Thermal distortion and birefringence in repetition-rate plasma electrode Pockels cell for high average power

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Received August 21, 2006

We numerically study thermally induced birefringence and distortion in plasma electrode Pockels cell based on KD*P as the electro-optic material. This device can repetitively operate under the heat capacity mode. Simulation results indicate that the excellent switching performances and low wave-front distortion are achieved within several tens seconds working time at average power in excess of 1 kW.

OCIS codes: 140.0140, 140.3540, 140.6810.

The advent of high average power diode pumped solid-state lasers has engendered the need for Pockels cell (PC), which can tolerate both high intra-cavity fluences and high average powers. The optical absorption in PC leads to a thermal load, and even weak absorption can lead to thermal effects which degrade its performance, such as wave-front aberrations, stress-induced depolarization, reduced contrast ratio, and thermal fracture[1−3]. At high average power, the performance of PC and other nonlinear optical system components can be maintained only by carefully controlling of the thermal, optical, and mechanical configuration of the crystals. Many papers have been devoted the transversely excited, thermal compensation Pockels cell (TCPC) that compensates internally for the heat from the laser beam[4−6]. But the TCPC required that the identical two crystals are mounted in thermally identical mounting fixtures and exposed to the same optical loading profile make it difficulty to use. The conventional longitudinally excited configuration, e.g., ring electrode geometry, requires that the crystal thickness along the optical axis increases as the switch aperture increases in order to maintain acceptable electric field uniformity. Optical absorption (proportional to thickness) and wavefront distortion (proportional to third power of thickness) place rather stringent limits on the average power capabilities of longitudinally excited ring electrode PC. Plasma electrodes Pockels cell (PEPC) is used as large-aperture optical switches in laser drivers for inertial-confinement fusion facilities[7], which allows the large-aperture thin plate crystals, employs longitudinally excited configuration to achieve sufficient electric field uniformity. For high average power requirement, we innovatively developed a repetition-rate plasma-electrode Pockels cell (RPEPC) capable of working at several kilowatts laser systems. In order to mitigate thermal load, it was necessary to use a crystal with an optical absorption coefficient lower than that of KDP. The material chosen was KD*P, which has an optical absorption coefficient of 0.005 cm^{-1} at 1.06 μm. Being different from the regular PEPC concept, the RPEPC is driven only through the positive and negative switching pulse voltage as the one-pulse-process. Namely, the plasma electrodes are obtained by the switching voltage itself breaking down the gas. Figure 1 shows schematic of a RPEPC and a simplified schematic diagram of the required external electronic circuit. According to our system design requirements, the hard aperture of crystal is 80×80 (mm), slightly larger than the laser beam transverse dimensions.

In the following, the effect of thermally induced birefringence and wave-front distortions on the RPEPC may be estimated with a computer which calculates the temperature distribution and the stress within a crystal subject to laser heating and thermal boundary conditions as well as mounting conditions. The calculation is carried out in three stages. During the first two stages the uncoupled quasi-stationary thermo-elasticity problem is solved based on the finite element method (FEM) (separately for the temperature field in the first stage and for the stress field in the second stage); during the third stage changes of the spatial distribution of the relative dielectric permittivity tensor induced by thermal stresses and the inhomogeneous temperature distribution in the element cross section are computed with the help of the index ellipsoid.

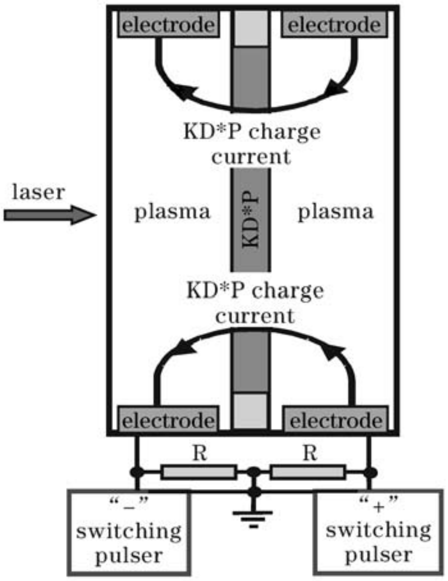

Fig. 1. Schematic of RPEPC.

