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Parametric Instabilities of Parallel Propagating Circularly Polarized Alfvén Waves: One-Dimensional Hybrid Simulations *

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By performing one-dimensional (1-D) hybrid simulations, we analyze in detail the parametric instabilities of the Alfvén waves with a spectrum in a low beta plasma. The parametric instabilities experience two stages. In the first stage, the density modes are excited and immediately couple with the pump Alfvén waves. In the second stage, each pump Alfvén wave decays into a density mode and a daughter Alfvén mode similar to the monochromatic cases. Furthermore, the proton velocity beam will also be formed after the saturation of the parametric instabilities. When the plasma beta is high, the parametric decay in the second stage will be strongly suppressed.

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Alfvén waves are the exact solutions of the ideal incompressible magnetohydrodynamic (MHD) equations regardless of their amplitudes, and the intensity of their total magnetic fields is a constant.^[1–4] However, since Galeev^[5] pointed out in 1963 that a monochromatic circularly polarized Alfvén wave can decay into one forward propagating ion acoustic wave and one backward propagating daughter Alfvén wave,^[5–10] numerous works have been devoted to investigate the parametric instabilities of Alfvén waves via both theoretical analysis and numerical simulations.^[5–24] In the MHD frame, the parametric instabilities of a monochromatic Alfvén wave can be divided into three types.^[13,16,18] The decay instability can occur in a low beta plasma and generates one forward propagating ion acoustic wave (k_s) and one backward propagating daughter Alfvén wave ($k^- = k_0 - k_s$).^[5–8,16,18] The beat instability generates one forward propagating ion acoustic wave (k_s) and two daughter Alfvén waves that propagate forward and backward, respectively ($k^\pm = k_0 \pm k_s$).^[16,18] Such an instability can occur in both low and high beta plasmas for a left-handed polarized Alfvén wave, while for a right-handed polarized Alfvén wave, the beat instability can only take place in a high beta plasma with the amplitude of the pump wave reaching a higher threshold value ($A > 2|\omega_0|(\beta - 1)$, where A and ω_0 represent the normalized amplitude and frequency of a pump wave, respectively).^[16,18] The modulation instability occurs in a two-fluid plasma and generates one forward propagating ion acoustic wave (k_s) and two forward propagating daughter Alfvén waves ($k^\pm = k_0 \pm k_s$).^[11–13] The modulation instability occurs in a low beta plasma for a left-handed polarized Alfvén wave and in a high beta plasma for a right-handed Alfvén wave.^[11–13,18]

Recently with 1-D hybrid simulations, Araneda *et*

al.,^[21] Nariyuki *et al.*^[25,26] and Kauffmann *et al.*^[27] found that ion dynamics can restrain the growth of the parametric decay of a parallel propagating Alfvén wave and can promote the excitation of the modulation instability.^[21,25–27] Further, with 2-D hybrid simulation models,^[28–31] Matteini *et al.*^[28] and Gao *et al.*^[30] have reported that the perpendicular parametric decay can occur for a parallel propagating either linearly or left-hand polarized pump Alfvén wave in a low beta plasma. Although a monochromatic pump Alfvén wave is preferentially used in the above studies, the Alfvén waves in plasma usually exhibit a spectral structure.^[32–36] Consequently with a 1-D hybrid simulation model for the spectrum of Alfvén waves, Nariyuki *et al.*^[26] and Matteini *et al.*^[37] have found that the modulation instability and ponderomotive effect of the magnetic field will dominate the dissipation of the pump Alfvén waves at an early time of the evolution. In this Letter, we analyze in detail the parametric instabilities of the Alfvén waves with a spectrum in a low beta plasma, which is observed to experience two stages.

