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Applications of laser-fabricated plasma structures in plasma nonlinear optics, ion acceleration and ultra-intense mid-infrared pulse generation

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A general method for fabricating transient plasma structures with high-intensity laser pulses has been developed to gain fine control on laser-plasma interaction [1]. Programmable fabrication of longitudinal spatial structures in a gas jet is achieved by using laser machining with a liquid-crystal spatial light modulator as the pattern mask [2]. These structures are used as programmable photonic devices in the development of laser-driven particle accelerators and plasma nonlinear optics driven by multi-terawatt lasers. Periodic plasma structures are used to achieve quasi-phase matching in relativistic harmonic generation [3]. By scanning the interaction length with the same method, tomographic measurements are carried out to resolve the injection/acceleration process in laser-wakefield accelerators and the amplification processes in plasma nonlinear optics [4-6]. Theoretical analysis and computer simulation are also carried out to provide insightful pictures of these processes. By adding a transverse heater pulse into the axicon-ignitor-heater scheme for producing a plasma waveguide, a variable three-dimensionally structured plasma waveguide can be fabricated [7]. With this technique, electron injection in a plasma-waveguide-based laser wakefield accelerator is achieved, resulting in production of a quasi-monoenergetic electron beam. Moreover, the intensity of X-rays from transverse betatron oscillations of the accelerating electrons is greatly enhanced with a transversely shifted section in the plasma waveguide [8].

For laser driven ion acceleration, it was proposed that magnetic vortices induced inside the plasma channel when an intense laser pulse propagating in a near-critical density plasma can be used to accelerate ions. Previous work proposed to prefer a plasma with smooth density ramp for ion acceleration [9]. However, in this case, because the ion acceleration process is just like target normal sheath acceleration or Coulomb explosion process, no obvious shock is observed and thus no mono-energetic ions are obtained. Through many simulations, we found that mono-energetic ions can be generated by magnetic-pressure-induced shocks using laser-fabricated plasma structure.

For midinfrared pulse generation, production of intense ultrashort midinfrared pulses from a laser-wakefield electron accelerator is demonstrated [10]. The midinfrared pulse generated by this method has an energy an order of magnitude larger than the most intense short pulse free-electron lasers, and three orders of magnitude larger than that of crystal-based nonlinear optical techniques. The midinfrared pulse is produced by the strong spectral broadening of the pump laser pulse occurring in a laser wakefield electron accelerator operated in the bubble regime. Recent experimental and simulation works show that we can largely extend the central length of the pulse to >5 μm while maintaining very high conversion efficiency by using laser-fabricated plasma structures. The advent of table-top multiterawatt femtosecond midinfrared laser has opened a new frontier in relativistically driven plasma nonlinear optics.

All these research works show that by controlling plasma structures with optical fabrication methods, laser-plasma interaction can be engineered to expand and enrich the frontier of high-field physics.

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