Generation of the Harmonic Structure of Upper Hybrid and Electron Cyclotron Waves Driven by Energetic Electrons

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This is the first report of the harmonic structure of upper hybrid waves (UHWs). Using a one-dimensional electromagnetic particle-in-cell simulation, it is demonstrated that the harmonic structure of UHWs can be generated by energetic electrons through non-linear wave-wave coupling, similar to that of lower hybrid waves by energetic ions. After the saturation of UHWs, furthermore, it is found that electron cyclotron waves (ECWs) gradually grow due to the injection of energetic electrons. The involvement of ECWs in non-linear wave-wave coupling can make the harmonic structure of UHWs more complex.

Keywords: upper hybrid waves, electron cyclotron waves, non-linear wave-wave coupling, energetic electrons

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Recently, increasing attention has been paid to the harmonic structure of lower hybrid waves (LHWs) excited by non-linear wave-wave coupling [1–3]. If the LHW is excited at a wavenumber and frequency of (k_1, ω_1), this structure is characterized as $(mk_1, n\omega_1) \equiv (k_m, \omega_n)$ where m and n are integers. As a result, the harmonic structure can form a lattice-like pattern in a wavenumber-frequency plane. Particle-in-cell (PIC) simulations have shown that the harmonic structure of LHWs can be generated by energetic ions with a ring-like velocity distribution through non-linear wave-wave coupling [1–3]. Harmonic LHWs, which can be excited by the same mechanism, were observed in space [4, 5] and fusion [6] plasmas.

Similar to LHWs excited by energetic ions, upper hybrid waves (UHWs) can be excited by energetic electrons with an anisotropic velocity distribution (e.g. Ref. [7, 8]). This suggests that the harmonic structure of UHWs can be generated by energetic electrons through non-linear wave-wave coupling, but it has not been confirmed yet. This paper is the first report of the PIC simulation on the harmonic structure of UHWs. The wavenumber-frequency spectra of electric field fluctuations are analyzed to investigate the harmonic structure in detail, and the bicoherence analysis is performed to confirm non-linear wave-wave coupling.

A plasma is assumed to consist of bulk electrons, protons, and energetic electrons. The bulk electrons have a Maxwellian velocity distribution with a thermal velocity, $v_{te}/c = 0.01$, while energetic electrons have a ring-like velocity distribution expressed as $f_h(v_\parallel, v_\perp) \propto \exp(-v_\parallel^2/2v_{te}^2)\delta(v_\perp - u_\perp)$ where $u_\perp = 10v_{te}$ is the ring speed of energetic electrons. In the simulation, energetic electrons (and also protons for charge neutrality) are continuously injected into a plasma. Refs. [1, 9] have shown that the energetic-particle injection significantly affects the time evolution of instabilities and non-linear wave-wave coupling. The density ratio of energetic to bulk electrons is zero at $\Omega_e t = 0$ but 5% at $\Omega_e t \simeq 655$. The ratio of the electron plasma frequency to the electron cyclotron frequency is $\omega_{pe}/\Omega_e = 5.0$. Thus, the upper hybrid resonance frequency is $\omega_{UH} \simeq 5.1\Omega_e$. The one-dimensional and electromagnetic simulation with the PASTEL code [10] is performed in the *x*-direction with a periodic boundary condition and background magnetic field along the *z*-direction.

First, simulation results during UHW saturation are shown in Figs. 1(a) and 1(c). The $\delta E_x(k_x, \omega)$ spectra in Fig. 1(a) show that the most unstable modes at $(k_x\lambda_D, \omega/\Omega_e) \simeq (\pm 0.15, 5.0) \equiv (k_{\pm 1}, \omega_1)$, marked by the white solid circles, are UHWs driven by energetic electrons. Additionally, the harmonic structure of UHWs at (k_m, ω_n) is clearly visible. In Fig. 1(c), the large bicoherence index is observed at the six points marked by the white solid circles. These points correspond to the wavenumbers of the harmonic structure of UHWs, indicating that it can be excited by non-linear wave-wave coupling. Thus, the harmonic structure of UHWs is very similar to that of LHWs [1].

Next, simulation results after the saturation of UHWs are shown in Figs. 1(b) and 1(d). In Fig. 1(b), new wave modes are observed at $(k_x\lambda_D, \omega/\Omega_e) \simeq (\pm 0.28, 2.6) \equiv (\pm k_A, \omega_A)$ and $(k_x\lambda_D, \omega/\Omega_e) \simeq (\pm 0.42, 2.3) \equiv (\pm k_B, \omega_B)$, marked by the