Here a 1-D hybrid simulation model under period boundary condition is employed, where the ions are described as particles, while the electrons are treated as the massless fluid.^[38–40] The hybrid simulation model not only can simulate the ion dynamics more accurately than the MHD simulation model, but also can save more computing time than the PIC simulation model. The basic equations solved in the hybrid simulations are listed as follows:

$$\begin{aligned} m_i \frac{dv_i}{dt} &= e(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) - e\eta \mathbf{J}, \\ 0 &= n_e m_e \frac{d\mathbf{V}_e}{dt} = -en_e(\mathbf{E} + \mathbf{V}_e \times \mathbf{B}) - \nabla p_e + en_e \eta \mathbf{J}, \\ \mu_0 \mathbf{J} &= \nabla \times \mathbf{B}, \quad \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \quad \frac{p_e}{n_e} = \text{const}, \end{aligned}$$

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with the electric field \mathbf{E} , the magnetic field \mathbf{B} , the current density \mathbf{J} , the ion velocity \mathbf{v}_i , the electron bulk velocity \mathbf{V}_e , the pressure of electrons p_e , and the number density n_e (charge neutrality $n_e = n_i = n$). Here e , m_i and m_e represent the charge unit, the masses of ion and electron, respectively; η is the resistivity, which represents wave-particle effects due to high frequency plasma instabilities that involve the electron mass. The state equation of electrons is adiabatic, where γ represents the adiabatic index.

The simulations are performed in x -axis parallel to the ambient magnetic field (\mathbf{B}_0), and all physical quantities depend only on one spatial coordinate x . Here the plasma density, magnetic field, and velocity are normalized by the initial uniform density ρ_0 , background magnetic field intensity B_0 , and background Alfvén velocity $v_A = B_0/\sqrt{\mu_0\rho_0}$, respectively. The time and space are normalized by the reciprocal of proton cyclotron frequency $\Omega_p^{-1} = m_p/e_p B_0$ (m_p is the mass of proton, and e_p is the charge of proton) and proton inertial length c/ω_{pp} (c is the speed of light in a vacuum, and ω_{pp} is the proton plasma frequency based on the proton number density n_p), respectively.

The initial pump Alfvén waves are given as^[26,37]

$$\delta\mathbf{B}_p = \sum_{k_0=k_1}^{k_n} \delta B_{k_0} [\cos(k_0 x - \omega_0 t + \phi_{k_0}) \hat{\mathbf{y}} + \sin(k_0 x - \omega_0 t + \phi_{k_0}) \hat{\mathbf{z}}], \quad (1)$$

$$\delta\mathbf{u}_p = \sum_{k_0=k_1}^{k_n} \delta u_{k_0} [\cos(k_0 x - \omega_0 t + \phi_{k_0}) \hat{\mathbf{y}} + \sin(k_0 x - \omega_0 t + \phi_{k_0}) \hat{\mathbf{z}}], \quad (2)$$

where $\delta\mathbf{B}_p$ is the magnetic fluctuation and $\delta\mathbf{u}_p$ is the associated transverse velocity. The initial phase ϕ_{k_0} is given randomly with a range $[0, 2\pi]$. By using Eqs. (1) and (2), the initial pump Alfvén waves are set to be a linear superposition of parallel propagating left-handed Alfvén waves, which have a spectrum structure. Each initial pump Alfvén wave with the wave number k_0 and frequency ω_0 is given by employing the dispersion relation obtained from the Hall-MHD equations,^[14] for left-handed Alfvén wave $\omega_0^2 = k_0^2(1 - \omega_0)$ and Walen's relation,^[25] $\delta u_{k_0} = -\delta B_{k_0}/(\omega_0/k_0)$.

The number of grid cells is $n_x = 600$, the size of grid cell is $\Delta x = 1.0c/\omega_{pp}$, the time step is $\Delta t = 0.025\Omega_p^{-1}$, and the electron resistive length is set to be $L_r = \eta/\mu_0 V_A = 0.02c/\omega_{pp}$, which is useful in eliminating unwanted high frequency noise. For protons, 900 macroparticles are initially evenly distributed in every cell. The total magnetic field energy of the initial pump Alfvén waves is set to be $\sum_{k_0=k_1}^{k_n} (\delta B_{k_0}/B_0)^2 = 0.04$, and the amplitude of each initial pump Alfvén wave is equal.

Three simulation runs are performed. The electron beta β_e , the proton beta β_p , and the wave numbers of the initial pump Alfvén waves for each run are listed in Table 1.

