Matter and Radiation at Extremes | EDITORIAL | scitation.org/journal/mre

Plasma optics: A perspective for high-power coherent light generation and manipulation

Cite as: Matter Radiat. Extremes 8, 023001 (2023); doi: 10.1063/5.0138996
Submitted: 16 December 2022 • Accepted: 21 December 2022 •
Published Online: 2 February 2023

View Online Export Citation CrossMark

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Note: This paper is a part of the Special Topic Collection on Plasma Optics.
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ABSTRACT

Over the last two decades, the importance of fully ionized plasmas for the controlled manipulation of high-power coherent light has increased considerably. Many ideas have been put forward on how to control or change the properties of laser pulses such as their frequency, spectrum, intensity, and polarization. The corresponding interaction with a plasma can take place either in a self-organizing way or by prior tailoring. Considerable work has been done in theoretical studies and in simulations, but at present there is a backlog of demand for experimental verification and the associated detailed characterization of plasma-optical elements. Existing proof-of-principle experiments need to be pushed to higher power levels. There is little doubt that plasmas have huge potential for future use in high-power optics. This introduction to the special issue of *Matter and Radiation at Extremes* devoted to plasma optics sets the framework, gives a short historical overview, and briefly describes the various articles in this collection.

I. INTRODUCTION: WHY PLASMAS?

The 2018 Nobel Prize in Physics honored G. Mourou and D. Strickland[1,2] for the invention of chirped-pulse amplification (CPA),[3] which has led the way to short-pulse, high-power lasers worldwide.[4] The scientific push for ever higher focused intensities requires ever larger optical elements, such as mirrors, parabolas, and compressor gratings. The increasing size stems from the intrinsic damage threshold of solid-state-based optical materials, which is a few hundred millijoules per square centimeter (depending on the pulse duration). This has motivated research into the use of plasmas to manipulate laser light, since they have no damage threshold in the conventional sense. Nevertheless, limitations do exist, since the collective plasma effects are dynamic and therefore have a characteristic time scale that will eventually destroy the coherence of the laser. Also, kinetic effects such as wave breaking in plasmas can destroy the collective nature of the plasma response.

Manipulating coherent light by plasmas requires that coherence be preserved during the interaction process. This implies that the interaction has to be based either on collective processes (e.g., waves or quasi-waves) or on quasi-stationary processes (plasma mirrors). The interaction process needs to be carried out in a controlled way, which can take place either as a self-organizing process or as an induced process (for more details, see Sec. III and Table I).

The intrinsic dynamic aspect of plasmas makes them useful for high-repetition-rate petawatt laser operation. These lasers can nowadays operate at the hertz level, which gives a very long time scale compared with the relaxation time of the plasma.

II. HIGHLIGHTS OF THE LAST TWO DECADES

The following brief historical interlude presents a few highlights without claiming any sort of completeness. Also, it starts with plasma optics in the context of high-power lasers, after the advent of CPA lasers (references to some of the older literature can be found in Ref. 5).

1998: A theoretical analysis of stimulated Raman scattering (SRS)-based plasma amplification is presented[6] that identifies a self-similar solution (or nonlinear regime) leading to ultra-intense and ultrashort pulses based on electronic time scales. This is an example where parametric instabilities can be employed in a beneficial way [in contrast to inertial confinement fusion (ICF), where they are considered to be detrimental to the implosion process].

TABLE I. Categorization of various plasma-optical processes. n_c denotes the critical plasma density. The notions of strong and weak coupling are discussed in Ref. 5 and references therein. The last column refers to proof-of-principle experiments in the context of high-power operation.

Plasma-optical element[a]	Time scale	Intensity	Density	Setup	Experiment
Amplification SRS	Electron	Weak coupling	$<n_c/4$	Multiple beam	Yes
Amplification SBS	Ion	Strong coupling	$<n_c$	Multiple beam	Yes
FEPG	Ion	Ionization	$<n_c$	Multiple beam	No
Beam combining	Ion	Weak coupling	$<n_c$	Multiple beam	Yes
Frequency-shift	Ion/electron	Ionization/wave coupling	$<n_c$	Multiple beam	No
Plasma mirror	Hydro	Ionization	$>n_c$	Single beam	Yes
Polarization change	Ion	Weak/strong	$<n_c$	Multiple beam	Partially
Spectral broadening	Electron/ion	Ionization/wave coupling	$<n_c$	Single/multiple beam	No
Harmonic generation	Electron	Ionization	$\lessgtr n_c$	Single beam	Partially
EPM focusing	Hydro	Ionization	$>n_c$	Multiple beam	Yes
Hologram	Ion	Weak/strong	$\lessgtr n_c$	Multiple beam	No
Gratings	Electron/ion	Weak/strong	$\lessgtr n_c$	Multiple beam	Partially

[a]SRS, stimulated Raman scattering; SBS, stimulated Brillouin scattering; FEPG, fast-extending plasma grating; EPM, ellipsoidal plasma mirror.

