Enhancement of Stimulated Electromagnetic Emission during Two Frequency Ionospheric Heating Experiments

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We have discovered that stimulated electromagnetic emission (SEE), excited by a powerful electromagnetic (EM) wave (pump 1) in the ionosphere, can be enhanced by a second high power EM wave (pump 2) with a higher frequency. For frequency separations near 0.4 MHz, the downshifted SEE in a 40 kHz band below the frequency of pump 1 is increased by 2 dB when pump 2 is turned on. We theorize that a second EM wave generates plasma irregularities that facilitate the mode conversion of electrostatic waves to yield enhanced EM emissions from pump 1.

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During ionospheric heating experiments, powerful ordinary-mode (O-mode) transmissions reflect where the wave frequency (f_0) equals the plasma frequency (f_p). The reflected electromagnetic (EM) wave returns to the ground with power loss due to heating of the plasma and by conversion to electrostatic (ES) waves near the reflection region.

Ionospheric heating experiments with powerful O-mode transmissions produce spectral sidebands called stimulated electromagnetic emission (SEE) [1-3]. The most commonly observed features in SEE are the continuum and the downshifted maximum (DM). The continuum is a broad ramp that usually forms on the downshifted side of the EM pump frequency (f_0). The frequency range of the continuum is highly variable and can be greater than 100 kHz [3]. The DM is a distinct peak that is found at a frequency approximately 10 kHz below the carrier frequency [2]. It is well known [4-6] that the DM feature is suppressed for transmission frequencies f_0 near harmonics of the electron cyclotron frequency f_{ce}.

A mechanism for the excitation of the DM feature was proposed by Leyser *et al.* [4]. The pump EM wave is converted into upper hybrid (UH) waves with the aid of field aligned density striations. Two processes thought to occur simultaneously are (1) the generation of artificial field aligned striations (AFAS) by an O-mode wave [7-9] and (2) direct mode conversion of the pump EM wave to UH waves [10]. The DM observed on the ground is a scattered EM wave resulting from parametric decay of the UH wave into lower hybrid (LH) and O-mode EM waves [11].

An alternative explanation for the generation of downshifted SEE is the creation of high frequency ES waves by parametric processes followed by mode conversion of the ES waves on density perturbations [1-3,12]. The plasma density irregularities required for mode conversion are produced by the O-mode pump as a result of the thermal parametric decay instability (TPI) near the UH resonance height [8,9,13] or the ponderomotive force at the peaks of the standing wave [12,14]. The latter process yields artificial quasiperiodic inhomogeneities (AQPI) in horizontal stratifications.

Both of these theoretical explanations for the continuum and DM emissions rely on the presence of ionospheric irregularities produced by the high power radio waves. The purpose of the experiments reported here is to determine the influence of density irregularities produced by a high power wave (pump 2) on the production of SEE from another high power wave (pump 1).

Experimental observations of two frequency heating were obtained at the SURA ionospheric modification facility in Russia (56.13° N latitude, 46.10° E longitude) during March 1993. For the experiments, the HF transmitter antenna was divided into two arrays [15]. On 21 March 1993, one-third of the antenna was used for pump 1 at 7.8164 MHz and two-thirds of the antenna was used for pump 2 at 8.2400 MHz. The frequencies were selected to be below the maximum plasma frequency of the ionosphere so that the waves reflected. The frequency separation (0.4236 MHz) was chosen to avoid plasma resonances such as the electron cyclotron frequency and to provide reflection altitudes separated by a few kilometers. The effective radiated power (ERP) and timing for the transmissions in a 6 min cycle are given in Table I. Pump 2 is on for 2 min during the 5-min transmission of pump 1. Both transmissions are off for 1 min at the end of the 6 min cycle.

The spectra of EM emissions were obtained with a

TABLE I. Two frequency heating cycle (ERP).

Pump i	Frequency (MHz)	Period 2 min (MW)	Period 2 min (MW)	Period 1 min (MW)	Period 1 min (MW)
1	7.8164	26	26	26	0
2	8.2400	0	105	0	0