Figure 1 displays the time evolution of the density fluctuations $\langle(\delta\rho/\rho_0)^2\rangle^{1/2}$ for run 1. It can be found that the evolution has two stages. In the first stage (up to $\Omega_p t \approx 550$), the density fluctuation increases up to $\langle(\delta\rho/\rho_0)^2\rangle^{1/2} \approx 0.08$ immediately, and then nearly remains constant except for some large oscillations. However, at the beginning of the second stage, the density fluctuation begins to increase rapidly until its saturation with $\langle(\delta\rho/\rho_0)^2\rangle^{1/2} \approx 0.2$ at about $\Omega_p t = 800$.

Table 1. The simulation parameters for runs 1–3.

Run	β_e	β_p	Wave numbers
1	0.1	0.01	$k_1=0.209, k_2=0.094$
2	0.1	0.01	$k_1=0.136, k_2=0.168, k_3=0.199,$ $k_4=0.230, k_5=0.262$
3	0.3	0.8	$k_1=0.209, k_2=0.094$

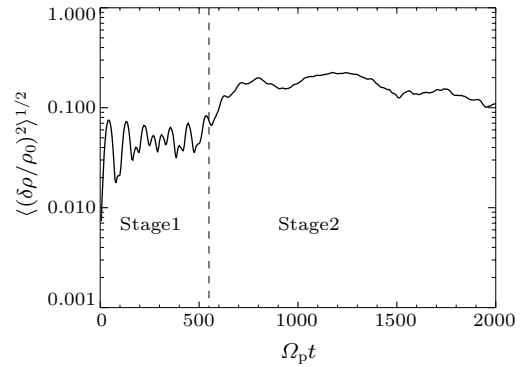


Fig. 1. Time evolution of the density fluctuations $\langle(\delta\rho/\rho_0)^2\rangle^{1/2}$ for run 1. The two stages (stage 1 and stage 2) of the time evolution are separated by a vertical dashed line at $\Omega_p t \approx 550$.

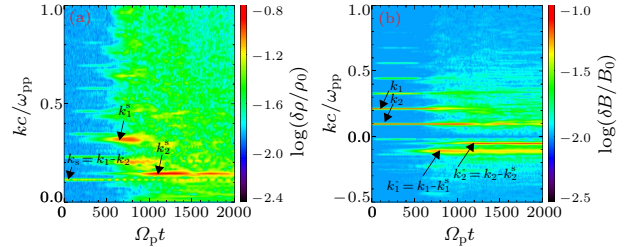


Fig. 2. Time evolution of the power spectra for (a) the density fluctuations and (b) the magnetic field fluctuations for run 1. In panel (a) the density modes (k_s , k_1^+ , and k_2^+) are denoted by arrows. In panel (b) the pump Alfvén wave modes (k_1 , k_2) and the daughter Alfvén wave modes (k_1^- , k_2^-) are also denoted by arrows, respectively.

Figure 2 displays the time evolution of the power spectra for the density fluctuations (Fig. 2(a)) and the magnetic field fluctuations (Fig. 2(b)) for run 1. In Fig. 2(a) we can find that in the first stage a density mode with the wave number ($k_s c/\omega_{pp} \approx (k_1 - k_2)c/\omega_{pp} \approx 0.115$) appears first, and such a density mode is the result of the envelope modulation of the two incoherent pump Alfvén waves. The higher harmonic density modes with wave numbers $2k_s$, $3k_s$, and $4k_s$ can also be excited. The interactions between these density modes and the pump Alfvén waves lead to the generation of several modes of magnetic fluctuation.

tuations. This can be demonstrated more clearly in Fig. 3, which plots the power spectra of the density fluctuations (Fig. 3(a)) and the magnetic fluctuations (Fig. 3(b)) at $\Omega_p t = 200$ for run 1. To fully understand the coupling processes between the density modes and the Alfvén modes, we have carefully calculated the wave-number relations of all wave modes in the system. The results have also been presented in Fig. 3. The wave numbers of the excited magnetic fluctuations include $(k_2 - k_s)c/\omega_{pp} \approx -0.021$, which propagates backward, and $(k_1 + k_s)c/\omega_{pp} \approx 0.324$, $(k_1 + 2k_s)c/\omega_{pp} \approx 0.439$, etc., which propagate forward.

