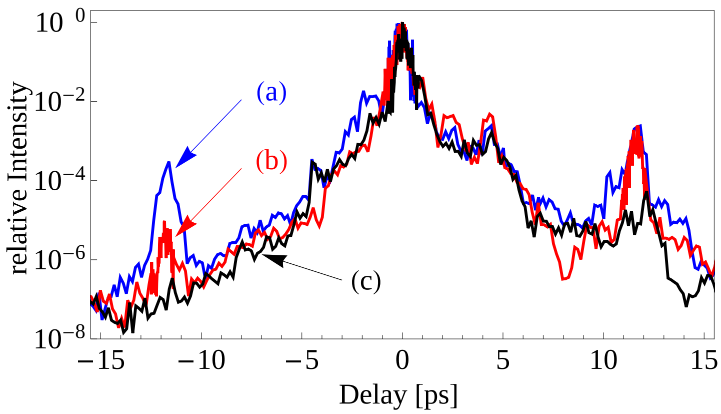

Fig. 1. TIC of POLARIS. The blue (a) and red line (b) were achieved with a HWP in the 2nd regenerative amplifier and an output energy of 30 mJ (blue line (a)) and 3 mJ (red line (b)), respectively, adjusted by the energy level of the pulse seeding this amplifier. These values correspond to B-Integrals of 0.7 rad (blue line (a)) and < 0.1 rad (red line (b)), respectively. The black line (c) shows the contrast scan after replacing the HWP with the same energy-level as (a).

refractive index n_{PP} of the PP, where c is the speed of light. Typical values are $d \approx 1...4$ mm which leads to $t \approx 10...40$ ps for $n_{PP} = 1.5$.

The measurements were performed with the fully diode-pumped POLARIS CPA-laser system [6] at the Institute of Optics and Quantum Electronics in Jena, Germany. In such CPA-systems it is necessary to prevent regenerative amplifiers from oscillating for the time interval when the amplifier medium is pumped but the seed pulse has not yet entered the cavity. Furthermore, the pulses need to be switched into and out of the cavity in a controlled way. For this reason a HWP is used to reduce the $Q-$factor of the cavity by rotating the polarization of the pulses inside with every round trip, while the amplifier is polarization sensitive [7]. When the seed pulse reaches the regenerative amplifier, a Pockels cell is switched on to compensate the HWP and the $Q-$factor reaches its optimum to amplify the pulse during several round trips. The HWP has a thickness of $d = 1.2$ mm and a parallelism of the two surfaces of better than 0.5 arcsec, thus it acts like a PP. Hence, a postpulse at $t = 12$ ps with an TIC of $\eta(t) = 4\times10^{-5}$ is generated with every round trip of the laser pulse inside the regenerative amplifier. Within POLARIS the pulses take 57 round trips in the regenerative amplifiers, leading to a TIC of $\eta(12\,ps) = 2\times10^{-3}$.

Figure 1 shows a measurement of the ps-contrast taken with a 3rd order cross-correlator (SEQUOIA, Amplitude Technology). The pulses shown here passed the stretcher, two regenerative amplifiers and the compressor of POLARIS [6, 7]. The measurement was performed with a HWP inside the second regenerative amplifier and output energies of 30 mJ (blue line, (a)) and 3 mJ (red line, (b)). The energy was adjusted by the level of the seed energy of the second regenerative amplifier, which corresponds to different values for the B-Integral of the pulses accumulated inside the cavity due to the different pulse intensities. The postpulse at 12 ps of $\eta(12\,\text{ps}) = 2.4\times10^{-3}$ was generated due to the limited AR coating of the HWP. The generation of the prepulse at $t = -12$ ps is also visible. The different prepulse TICs of 2.4×10^{-4} (blue line (a)) and 8×10^{-6} (red line (b)) are due to two different values of the B-Integral of 0.7 rad and less than 0.1 rad, respectively. The B-integral was estimated taking into account all round trips of the pulses in the regenerative amplifier. The prepulse generated by the postpulse can be expected to be smaller by a factor of ~ 50 according to Eq. (1). The prepulse shown by the red line (b) is the artificial feature at the appropriate intensity level caused by the 3rd order