To estimate the difference of the thermal effects between different intensity distributions of laser beam, we have performed a numerical investigation of wave-front distortion and depolarization factor with spatially uniform and Gaussian beams, both have square-shaped cross section, while the clear aperture of spatially uniform beam is 60×60 (mm). The intensity of the Gaussian beam was considered to be

$$I(x, y) = I_0 \exp[-2(x^2 + y^2)/R^2], \tag{1}$$

while $2R = 60$ mm, $I_0 = Ef/b^2$, where E is the energy per pulse, f is the repetition rate, b^2 is the area of beam aperture. We thought that the temporal distributions of pulse produced almost no effect on thermal distributions. So we assumed that the pulse has rectangular shape. Due to symmetries of the crystal and laser intensity in x- and y-directions, the heat-transfer problem and the thermo-elasticity problem analysis only had to be carried out for a quarter of the crystal, while in solution of the heat-transfer problem, we used adiabatic boundary conditions, because the working gas is rarefaction, so the heat exchange coefficient of a free convection of gas is very small. For mechanical boundary condition, considering that the elastic modulus of glue ($E \leq 0.1$ GPa) is much smaller than that of KD*P ($E \sim 300$ GPa), we let the boundary of the medium to be free, i.e., no constraint. In the calculation we used the values of the various constants from Ref. [1] for KD*P slab, specific heat $C = 2338$ J/(kg·K), density $\rho = 700$ kg/m^3, thermal conductivities $k_{11} = k_{22} = 1.76$ W/(m·K), $k_{33} = 1.3$ W/(m·K), thermal expansion coefficients $a_{11} = a_{22} = 25 \times 10^{-6}$ K^{-1}, $a_{33} = 44 \times 10^{-6}$ K^{-1}. The elements of the elastic constants $s_{11} = 15.3 \times 10^{-12}$ Pa^{-1}, $s_{12} = 2.1 \times 10^{-12}$ Pa^{-1}, $s_{13} = -3.8 \times 10^{-12}$ Pa^{-1}, $s_{33} = 19.6 \times 10^{-12}$ Pa^{-1}, $s_{44} = 77.5 \times 10^{-12}$ Pa^{-1}, $s_{66} = 168 \times 10^{-12}$ Pa^{-1}. The elements of the elastic-optic matrixes $p_{11} = 0.287$, $p_{12} = 0.282$, $p_{13} = 0.174$, $p_{33} = 0.122$, $p_{44} = -0.019$, $p_{66} = -0.064$, and thermal-optic coefficient $\beta = -3.2 \times 10^{-5}$ K^{-1}.

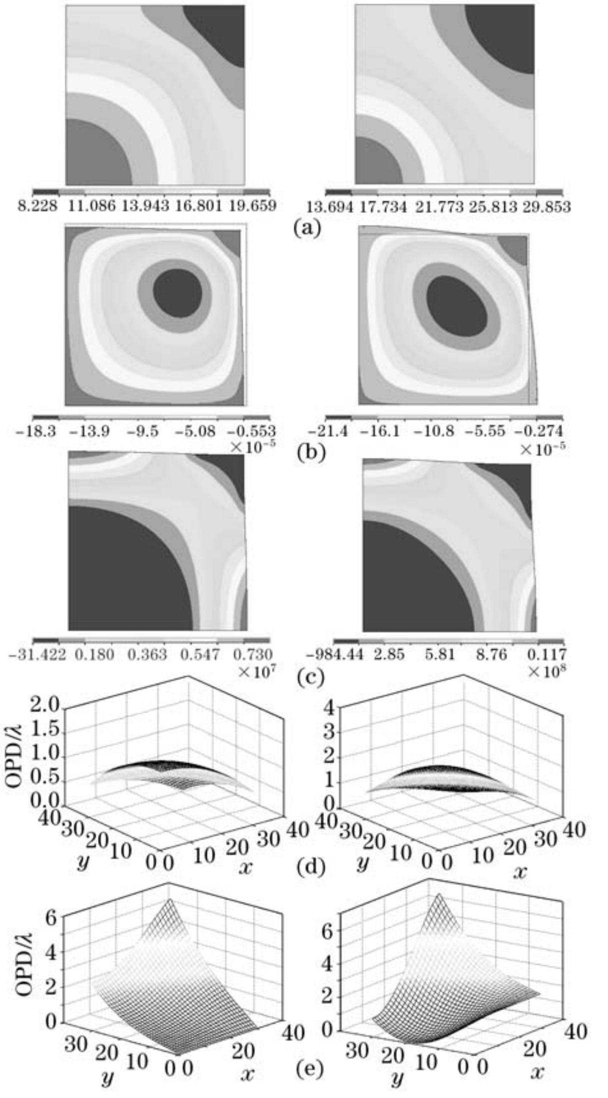

Fig. 2. Distributions of (a) the temperature field, (b) x-y plane shear strain component, (c) tensile stress, (d) the OPD due to temperature gradient, (e) the OPD due to surface deformation. The laser beam intensity distributions are corresponding to spatially uniform (left) and Gaussian (right) respectively. $\lambda = 1.064$ μm.

