Spatio-temporal dynamics of femtosecond Bessel beams for high-aspect ratio nanochannel drilling in dielectrics

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Abstract: Femtosecond high angle Bessel beams have been recently used to generate high aspect ratio (100:1) nanochannels in glass with a single laser shot. We report a numerical investigation of the spatiotemporal dynamics of the Bessel femtosecond pulse and obtain very good agreement with the experimental results. We show that the extended light-matter interaction length of Bessel beams generates a free electron-hole plasma with a spatial distribution that is highly sensitive to the ionization dynamics. High angle Bessel beams allow the generation of a plasma nanochannel with density higher than the critical value which can reach more than 90% ionization rate.

The fabrication of high-aspect ratio nano-channels is a particularly important challenge for nanofluidics and nanophotonics. We have previously reported a novel approach based on femtosecond Bessel beams to process nanochannels in glass with unprecedented aspect ratio (100:1) with a single laser shot. Although this effect was experimentally well-characterized by post-mortem analysis, the specific effect of high conical angle on the Bessel pulse and plasma generation were unknown. Here, we report the results of a detailed numerical study based on the nonlinear Schrödinger equation (NLSE) coupled to a rate equation describing the generation of an electron-hole plasma. We show that the extended light/matter interaction length of Bessel beams compared to Gaussian beams provides very high sensitivity to the ionization dynamics. We also show for the first time to our knowledge that this beam configuration allows the generation of a plasma nanochannel (typically 400 nm in diameter, 40 µm in length) with a density higher than the critical density at which plasmas become opaque and where the ionization degree can reach more than 90% with only a 1 µJ pulse. This explains the high degree of control on the nanochannel parameters that was observed experimentally. In addition, we show that the propagation dynamics is close to stationary such that Kerr-induced spatial and spectral dynamics is reduced even though the intensity can locally exceed extreme values ($>10^{14}$ W/cm^2). Interesting effects of pulse self-compression are also observed due to the rapid buildup of the plasma.