Narrow Cyclotron Harmonic Absorption Resonances of Stimulated Electromagnetic Emission in the Ionosphere

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We present measurements of stimulated electromagnetic emission (SEE) excited in the ionosphere by a powerful high-frequency ordinary mode radio wave vertically injected from a ground-based transmitter, at frequencies f_0 near high harmonics of the ionospheric electron cyclotron frequency f_c. A prominent lower-sideband SEE feature was found to be absent in an extremely narrow f_0 range of $\Delta f_0/f_0 \approx 2\times10^{-5}$. This absorption resonance width allows an estimate of f_c with an accuracy of a few tens of Hz, corresponding to a magnetic field magnitude accuracy of about 1 nT.

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In this Letter we report new experimental findings concerning the suppression of the commonly observed downshifted maximum (DM) feature in the stimulated electromagnetic emission (SEE) spectrum [1,2], excited by a powerful high-frequency pump wave in the ionosphere, for f_0 near harmonics of the ionospheric f_c [3,4]. Studies of the SEE sidebands have shown that in general the DM is most prominent when $|f_0 - nf_c| \ll f_c$, where $f_c \equiv eB/2\pi m_e \approx 1.1$-$1.4$ MHz, with e, B, and m_e the magnitude of the electron charge, geomagnetic field, and electron mass, respectively. However, for small changes in f_0 very near nf_c, the SEE spectra change dramatically and in earlier experiments it was observed that the DM emissions were suppressed when $|f_0 - nf_c| < 10$ kHz for $n=3,4,5$ [3,4]. In the experiments reported here we made a detailed study of the DM suppression for much higher f_0 than used in previous SEE experiments and it was found that the DM was suppressed for $n=4,5,6,7$.

The experiments were carried out during daytime at the Sura ionospheric modification facility near Vasilsursk, 100 km east of Nizhniy Novgorod (formerly Gorky) in Russia (geographic coordinates 56.13° N, 46.10° E). The effective radiated pump power was approximately 270 MW, corresponding to a power flux of 0.3 mW/m^2 at a typical interaction height of 250 km in the F region, neglecting ionospheric absorption. At that altitude, the angle between the geomagnetic field and the downward vertical is approximately 19°. The experimental results concern the steady-state spectrum of SEE, attained after a few seconds of continuous pumping.

Figure 1 shows a DM feature excited to a maximum power level of more than 20 dB above the background noise level. Its peak is approximately 13 kHz below the ionospherically reflected pump wave at $f_0=9.253$ MHz, a frequency which is relatively close to $7f_c$. Nearer $7f_c$ the DM was significantly weakened in a 10–20-kHz-wide f_0 range in accordance with earlier findings as mentioned above. The narrow features marked "interference" in the displayed spectrum are signals from radio transmitters.

Our new results, summarized in the successively recorded spectra in Fig. 2, show that the DM emission disappears completely only when f_0 is varied within an extremely narrow frequency band of 100–200 Hz width, corresponding to $\Delta f_0/f_0 \approx 2\times10^{-5}$. In Fig. 2(a), $f_0=9.2679$ MHz and a weak DM, with its right steep edge downshifted approximately 8 kHz below f_0, can be seen. Increasing f_0 to 9.2681 MHz the narrow DM is absent [Fig. 2(b)]. To find the lowest f_0 for which the DM is absent f_0 is lowered to 9.2680 MHz where the narrow peak is again present [Fig. 2(c)]. To find the high-frequency edge of the resonance f_0 is then increased to 9.2682 MHz [Fig. 2(d)] when a suppressed DM can be identified. Increasing f_0 to 9.2683 MHz the DM is again clearly identified [Fig. 2(e)], as is also the case for higher f_0. Notice that the down-shift of the weak DM in Figs. 2(a) and 2(c)–2(e) coincides strikingly well with the right flank of the strong DM in Fig. 1, consistent with previous observations at lower f_0 [4]. The results in Fig. 2 are from a 16-min period during which the DM was measured to be absent in a 200-Hz-wide f_0 range four additional times.

