LAWRENCE LIVERMORE NATIONAL LABORATORY

LLNL-TR-741098

FINAL REPORT "Extreme non-linear optics of plasmas" Pierre Michel (16-LW-022)

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November 3, 2017

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

FINAL REPORT

"Extreme non-linear optics of plasmas"

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Abstract

Large laser facilities such as the National Ignition Facility (NIF) are typically limited in performance and physical scale (and thus cost) by optics damage. In this LDRD, we investigated a radically new way to manipulate light at extreme powers and energies, where "traditional" (crystal-based) optical elements are replaced by a medium that is already "broken" and thus does not suffer from optics damage: a plasma. Our method consisted in applying multiple lasers into plasmas to imprint refractive micro-structures with optical properties designed to be similar to those of crystals or dielectric structures used in optics. In particular, we focused our efforts on two elements used to manipulate the polarization of lasers (i.e. the orientation of the light's electric field vector): i) a polarizer, which only lets a given polarization direction pass and blocks the others, and ii) a "Pockels cell", which can "rotate" the polarization direction or convert it from linear to elliptical or circular. These two elements are essential building blocks in almost all laser systems – for example, they can be combined to design optical gates. Here, we introduced the new concepts of a "plasma polarizer" and a "plasma Pockels cell". Both concepts were demonstrated in proof-of-principle laboratory experiments in this LDRD. We also demonstrated that such laser-plasma systems could be used to provide full control of the refractive index of plasmas as well as their dispersion (variation of the index vs. the light wavelength), which constituted the basis for a final experiment aimed at demonstrating the feasibility of "slow light" in plasmas, i.e. the capability to slow down a light pulse almost to a full stop.

Background and Research Objectives

Optics damage is the main limiting factor currently determining the physical scale and cost of large laser facilities. Indeed, when the laser power becomes high enough to damage the optical elements (lenses, mirrors etc.), beams need to be enlarged in space in order to reduce their fluence (energy per unit surface). For example, on the NIF, reaching the 2 mega-joules (MJ) of laser energy presumably required to achieve thermonuclear ignition requires the beam size to be increased to approximately 30 m^2 (192 beams of 40x40 cm each), in order to stay below the optics damage threshold of ~7 J/cm^2 (since [2 MJ]/[7 J/cm^2] ~ 30 m^2). Our goal is to investigate the potential of plasmas to manipulate intense lasers, at fluences many orders of magnitude beyond what traditional optics could endure. Plasmas are traditionally known as an optically isotropic medium (in the absence of external magnetic field), due to their intrinsically disorganized nature (they are sometimes described as ionized gases). However, by applying intense lasers in plasmas, it is possible to imprint modulations in the electron density at the wavelength-scale, via the "ponderomotive force" which pushes charged particles away from regions of high intensity. These modulations can act in the same way as the periodic refractive structures naturally found in some crystals, or produced in periodic dielectric coatings such as those used in modern optical elements (cf. Fig. 1).

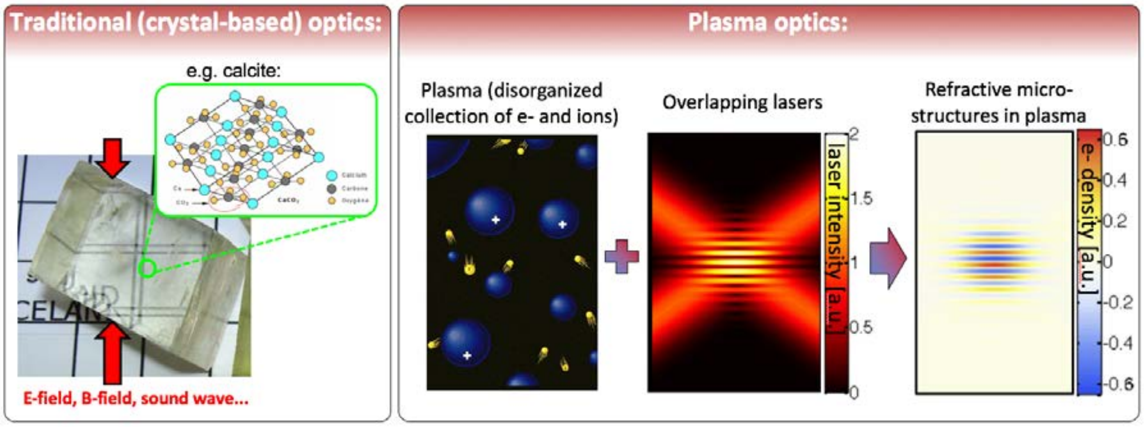

Figure 1. Schematic description of traditional vs. plasma optics. Our goal is to imprint wavelength-scale micro-structures in the plasma via multiple interfering lasers, in order to reproduce structures such as those found in crystal-based optical systems.

