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Frequency shift of an intense laser pulse induced by plasma wave

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ABSTRACT

Spectral modification of an intense ($\geq 10^{18}$ W cm^{-2}) laser pulse propagating in a helium gas target was studied using Thomson scattering diagnostic. The spectra recorded at 90° to the laser propagation and polarization direction show a significant modulation and modification of the incident laser pulse during its interaction and propagation through the helium gas target. Simulations suggest that such a modulation in the spectrum of the laser pulse could arise due to its interaction with the self excited plasma waves.

1. Introduction

Frequency conversion of a laser pulse propagating through a medium having varying refractive index is a subject of considerable attention. In the case of laser gas interaction the variation in the refractive index could arise due to the two main basic mechanisms. First, through the rapid ionization of the medium [1] and second, by the interaction of the electromagnetic wave with the plasma wave [2].

When an intense ultrashort laser pulse propagates through a gaseous medium, it changes the refractive index of the medium through ionization, which in turn changes the phase and amplitude of the incident wave [3]. The phase and amplitude change induces modification in the spectral and spatial profile of the pulse. In addition to the ionization, the laser pulse excites collective electron density oscillations or electron plasma wave. The electron plasma wave consists of regions of high and low electron densities, which give rise to a modulating refractive index. Laser pulse interacting with such an oscillating refractive index experiences frequency shift.

Most of the earlier investigations on the frequency up-shift of the laser pulse incident on a gas jet target were related with the ionization induced refractive index change of the medium [4–8]. The first experimental observation of the frequency conversion induced by the laser wakefield was reported by Murphy et al. [9]. An experimental observation of the frequency conversion, arises from the modulation instability, was reported by Trines et al. [10]. In their study spectral modulation and mainly blue shift of the incident laser pulse was observed. A maximum shift close to 50 nm was found.

This paper reports on an experimental observation of the frequency shift of a single, intense, short laser pulse induced by the self generated plasma waves. The shift in the spectrum was recorded at 90° to the laser propagation and polarization direction using Thomson scattering diagnostic. An up-shift, exceeding 100 nm in the wavelength has been observed. This is for the first time, in the best of our knowledge, such a large shift is recorded in a single laser pulse experiment using Thomson scattering configuration.

The purpose behind the 90° Thomson scattering observation is to get some information, which could help in understanding the nature of the interaction of the laser pulse during its propagation inside the medium. Thomson scattering diagnostic could serve as an alternative way of detecting the change in the spectral profile of the laser pulse. The scattered radiations carry information about the scattering centers. The modulations observed in the scattered radiations are an evidence of the interaction of the laser pulse with the plasma waves.

The paper is organized as follows: in Section 2, brief description of the experimental set up is given. In Section 3, experimental results and discussion on its origin are given. In Section 4, numerical simulation of wave propagation and its modulation are presented

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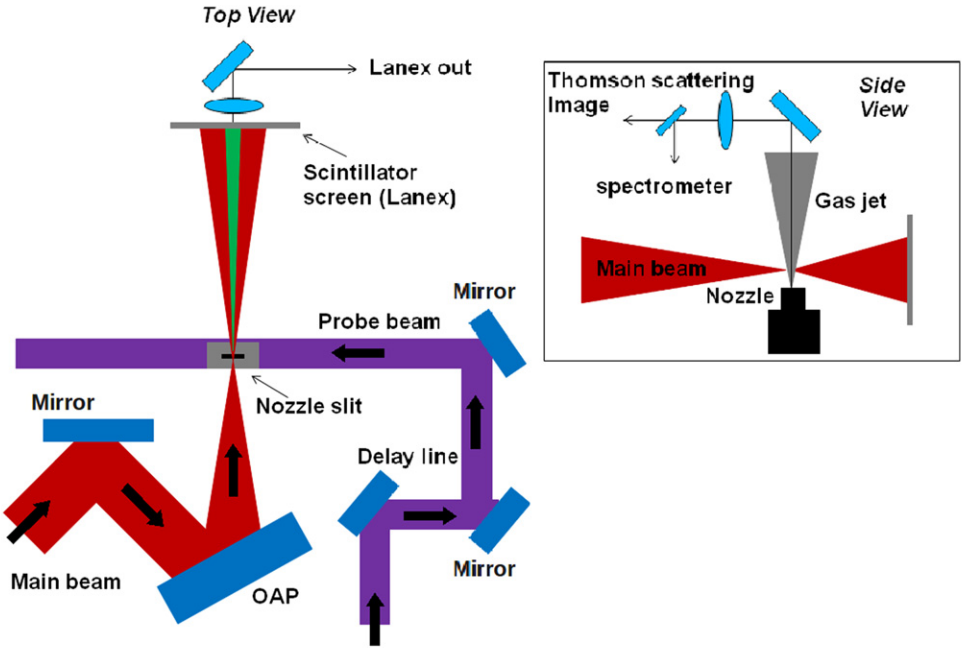