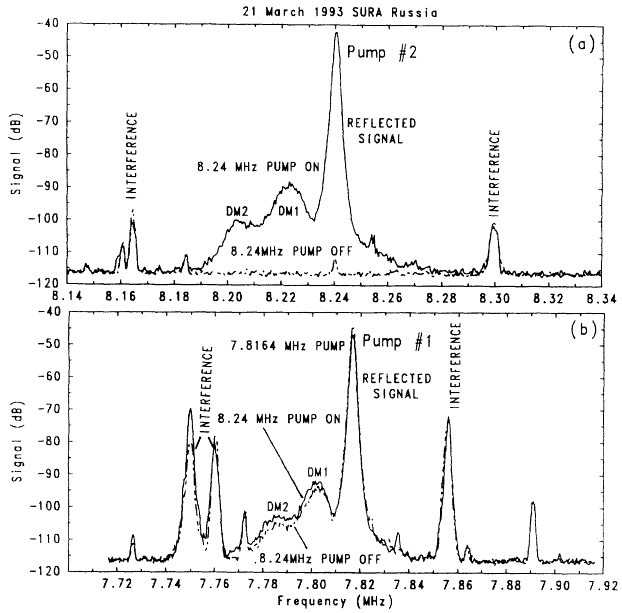

FIG. 1. Two frequency SEE spectra recorded together on 21 March 1993 between 12:00 UT and 12:04 UT at the SURA heating facility in Russia. The 8.2400 MHz electromagnetic pump 1 (a) is turned off (dashed line) for 2 min and on (solid) for 2 min while the 7.8164 MHz pump 2 (b) remains on for the 4 min interval. The downshifted spectral emissions (DM1 and DM2) for pump 1 are enhanced by 2 dB when pump 2 is turned on.

computer-controlled, HP 8595E Spectrum Analyzer. A new power spectrum was measured and recorded every 10 s. The analyzer spectral range was 100 kHz on either side of a center frequencies which alternated between $f_1=7.8164$ and $f_2=8.2400$ MHz. The spectral resolution was 1 kHz. The spectrum analyzer obtained signals from a broadband receiving array with a vertically directed antenna pattern [6].

Average spectra between 12:00 and 12:02 UT with pump 2 off (dashed line) and between 12:02 and 12:04 UT with pump 2 on (solid line) are illustrated in Fig. 1. Average spectra are obtained from 6 individual spectra centered on 8.24 MHz [Fig. 1(a)] or 7.8184 MHz [Fig. 1(b)]. The 8.24 MHz pump 2 transmissions produce two maxima (DM1 and DM2) downshifted by about 17 and 38 kHz, respectively [Fig. 1(a)]. The primary downshifted maximum (DM1) is 27 dB above the noise floor of the analyzer.

When pump 2 is turned on, the downshifted maxima associated with pump 1 are enhanced by about 2 dB. Figure 1(b) shows a sample of the spectra near 7.8164 MHz (pump 1) with pump 2 off (dashed line) and on (solid line). The enhancement is limited to the downshifted frequency region between 7.765 and 7.808 MHz. The reductions in the power from pump 1 are due to either (1) enhanced absorption associated with *D*-region heating [16] by pump 2 or (2) enhanced conversion of EM waves into ES waves and, ultimately, into SEE.

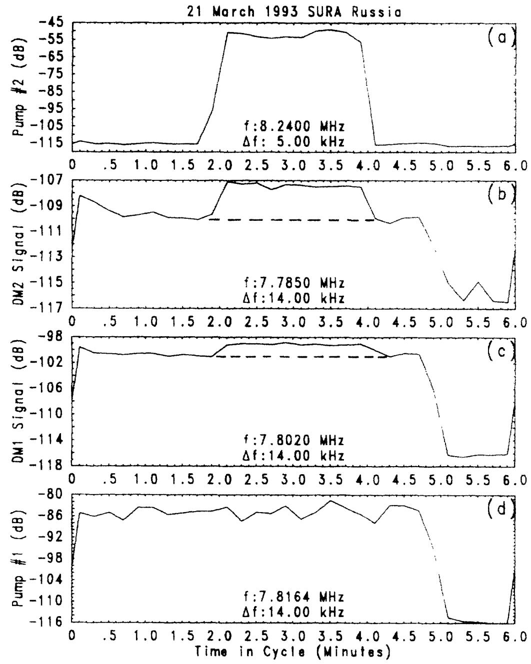

FIG. 2. Superposition of received powers for ten 6 min cycles of two frequency heating between 13:00 and 14:00 UT on 21 March 1993. Average powers for (a) pump 2, (b) DM2 of pump 1, (c) DM1 of pump 1, and (d) the carrier of pump 1 are obtained for the center frequencies (f) and bandwidths (Δf) shown. The average power for the downshifted spectrum from pump 1 is enhanced by 2 dB when pump 2 is transmitting.