A trigger for this LDRD project was the observation, from experimental measurements in inertial confinement fusion (ICF) experiments, that overlapping multiple lasers in plasma was affecting their polarizations (i.e. the orientation of the electric field carried by the light waves). A theoretical investigation of this process [Michel 2014] led to the realization that laser-plasma systems could be used to modify the polarization of a light wave propagating through them. This led us to propose new concepts of a "plasma polarizer" and a "plasma Pockels cell". We also realized that plasmas may be able to accomplish "slow light", i.e. the capability by an optical medium to slow down a light pulse almost to a full stop, also by manipulating the optical properties of plasmas.

As soon this LDRD started, we received the opportunity to get time for experimental campaigns at the Jupiter Laser Facility (JLF, LLNL). While the initial goal of this LDRD was to pursue theoretical studies to investigate new plasma optics concepts, we decided to seize the opportunity to actually test these ideas in experiments and shifted our focus towards a more experimental effort. From FY16 to FY17 (and one month in FY18), we were able to experimentally test our concepts of: i) plasma polarizer; ii) plasma Pockels cell; and iii) slow light using plasmas. The third experiment is still on-going at the time of writing, but the first two are summarized below.

Scientific Approach and Accomplishments

The concept of "plasma Pockels cell" was tested first. The idea is illustrated in Fig. 2. A Pockels cell is a key building block of any laser system, and consists in a birefringent crystal whose degree of birefringence can be modified by applying a high voltage through the crystal. This results in a change of the polarization state of a light wave propagating through it – for example, from linear (i.e. the electric field of the light oscillate along a fixed direction) to circular (whereby the electric field oscillations describe a circle). In our proposed plasma Pockels cell, a plasma is used in lieu of the crystal, and the electric field modifying the optical properties of the plasma is that of an auxiliary laser (the "pump"). This system could, according to our theory [Michel 2014], modify the phase of the electric field of an incoming light wave along one specific direction, which could result in the same behavior as a traditional Pockels cell with the right conditions for the plasma and the pump laser.

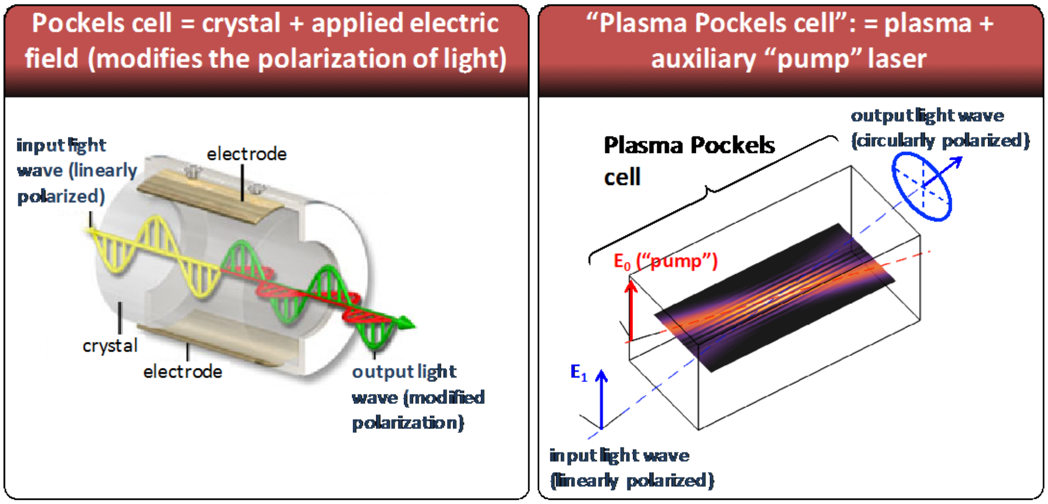

Figure 2. Conceptual design for a "plasma Pockels cell". The electric field of an auxiliary laser introduces birefringence in the plasma, which can lead to a change in the polarization state of a separate light wave (shown in blue) propagating through the plasma.

The experimental setup consisted in a high energy pump laser (200-700 J, in 3 ns) creating and preforming a plasma by ionizing the gas from a supersonic nozzle. Once the plasma reached the desired conditions of density and temperature, a low energy probe beam is sent to propagate through it and interact with the pump's electric field. The plasma was diagnosed using interferometry and optical Thomson scattering, and the probe was diagnosed after propagation through the plasma by polarimetry diagnostics. The setup is shown in Fig. 3.