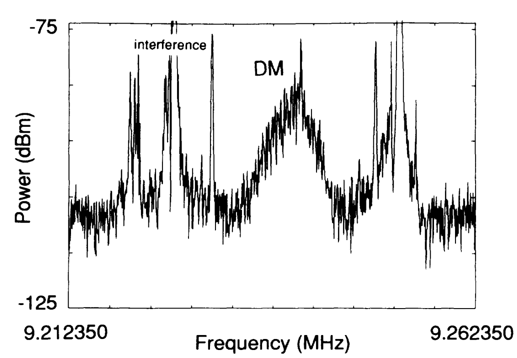

FIG. 1. SEE spectrum for the pump at $f_0=9.253$ MHz, showing a DM emission with its peak down-shifted by approximately 13 kHz from the pump (7:58:57 UT on 27 September 1990).

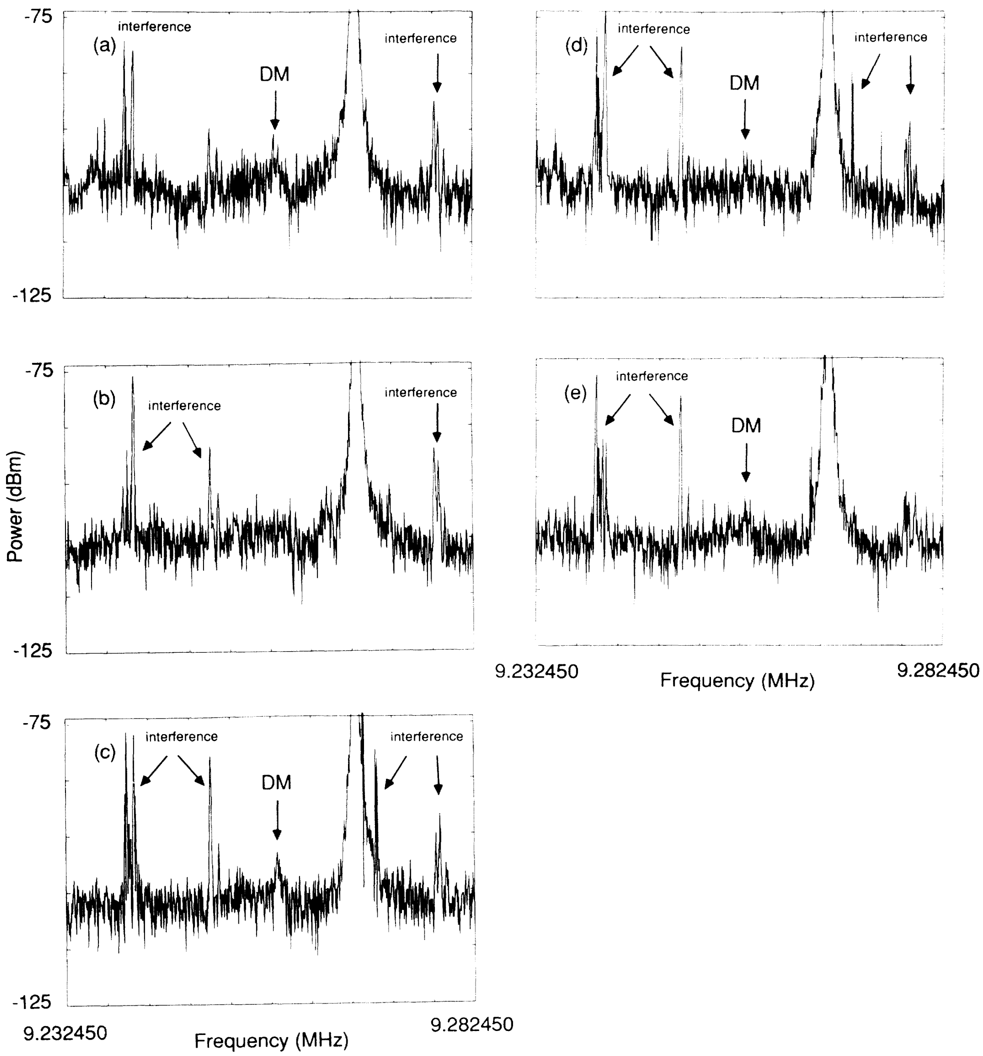

FIG. 2. SEE spectra for different f_0 (27 September 1990). The spectra were recorded consecutively after each change of f_0 during continuous transmission of the pump wave. (a) f_0=9.2679 MHz (9:12:15 UT). (b) f_0=9.2681 MHz (9:12:37 UT). (c) f_0=9.2680 MHz (9:12:49 UT). (d) f_0=9.2682 MHz (9:13:01 UT). (e) f_0=9.2683 MHz (9:13:12 UT).

In experiments in September 1991, one year after the observations reported above, the f_0 range in which the DM is not excited was measured for different n. This f_0 range decreases with increasing n and the average values obtained were approximately 5, 3, and 1 kHz, for $n=4$, 5, and 6, respectively. At $n=7$ the DM was not observed to be completely absent, which is attributed to the ionospheric conditions not being sufficiently quiet.

Hereafter we will focus primarily on the case $n=7$. For the absence of the DM (Fig. 2), $\Delta\omega_0 \approx 2\pi \times 200\ \mathrm{s}^{-1} > \nu_{ei} \approx 2\pi \times 100\ \mathrm{s}^{-1}$, where ν_{ei} is the daytime effective electron-ion collision frequency at 250 km altitude [5], so we assume that the electron-ion collisions