Investigation of Transient Plasma Photonic Crystals

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Introduction

Since the first demonstration of chirped pulse amplification (CPA) in the mid-1980s [1], ultrashort pulse, high-peak-power lasers have been key to advancing research, often with societal importance. The next-generation facilities, such as Apollon [2], the Shanghai Superintense Ultrafast Laser Facility (SULF) [3] and the Extreme Light Infrastructure (ELI) [4, 5, 6, 7], are based on 10s PW laser systems. These facilities will provide high-energy charged particle and photon beams that will be used as powerful time resolved research tools for the development of new technologies, such as novel cancer therapy, and probing dense matter for border security and the nuclear industry.

A significant challenge in the design and operation of high-power laser facilities is the robustness of their optical components, which have damage thresholds on the order of $1\,\mathrm{J\,cm^{-2}}$, which makes them bulky and expensive. Damage to these sensitive components can lead to costly maintenance and downtime that can severely disrupt facility operation.

Plasma is an optically active medium, with the potential to replace optical components of high power lasers. It has a damage threshold several orders of magnitude greater than any solid state device, and is readily replenishable at the laser repetition rate. Numerous plasma-based optical device schemes have been proposed and experimentally demonstrated. For example, Raman [8, 9, 10, 11] and Brillouin [12, 13] amplification can yield high gain in probing laser pulses. Plasma mirrors [14] are commonly used to increase the temporal contrast of intense laser pulses used for studying laser-solid interactions. Plasma waveguides [15] are routinely used to guide high-power laser pulses and solid density plasma has been used as a source of high-harmonics [16]. Plasma holograms have been used to manipulate the mode structure of laser beams [17].

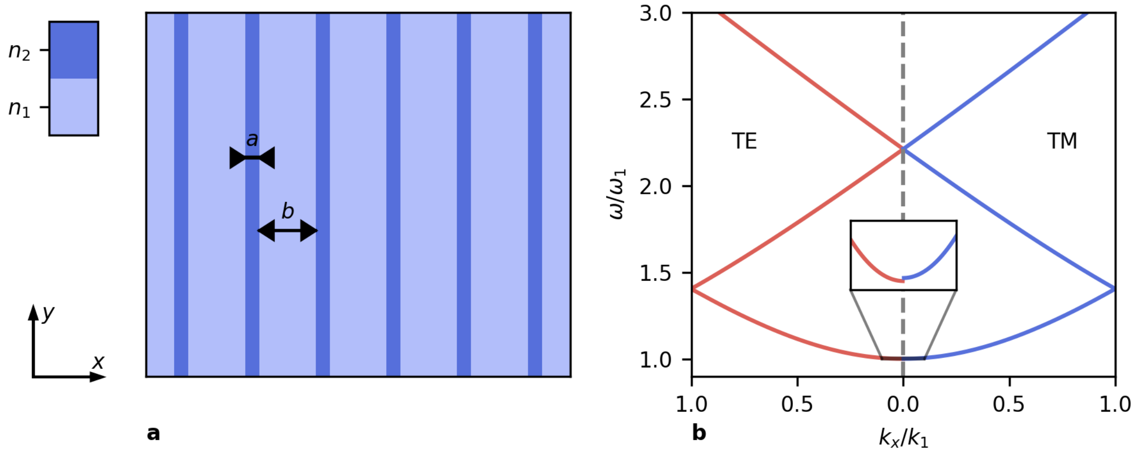

Figure 1: **a)** *Representation of a plasma grating formed by pump lasers with* $\vec{k} = k\hat{x}$. **b)** *Dispersion relation of transverse electric (TE) and transverse magnetic (TM) electromagnetic waves in a subcritical plasma grating calculated using the method in [21]. The discontinuity in* ω *between the waves shown in the inset indicates birefringence of the structure.*

Volume Plasma Density Gratings

One way of enhancing the utility of plasma optical elements is to structure plasma into a volume diffraction grating [18, 19], which can be used to manipulate high-intensity, ultrashort laser pulses [20, 21, 22].

If two, short duration ($\sim$ 1 ps), counter-propagating "pump" laser pulses of moderate intensity ($a_{0,\mathrm{pump}} \sim 0.01$, where $a = eE/m_e\omega c$ is the dimensionless laser field strength) collide in underdense plasma ($n_e < \varepsilon_0 m_e \omega^2/e^2$), the ponderomotive force associated with their beat wave causes electrons to be expelled from the beat antinodes to form a volume density grating. Because of their high inertia, ions only acquire momentum from the space-charge fields of electrons, before bunching after a short delay. The resulting structure is spatially periodic with wavelength equal to half of the pump wavelength.