Figure 2 shows the distributions of temperature rising, shear strain component ε_{xy}, tensile stress, and optical path difference (OPD) with laser beam heating 5 minutes where different laser intensity distributions such as the beam with uniform profile and Gaussian beams are analyzed and compared. It is obvious that the influence of nonuniformity of a light beam is significant. As expected, uniform profile has lower thermal distortions over Gaussian beams in high average power laser operation. From Fig. 2 we also see that strain near the center is compressive while near the edges of beam it is tensile, and near the edges of beam the thermal induced depolarization is more serious.

Figure 3 shows the maximum temperature rising and the maximum tensile stress behaviour relative to time heated by laser beam with uniform profile.

Figure 4 shows the influence of varying the crystal thickness and the repetition rate of laser pulse on the thermal depolarization inside the clear aperture, the laser beam has uniform profile. One can see that depolarization becomes more seriously with increasing the KD*P thickness and the repetition rate of laser pulse. From these simulations we concluded that the RPEPC is based on KD*P (thickness is 0.5 cm) at an average power loading of 1 kW, the aperture integrated depolarization loss at 1.06 μm is less than 10% in 5-min working time.

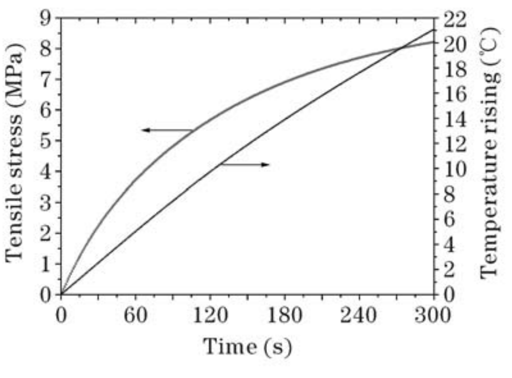

Fig. 3. Maximum temperature rising and tensile stress behaviour in the crystal. Pulse energy is 100 J, repetition rate is 10 Hz, thickness of KD*P is 0.5 cm.

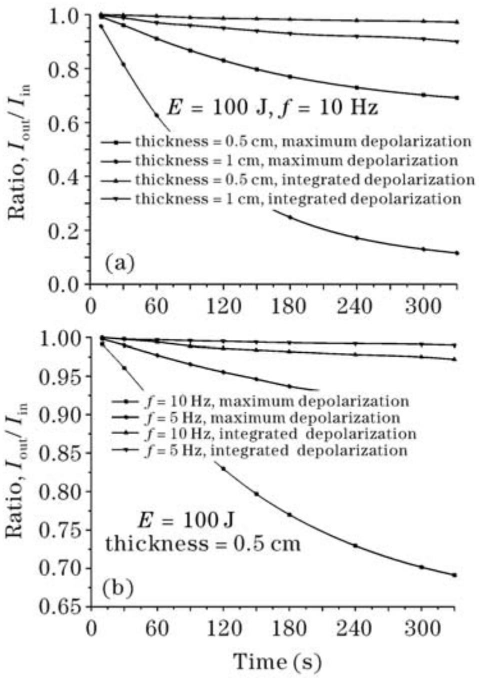

Fig. 4. Thermal depolarization inside the beam aperture versus time for (a) different thicknesses of crystal and (b) different repetition rates of laser.

In conclusion, we have presented the results of numerical investigation of thermal-optical distortions in KD*P RPEPC which operated under the heat capacity mode. Simulation results show that it is possible to maintain a high contrast ratio and acceptable wave-front distortion at 1.06 μm in excess of 1-kW average power within several tens seconds working time.

This work was supported by the National Natural Science Associated Foundation (No. 10576038) and the Science & Technology Foundation of CAEP (No. 20050436). D. Cao's e-mail address is caodingxiang02@yahoo.com.cn.

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