2005: A remarkable experiment is performed that is able to show Raman amplification in the nonlinear regime.[7]

2006: Plasma amplification is analyzed using ion-based gratings in the so-called strong-coupling regime of stimulated Brillouin scattering (sc-SBS). A self-similar solution in this regime is also identified.[5]

2009: A multicolor scheme for controlled cross-beam energy transfer allowing tuning of the implosion symmetry in ICF experiments is proposed.[8]

2010: It is shown that ellipsoidal plasma mirrors can be used to refocus high-power laser beams for intensity enhancement.[9,10]

2014: Generation of spatial structuring of overdense plasmas at the surface of initially plain solid targets by optical lasers is experimentally demonstrated. The interaction of these transient structures with an ultra-intense laser pulse is also reported.[11] Plasma mirrors and their optical properties, including harmonic generations, are presented.[12]

2016: A scheme for generating transient photonic crystals for high-power lasers involving matching counterpropagating laser beams in a plasma in the sc-SBS regime is proposed.[13] An experimental demonstration of a plasma wave plate based on laser-induced birefringence is reported, in which a large-spot-size, low-intensity ($I = 10^{13}$ W/cm^2) laser beam interacts with a second beam in a gas-jet plasma.[14]

2017: Extremely high gain and significant energy transfer via the Raman amplification scheme are reported, with 170 mJ being obtained from a 70 J pump laser.[15] It is demonstrated that a holographic prepulse beam focused on a flat solid target creates modulations that can exist for picoseconds and can be used as plasma holograms.[16]

2018: It is suggested that redistribution of energy between multiple energy beams interacting in a plasma can generate a well-collimated beam. Such a plasma-based beam combiner is experimentally demonstrated at the National Ignition Facility.[17]
Frequency up-conversion in an ionizing media/plasma is suggested. The evolution of the wave frequency, amplitude, and energy density in a plasma with a temporally decreasing refractive index is studied.[18]

2019: Record energy transfer above the joule level and a very high efficiency up to 20% of laser-plasma based amplification in the sc-SBS regime is experimentally demonstrated.[19]
A fluid model is proposed to predict the nonlinear dynamics and characteristics of quasi-neutral gratings in a spatially periodic ponderomotive potential. Such gratings can be generated by two intense lasers at the same frequency and are found to have a typical growth time that depends on the laser amplitude.[20]

2020: A review of experimental results on plasma-based amplification via SRS and sc-SBS is presented. Through analysis of the nonlinear (or self-similar) regime, criteria are suggested to improve the efficiency of the scheme.[21]

2021: A new scheme for plasma-based frequency conversion and broadening by dynamic plasma gratings is proposed.[22]

2022: A theoretical scheme to generate a holographic plasma lens capable of focusing or collimating a probe laser in an underdense plasma is proposed and experimentally demonstrated.[23]
Plasma-based CPA is suggested, based on a compact high-power laser system that uses plasma transmission gratings with currently achievable parameters.[24]

III. MECHANISMS

Laser light is characterized by a set of fundamental parameters: pulse length, pulse shape, intensity, frequency, and polarization. All these properties can be altered in a controlled way by a plasma. The plasma itself has attributes such as density, profile, and temperature. For most plasma-optical applications, the charge state does not matter, and in general a fully ionized plasma made of protons and electrons is considered. Also, the temperature is not a dominant parameter, although it can play a role in threshold conditions such as the transition to the strong-coupling regime for wave phenomena. All plasma-optical approaches are based on collective effects in the medium and have to preserve the coherence of the laser beams under consideration. The plasma-optical interaction processes depend on several configurational aspects:

Laser: Plasma-based devices are by definition single-use devices. The lifetime of perturbations in the plasma is short compared with the repetition rate of the laser. For some of the effects that have been investigated, the frequency of the interacting laser needs to be adjusted *a priori* (e.g., downshifted for Raman-based amplification).