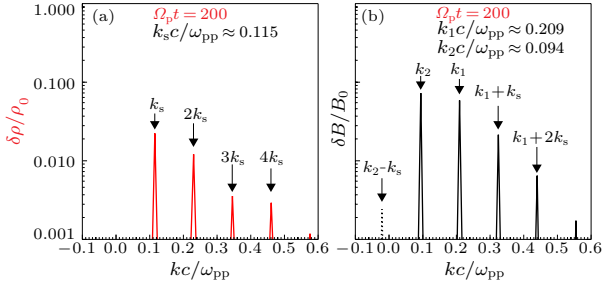


Fig. 3. The power spectra of (a) the density fluctuations and (b) the magnetic field fluctuations at $\Omega_p t = 200$ for run 1. The black lines and red lines show the magnetic and density fluctuations, respectively. The forward modes and backward modes are denoted by solid lines and dashed lines, respectively. In panel (a) the density mode (k_s) and its higher harmonic modes ($2k_s$, $3k_s$, and $4k_s$) are denoted by arrows, respectively. In panel (b) the pump Alfvén wave modes (k_1 , k_2) and the daughter Alfvén wave modes ($k_2 - k_s$, $k_1 + k_s$, and $k_1 + 2k_s$) are denoted by arrows, respectively.

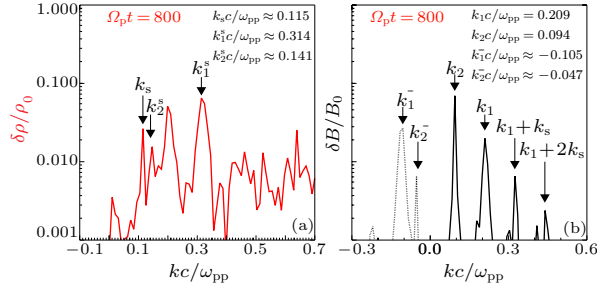


Fig. 4. The power spectra of (a) the density fluctuations and (b) the magnetic field fluctuations at $\Omega_p t = 800$ for run 1. The black lines and red lines show the magnetic and density fluctuations, respectively. The forward modes and backward modes are denoted by solid lines and dashed lines, respectively. In panel (a) the density modes (k_s , k_1^s , and k_2^s) are denoted by arrows, respectively. In panel (b) the pump Alfvén wave modes (k_1 , k_2), the daughter Alfvén wave modes (k_1^- , k_2^- , $k_1 + k_s$, and $k_1 + 2k_s$) are denoted by arrows, respectively.

Figure 4 demonstrates the power spectra of the density fluctuations (Fig. 4(a)) and the magnetic fluctuations (Fig. 4(b)) at $\Omega_p t = 800$ for run 1. All the dominant modes and the wave-number relations among them are also provided in both the panels. It is found that, in the second stage, in addition to the residual wave modes excited in the first stage, each pump Alfvén wave will decay into a forward propagating density mode and a backward propa-

gating daughter Alfvén wave. The wave numbers of the density modes corresponding to the pump waves ($k_1 c/\omega_{pp} = 0.209$ and $k_2 c/\omega_{pp} = 0.094$) are $k_1^s c/\omega_{pp} \approx 0.314$ and $k_2^s c/\omega_{pp} \approx 0.141$, respectively, while the daughter Alfvén waves have wave numbers $k_1^- c/\omega_{pp} \approx (k_1 - k_1^s)c/\omega_{pp} \approx -0.105$ and $k_2^- c/\omega_{pp} \approx (k_2 - k_2^s)c/\omega_{pp} \approx -0.047$. This physical process in the secondary stage can be roughly considered as the superposition of the parametric decay of each pump Alfvén wave.