A third, ultrashort, "probe" laser pulse can be used to probe the birefringent volume grating. As an example, a probe with $\vec{k}_{\mathrm{probe}} = k_{\mathrm{probe}}\hat{y}$ and $\omega_{\mathrm{probe}} = \omega_{\mathrm{pump}}$ interacting with a plasma grating formed by pump pulses with $\vec{k}_{\mathrm{pump}} = \pm k_{\mathrm{pump}}\hat{x}$ will have a polarisation-dependent phase velocity inside the grating [21] (see Fig. 1). If the pump and initial plasma parameters are chosen to have a peak electron density below critical, the birefringent structure will act as a waveplate.

Experiment Investigation of Volume Plasma Density Gratings

An experiment has been performed at the Central Laser Facility (Rutherford Appleton Laboratory, UK) using the Astra-Gemini laser to investigate the use of a volume plasma density grating as a waveplate. In the experiment, shown schematically in Fig. 2, two nearly-counter-propagating beams are made to collide in a gas jet (formed using a gauge 20 needle

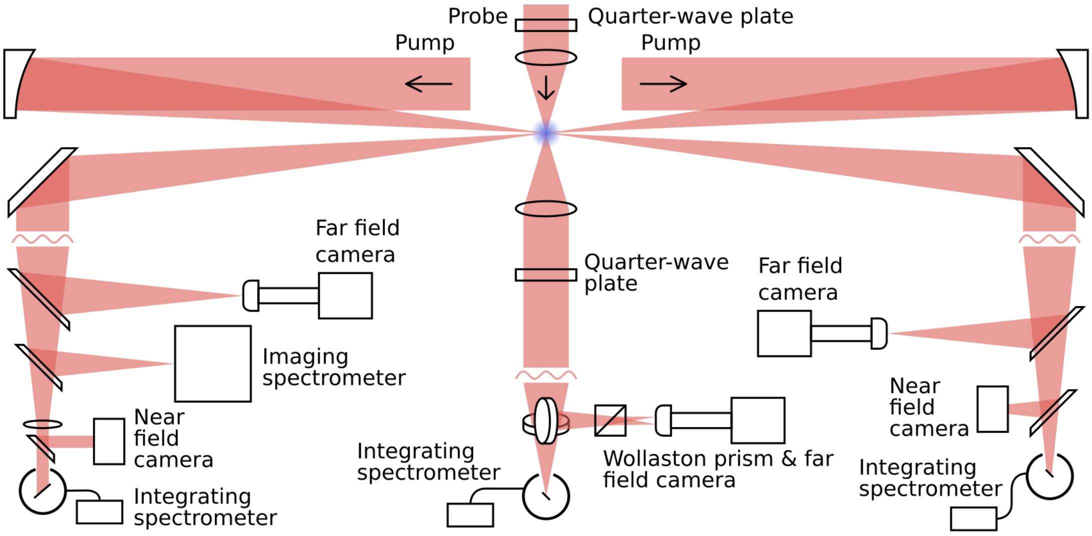

Figure 2: *Schematic of the Astra-Gemini experiment layout.*

nozzle pressurised with up to 100 bar of hydrogen). Pump beams have intensities of up to $I_{\text{pump}} = 5 \times 10^{15}\,\text{W}\,\text{cm}^{-2}$ and pulse durations of $\tau_{\text{pump}} = 1\,\text{ps}$. Each pump beam is apertured before the final amplifier to enable large, clean focal spots with a waist $w_{\text{pump}} = 16\,\mu\text{m}$ to be produced. A probe beam is produced by separately compressing a pick-off of one of the pump beams to $\tau_{\text{probe}} = 100\,\text{fs}$. Its polarisation is transformed to circular by a quarter-wave plate before being focused into the gas jet, as shown in Fig. 2.

Spatial overlap of the two pump beams is achieved by imaging the plasma channels produced by the pump beams. Each beam line had independent delay settings and timing between the three beams is fully adjustable. A fast diode is first used to ensure rough timing of the three pulses. One of the pump beams is fixed in time and the arrival of the probe is adjusted until modulations are seen in its far field image. The probe is then fixed and the second pump adjusted until the modulations are seen again.

Following interaction, the probe is re-collimated and transported outside the vacuum chamber. $\pi/2$ phase is then added by a second quarter-wave plate. The probe is then focused and passed through a periscope comprising a wedged window, to attenuate the orthogonal polarisation components equally. The spectrum of the transmitted portion is measured after being collected by an integrating sphere. The reflected part is passed through a Wollaston prism and the far field image of each polarisation component is magnified by a microscope objective onto a 16-bit camera. The probe energy is kept below 1 mJ to avoid ionising the hydrogen gas.

Following optimisation of the pump energy and timing between the pulses, a phase shift is induced in the probe beam during interaction with the plasma, which is attributable to the formation of a volume plasma density grating.

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