The distance L between side densified regions depends on the pulse energy as shown in Fig. 6. As E_p increases, strong heating of irradiated regions is observed (bright regions in Fig. 6 at time moment $T = 5$ ns). Strong heating and glass melting reduces acoustic velocity. This explains why length L increases with pulse energy (Fig. 7). The pressure which drives micro-explosion scales with absorbed energy, however, when $E_p > 40$ nJ the proportionality fails. At those conditions, the pulse energy is already more than twice larger as required for the permanent modification to be recorded by a single pulse. The departure of $L \propto E^1$ indicates that validity of the Eq. (1) seizes as pulse energy is increased. However, the departure from linear scaling is gradual and the qualitative explanation of the observed side-spots phenomenon as being acoustically induced phenomenon is satisfactory.

It is interesting to see (Figs. 2, 4, and 6) that the central densification is not linearly proportional to the pulse energy as can be inferred from Fig. 5. A possible explanation is an absorption by free and trapped electrons which provides additional absorption channel. The free electrons generated by optical breakdown are recombining and thermalizing with ions on a few picosecond time scale. Recombination of electrons and holes proceeds via traps in glasses [40]. When separation of pulses in time becomes larger than 10 ps (an electronic excitation lifetime) we see strong decrease in the phase modification at the middle point between two laser irradiation spots (Fig. 3(a)).

Phase snap-shots show that at certain time moments phases singularities (see, Fig. 6) are developed around the irradiation locations and side spots. The singularities are recognizable as strongly laterally localized phase jumps over more than 2π. Such apparent phase changes are caused by large and spatially localized material density alterations. The phase singularity would change the wave front of the light wave propagating through such regions and an optical vortex would be generated in the transmission beam. Analysis of the light passed throughout the phase singularity can be carried out in the optical far-field by imaging and polariscopy [41]. Polarization analysis of the out going light provides a direct readout of the density changes at the singularity site and has capability of super-resolution as we demonstrated recently [42]. This method can be applied to characterize sub-wavelength modifications inside glasses and crystals.

4. Conclusions

We have demonstrated that propagating of acoustic excitations in glass can cause a permanent densification during direct laser writing by a pair of closely-spaced ultra-short laser pulses. Acoustic localization of energy within volumes of sub-micrometer cross sections takes place and is sensitive to the spatial and temporal separation of the writing pulses. Since direct fs-laser writing by few pulses and beam arrays is widely used in waveguide recording and micro-fabrication [43, 44], it is important to control this phenomenon. Similar effects are expected in other glass and crystalline materials [18, 22, 41, 45], where anisotropy can cause more complicated patterns of modification.

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