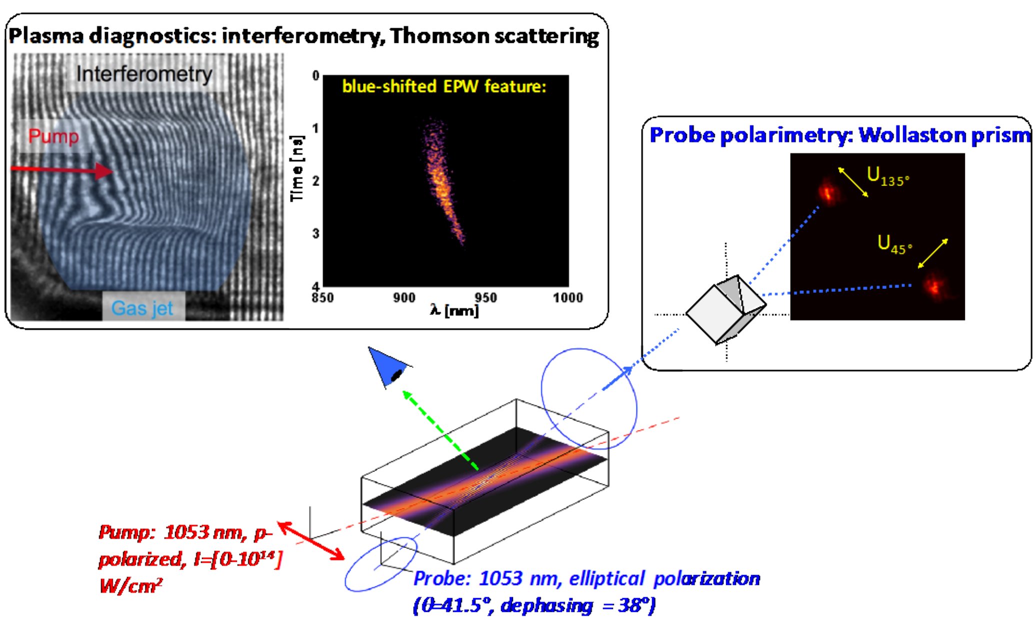

Figure 3. Experimental setup for the demonstration of the plasma Pockels cell at the Jupiter Laser Facility.

The results of the experiment are shown in Fig. 4, representing the measured vs. predicted dephasing of the probe's electric field – i.e. its polarization rotation (0° dephasing means that the polarization is linear; 90° means it's circular). This constituted the first validation of our theoretical prediction concerning the possibility to make a plasma birefringent (i.e. optically anisotropic) by using lasers, and the first proof-of-principle demonstration of a plasma-based Pockels cell.
These results were published in Phys. Rev. Lett., and selected as an "editor's pick".

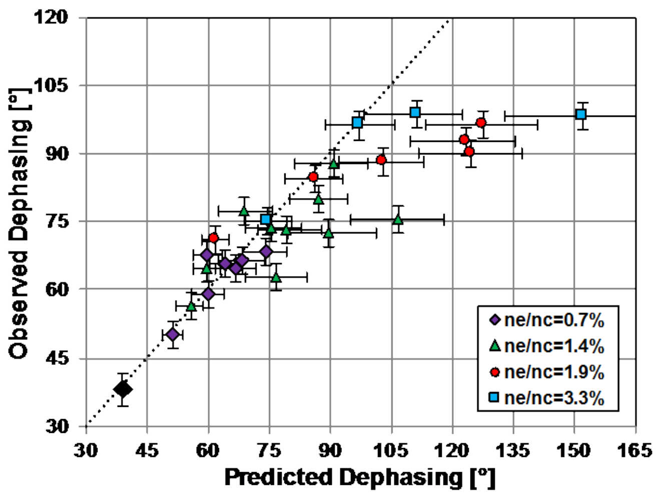

Figure 4. [from Turnbull 2016] Measured vs. predicted dephasing of the probe's electric field in our plasma Pockels cell experiment. This constituted the first validation of the concept of laser-induced plasma birefringence, and the first demonstration of a plasma-based Pockels cell.

In a follow-up experimental campaign in 2017, we tested the concept of a plasma polarizer, illustrated in Fig. 5. This experiment required a careful tuning of the wavelength of the pump beam, by up to a few Angstroms and with a sub-0.1 Å accuracy. The goal is for the wavelength separation to have the beat-wave between the pump and the probe match a resonant plasma mode (so-called "ion acoustic mode"). This leads to a transfer of energy from the probe toward the pump, but only for the probe's electric field component aligned with the pump. The other component (orthogonal to the pump's electric field, i.e. horizontal in Fig. 5) is the only one left after propagation through the plasma. In that regard, our plasma polarizer acts similarly to a "birefringent polarizer", whereby the unwanted polarization component is sent to propagate in a different direction (in our case, the unwanted component recombines with the pump and gives its energy to it).

