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Observation of ion acoustic multi-Peregrine solitons in multicomponent plasma with negative ions

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ABSTRACT

The evolution of the multi-Peregrine soliton is investigated in a multicomponent plasma and found to be critically dependent on the initial bound state. Formation and splitting of Peregrine soliton, broadening of the frequency spectra provide clear evidence of nonlinear-dispersive focusing due to modulational instability, a generic mechanism for rogue wave formation in which amplitude and phase modulation grow as a result of interplay between nonlinearity and anomalous dispersion. We have shown that initial perturbation parameters (amplitude & temporal length) critically determine the number of solitons evolution. It is also found that a sufficiently long wavelength perturbation of high amplitude invoke strong nonlinearity to generate a supercontinuum state. Continuous Wavelet Transform (CWT) and Fast Fourier Transform (FFT) analysis of the experimental time series data clearly indicate the spatio-temporal localization and spectral broadening. We consider a model based on the frame work of Nonlinear Schrodinger equation (NLSE) to explain the experimental observations.

1. Introduction

Plasmas being a nonlinear dispersive media, have vast opportunity to observe different nonlinear wave phenomena e.g. ion acoustic solitons, shocks and different kinds of instabilities. Solitons in nonlinear dispersive media arises due to delicate balance between nonlinearity and dispersion. For ion acoustic wave in normal electron–ion plasma, only the positive potential soliton can propagate which is described by the well-known Korteweg–de Vries (KdV) equation [1]. In a double plasma device, ion acoustic solitons were first observed by Ikezi et al. [2]. The presence of negative ions in plasma significantly modifies charge neutrality condition and hence the dispersive property of the plasma medium. In such plasmas, solitons with negative potential known as rarefactive soliton can propagate [3]. In laboratory, the multicomponent plasmas with negative ions are produced by injecting electronegative gases such as sulfur hexafluoride (SF_6) gas into normal argon (Ar) plasma. At a critical concentration of negative ions, the coefficient of nonlinear term in KdV equation becomes zero and a higher order nonlinearity has to be considered. In such condition, solitons with both polarity can propagate simultaneously, known as modified KdV (m-KdV) soliton [4].

During last few decades, the evolution of high amplitude wave event in nonlinear dispersive media has received great importance. A rogue wave, also known as freak wave, killer wave etc. represents a very high local concentration of wave energy compared with the average of the field [5,6]. The nonlinear Schrodinger equation (NLSE), in its many forms provides a variety of solutions to understand rogue wave evolution [7]. Spatially localized breather solutions (soliton pulses) were obtained in various plasma systems by early researchers [8–11]. In optics, Akhmediev found temporally localized breather solution of NLSE later known as Akhmediev breathers [12]. In hydrodynamics, Peregrine has formulated a doubly localized rational solution of NLSE, later known as Peregrine soliton, which has been considered as a prototype of rogue wave in ocean [13]. One generic mechanism, considered responsible for the generation of such high amplitude wave is the modulational instability. It is a process where phase and amplitude modulation grow as a result of nonlinearity and dispersion in a nonlinear dispersive media. In this process, wave energy self-focuses into a small isolated wave group leads to formation of very high amplitude localized wave structure. Stability of ion acoustic waves with respect to modulation in low temperature collisionless plasma have been investigated by many authors. Shimizu et al. have shown that ion acoustic waves in normal electron–ion plasma are stable with respect to modulation in the small wave number region [14]. Using reductive perturbation theory to the fluid equations, they have obtained the finite wavenumber limit ($k \geq 1.47k_D$, where k is the wave vector and k_D is the inverse of Debye length λ_D) for modulational instability of ion acoustic waves described by NLSE. For such large wavenumber range ion acoustic wave suffers heavy Lan-

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dau damping and modulational instability could not be observed in electron–ion plasma. Saito et al. examined the condition for modulational instability of ion acoustic wave in multicomponent plasma (with additional negative ion component in electron–ion plasma) and derived the NLSE [15]. In the light of well-known Lighthill's condition for modulational instability (the product of dispersion coefficient and nonlinear coefficient of the NLSE should be positive) they have shown that with the increase in the negative ion density the wave number range for modulational instability to occur reduces and at a critical value of negative ion density, the ion wave becomes modulationally unstable for any wave number. Experimentally this is a favorable condition to observe modulational instability of ion acoustic wave and has been observed in an earlier experiment [16]. Due to the presence of negative ions in multicomponent plasma, ion acoustic solitons with both positive and negative potential are excited simultaneously at a critical density of negative ions [4]. Under this condition the waves are described by the modified KdV equation where higher order nonlinearity has to be considered. Plasma response to both positive and negative initial perturbation (potential or density) becomes effectively equal and opposite due to modified nonlinearity supporting coexistence of solitons of both polarity. The NLSE derived for such plasma is equivalent to the modified KdV equation and the nonlinear coefficient of the NLSE is negative for any wavenumber [15]. Since the dispersion coefficient for ion acoustic wave is always negative, the condition for modulational instability is satisfied. The Peregrine soliton that has spatio-temporal localization, has been observed experimentally in multicomponent plasma with a critical concentration of negative ions induced by self-modulation of an initial amplitude modulated ion wave packet due to modulational instability [17,18]. Theoretically, Rogue wave (Peregrine soliton) structures of various types of plasma waves have been actively studied in recent years. Using NLSE framework, Langmuir rogue wave have been investigated in collisionless electron positron plasma by Moslem [19]. Moslem and his co-workers also investigated the existence of dust acoustic rogue waves in dusty plasma containing negatively charge dust particles as well as non-extensive electrons and ions [20]. In a dusty plasma with superthermal electrons and warm ions, existence of dust ion acoustic rogue wave have been investigated by Shalini et al. [21]. Recently, Singh et al. have discussed formation of rogue wave in multicomponent dusty plasma context considering the modulationally unstable wave packets described by the rational solution of NLSE [22]. Rogue waves are also studied in solid state physics. Yahia et al. have investigated the rogue wave phenomena in GaN semiconductor within the framework of NLSE triggered by modulational instability and found that rogue wave is responsible for the production and concentration of very high wave energy in the semiconductor [23]. One important characteristic of rogue wave described by the rational solution of Peregrine is that it is single isolated pulse with amplitude amplification ~3 times that of the background waves [17,18]. NLSE also supports higher order rogue wave solutions with increasing order of magnitude [24–28]. The second order Peregrine breather is also an isolated single pulse flanked by two smaller pulses and with amplitude amplification ~5 times has been observed in plasma and in water waves [29,30]. In all above cases, the initial perturbation (a single modulated wave packet) parameters (modulation, amplitude) are so adjusted that a single isolated and localized soliton (either a fundamental Peregrine or a second order Peregrine soliton) is excited. These high amplitude wave events are considered to be prototypes of super rogue waves in the ocean and emerge due to self-focusing resulting from the same generic mechanism of modulational instability.

