Polarization State Changes of Femtosecond, Polarization-shaped Pulsed Beams on Free Space Propagation

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Abstract: We show that free space propagation of polarization-shaped pulsed beams induces substantial changes in their polarization state. The physical origin of this effect, its theoretical description, and classical polarization measurements reflecting this phenomenon, are presented.

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1. Introduction

It is generally assumed that the polarization state of a beam of light does not change during free space propagation. However, it has been recently shown that for few-cycle pulsed beams this assumption is not true [1]. This is especially interesting regarding that polarization shaped pulses are applied more and more widely in experiments of physics and related scientific disciplines [2–4]. In this work we show that the physical origin of the instantaneous polarization state changes predicted by [1] are related to the spectrum reshaping on propagation due to Wolf's effect [5]. We also present formulas which show the relationship between the properties of the instantaneous polarization ellipse (orientation and ellipticity) for the source and the propagated pulse. We demonstrate how these instantaneous polarization state changes appear in classical measurements of the polarization state.

2. Theory of instantaneous polarization state changes

The polarization state of ultrashort pulsed beams is characterized by the ellipticity χ and orientation ψ of the instantaneous polarization ellipse [6]. For pulses these parameters generally vary with time ($\chi=\chi(t)$, $\psi=\psi(t)$), and the instantaneous ellipse is well-defined for pulses as short as one cycle within the FWHM [7].

We have studied the polarization state changes induced by beam propagation from a source of finite size. In the paraxial- and under other common approximations to pulsed beam propagation [1], the orientation and ellipticity of the instantaneous polarization ellipse of the propagated pulse are related to those at the source at $z=0$ by

$$\psi^{(p)}(\tau)\simeq\psi(\tau)+\frac{a_0'}{a_0}\frac{1}{1-\tan^2\chi(\tau)}\frac{\mathrm{d}\tan\chi(\tau)}{\mathrm{d}\tau},\quad \tan\chi^{(p)}(\tau)\simeq\tan\chi(\tau)-\frac{a_0'}{a_0}[1-\tan^2\chi(\tau)]\frac{\mathrm{d}\psi(\tau)}{\mathrm{d}\tau},\qquad(1)$$

$\tau=t-\varphi_0'$ being the local time; $a=a(\vec{r},\omega)$ and $\varphi=\varphi(\vec{r},\omega)$ are the amplitude and phase that the spectrum $E(0,\omega)$ acquired in propagation to a point $\vec{r}$, that is $E(\vec{r},\omega)=a(\vec{r},\omega)\exp[i\varphi(\vec{r},\omega)]E(0,\omega)$; where prime denotes derivation with respect to angular frequency and subscript zero evaluation at the carrier angular frequency ω_0 of the pulse.

The formulas above predict that a time-varying ellipticity of the source pulse induces a rotation in the orientation of the instantaneous polarization ellipse on propagation, and that a time-variation of orientation in the source pulse results in an ellipticity shift on propagation. One of this simple relations can be illustrated by the polarization gate (PG) pulse commonly used for isolated attosecond pulse generation [3]. In the case of the PG pulse the orientation of the instantaneous polarization ellipse is time-independent and the ellipticity is time-varying, and due to this property its orientation rotates during propagation, while ellipticty remains the same as that of the source (see Fig. 1. (a)).

The preceding observation can be surprising at first, since changes in the polarization state are only expected for partially coherent and polarized sources, not for completely coherent and polarized sources as these few-cycle pulses.

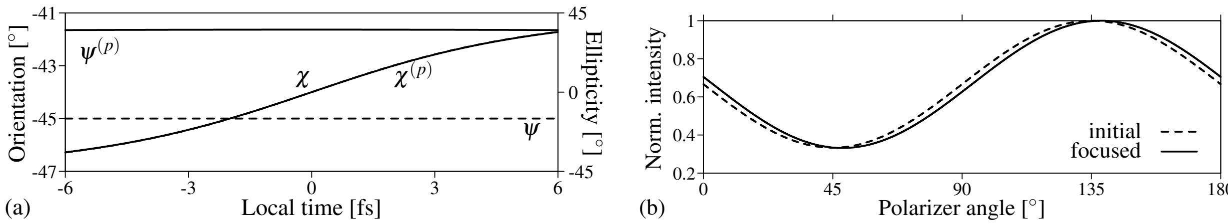

Fig. 1. (a) The simulated time-variation of the orientation ψ and ellipticity χ of the instantaneous polarization ellipse of the initial (dashed) and focused (continuous) PG pulse generated by sending a 10 fs long Gaussian pulse through a multiple-order and a zero-order quarter-wave plate. The first wave-plate causes 10 fs delay between fast- and slow-axis. Initial means the pulse right after the waveplates. (b) The dependence of the measured time-integrated intensity on the azimuthal angle of the polarizer behind which the standard detector (e. g. photodiode) is placed for the same initial and focused PG pulses as in (a).

Note that the 'statistically stationary' spectral components of these pulses in fact maintain their polarization states during propagation [8]. The change of the instantaneous polarization state originates from the spectral reshaping in propagation known as Wolf's effect [5], which is solely due to the finite extent of the source in the case of coherent sources, and is accounted for by the dependence of the spectral amplitude $a(\vec{r},\omega)$ acquired during propagation on frequency. This type of polarization state change, which has to be differentiated from the ones caused by partial coherence or strong focusing, disappears for quasi-monochromatic light or pulses with time-independent polarization.

3. Classical measurement of polarization state

In general, instantaneous polarization state changes can only be observed by the total reconstruction of the electric field, which requires sophisticated measurement techniques [9]. The question then arises whether these instantaneous polarization changes are observable in classical measurements of the polarization state using standard methods [6]. A simulation of such simple measurement using a polarizer and a time-integrating detector placed behind it is depicted in Fig. 1. (b). The measured intensity in this experimental setup depends on the azimuthal angle of the polarizer, and the maximum signal could be detected when the polarizer is parallel to the orientation of the instantaneous polarization ellipse, which can be shown to be time independent in the case of the PG pulse. In case of focusing the PG pulse, which can be a practical realization of propagation up to the far field as in both cases $a_0'/a_0 = 1/\omega_0$, the angle of maximal signal is shifted by the same degrees as it is predicted by (1).

4. Summary

We have shown, on the contrary to the usual belief, that polarization state of femtosecond pulses can change on free space propagation, and in particular upon focusing. We have also formulated simple rules which can predict these variations and show the relations of polarization properties. We have also revealed the underlying physical origin of these phenomena, which appears to be Wolf's effect. We presented how these effects show up in classical measurements of the polarization state. We believe that these findings make possible to avoid common mistakes which can be originated from the assumption that the polarization state of on ultrashort pulse does not change during propagation.

5. References

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