Figure 5 shows the time evolution of the power spectra for the density fluctuations (Fig. 5(a)) and the magnetic fluctuations (Fig. 5(b)) during the parametric instabilities of five pump Alfvén waves in run 2. Similar to the parametric instabilities of the two pump Alfvén waves in run 1, this evolution can also be divided into two stages. In the first stage, more density modes are excited due to the envelope modulation of the five pump Alfvén waves, and more modes of the magnetic fluctuations are generated due to the interactions between the density modes and the pump Alfvén modes. In the second stage, each pump Alfvén wave can decay into a forward propagating density mode and a backward propagating daughter Alfvén wave mode. Compared with the case of two pump waves in run 1, both the density and magnetic fluctuations show a broader and more continuous spectrum in run 2.

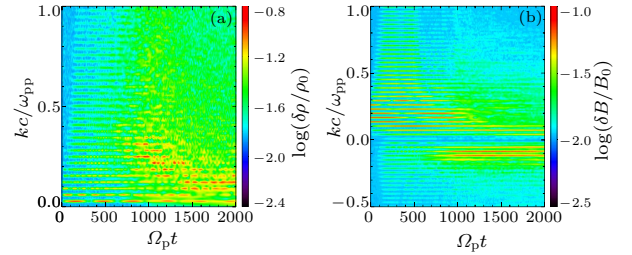


Fig. 5. Time evolution of the power spectra for (a) the density fluctuations and (b) the magnetic field fluctuations with five initial pump Alfvén waves for run 2.

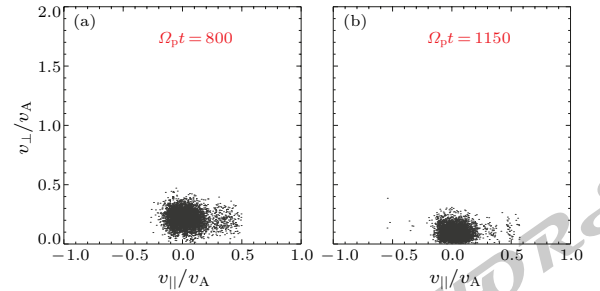


Fig. 6. Scatter plots of protons in the $(v_{\parallel}, v_{\perp})$ space, panel (a) for run 1 at $\Omega_p t = 800$ and panel (b) for run 2 at $\Omega_p t = 1150$.

Figure 6 shows the velocity distributions of protons at $\Omega_p t = 800$ for run 1 in Fig. 6(a) and at $\Omega_p t = 1150$ for run 2 in Fig. 6(b). A proton beam can be observed just after the saturation of parametric instabilities in both runs, which is due to the Landau resonance with the excited ion acoustic waves.

Figure 7 presents the time evolution of the power

spectra for the density fluctuations (Fig. 7(a)) and the magnetic fluctuations (Fig. 7(b)) in run 3. As shown in Fig. 7(a), the density fluctuations k_s are also generated rapidly.^[37] Then the wave-coupling processes between these density fluctuations and pump waves can be observed in the early stage in Fig. 7(b). However, compared with the results of run 1, the subsequent parametric decay for each pump wave is strongly suppressed (Figs. 7(a) and 7(b)), which may be due to the strong damping of ion acoustic waves in the high beta plasma.

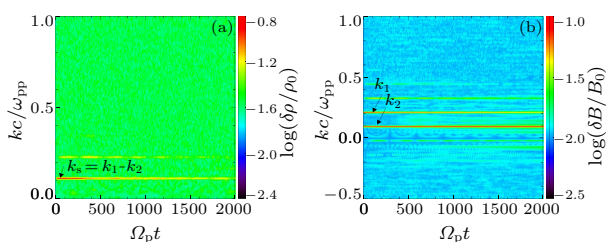


Fig. 7. Time evolution of the power spectra for (a) the density fluctuations and (b) the magnetic field fluctuations for run 3. In panel (a) the density mode (k_s) is denoted by an arrow. In panel (b) the pump Alfvén wave modes (k_1 , k_2) are also denoted by arrows, respectively.