do not determine the absorption bandwidth. The DM emission has been attributed to nonlinear interaction of upper hybrid (UH) and lower hybrid (LH) waves [3,6,7], the UH waves being excited by the pump wave scattering off geomagnetic-field-aligned plasma density striations [8]. The suppression of the DM at nf_c has been attributed to cyclotron harmonic damping of the UH waves [4,6], to the decreasing altitude range within which the UH waves can exist as the wave frequency approaches nf_c [9], and to absorption of the UH mode due to resonance excitation of electron Bernstein modes [10]. Here we discuss the first two of the above-mentioned mechanisms. First, the cyclotron harmonic damping rate ω_i for UH waves of angular frequency ω_r and wave number k, with the component transverse (parallel) to the geomagnetic field k_x (k_z), is ($|\omega_r| \gg |\omega_i|$ and $\omega_r \approx n\omega_c$) [11]

$$\omega_i = -\left(\frac{\pi}{8}\right)^{1/2} \frac{k_D^3 \omega_p}{k^2 |k_z|} e^{-b} I_n(b) e^{-a_n^2}, \qquad (1)$$

where $k_D = \omega_p / v_e$, ω_p is the electron plasma frequency, v_e

is the electron thermal speed, $b \equiv k_x^2 \rho_e^2$, I_n is a modified Bessel function, $\alpha_n \equiv (\omega_r - n\omega_c)/\sqrt{2} k_z v_e$, $\omega_c = 2\pi f_c$, and $\rho_e = v_e/\omega_e$. Expression (1) is valid for $|\alpha_n| \gg 1$ and $|\alpha_n| \ll 1$.