The new discovery, that a powerful *O*-mode pump will enhance the downshifted SEE of a lower frequency *O*-mode pump, was consistently observed during the 3 h observation period between 11:00 and 14:00 UT on 21 March 1993. A superposition of ten 6 min cycles is illustrated in Fig. 2 for specified frequencies (f) and bandwidths (Δf) accumulated in thirty 12 s time windows. The top graph [Fig. 2(a)] shows the average strength of reflected signal from pump 2. The downshifted sidebands of pump 1 (DM1 and DM2) display two types of variations [Figs. 2(b) and 2(c)]. First there is about a 1 dB overshoot when pump 1 is first turned on. This overshoot has been attributed to enhanced continuum emission before the pump is depleted by striation formation and direct mode conversion processes [5]. Second, there is a 2 dB enhancement in both the DM1 and the DM2 of pump 1 when pump 2 is transmitting. The depression in the pump 1 return by the pump 2 transmissions is sporadic [Fig. 2(d)].

The SEE enhancement can be explained in terms of plasma density irregularities produced by pump 2 that affect the conversion of pump 1 into scattered EM waves. This explanation requires knowledge of the plasma densities, the EM wave interaction altitudes, and the strength of the electric fields at these altitudes.

During the two frequency heating experiments, the ionosphere was monitored every 15 min with an ionosonde located at the SURA facility. Electron density

TABLE II. Reflection and upper hybrid altitudes.

Pump i	Frequency f_i (MHz)	Height	Time, UT 11:21:19 (km)	Time, UT 13:52:15 (km)
1	7.8164	Upper hybrid	226.1	228.7
		reflection	227.5	230.2
2	8.2400	Upper hybrid	231.7	234.8
		reflection	233.2	236.6

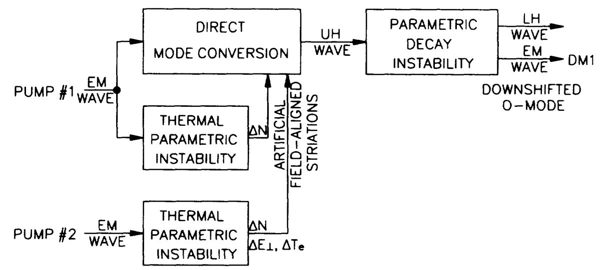

FIG. 3. Mechanism for the production of SEE with an intermediate upper hybrid (UH) wave. Two frequency electromagnetic (EM) wave interaction processes lead to enhanced downshifted maximum (DM1) emission. The addition of a second pump wave can enhance the mode conversion to upper hybrid waves by introducing additional field aligned striations.

profiles were obtained from digitized ionograms with the Polynomial Analysis program POLAN [17].

The SURA ionograms on 21 March 1993 were analyzed to yield the reflection height and the upper hybrid resonance level for each transmission frequency (Table II). The reflection height is found where the plasma frequency (f_{pe}) is equal to the wave frequency. The UH resonance occurs where the upper hybrid frequency $f_{\mathrm{UH}}=(f_{pe}^2+f_{ce}^2)^{1/2}$ equals the pump frequency. The UH levels for pumps 1 and 2 are separated by about 6 km during the time periods between 11 and 14 UT on 21 March 1993. The difference between the reflection and the UH levels is between 1.5 and 1.8 km for either pump frequency.

The electric field components of the two pump waves are computed using solutions of one-dimensional wave equations for a magnetoionic plasma [18,19]. The wave model uses a background magnetic field $B=4.737\times10^{-5}$ W/m^2 and a dip angle $I=71°$ at SURA. Vertical propagation of the two pump waves in the density profile at 11:21:19 UT yields standing wave (Airy) patterns [19]. At the reflection levels, the electric fields parallel to B for pumps 1 and 2 have peak values of 2.9 and 5.8 V/m, respectively. The perpendicular electric fields at and below the UH altitudes for pumps 1 and 2 are 0.22 and 0.44 V/m, respectively. D-region absorption may reduce the electric field strengths by 10 dB below the values given.

The enhancement of downshifted SEE by the introduction of pump 2 is the result of either (1) field aligned irregularities of pump 2 extending down to the interaction region of pump 1 or (2) the direct introduction of density structures by pump 2 into the pump 1 region. The effectiveness of either process provides a test of the theories for generation of SEE.

A block diagram of the DM1 production is illustrated in Fig. 3. The EM wave (pump 1) at frequency f_1 drives (1) the thermal parametric instability yielding AFAS (ΔN) and (2) direct mode conversion on the ΔN structures to produce UH waves. These two processes occur where the frequency of pump 1 equals the UH frequency (i.e., $f_1=f_{\mathrm{UH}}$). Next, a parametric decay instability causes the UH wave to excite both an EM wave with frequency $f_{\mathrm{DM1}}=f_{\mathrm{UH}}-f_{\mathrm{LH}}=f_1-f_{\mathrm{LH}}$ and a lower hybrid wave at frequency $f_{\mathrm{LH}}\simeq(f_{ce}f_{ci})^{1/2}$, where f_{ci} is the ion cyclotron frequency.