In summary, by using 1-D hybrid simulations, we have analyzed in detail the parametric instabilities of the pump Alfvén waves with a spectrum in a low beta plasma and found that the evolution has two stages. Before the parametric decay of each pump Alfvén wave, the modulation of the pump Alfvén waves due to spatial inhomogeneity of the magnetic pressure (i.e., ponderomotive force) can cause density fluctuations and their interactions with the pump Alfvén waves can further lead to magnetic fluctuations. Therefore, compared with the monochromatic cases, much more density and magnetic wave modes with a broad spectrum can be generated during the evolution of the parametric instabilities of the Alfvén waves with a spectrum. Moreover, the proton velocity beam will also be formed after the saturation of the parametric instabilities. In the high beta case, due to the strong damping of ion acoustic modes, the parametric decay in the second stage will be strongly suppressed.

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Chinese Physics Letters

Volume 32

Number 11

November 2015

GENERAL

- 110301 **The Harmonic Potential Theorem for a Quantum System with Time-Dependent Effective Mass**
LAI Meng-Yun, XIAO Duan-Liang, PAN Xiao-Yin
- 110501 **Optimal Size for Maximal Energy Efficiency in Information Processing of Biological Systems Due to Bistability**
ZHANG Chi, LIU Li-Wei, WANG Long-Fei, YUE Yuan, YU Lian-Chun
- 110502 **Target Inactivation and Recovery in Two-Layer Networks**
SONG Xin-Fang, WANG Wen-Yuan
- 110503 **Analytical Results for Frequency-Weighted Kuramoto-Oscillator Networks**
LIU Yu-Long, YU Xiao-Ming, HAO Yu-Hua

THE PHYSICS OF ELEMENTARY PARTICLES AND FIELDS

- 111101 **Analysis of the Longitudinal Structure Function F_L from the Non-linear Regge Gluon Density Behavior at Low- x**
BOROUN G. R., REZAEI B.
- 111102 **Critical Behavior of Dynamical Chiral Symmetry Breaking with Gauge Boson Mass in QED₃**
WANG Xiu-Zhen, LI Jian-Feng, YU Xin-Hua, FENG Hong-Tao
- 111201 **The 't Hooft Coupling and Baryon Mass Splitting in the Large- N_c Quark Model**
JIA Duo-Jie, ZHANG Jia-Shen

NUCLEAR PHYSICS

- 112101 **Hyperon Effects on the Spin Parameter of Rotating Neutron Stars**
QI Bin, ZHANG Nai-Bo, WANG Shou-Yu, SUN Bao-Yuan

ATOMIC AND MOLECULAR PHYSICS

- 113301 **Production and Detection of Ultracold Ground State $^{85}\text{Rb}^{133}\text{Cs}$ Molecules in the Lowest Vibrational Level by Short-Range Photoassociation**
ZHAO Yan-Ting, YUAN Jin-Peng, LI Zhong-Hao, JI Zhong-Hua, XIAO Lian-Tuan, JIA Suo-Tang

FUNDAMENTAL AREAS OF PHENOMENOLOGY (INCLUDING APPLICATIONS)

- 114101 **Containerless Heating Process of a Deeply Undercooled Metal Droplet by Electrostatic Levitation**
WANG Fei-Long, DAI Bin, LIU Xue-Feng, SUN Yi-Ning, SUN Zhi-Bin, YU Qiang, ZHAI Guang-Jie
- 114201 **Localized Effect of Light Diffraction by Capillary Wave**
MIAO Yang, NIE Song-Lin
- 114202 **High-Pulse-Energy All-Normal-Dispersion Yb-Doped Fiber Laser Based on Nonlinear Polarization Evolution**
WANG Jun-Li, WANG Xue-Ling, HE Bo-Rong, WANG Yong-Gang, ZHU Jiang-Feng, WEI Zhi-Yi
- 114203 **Effects of Finite Surface on Polarization State of Thermal Emission**
LIU Fei, SHAO Xiao-Peng, XIANGLI Bin, GAO Ying, HAN Ping-Li, WANG Lin
- 114204 **Experimental Investigation of All-Optical NRZ-DPSK to RZ-DPSK Format Conversion Based on TOAD**
MAO Ya-Ya, SHENG Xin-Zhi, WU Chong-Qing, ZHANG Tian-Yong, WANG Ying
- 114205 **A Narrow Linewidth Continuous Wave Ho:YAG Laser Pumped by a Tm:YLF Laser**
BAI Fang, CHEN Xin-Yu, LIU Jing-Liang, WU Chun-Ting, HUANG Zhu-Long, JIN Guang-Yong