Plasma: The plasma medium can be generated from gas jets, solids, or foams. For many applications, either a homogeneous or tailored plasma profile is needed. Foam targets, whether chemically grown or 3D-printed (see Ref. 25 and references therein), are particularly useful in this respect. In the case of a prepared plasma structure, additional laser beams are used (e.g., gratings). Depending on the time scale under consideration, either the electron dynamics or the ion dynamics are important.

Time scale: A typical underdense plasma ($n_e < n_c$) evolves on the ion-acoustic time scale $t_{cs} \approx L_c/c_s$, where L_c is a characteristic length scale and c_s is the ion-acoustic velocity. This will set limits on the pulse duration of the coherent light pulse. Typical plasma dynamics have characteristic time scales of the order of hundreds of picoseconds or several nanoseconds, depending on the process in question. In most applications, the characteristic time scale is given by either the electron or the ion time scale in the plasma, based on the eigenmode regimes. However, in some applications, such as plasma amplification in the strong-coupling regime, the characteristic time scale is driven by the laser intensity, exciting a quasi-mode in the plasma.

Setup/beam configuration: For some of the more interesting applications, more than one laser beam is needed. This requires synchronized beams, which can be a challenge for short pulses. This is also a reason why not too many experiments have yet been performed, owing to the limited infrastructures available in this field.

Process (passive vs active): This distinction is related to what kind of plasma will be used. "Passive" means that the process under consideration is self-generated by the laser beam interacting with a plasma under various specific conditions (e.g., a plasma mirror). "Active" implies that the plasma is prepared in a controlled way to achieve the desired result (e.g., through amplification or gratings).

Table I provides a schematic categorization of various plasma-optical processes without pretending anything like completeness. Illustrative examples are provided in Figs. 1–3 for a grating, an ellipsoidal plasma mirror, and plasma amplification, respectively.

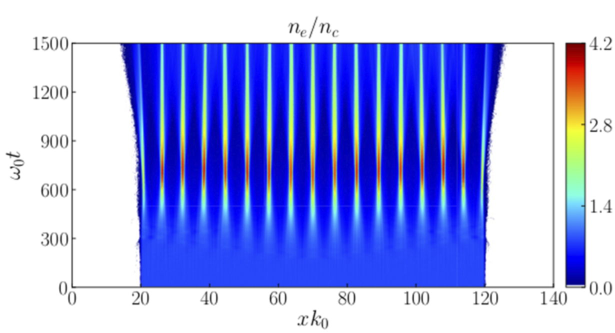

FIG. 1. Example of a very regular density grating generated by two crossing laser beams in a plasma. Reproduced with permission from Peng *et al.*, Phys. Rev. Appl. **15**, 054053 (2021). Copyright 2021 American Physical Society.[22]

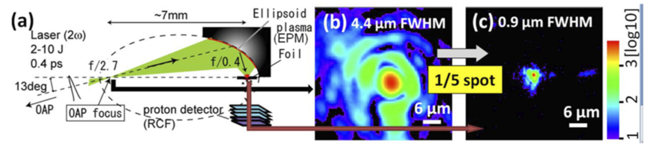

FIG. 2. Proof-of-principle experiment for an ellipsoidal plasma mirror (EPM) used for re-focusing. Reproduced with permission from Nakatsutsumi *et al.*, Opt. Lett. **35**, 2134 (2010). Copyright 2010 Optical Society of America.[9]

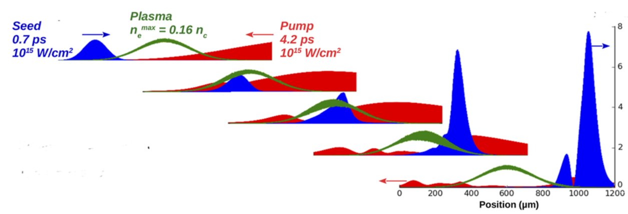

FIG. 3. Principle of plasma amplification. Result of a one-dimensional kinetic simulation. The intensity scale is in units of 10^{15} W/cm^2. Courtesy of J.-R. Marquès.

IV. OVERVIEW OF THE MRE SPECIAL ISSUE ON PLASMA OPTICS

The articles in this special issue devoted to plasma optics touch upon a variety of important topics, briefly presented in the following.