Fig. 1. Experimental set up. Left side in the figure is the top view of the interaction region and right side shows the side view of the interaction region. OAP in the figure indicates off axis parabolic mirror.

using PIC code. Finally, in Section 5, conclusion of the manuscript is given.

2. Experimental set up

The experiment was carried out at ILIL of Istituto Nazionale di Ottica (INO) with a Ti:Sapphire laser system, which delivers 800 nm, 65 fs laser pulse. A small part of the pulse was split, double in frequency (using a KDP crystal) and used as a probe pulse for interferometry. The main laser pulse was focused down to 10 μm spot using an F/6 off axis parabolic mirror (OAP). The energy content in the focused spot was around 100 mJ. The experimental set up is illustrated in Fig. 1. The experiment was mainly devoted to optimize the conditions for electron acceleration. By scanning the position of the best focus onto the gas-jet optimum conditions for electron acceleration were found. The probe laser pulse was used for Nomarsky modified interferometry [11] to obtain the electron density evolution. Thomson scattering diagnostic, which consists of an imaging system for the scattering region and a spectrometer (as shown in Fig. 1) was used to retrieve information on the laser propagation. A phosphor screen (LANEX) placed along the laser propagation axis was used to detect the accelerated electron bunch. The electron acceleration studies were successful and reported elsewhere [12].

3. Experimental result and discussion

For a laser pulse propagating in an underdense plasma the spectral analysis is normally carried out by sending the transmitted pulse directly into a spectrometer. This provides space and time integrated information on the pulse spectrum modification. All the information regarding laser–matter interaction remains encoded in the pulse spectrum without revealing how it developed in the pulse during its propagation in the medium. If this information could be obtained, then it could be possible to study the evolution of the nonlinear laser–matter interaction phenomena. One such method to characterize the ultraintense and ultrashort laser fields and to study the ultrafast dynamics of the electrons was proposed by Gao [13,14]. For an excellent review on nonlinear Thomson scattering of an intense laser pulses from beams and plasma the reader can refer Ref. [15].

In the present work, we exploit the Thomson scattering radiations to study the frequency modulation of the laser pulse during its interaction and propagation through the helium gas target. The Thomson scattering (TS) diagnostic is generally used to monitor the propagation of the laser pulse in the medium. In addition, we used a fiber optics based spectrometer to analyse the TS radiations. The detection range of the spectrometer was from 200 nm to 850 nm.[1]

In the experiment modulation and broadening of the incident laser pulse, mostly towards blue region, has been recorded. Fig. 2(a)–(c) show the Thomson scattered spectrum obtained from the helium gas target at a backing pressure of 35, 40 and 50 bar, respectively. Blue line in these figures show the spectrum of the laser pulse in the vacuum. The noteworthy features in the Thomson scattered radiations are the modulation of the spectrum and progressive frequency shift. The modulations in the spectrum increase with increasing backing pressure, indicating the dependence of the modulation in the scattered spectrum on the plasma electron density. At high pressure the frequency of the scattered radiation shows both up and down shift. No filters have been used during the recording of the spectrum. In our experimental conditions the frequency up-shift is likely to originate from the interaction of the laser pulse with the plasma waves, as discussed below.

At the intensity level and time scale of the laser pulse the ionization occurs at very early stage of the interaction. The major portion of the pulse propagates as if it is propagating in a preformed plasma. During propagation, front part of the pulse excites plasma wave. As soon as the plasma wave develops it

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[1] The laser spectrum in vacuum was measured with a separate fiber optics based spectrometer having different detection range.