For the pump-excited UH waves, we take $k_z = k_0$, which is the pump wave number. The cold-fluid dispersion relation of the parallel propagating ordinary mode pump wave gives $k_0 = \omega_0/\sqrt{7}c \approx 0.073$ m^{-1} at the UH resonance level where $\omega_0 = \omega_u \equiv (\omega_p^2 + \omega_c^2)^{1/2}$, and we take $\omega_0 = 7\omega_c = 2\pi \times 9.2681 \times 10^6$ s^{-1} as in Fig. 2(b) (c is the light speed). The damping increases significantly with k_x, since $e^{-b} I_7(b) \approx (k_x \rho_e)^{14}/2^7 7!$ for $b \ll 1$. Thus, positive-group-dispersive UH waves, having smaller k_x, are damped at smaller $|\omega_r - 7\omega_c|$, compared to negative-group-dispersive waves which have larger k_x, for a given k_z. For $|\omega_r - 7\omega_c| = 2\pi \times 100$ s^{-1} ($|\alpha_7| \ll 1$), ω_i exceeds collisional damping by an order of magnitude for $k_x > 30$ m^{-1}, which in a homogeneous plasma only leaves a small phase space of UH waves weakly damped and could, thus, explain the observed quenching of the DM emission in the SEE spectrum. For $|\omega_r - 7\omega_c| = 2\pi \times 5000$ s^{-1} ($|\alpha_7| \gg 1$), ω_i is high for $k_x > 40$ m^{-1} and, in addition, the plasma density range in which UH waves can exist is significantly larger compared to the case of smaller $|\omega_r - 7\omega_c|$, which would contribute to the excitation of the DM. As seen from Figs. 1 and 2, when f_0 approaches nf_c the low-frequency components of the DM are first damped out. Since then for $|\omega_r - 7\omega_c| = 2\pi \times 5000$ s^{-1} only the lowest-frequency components of the DM are quenched, these are due to UH waves with larger k_x according to (1). Also, whereas the down-shift from f_0 of the high-frequency part of the DM is roughly independent of f_0, the down-shift of the lowest-frequency components increases with increasing f_0 [4]. It is interesting to note that k_x for the linear dispersion of UH waves near nf_c increases with increasing n, which is consistent with that of the low-frequency components of the DM are excited by UH waves having larger k_x.

The second effect which is weakening the DM emission as f_0 approaches nf_c is due to the dispersion characteristics of weakly damped UH waves and the opposite gradients of the background ionospheric plasma density and geomagnetic field magnitude, the density increasing with altitude and the magnetic field decreasing with altitude. The plasma density range, and associated altitude range, in which UH waves can exist decreases as f_0 approaches nf_c.

We consider all k_z, not only $k_z = k_0$, and estimate the altitude range Δz necessary for the UH waves, by using the fact that UH waves with $b \ll 1$ can exist approximately in the altitude range between where $\omega_w(z_w) = \omega_0$ and $n\omega_c(z_c) = \omega_0$, where $\omega_w = (\omega_u^2 + 3k_x^2 v_e^2)^{1/2}$, giving $\Delta z = |z_c - z_w|$. Starting from the linear dispersion equation for high-frequency electrostatic waves in a homogeneous plasma with Maxwellian distributed electrons (for example, Ref. [12]), and introducing a weak and linear altitude (z) dependence of the plasma density (scale length $L_N \gg k_z^{-1}$) and the geomagnetic field (scale length $L_B \gg L_N$), an expression for $k_z(z)$ can be derived. The condition $\int_0^{\Delta z} k_z(z) dz > \pi$ and taking $|\alpha_7| > 1$ to ensure weak cyclotron harmonic damping gives $\Delta z > \Delta z_{\min} \equiv 2(2\rho_e L_B/n)^{1/2}$, which corresponds to

$$|f_0 - nf_c| > 2f_0(2\rho_e/nL_B)^{1/2}. \qquad (2)$$

Taking $f_0 = 9.2681$ MHz [Fig. 2(b)], $\rho_e = 1.87 \times 10^{-2}$ m, $n = 7$, and $L_B = 2240$ km from the international geomagnetic reference field (IGRF) model of the geomagnetic field gives $|f_0 - nf_c| > 0.9$ kHz for weakly damped UH waves, which is consistent with the observation that the DM was not detectable only in the more narrow f_0 range of approximately 200 Hz. Also, during the experiment the ionospheric plasma must have been sufficiently homogeneous in the horizontal plane across the pump wave beam, so that the DM emission could not be excited locally somewhere within the beam. Further, $\Delta z_{\min} \approx 200$ m which is significantly longer than the pump wavelength. It should be noted that at these and longer length scales the nonuniformity of the geomagnetic field affects the possibility of the waves resolving the cyclotron harmonic resonance. For cyclotron harmonic resonance in a weakly nonuniform plasma we have

$$\omega - n\omega_c - k_z v_e \approx \omega - n\omega_{c0}(1 - \Delta z/L_B) - k_z v_e \approx 0,$$

so that $k_z v_e > n\omega_{c0}\Delta z/L_B$ for the magnetic field nonuniformity to be negligible.