- 114206 An Effective Thermal Splicing Method to Join Fluoride and Silica Fibers for a High Power Regime**
ZHENG Zhi-Jian, OUYANG De-Qin, ZHAO Jun-Qing, RUAN Shuang-Chen, YU Jun, GUO Chun-Yu, WANG Jin-Zhang
- 114207 H₂ Stimulated Raman Scattering in a Multi-pass Cell with a Herriott Configuration**
CAI Xiang-Long, ZHOU Can-Hua, ZHOU Dong-Jian, LIU Jin-Bo, GUO Jing-Wei, GUI Lin
- 114208 Color Ghost Imaging with Pseudo-White-Thermal Light**
CAO De-Zhong, XU Bao-Long, ZHANG Su-Heng, WANG Kai-Ge
- 114301 Hydrodynamic Sensing Based on Surface-Modified Flexible Nanocomposite Film**
SHU Yi, TIAN He, WANG Zhe, ZHAO Hai-Ming, MI Wen-Tian, LI Yu-Xing, CAO Hui-Wen, REN Tian-Ling

PHYSICS OF GASES, PLASMAS, AND ELECTRIC DISCHARGES

- 115201 Excitation of Zonal Flows by ion-temperature-gradient Modes Excited by the Fluid Resonance**
WANG Guan-Qiong, MA Jun, WEILAND J., ZAGORODNY A.
- 115202 Parametric Instabilities of Parallel Propagating Circularly Polarized Alfvén Waves: One-Dimensional Hybrid Simulations**
HE Peng, GAO Xin-Liang, LU Quan-Ming, ZHAO Jin-Song

CONDENSED MATTER: STRUCTURE, MECHANICAL AND THERMAL PROPERTIES

- 116101 Local Five-Fold Symmetry and Diffusion Behavior of Zr₆₄Cu₃₆ Amorphous Alloy Based on Molecular Dynamics**
GAO Wei, FENG Shi-Dong, QI Li, ZHANG Shi-Liang, LIU Ri-Ping
- 116102 Illumination and Voltage Dependence of Electrical Characteristics of Au/0.03 Graphene-Doped PVA/n-Si Structures via Capacitance/Conductance–Voltage Measurements**
SAHAR Alialy, AHMET Kaya, İ Uslu, ŞEMSETTİN Altındal
- 116801 Forces Acting on Submillimeter Spheres at the Air–Water Interface**
WANG Le-Feng, LIU Lu, XU Hui-Chao, RONG Wei-Bin, SUN Li-Ning
- 116802 Improvement of Surface Morphology of Yttrium-Stabilized Zirconia Films Deposited by Pulsed Laser Deposition on Rolling Assisted Biaxially Textured Substrate Tapes**
WANG Meng-Lin, LIU Lin-Fei, LI Yi-Jie,

CONDENSED MATTER: ELECTRONIC STRUCTURE, ELECTRICAL, MAGNETIC, AND OPTICAL PROPERTIES

- 117201 Phonon-Assisted Spin Current in Single Molecular Magnet Junctions**
NIU Peng-Bin, SHI Yun-Long, SUN Zhu, NIE Yi-Hang, LUO Hong-Gang
- 117202 Al_{0.30}Ga_{0.70}N/GaN/Al_{0.07}Ga_{0.93}N Double Heterostructure High Electron Mobility Transistors with a Record Saturation Drain Current of 1050 mA/mm**
LI Xiang-Dong, ZHANG Jin-Cheng, GUO Zhen-Xing, JIANG Hai-Qing, ZOU Yu, ZHANG Wei-Hang, HE Yun-Long, JIANG Ren-Yuan, ZHAO Sheng-Lei, HAO Yue
- 117203 Express Methods for Measurement of Electroconductivity of Semiconductor Layered Crystal**
FILIPPOV V. V., VLASOV A. N.
- 117204 Improvement of Metal-Graphene Ohmic Contact Resistance in Bilayer Epitaxial Graphene Devices**
HE Ze-Zhao, YANG Ke-Wu, YU Cui, LI Jia, LIU Qing-Bin, LU Wei-Li, FENG Zhi-Hong, CAI Shu-Jun
- 117301 Room-Temperature Organic Negative Differential Resistance Device Using CdSe Quantum Dots as the ITO Modification Layer**
JIAO Bo, YAO Li-Juan, WU Chun-Fang, DONG Hua, HOU Xun, WU Zhao-Xin