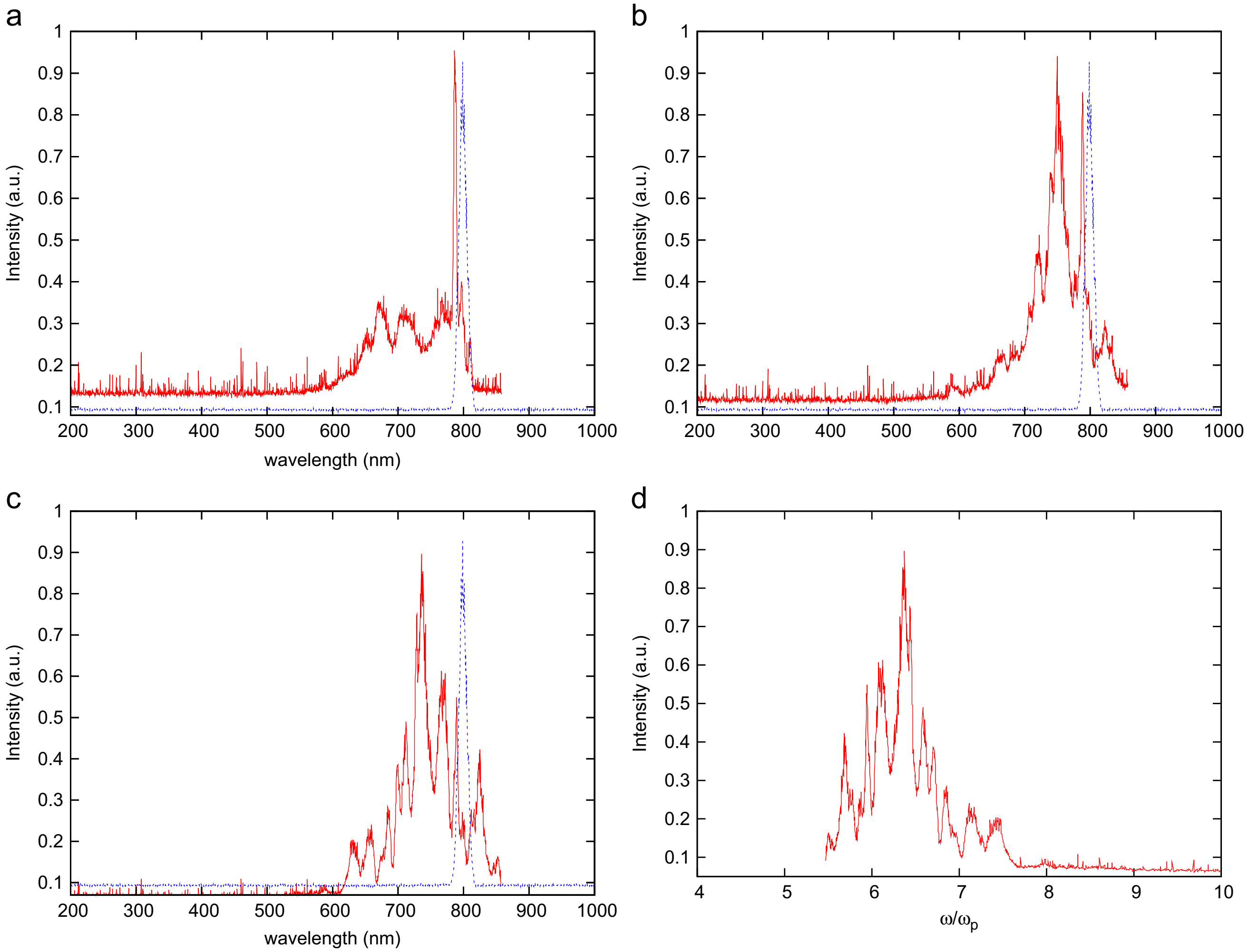

Fig. 2. (a) Spectrum of the Thomson scattered radiations from the helium gas target at a backing pressure of 35 bar, (b) 40 bar and (c) 50 bar. Blue line shows the laser spectrum in the vacuum. (d) The modulation at a backing pressure of 50 bar in the normalized angular frequency units, where ω is the laser angular frequency and ω_p is the plasma frequency. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

starts interacting with the rear part of the laser pulse. Consequently, the rear part of the pulse experiences changes in its phase and causes spectral modification. This is due to the fact that plasma waves consist of regions of high and low electron densities, which give rise to a modulating refractive index. When the rear part of the pulse interacts with such a time varying refractive index its phase modulates and consequently gives rise to new frequency components.