The ultra-fine wavelength-tuning capability was not initially present at JLF, but the facility agreed to implement it for us on the Janus laser, thus allowing us to test the companion experiment to the successful demonstration of the plasma Pockels cell in 2016. The experimental setup was otherwise similar to the one shown in Fig. 3 – except of course for the wavelength tuning capability of the pump beam.

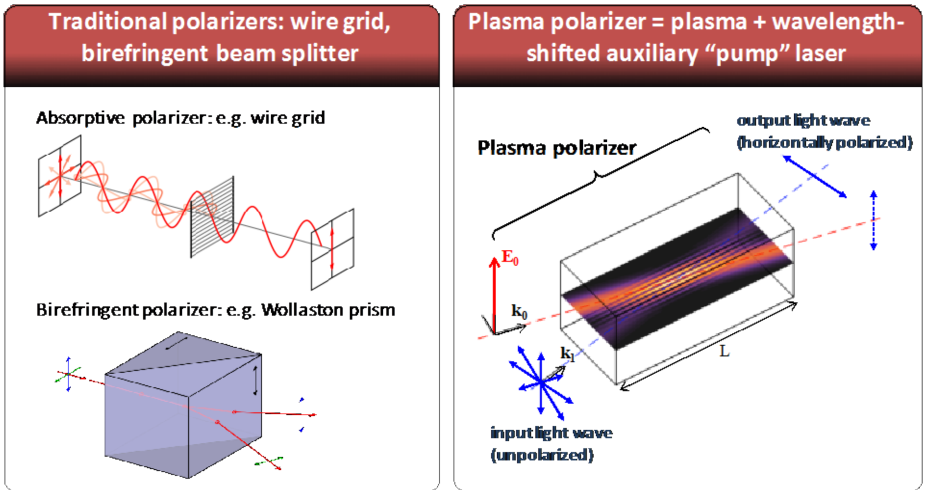

Figure 5. Conceptual design for a plasma polarizer, and comparison to traditional polarizers.

The experiment was another success; we not only demonstrated the plasma polarizer concept, but thanks to the new wavelength tuning capability, we were able to map out the refractive index of our plasma-optics system. These results are summarized in Fig. 6, and were published in another Phys. Rev. Lett. Paper.

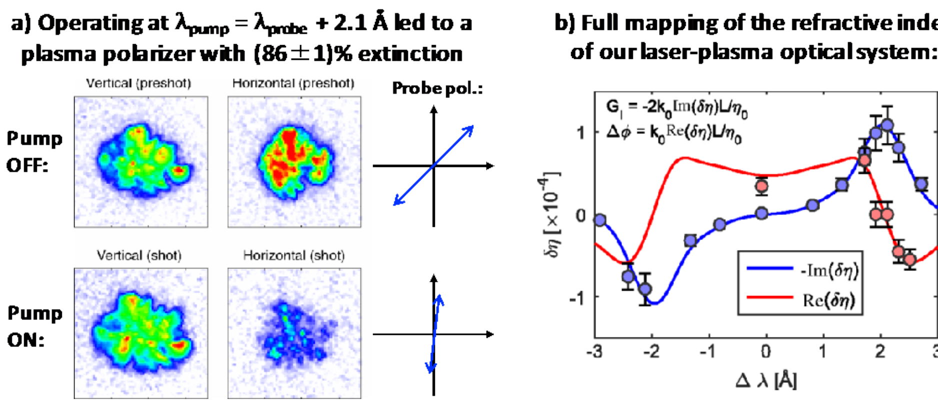

Figure 6. [from Turnbull 2017] a) Experimental demonstration of the plasma polarizer concept: when the pump is present, only the probe's electric field vertical component is transmitted. b) Mapping of the refractive index of our [pump+plasma] optical system as a function of the wavelength shift between the pump and the probe.

In addition, the capability to modify the refractive index of our system led us to propose the concept of "slow light" in plasmas, whereby a light pulse is slowed down almost to a full stop via the manipulation of the refractive index (this has been demonstrated in other optical media but never in plasmas). An experiment was schedule for October 2018, and is still in progress at the time of writing.