Qu and Fisch[26] investigate mechanisms to broaden the frequency spectrum of a laser pulse propagating in an underdense plasma. Depending on the pulse length and intensity of the laser pulse, either four-wave mixing or forward Raman scattering can play the dominant role. Manipulation of the frequency spectrum of high-power lasers in a controlled way is becoming an important research topic in ICF,[27,28] with the aim of controlling hot-electron production originating from parametric instabilities, as well as unwanted cross-beam energy transfer in overlapping driver beams.

Zhu *et al.*[29] show that tailored plasmas together with the well-established wakefield electron acceleration mechanism can be used to generate relativistic light intensities at wavelengths above 20 μm. Coherent light in the infrared regime is sought after for many applications in biology, medicine, and ultrafast dynamics of molecules. Infrared fields are also of interest for investigating strong-field phenomena.[30]

Bacon *et al.*[31] use plasmas generated from ultrathin foils to tailor the spatiotemporal properties of fundamental and second-harmonic light generated during the interaction process. Making use of a well-defined plasma aperture, they show that the modal structure of the light can be controlled.[32] In particular, this approach would allow the generation of high-power/high-intensity orbital angular momentum (OAM) beams, which would provide unique secondary sources.

Lehmann and Spatschek[33] analyze the properties of laser-generated plasma gratings with the aim of changing the polarization or splitting a subsequent laser pulse interacting with such a structure on very short time scales (far below the inverse ion plasma frequency). On this time scale, the grating consists of pure electron density modulation acting like a plasma photonic crystal.[13]

The transient nature is perfectly adapted to the manipulation of short-pulse laser beams at extremely high fluences, far beyond what any solid-state material can sustain.

Wu *et al.*[34] investigate a new aspect of plasma amplification. The proposed scheme compresses and amplifies the pulse by exploiting a fast-extending plasma grating (FEPG) based on stimulated Brillouin backscattering. In contrast to other schemes based on a three-wave coupling process, this new approach is a two-wave process based on the incident pump laser and the reflected pulse. No dedicated seed pulse need be injected into the plasma.

Mikheytsev and Korzhimanov[35] propose a scheme to generate synchronized x-rays and mid-infrared pulses through the interaction of relativistic laser pulses with near-critical plasmas. This would allow for high-precision pump–probe experiments such as laser-induced electron diffraction and transient absorption spectroscopy. The internal synchronization is on a sub-femtosecond level and will provide interesting possibilities for studies in materials science, including those currently pursued with more conventional wakefield setups.[36]

Li *et al.*[37] exploit the use of a fast-extending plasma grating to generate intense few-cycle infrared pulses. Such pulses have important applications in the investigation of electron dynamics in strong-field interactions and, for example, time-resolved imaging of molecular dynamics. This method enables picosecond pulses to be compressed into tens of femtoseconds pulses. In general, infrared-class coherent light sources such as CO_2 lasers have pulse durations of not less than a few picoseconds.[38]

The above examples show clearly how properties of plasmas can be used to affect the spectrum, wavelength, modal structure, polarization, and intensity of coherent light.

V. CONCLUSION AND OUTLOOK

Although in some respects plasmas have been used very successfully to control laser light, some other applications at the moment are either at a conceptual stage (e.g., plasma gratings for high-power beams) or at the stage of purely academic studies (e.g., high-energy scenarios for plasma amplification). Many proof-of-principle experiments have been performed. Whereas theory and simulation of plasma optics have advanced considerably over the last decade, experiments are lagging behind, particularly in the high-power regime. Partially, this is due to the limited number of laser installations where multiple synchronized beams are available. The potential of plasmas as high-power optical elements is no doubt considerable. If short-pulse lasers can be pushed beyond the multi-petawatt level, then the controlled use of plasmas will most likely become an essential tool.

ACKNOWLEDGMENTS

C.R. acknowledges support from the Federation Plas@par project and the support of Tremplin 2022 call (Sorbonne University, Science Faculty). S.W. acknowledges support from the Advanced Research Using High Intensity Laser Produced Photons and Particles (ADONIS) Project (No. CZ.02.1.01/0.0/0.0/16_019/0000789) and by the High Field Initiative Project (No. CZ.02.1.01/0.0/0.0/15_003/0000449) (HiFI), both from the European Regional Development Fund.

AUTHOR DECLARATIONS

CONFLICT OF INTEREST

The authors have no conflicts to disclose.

AUTHOR CONTRIBUTIONS

Caterina Riconda: Writing – review & editing (equal). **Stefan Weber**: Writing – review & editing (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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