4. Numerical simulation

To analyse the underlying mechanism of the laser pulse propagation and its spectral modification, PIC simulation with EPOCH code was performed. The medium was assumed to be fully ionized. The pre-plasma assumption was partially valid for helium gas where rapid ionization takes place in the early stage of the interaction. The laser pulse parameters and the pre-plasma density were chosen similar to the experimental conditions.

Fig. 3 shows the snapshots of the pulse propagation and electric field evolution at different time intervals. Simulation reveals that after propagating in the preformed plasma the laser pulse starts focusing. The pulse as a whole does not focus. The central part of the laser pulse focuses more than the wings. The front part of the pulse tends to defocus and the rear part of the pulse is effectively modulated by the self-generated plasma waves. Fig. 4 shows the plasma wave generation and modulation of the laser pulse obtained from the simulation. One can observe that the electric field modulation of the laser pulse follows the electron density modulation in the plasma wave. Fig. 5 shows the modulated spectrum of the laser pulse after propagating 250 μm in the pre-formed plasma, obtained from the simulation. The simulated spectrum in Fig. 5(a)–(c) is corresponds to the backing pressure of 35, 40 and 50 bar, respectively.

There is an agreement between the experimentally recorded spectrum and the simulated spectrum (in particular at higher pressure), in terms of the spectral modulation and modification. Their might be some red shift as well, which is not visible in the experimental data due to the limitation in the detection range of the spectrometer. The recorded spectrum cannot be directly compared with the simulated spectrum, as it was recorded 90° the propagation direction. However, it can be cross co-related with it as it reflects the coupling of the incident laser pulse with the plasma wave. During this coupling part of the laser energy is scattered by the plasma wave. The scattered radiation spectrum provides signature of its origin from the electron density modulation.

In the experiment the scattered light was detected at 90° to the laser propagation and polarization direction. In this way we have a two step process: (1) interaction of the laser pulse with the

