Polarization rotation due to femtosecond filamentation in an atomic gas

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The linear-to-elliptical transformation of a 400 nm femtosecond-probe pulse in the birefringent filament in argon of an 800 nm linearly polarized femtosecond-pump pulse is studied numerically and experimentally. The rotation of the probe elliptical polarization is the largest in the high-intensity filament core. With propagation, the rotated radiation diffracts outward by the pump-produced plasma. The transmission of the analyzer crossing the probe’s polarization is maximum at the pump–probe angle of 45° and gives equal values for each pair of angles symmetrically situated at both sides of the maximum. © 2010 Optical Society of America

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The Kerr nonlinearity, which makes filamentation of femtosecond laser pulses in gases [1] possible, may induce birefringence in the initially isotropic optical medium. In the general case of four-wave mixing, the polarization state of the radiation can be changed so that the major axis of the polarization ellipse rotates in the course of propagation [2]. Numerical simulations have shown [3] the self-induced deviation of femtosecond pulse polarization from linear to elliptical and to rotate the pairs of the pump-probe angles symmetrically situated at both sides of the maximum. © 2010 Optical Society of America

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A set of coupled vector equations is written for the light field complex amplitude \( \mathbf{E} = (E_x, E_y) \) in the plane \((x, y)\) perpendicular to the propagation direction \(z\). The transition to the circularly polarized basis \(E_{\pm} = (E_x \pm iE_y)/\sqrt{2}\) yields the intensity \(I = c n_0 (|E_{+}|^2 + |E_{-}|^2)/(16\pi)\). The coordinate system moves with the group velocity \(v_{\text{gw}}(\tau = t - z/v_{\text{gw}})\), the subscripts \(\omega\) and \(2\omega\) denote the pump- and the probe-related values, respectively:

\[
2i k_{\omega} \partial_z E_{\omega \pm} = \Delta_1 E_{\omega \pm} - k_{\omega} k'_{\omega} \partial^2_{\tau \tau} E_{\omega \pm} + 2 k^2_{\omega} \Delta n_{\omega \pm} E_{\omega \pm} + 2 k^2_{\omega} \delta n_{\omega \pm} E_{\omega \mp} - i k_{\omega} \epsilon_{\omega} E_{\omega \pm},
\]

\[
2i k_{2\omega} \partial_z E_{2\omega \pm} = \Delta_1 E_{2\omega \pm} - 2 i k_{2\omega} \delta_{\omega} E_{\omega \pm} - k_{2\omega} k'_{2\omega} \partial^2_{\tau \tau} E_{2\omega \pm} + 2 k^2_{2\omega} \Delta n_{2\omega \pm} E_{2\omega \pm} + 2 k^2_{2\omega} \delta n_{2\omega \pm} E_{2\omega \mp} - i k_{2\omega} \epsilon_{2\omega} E_{2\omega \pm},
\]

where \(\Delta_1 = (1/r) \partial/\partial r (r \partial/\partial r)\) is a Laplacian; \(k_{\omega}, k_{2\omega}, k'_{\omega},\) and \(k'_{2\omega}\) are the wave numbers and the second-order dispersion coefficients; and \(\delta_{\omega} = v_{\text{gw},1} - v_{\text{gw},0}\) is the group velocity walk-off. The self- and cross-action terms in an isotropic medium with comparatively weak dispersion in the visible range [4] are given by

\[
\Delta n_{\omega \pm} = n_2 (|E_{\omega \pm}|^2 + |E_{2\omega \pm}|^2) / 6 - 2 \pi^2 N_e / (m_{\omega} \omega^2),
\]

\[
\delta n_{\omega \pm} = n_2 E_{\omega \pm}^* E_{2\omega \pm} / 6,
\]

\[
\Delta n_{2\omega \pm} = n_2 (|E_{2\omega \pm}|^2 + |E_{2\omega \mp}|^2) / 6 - \pi^2 N_e / (2 m_{\omega} \omega^2),
\]

\[
\delta n_{2\omega \pm} = n_2 E_{\omega \pm}^* E_{2\omega \mp} / 6,
\]

\[
\partial_{\tau} N_e = (R_{\omega} + R_{2\omega}) |N_0 - N_e(\tau)|.
\]
where $N_0$ is the density of neutrals before the pulse. The free electron density $N_e$ is calculated through the rates $R_\Psi$ and $R_{\text{cw}}$ [8]. Initially linearly polarized Gaussian pump ($\mathbf{E}_p \parallel \mathbf{OX}$) and probe ($\mathbf{E}_{2\omega}$ at an angle $\psi$ to the pump) pulses copropagate in the focusing geometry ($f = 50$ cm) in argon (1–3 bars) with the optimized 40 fs delay of the pump yielding the highest probe intensity in the normal group-velocity-dispersion (GVD) regime. The central pump and probe wavelengths are 800 and 400 nm, the beam radii are 0.5 mm, the initial pulse durations are 45 and 100 fs, the energy is 1 mJ and 1 $\mu$J, and the critical powers for self-focusing are 9 and 2.25 GW, respectively, for $n_2 = 10^{-16}$ cm$^2$/W. The GVD coefficients and the walk-off are $k'_{\omega} = 1.4 \times 10^{-21}$ s$^2$/cm, $k''_{\omega} = 3.1 \times 10^{-21}$ s$^2$/cm, and $\delta_{sc} = 7.1 \times 10^{-16}$ s/cm, respectively. The pump propagates in a single-filament regime, while the weak probe generates the component crossed to its original direction, $\mathbf{E}_{2\omega}$, only in the presence of the pump. The simulated distribution of the light field $E_{2\omega}(r, z, \tau)$ is projected onto an analyzer and then integrated in time, yielding fluence similar to the experiment.