In this report, we present the experimental observation of ion acoustic multi rogue waves in multicomponent plasma with critical concentration of negative ions. The number of solitons evolve is critically dependent on the initial perturbation parameters e.g. temporal length and amplitude. In Sec. 2, we have discussed the experimental setup and procedure to excite a multi rogue wave. The theory of breather evolution is based on the focusing NLSE which is appropriate for the description of wave envelops evolution. We numerically solve the NLSE to show the evolution of multi-Peregrine breathers and discussed in Sec. 3. The experimental observation of multi rogue waves and its analysis have been conferred in Sec. 4. Our experiment also leads to the observation of ion acoustic supercontinuum generation seeded by a very weakly amplitude modulated carrier pulse undergoing anomalous group velocity dispersion. Finally, we have summarized the results with concluding remark in Sec. 5.

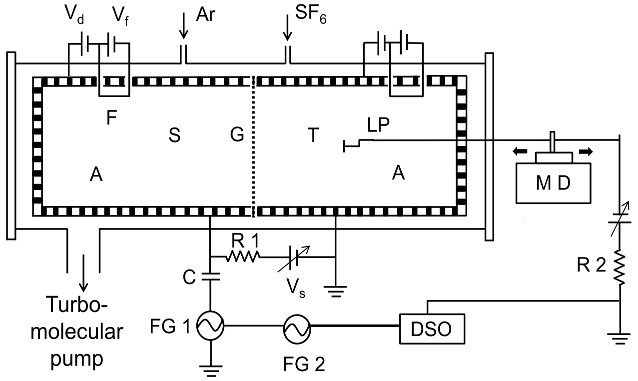

Fig. 1. Schematic diagram of the experimental setup. S – Source, T – Target, LP – Langmuir Probe, R1 & R2 – Resistors, C – blocking capacitor, V_d – Discharge voltage, V_f – Filament voltage, G – Grid, F – Filament, V_s – Source bias, LMD – Linear Motor Driver, FG1 & FG2 – Function Generators, DSO – Digital Storage Oscilloscope.

2. Experimental setup and procedure

The experiment has been carried out in a double plasma device of length 120 cm and diameter 30 cm. The schematic diagram of the device is shown in Fig. 1. The device consists of two plasma sources named as source and target section. Each section is made of 25 stainless steel rectangular pipes filled with permanent magnets (~1 kilo Gauss) to form a cusp magnetic field for surface plasma confinement. The source and target sections are separated by a stainless steel mesh grid of 50 lines per inch with 83% transparency. In each section, 5 tungsten filaments (1% thoriated) of length 5 cm and 0.1 mm in diameter, are placed 6 cm away from the surface. The chamber is evacuated down to 1.0×10^{-6} Torr by a turbo-molecular pump backed by a rotary pump. Argon gas is introduced into the chamber at a pressure range of $2\text{–}4 \times 10^{-4}$ Torr and plasma is produced by dc discharge between the magnetic cages as anode and hot tungsten filaments as cathode. In both sections, discharge voltage and current are maintained at 50–60 V and 30–50 mA respectively. Typical values of plasma parameters measured with the axially movable planar Langmuir probe of 6 mm diameter are: electron density $n_e \sim 3\text{–}8 \times 10^8$ cm^{-3} and electron temperature $T_e \sim 1\text{–}1.5$ eV. Ions are found to be in room temperature ~0.03 eV ($T_i \ll T_e$), so that Landau damping is small and ion acoustic wave can propagate longer distance. To produce the negative ion plasma, sulfur hexafluoride (SF_6) gas is injected into the Ar plasma at a partial pressure of $\sim 2 \times 10^{-5}$ Torr using a double valve system. Due to the dissociative attachment process, several species of positive and negative ions are produced such as SF_5^+, SF_4^+, SF_3^+ and F^-, SF_5^-, SF_6^-, etc. [3]. However, it is well known that the ions of lighter mass effectively modify the propagation of ion acoustic wave [3,31]. Hence, the multicomponent plasma is considered to be composed of Ar^+, F^- and electrons which have been confirmed earlier [32]. The density ratio of negative (F^-) ions to positive ions

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