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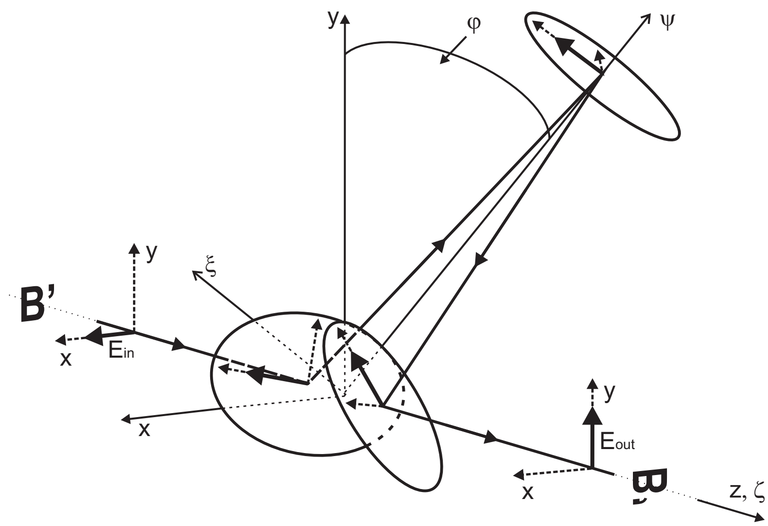

Fig. 2. Principle of all-reflective polarization rotation. The near field profile, represented by the letter **B'**, as well as the incident polarization, $\vec{E}_{\text{in}}$ are rotated by an angle of 2φ, while the mirror arrangement is rotated by φ. To improve the traceability, the polarization states on the individual mirrors are depicted.

cross-correlation measurement. This also implies that a *real* prepulse can no longer be detected since it would be superimposed by this artifact from the correlation.

3. Reflective device for polarization rotation

Equation 1 implies that there are two possibilities to improve the TIC of the newly generated prepulse, while the output energy and the spectral bandwidth of the laser system remain unchanged. Reducing the B-Integral during the pulse amplification would require a larger beam diameter leading to cost intensive and impractical changes in the laser system. Hence, decreasing the intensity, or even better, the complete suppression of the postpulse is highly desirable.

For this second approach, we developed a purely reflective device for polarization rotation (RDPR) [8] for the application in high-power short-pulse laser systems, which completely avoids the generation of postpulses.

Figure 2 shows the setup of the RDPR as described in [8]. Since the polarization has a fixed orientation to the near field profile of the pulse, the 3-mirror arrangement mirrors the near field profile, schematically shown by the letter **B'**, as well as the polarization, $\vec{E}_{\text{in}}$, with respect to the ξ-axis of the RDPR. For a polarization rotation of e.g. 90°, the RDPR, and thus the ξ-axis, needs to be rotated by $\varphi = 45°$. The fixed relation between the near field profile and the polarization is conserved by using dielectric zero-phase-shift mirrors. The reflective characteristic as well as the phase shift vs. the wavelength for the used mirrors are shown in Fig. 3. The mirrors provide a laser induced damage threshold (LIDT) of $50\,\mathrm{J/cm^2}$ for pulse durations of $10\,\mathrm{ns}$ and $200\,\mathrm{mJ/cm^2}$ for $150\,\mathrm{fs}$, which allows for their application for intense short pulses. HWPs typically provide a LIDT of $7\,\mathrm{J/cm^2}$ for $10\,\mathrm{ns}$ pulses and $20\,\mathrm{mJ/cm^2}$ for $150\,\mathrm{fs}$ [9]. Zero-phase-shift mirrors are easily available up to a bandwidth sufficient for $10\,\mathrm{fs}$ pulses for $800\,\mathrm{nm}$ central wavelength, but a design for a broader spectrum and thus shorter pulses is feasible [10]. Furthermore the RDPR is easily scalable for larger beam diameters. Due to these properties the replacement of commonly used HWPs is possible in any application. Usually HWPs are used to give a fixed rotation of the polarization within high-power laser

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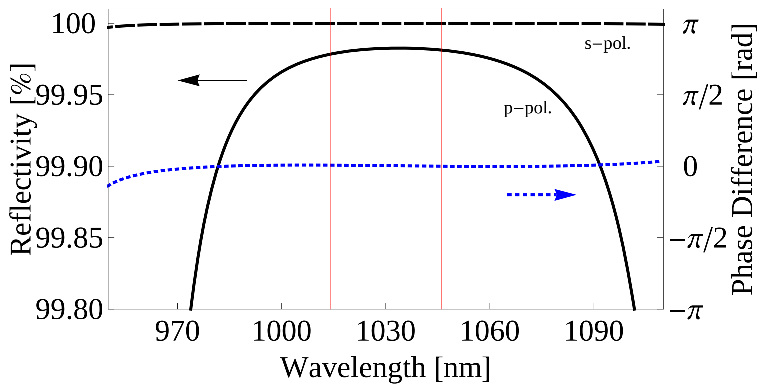