The simulated probe fluence is localized transversely [Fig. 1(b)] due to the cross action in the high-intensity pump filament [Figs. 1(a) and 1(c)]. Figures 1(d)–1(g) show the transmission of the probe fluence through the analyzer as the latter rotates, i.e., as the angle between the probe’s initial linear polarization and the analyzer’s transmission axis varies. Essentially, Figs. 1(d)–1(g) show the evolution of the probe polarization ellipticity and its rotation along the propagation axis. The polarization ellipse itself transforms across the beam [Figs. 1(h)–1(k)]. The linear polarization [cosine squared, dashes in Fig. 1(d)] changes to the elliptical one and rotates by 65° [solid curve in the upper plots of Figs. 1(d) and 1(e)] and the rotated ellipse in the center of Figs. 1(h) and 1(i)]. This is due to the Kerr cross action, which affects differently the probe light field vector components oriented parallel ($E_{2\omega x}$) and perpendicular ($E_{2\omega y}$) to the pump [2, 4]. The filament-induced “cross-focusing” (i.e., the probe is guided into the filament) develops simultaneously with the cross-phase modulation (XPM), the latter introducing the ellipticity through the phase shift between the $E_{2\omega x}$ and $E_{2\omega y}$ [2, 4]. This phase shift and “cross-focusing” are transformed into the disproportional amplitude growth after propagating through a distance and result in the ellipse rotation from the probe to the pump (clockwise) according to the direction of the medium polarization wave vector $\mathbf{P}_{3\omega}$ [2]. The radiation from the core with the transformed polarization is then diffracted outward by the pump-produced plasma, as seen from the similarity of the angular fluence distributions in Fig. 1(e) (upper plot) and Fig. 1(f) (lower plot). The decay of the pump filament reduces the instantaneous cross action and leads to the ellipticity decrease in the probe beam center [transfer from Fig. 1(j) to Fig. 1(g)], the upper plots; narrowing of ellipses from Fig. 1(j) to Fig. 1(k)]. The ellipse rotates in the counterclockwise direction [from Fig. 1(f) and 1(g), the lower panels] due to the restoration of the original ratio between the probe light field components.

At different pressures, the probe polarization evolves similarly along the filament [Figs. 2(a) and 2(b)]. The polarization ellipse’s major axis is along the maximum transmission direction of the analyzer, while the rotation angle (<90°) is defined in the inset to Fig. 2(d). In 1–3 bars, the maximum rotation angle remained almost unchanged at 79°–87° [Figs. 2(c) and 2(d)] and is reached earlier in the propagation at higher pressure due to the shorter filament formation distance [ellipses “1a” and “1b,” Figs. 2(a) and 2(b)]. In 3 bars, the rotation continues near the refocusing position at $z = 44$ cm [ellipses “2b,” Fig. 2(b)]. The monotonic increase of the rotation angle with pressure is due to XPM [Fig. 2(c), squares]. This rotated radiation is partially diffracted outward by the filament plasma [Fig. 1(j)] and can be detected at the end of the filament by selecting a small portion of the probe beam [Fig. 2(d), the vertical line $r = 250 \mu$m], so that the adjustment of the detector position in the transverse beam profile can lead to the polarization rotation angle increase with the pressure in agreement with [4]. In the beam periphery [Fig. 2(d), $r > 500 \mu$m], the rotation angle is almost the maximum one (~90°), which corresponds to the half-wave plate effect [4].
independence of the maximum rotation angle is associated with the clamped intensity invariance with pressure [9]. Indeed, the simulated peak pump intensity varies slowly from 1.2 to $1.4 \times 10^{14}$ W/cm$^2$ as the pressure increases from 1 to 3 bars.

As the initial pump–probe angle $\psi$ is increased [Fig. 3(b)], the energy integrated over all polarization directions and over the probe beam center decreases monotonically [bars in Fig. 3(a)]. However, the probe energy transmitted by the crossed analyzer only reaches the maximum at $\psi = \alpha = 45^\circ$ and gives equal values for the pair of angles $\psi = (\alpha; 90^\circ - \alpha)$ in both the experiment and the simulations [Fig. 3(a), starred and dashed curves]. To understand this, we choose the coordinate system $(x', y')$, where $E_{2\omega} \| OX'$ [Fig. 3(b)], and reduce the third-order nonlinear polarization of the probe [2] parallel to the crossed analyzer to $P_{2\omega y}^{(3)} = -\chi^{(3)}_{y\omega y_{\omega}} E_{2\omega}^y |E_\omega|^2 \sin 2\psi$, yielding equal signals for $\psi = (\alpha; 90^\circ - \alpha)$. Here we assumed that the $\chi^{(3)}$ tensor components are invariant relative to the coordinate system rotation and the probe component $E_{2\omega}^y \ll E_\omega$. The change of the pump polarization is negligible in the filament since there is no self-induced polarization rotation and the XPM induced by the weak probe does not affect the pump.

In summary, the probe pulse’s initial linear polarization develops into a rotating elliptical one due to the filament-induced cross action in the beam center. By the end of the filament, the elliptically polarized and rotated probe radiation diffracts outward, while the beam center approaches the original polarization direction with the decreased ellipticity due to the decay of the nonlinear cross action. At higher pressure, the polarization changes are faster in the propagation with the most intense rotation corresponding to the pump filament’s focusing and refocusing positions. The maximum rotation angle is pressure independent; however, by choosing a specific position in the beam transverse section, the increase of the rotation angle with the gas pressure can be obtained. The probe component transmitted by the crossed analyzer maximizes at the initial pump–probe angle of $45^\circ$ and gives equal values for a pair of angles situated symmetrically about this angle. This symmetry is valid in both the experiment and the simulations.

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