- 117302 Positive Bias Temperature Instability and Hot Carrier Injection of Back Gate Ultra-thin-body $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ -on-Insulator n-Channel Metal-Oxide-Semiconductor Field-Effect Transistor**
TANG Xiao-Yu, LU Ji-Wu, ZHANG Rui, WU Wang-Ran, LIU Chang, SHI Yi, HUANG Zi-Qian, KONG Yue-Chan, ZHAO Yi
- 117303 Nanojunctions Contributing to High Performance Thermoelectric ZnO-Based Inorganic–Organic Hybrids**
WU Zi-Hua, XIE Hua-Qing, WANG Yuan-Yuan, XING Jiao-Jiao, MAO Jian-Hui
- 117304 Miniband Formation in GaN/AlN Constant-Total-Effective-Radius Multi-shell Quantum Dots**
Solaimani M.
- 117401 Superconductivity in Pd-Intercalated Ternary Rare-Earth Polychalcogenide NdSeTe_2**
WANG Pei-Pei, XUE Mian-Qi, LONG Yu-Jia, ZHAO Ling-Xiao, CAI Yao, YANG Huai-Xin, LI Jian-Qi, REN Zhi-An, CHEN Gen-Fu
- 117402 Electronic Structure Properties in the Nematic Phases of FeSe**
LIANG Yi, WU Xian-Xin, HU Jiang-Ping
- 117701 Electric-Field Tunability of Dielectric in Polycrystalline $\text{Sr}_{1-x}\text{Mn}_x\text{TiO}_3$ Thin Films**
HOU Yan-Yan, HE Ju, XU Ting-Ting, XIAO Shu-Yu, LU Xue-Liang, HUANG Feng-Zhen, LU Xiao-Mei, ZHU Jin-Song
- 117801 Tuning Photoluminescence Performance of Monolayer MoS_2 via H_2O_2 Aqueous Solution**
CHENG Ying, WANG Jun-Zhuan, WEI Xiao-Xu, GUO Dan, WU Bing, YU Lin-Wei, WANG Xin-Ran, SHI Yi
- 117802 The Evolution of the Extinction and Growth Mechanism of the Silver Nanoplates**
PENG Xiao-Niu, WANG Ya-Lan, WANG Hao

CROSS-DISCIPLINARY PHYSICS AND RELATED AREAS OF SCIENCE AND TECHNOLOGY

- 118401 Conversion Efficiency Enhancement of Multi-crystalline Si Solar Cells by Using a Micro-structured Junction**
LI Li, YU Dong, WU Shi-Liang, WANG Wei, LIU Wen-Chao, WU Xiao-Shan, ZHANG Feng-Ming
- 118501 High-Frequency AlGaN/GaN High-Electron-Mobility Transistors with Regrown Ohmic Contacts by Metal-Organic Chemical Vapor Deposition**
GUO Hong-Yu, LV Yuan-Jie, GU Guo-Dong, DUN Shao-Bo, FANG Yu-Long, ZHANG Zhi-Rong, TAN Xin, SONG Xu-Bo, ZHOU Xing-Ye, FENG Zhi-Hong
- 118701 All-Atom Direct Folding Simulation for Proteins Using the Accelerated Molecular Dynamics in Implicit Solvent Model**
LI Zong-Chao, DUAN Li-Li, FENG Guo-Qiang, ZHANG Qing-Gang
- 118901 Co-operation and Phase Behavior under the Mixed Updating Rules**
ZHANG Wen, LI Yao-Sheng, XU Chen
- 118902 Phase Transitions of Majority-Vote Model on Modular Networks**
HUANG Feng, CHEN Han-Shuang, SHEN Chuan-Sheng

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