The IGRF model gives an upward vertical gradient $df_c/dh \approx -0.59$ Hz/m for $f_c = 9.2681/7$ MHz $= 1.3240$ MHz [Fig. 2(b)] which occurs at 240 km altitude. Determination of $7f_c$ with a resolution of 200 Hz then corresponds to an altitude resolution of the order of $\Delta h \approx (df_c/dh)^{-1} \Delta f_c \approx 50$ m in the F region. The precision measurements reported here are thus indicative of an extremely local generation region for the DM in the SEE spectrum. The measurements of the narrow f_0 range for which the DM disappears enables an estimate of the local f_c with an accuracy of about 30 Hz and, hence, the local magnetic field to an accuracy of 1 nT. Further, for $f_c = 1.3240$ MHz and taking the ion composition at 240 km altitude according to the IRI-86 model (92% O^+, 1% $O_2{}^+$, and 7% NO^+), the LH resonance frequency is $f_{LH} = 7.5$ kHz, which coincides with the down-shift of the highest-frequency components of the weak DM in Fig. 2.

Successful detection of the narrow absorption resonance requires a quiet ionosphere and a sufficiently rapid measurement. The experiment reported in Fig. 2 was done near local mid-day when diurnal variations in the ionospheric plasma density were small and the maximum plasma frequency exceeded 9.5 MHz. During the entire experiment, f_0 at which the absorption resonance occurred increased by 44 kHz in 95 min. This corresponds to an increase of f_c by 6.3 kHz and is consistent with a lowering of the bottom-side F region as observed from ionograms. From the height variation of the geomagnetic field in the IGRF model we then conclude that the ionospheric density profile moved downwards with an average velocity of approximately 2 m/s, indicating a quiet-time F region. During the first 79 min of the experiment the DM was only suppressed and did not disappear completely at the resonance. The resonance frequency increased on the average 9 Hz/s, or 90 Hz during the 10-s sweep time of the spectrum analyzer with which the SEE spectra were recorded, indicating that the background variations were too large for the DM to disappear completely in a 100–200-Hz f_0 range. During the last 16 min of the experiment the DM was absent at the resonance (Fig. 2) and the average rate of change of the resonance frequency was only 3 Hz/s. Also, two days earlier when the narrow resonance was first observed, six measurements were made during 10 min in which the DM disappeared completely within a 200-Hz f_0 range. During that time the resonance frequency increased by 5 Hz/s, which also indicates quiet ionospheric conditions. However, on that occasion no spectra were recorded, but only logbook notes were made of the f_0 dependence.

In conclusion, we have studied the prominent and commonly observed DM emission in the SEE spectrum for much higher pump frequencies than previously. The experimental results show that the properties of this feature are very sensitive to even small change of the pump frequency. For pump frequencies at the seventh electron cyclotron harmonic, the DM disappeared completely for pump frequencies in an extremely narrow range of approximately 200 Hz, although the DM was significantly weaker in a much wider range of 10–20 kHz, compared to pump frequencies further away from the cyclotron harmonic. The results support the interpretation that the DM is excited by nonlinear interaction of upper and lower hybrid waves and that the disappearance of the emission occurs exactly when the pump frequency passes through a harmonic of the local electron cyclotron frequency in the interaction region. The narrowness of the absorption resonance allows the determination of the local magnetic field magnitude with an accuracy of 1 nT.

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