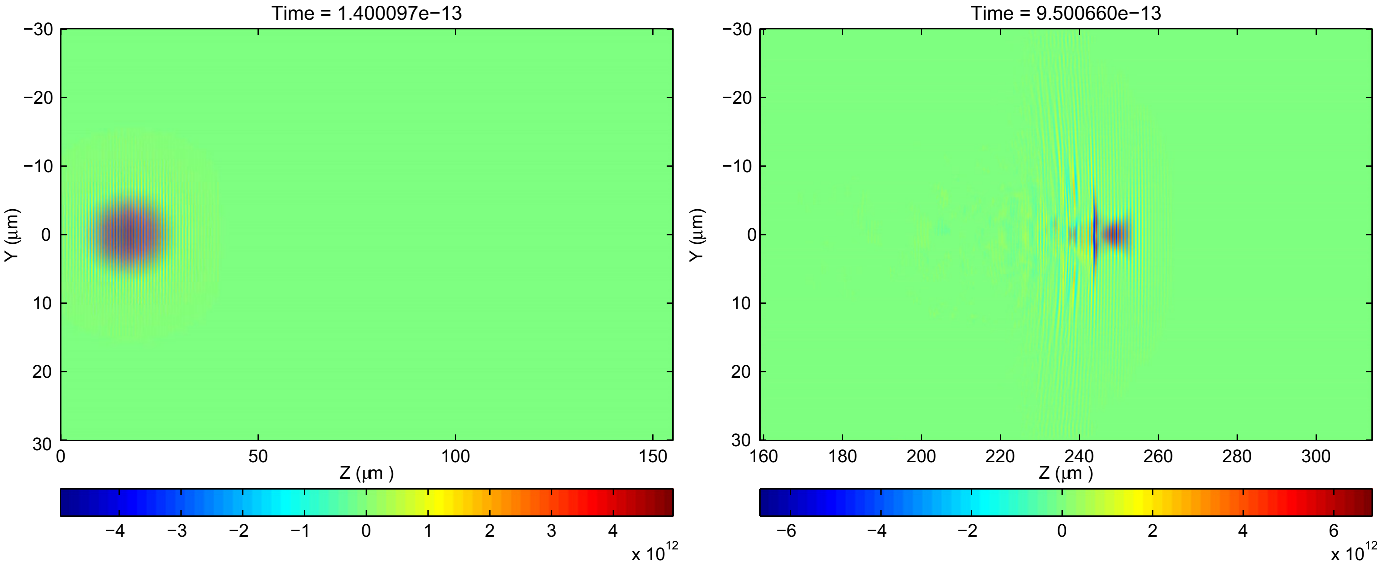

Fig. 3. Simulated electric field of the laser pulse at two different times during propagation. Laser pulse is propagating from left to right. The electric field of the laser pulse is modulated after propagating in the medium. The color bar at the bottom represents field values in V m^{-1}. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

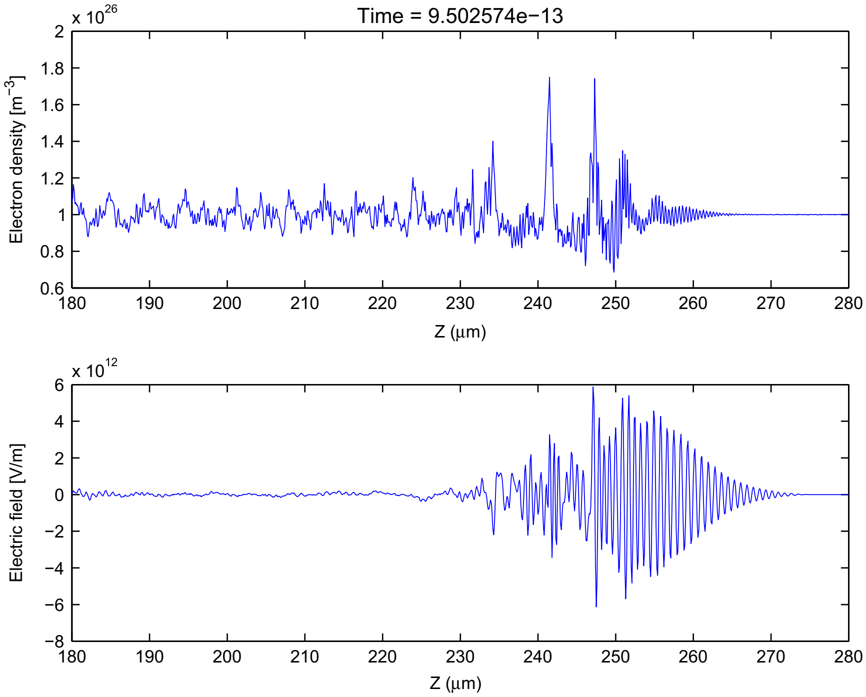

Fig. 4. Figure obtained from simulation shows the modulation in the laser pulse induced by the plasma wave. Upper fig.: plasma wave excited by the laser pulse. Lower fig.: modulation of the rear part of the laser pulse due to the plasma wave.

gaseous medium and its ionization and (2) scattering of the incident laser pulse by ionized medium. Thus, a wave propagation model that includes the ionization process and Thomson scattering configuration can give an actual estimation of the frequency shift that takes place during the interaction process.

5. Conclusion

In conclusion, we discussed the frequency up-shift phenomena observed during the interaction of an intense laser pulse with the helium gas target. Preliminary study suggests that the spectrum is shifted due to the wakefield-induced modulation of the laser pulse. Numerical study on the propagation of the laser pulse in underdense plasmas was done with PIC code. Pre-plasma assumption prevents to simulate the effect of the ionization on the intensity distribution during the propagation of the pulse in the medium. However, it still provides useful insight of the physical mechanism. It could be possible that in addition to the plasma wave-induced phase modulation, some other mechanism may also be involved in this process and is responsible for frequency up-shift. A detailed of this frequency shift phenomena