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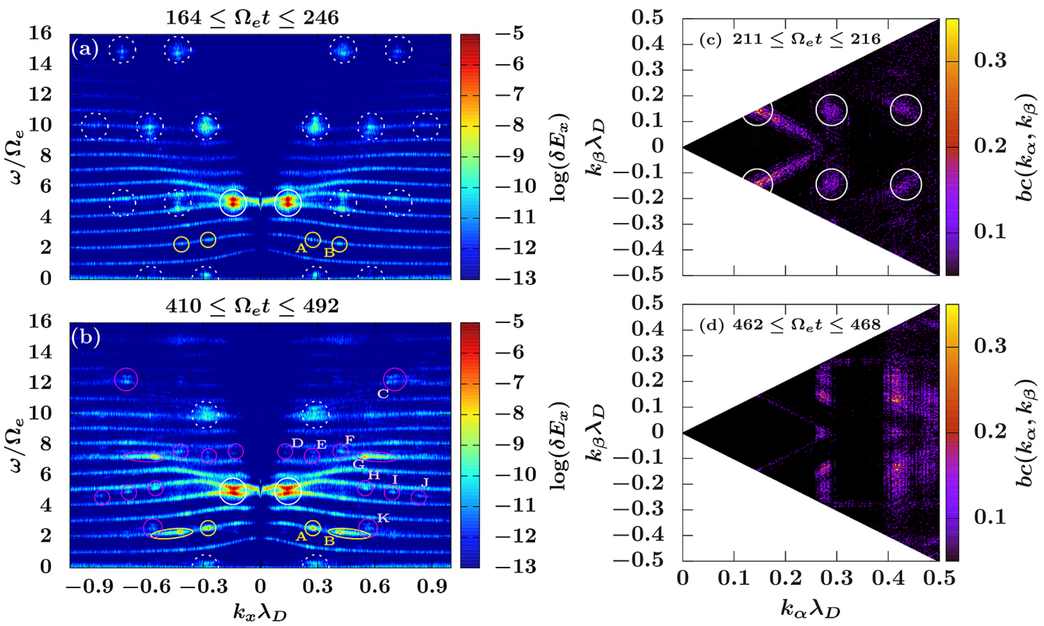

Fig. 1. (a and b) Wavenumber-frequency spectra of electric field fluctuations for two time intervals. The wavenumber is normalized by the Debye length λ_D. White solid circles represent the pump UHWs with $(k_{\pm 1}, \omega_1)$, white dashed circles represent the harmonic structure of UHWs with (k_m, ω_n), yellow solid circles represent ECWs, and magenta solid circles represent the new harmonic structure of UHWs and ECWs. (c and d) Bicoherence index (between 0 and 1) for two time intervals (for details see Ref. [1]).

yellow solid circles. These modes, A and B, are electron cyclotron waves (ECWs) excited by energetic electrons and their amplitudes are larger than those of the second harmonic modes of UHWs with $(k_{\pm 2}, \omega_2)$. Moreover, many waves are observed in a wide range of wavenumbers and frequencies, marked by the magenta solid circles.

The wave modes, C to K, are excited by non-linear wave-wave coupling. As summarized in Table 1, three types of coupling are observed: (I) between ECWs (modes A and B), (II) between UHWs and ECWs, and (III) between harmonic UHWs and ECWs. This is supported by the fact that the bicoherence index is large at wavenumbers corresponding to those of UHWs, harmonic UHWs, and modes A to K in Fig. 1(d). Consequently, the involvement of modes A and B in coupling can lead to a more complex harmonic structure compared to the harmonic structure of UHWs alone in Fig. 1(a).

In summary, it is shown that the harmonic structure of UHWs can be excited by non-linear wave-wave coupling through large amplitude UHWs generated by energetic electrons. The lattice-like pattern of this structure in the wavenumber-frequency spectra is very similar to that of LHWs driven by energetic ions. ECWs are similarly excited by energetic electrons, growing to large amplitudes after the saturation of UHWs. Three distinct types of non-linear wave-wave coupling can generate the new harmonic structure of UHWs and ECWs across a wide range of wavenumbers and frequencies. Our results will help to understand the nonlinear harmonics of the UHWs that have been recently observed in the Earth's magnetosphere [11].

Reference [1] conducted PIC simulations with varying conditions of injected energetic ions and showed that harmonic LHWs can persist even after the injected energetic ions are artificially removed. This suggests that harmonic LHWs may be observed even if energetic ions are not detected. Although simulations with different injection conditions for energetic electrons will be our future work, similar results to those for energetic ions can apply.

Table 1. Summary of non-linear wave-wave coupling.

Mode	Type	Resonant condition
C	III	$(k_2, \omega_2) + (k_B, \omega_B)$
D	II	$(k_{-1}, \omega_1) + (k_A, \omega_A)$
E	II	$(k_{-1}, \omega_1) + (k_B, \omega_B)$
F	II	$(k_1, \omega_1) + (k_A, \omega_A)$
G	II	$(k_1, \omega_1) + (k_B, \omega_B)$
H	I	$(k_A, \omega_A) + (k_A, \omega_A)$
I	I	$(k_A, \omega_A) + (k_B, \omega_B)$
J	I	$(k_B, \omega_B) + (k_B, \omega_B)$
K	III	$(k_2, \omega_0) + (k_A, \omega_A)$

Type I: ECW+ECW, Type II: UHW+ECW, Type III: harmonic UHW+ECW

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