Figure 3 shows that the introduction of a second EM wave (pump 2) can yield AFAS that perturb the UH interaction region of pump 1. The perturbations are the result of perpendicular ES fields ($\Delta E_\perp$), electron temperature fluctuations (ΔT_e), as well as density irregularities (ΔN) that extend along the nearly vertical magnetic fields connecting the two HF interaction regions.

The 2 dB enhancements in the DM1 signal strength (Figs. 1 and 2) are consistent with the introduction of additional irregularities extending down from the UH region of pump 2. Such irregularities have been previously detected with ground based radio scatter [20]. The AFAS from the pump 2 UH and reflection levels may have extended a distance of 6 km to the UH region of pump 1 enhancing the DM1 emission from this lower region.

Remember that both DM1 and DM2 were enhanced by the same factor (2 dB) with the second pump. Leyser [21] states that a source for the DM2 could be the decay of the initial EM pump into an UH and LH wave rather than direct conversion to a UH wave in the presence of AFAS. The new UH wave decay product would decay into an EM wave that is downshifted from the initial EM pump by twice the LH frequency. This process is not consistent with the observations in Figs. 1 and 2 because it is independent of AFAS and should not be affected by structures generated with pump 2.

Grach and Shvarts [22] propose a process involving UH and LH wave interactions that is consistent with the enhanced SEE observations. The UH wave in Fig. 3 can parametrically decay into a second upper hybrid wave (UH2) and a LH wave. The decay of UH2 into EM and LH waves yields the required DM2. The only wave component affected by field-aligned striations driven by pump 2 is the original UH wave from EM pump 1.

Another process that provides wideband enhancement is illustrated in Fig. 4. The parametric decay instability driven by pump 1 yields high frequency Langmuir waves shifted in frequency by ion-acoustic wave frequencies. Downshifted O-mode waves in the form of continuum, DM1 and DM2 emissions can be produced by mode conversion scattering of the Langmuir waves on artificial

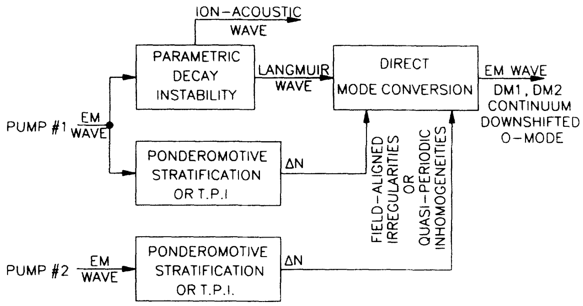

FIG. 4. Alternate mechanism for the production of SEE with an intermediate Langmuir wave. The addition of a second, higher-frequency EM pump leads to enhanced downshifted emissions. By itself, pump 1 produces horizontal stratifications from the wave ponderomotive force or field aligned irregularities by the thermal parametric instability (TPI). Pump 1 decays into Langmuir waves that are mode converted to EM waves on the density structures. The addition of pump 2 enhances density structures increasing the efficiency of the mode conversion to continuum and the downshifted maxima (DM1 and DM2) emissions.

plasma structures such as AFAS or AQPI [1,2].

The introduction of pump 2 yields additional electron density structures in the form of AFAS or AQPI. The reflection altitude for pump 2 is higher than the reflection altitude for pump 1. The horizontal stratifications from the Airy pattern of pump 2 electric field (0.44 V/m) lie on top of the Airy pattern maximum for the pump 1 electric field (2.9 V/m). Direct mode conversion in this region is enhanced by these horizontal stratifications. Also, field aligned irregularities from the UH region of pump 2 will extend down magnetic field lines into the reflection region of pump 1. Thus, downshifted SEE amplitudes will be enhanced by the structures created by pump 2.

The relative importance of AFAS and AQPI can be tested during future two frequency ionospheric heating experiments. By using a pump 2 frequency that is lower than that of pump 1, the AQPI generated by pump 2 will not overlap the reflection altitude of pump 1 and AQPI will not be a source for the enhanced direct mode conversion. The growth time for AFAS [10] (~ 1 s) is much larger than the formation time for AQPI [14] (~ 10 ms). Consequently, another technique to distinguish between the effects of AFAS and AQPI is to measure the response time of the increase in pump 1 SEE intensity when pump 2 is turned on [23].

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