Impact on Mission

Using plasmas to manipulate light has an enormous potential for raising the fluence tolerable by such optical elements. Indeed, the physical mechanisms that constitute "damage" (thermal effects leading to melting and re-solidification, or ionization for the most intense laser pulses) do not exist in the plasma state, where matter is already ionized. The only limit remaining in terms of fluence is the development of non-linearities in plasma waves which can complicate the control and stability of optical structures; still, these processes should not be a concern until one reaches fluences on the order of millions of Joules per square centimeter, i.e. at least six orders of magnitude beyond what the current technology allows. This research has the potential to lead to transformational technologies that could enable us to achieve unprecedented laser intensities, thus opening a new era of fundamental and applied laser science.

Conclusion

Our research, while radically novel and promising, is still at the stage of proof-of-principle demonstrations and far (5-10 years) from a potential transfer to industry or implementation in actual laser systems. In particular, one obstacle is the fact that our experiments required more laser energy to condition the plasma and create the optical structure in it, than the energy of the probe beam that was being manipulated by those structures. An important step towards real applications of these concepts will be to demonstrate a favorable energy balance. Follow-up studies should also focus on the optical elements that are most critically prone to optics damage in laser systems, and develop plasma-based concepts to alleviate the damage problem for these particular elements (e.g. the last grating in a laser pulse compressor system). These two topics are the subject of a new LDRD-ER we are submitting in FY18.

References

[Michel 2014]: P. Michel, L. Divol, D. Turnbull & J.D. Moody: "Dynamic control of the polarization of intense laser beams via optical wave mixing in plasmas", *Phys. Rev. Lett.* **113**, 205001 (2014).

[Turnbull 2016]: D. Turnbull, P. Michel, T. Chapman, E. Tubman, B. B. Pollock, C. Y. Chen, C. Goyon, J. S. Ross, L. Divol, N. Woolsey, and J. D. Moody: "High Power Dynamic Polarization Control Using Plasma Photonics", *Phys. Rev. Lett.* **114**, 125001 (2016).

[Turnbull 2017]: D. Turnbull, C. Goyon, G. E. Kemp, B. B. Pollock, D. Mariscal, L. Divol, J. S. Ross, S. Patankar, J. D. Moody, and P. Michel: "Refractive index seen by a probe beam interacting with a laser-plasma system", *Phys. Rev. Lett.* **118**, 015001 (2017).

Publications and Presentations

- *Publications in refereed journals:*

D. Turnbull, P. Michel, T. Chapman, E. Tubman, B. B. Pollock, C. Y. Chen, C. Goyon, J. S. Ross, L. Divol, N. Woolsey, and J. D. Moody: "High Power Dynamic Polarization Control Using Plasma Photonics", *Phys. Rev. Lett.* **114**, 125001 (2016). (editor's pick)

D. Turnbull, C. Goyon, G. E. Kemp, B. B. Pollock, D. Mariscal, L. Divol, J. S. Ross, S. Patankar, J. D. Moody, and P. Michel: "Refractive index seen by a probe beam interacting with a laser-plasma system", *Phys. Rev. Lett.* **118**, 015001 (2017).

- *Oral presentations at international conferences and invited seminars:*

P. Michel: "Plasma Photonics for ICF & HED experiments", Inertial Fusion Sciences & Applications conference 2015

P. Michel: "Plasma Photonics for ICF & HED experiments", American Physical Society - Division of Plasma Physics conference 2015

P. Michel: "Plasma Photonics for ICF & HED experiments", Bordeaux University (France), **invited seminar** (2015)

D. Turnbull: "Scattered Light Polarimetry as a Diagnostic of Multibeam Hohlraum Physics", American Physical Society - Division of Plasma Physics conference 2015 (**invited talk**)

P. Michel: "Multi-beams laser-plasma interactions: from ICF to "plasma photonics" applications", Anomalous Absorption Conference 2016 (**plenary talk**)

P. Michel: "Multi-beams laser-plasma interactions: from ICF to "plasma photonics" applications", Bordeaux University (France) and Ecole Polytechnique (France), **invited seminars** (2016)

S. Shrauth: "Experimental Investigation of Self-Diffraction from Laser Generated Plasma Gratings", Anomalous Absorption Conference 2016

A. Colaitis: "Study of Raman-Nath Diffraction Experiments on OSL and NIF", Inertial Fusion Sciences & Applications conference 2017

P. Michel: "Multi-beams laser-plasma interactions: from ICF to "plasma photonics" applications", University of Rochester, **invited seminar** (2017)

Notes to the Editors

Please watch for:
- superscripts at the end of first paragraph in section "Background and Research Objectives" (p. 1)
- "degree" symbol at the beginning of p. 7 (third paragraph of section "Scientific Approach and Accomplishments")
- "Angstrom" symbol, also p. 7