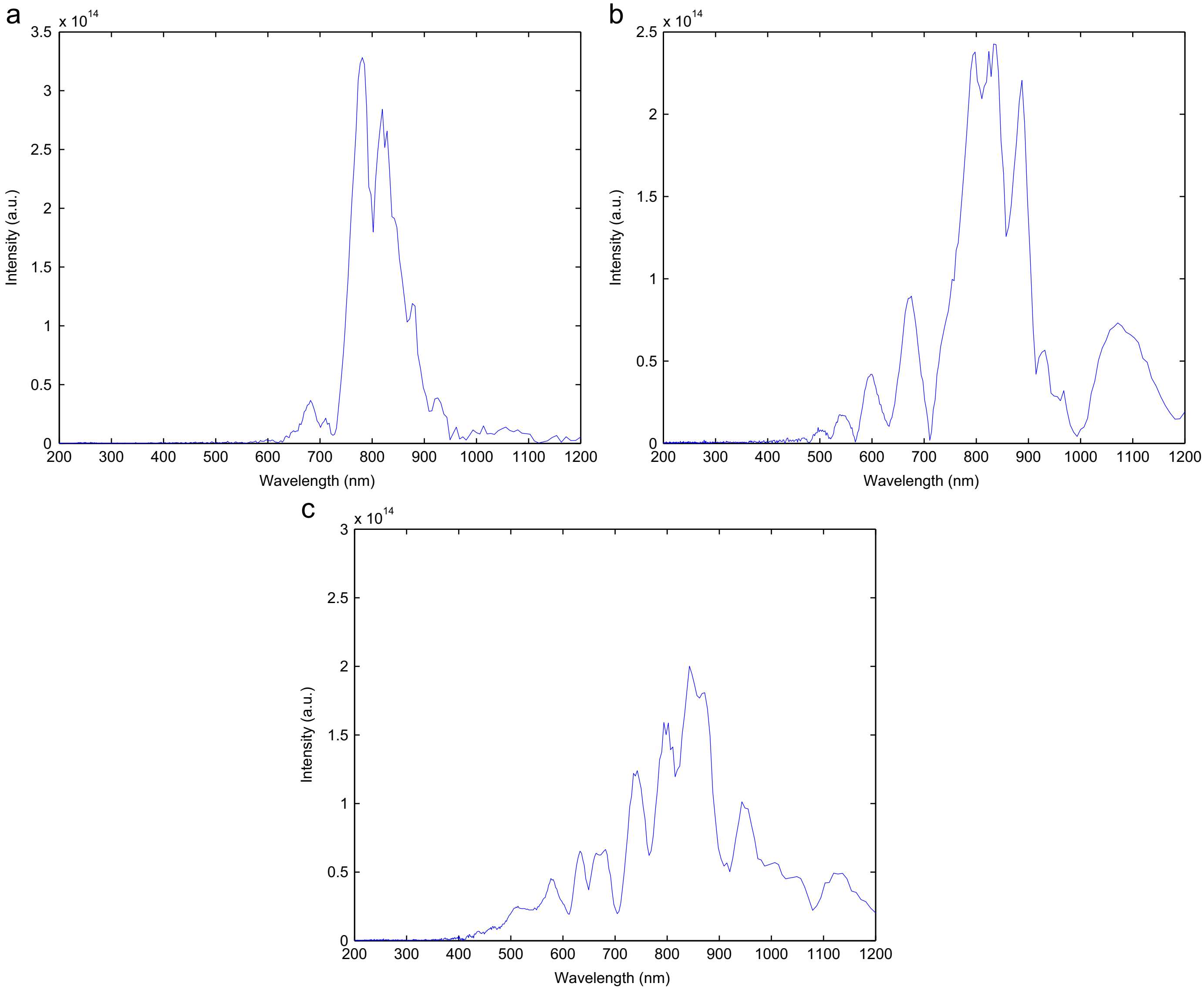

Fig. 5. Laser pulse spectrum obtained from the simulation at different plasma densities corresponding to (a) 35, (b) 40 and (c) 50 bar pressure. These figures displayed a clear dependence of the spectral modification and modulation on the plasma density.

is under investigation and will be explained with more physics in near future.

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