Fig. 3. Reflectivity for s- (black, dashed) and p- (black, solid) polarized light and the corresponding phase difference (blue, dotted) of dielectric zero-phase-shift mirrors. The vertical red lines indicate the spectral bandwidth of the POLARIS pulses.

systems. Replacing these HWPs with the RDPR is easy to realize, because only the longer propagation distance has to be considered. For applications which require variable polarization rotation direction and position of the incident laser beam have to be adjusted with respect to the optical axis of the RDPR, until a rotation of the RDPR causes no more beam displacement. This can be realized with any required accuracy.

In Fig. 4 the degree of polarization rotation first using the RDPR (red circles) and for comparison a HWP (blue crosses) was measured between two crossed Glan-Laser a-BBO polarizers (*metrolux Optische Messtechnig GmbH*), each having an extinction ratio of 2×10^{-6}. At an angle of $\varphi = 0^{\circ}$ the polarization is not rotated by the RDPR and thus blocked up to an intensity ratio of 6×10^{-6} by the second polarizer. This value is likely to be limited by a minimal residual phase shift of the used zero-phase-shift mirrors but nearly half an order of magnitude better as compared to the HWP. By varying the rotation angle between -45° and 45°, both measurements show a cosine square transmission function (black line). The behavior and the extinction ratio of the RDPR located between two polarizers was also measured with equally

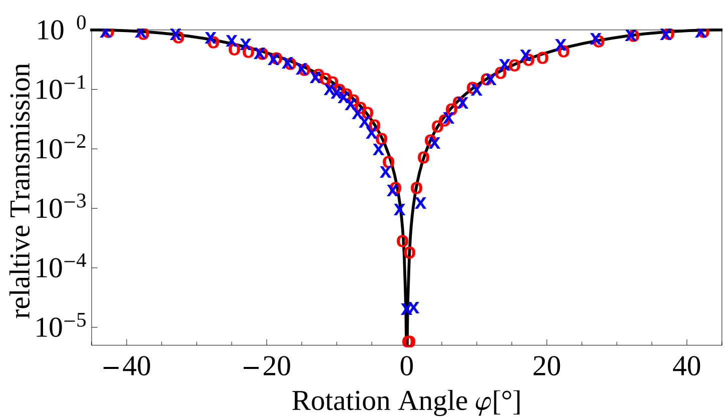

Fig. 4. Transmission through two crossed polarizers with the 3-mirror assembly (red circles) and a half wave plate (blue crosses). The black solid line shows an ideal $\cos^2$ transmission function. Each polarizer had an extinction ratio of 2×10^{-6}.

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oriented polarizers, where transmission minimum is at $\varphi = 45^\circ$ leading to similar results.

Due to the purely reflective design of the RDPR no post- or prepulses were generated. This was demonstrated by another TIC measurement in Fig. 1 (black line (c)). Here, the HWP inside the cavity of the second regenerative amplifier was replaced by an RDPR. The postpulse at 12 ps is reduced to a TIC of $\eta(12\,ps) = 4 \times 10^{-5}$, which is due to additional HWPs inside the laser chain, that will be replaced in the near future. This measurement was performed with an output energy of 30 mJ comparable to the blue line representing a B-Integral of 0.7 rad. An intensity reduction by more than 3 orders of magnitude could be achieved at $t = -12$ ps using the RDPR.

4. Conclusion

We conclude that for the suppression of postpulses plan-parallel optics have to be avoided throughout the laser chain. We demonstrated that the RDPR is a preferable alternative to conventionally used HWPs. In comparison to those, RDPRs create no post- or prepulses and provide a higher accuracy regarding the polarization rotation. The spectral transfer function is widely selectable, due to the purely reflective design and the use of dielectric zero-phase-shift mirrors. Moreover, the device is scalable in size and the damage threshold is only limited by the dielectric mirrors, which is considerably higher than for HWPs. Hence, RDPRs are also suitable for the manipulation of the polarization of compressed, and therefore ultra-short, high-power laser pulses.

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