Two-Component Nature of the Broad Up-shifted Maximum in Stimulated Electromagnetic Emission Spectra

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The broad up-shifted maximum (BUM) is one of the most prominent stimulated electromagnetic emission features and has been the subject of intensive investigation in past ionospheric modification experiments. The spectral properties representing the BUM have been regarded as belonging to one uniform feature. Here we present experimental evidence that the BUM actually consists of two separate components, and we elaborate their characteristic properties. [S0031-9007(98)06868-9]

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Since the first observations of stimulated electromagnetic emissions (SEE), excited in the ionospheric F region plasma by a powerful hf electromagnetic wave [1], the investigation of their features has become one of the leading methods to study the properties of artificial turbulence in the ionospheric plasma. The physical strength of the SEE phenomenon has its origin in the compound structure of the spectra and in the individual temporal evolutions of different spectral components, reflecting the development of and competition between various wave interaction processes, from their initial growth to their nonlinear saturation. These experiments, although performed in a geophysical environment, have the character of pure plasma physics experiments, and their results are transferable to other than ionospheric plasmas.

Recently, considerable attention has been focused on investigations of the SEE features when the pump wave frequency f_0 is close to a harmonic of the electronic cyclotron frequency, nf_{ce}. The experiments performed have shown that in a narrow frequency band for $f_0 \simeq nf_{ce}$, the SEE features are very sensitive to the pump frequency offset from nf_{ce}, $\delta f \equiv f_0 - nf_{ce}$ [2–7]. The main results obtained in these experiments are a weakening and quenching of the down-shifted maximum (DM) in the SEE spectra when f_0 is very close to nf_{ce}, and the appearance of a broad up-shifted maximum (BUM) when f_0 is slightly higher than nf_{ce}. The DM is a spectral maximum occurring at a frequency offset of approximately -10 kHz from the pump frequency. The BUM is a SEE feature that exists on the up-shifted side and may reach out to 200 kHz above the pump frequency. The suppression of the DM has been proposed to occur when the pump frequency coincides exactly with a harmonic of the electron cyclotron frequency in the upper hybrid resonance region and results from strong cyclotron damping of plasma waves. The narrowness of the DM resonance absorption provides a possibility to determine experimentally the magnitude of the gyroharmonic frequency with an accuracy of a few kHz [5]. Investigations of the BUM features have revealed that the frequency of the BUM peak intensity (f_{BUM}) versus pump frequency closely follows the relation $f_{\mathrm{BUM}} = 2f_0 - nf_{ce}$ or $\Delta f_{\mathrm{BUM}} = \delta f$, where Δf_{BUM} is the shift of the BUM spectral peak from f_0 [2]. This has been taken as a hint that the BUM might be generated through a four-wave interaction process, involving two pump photons (or upper hybrid plasmons), a decay mode at nf_{ce}, and the stimulated electromagnetic emission at f_{BUM} [3]. More recently, it has been found that in a rather narrow frequency range $0 \le \delta f \le 30$ kHz the value of Δf_{BUM} remains constant or has a considerably weaker dependence on the pump frequency in comparison with the case of larger δf, for which the above mentioned relation $\Delta f_{\mathrm{BUM}} = \delta f$ is closely satisfied [6–8]. Besides, in these measurements the BUM generation has been observed not only for $f_0 \ge nf_{ce}$, but also for f_0 slightly below the cyclotron harmonic frequency. Further characteristics of the BUM feature are the existence of a cutoff frequency at the low frequency flank [4], the occurrence of multiple maxima in the BUM spectra [2,7], and a pronounced dependence of the BUM intensity on δf [8].

The most intriguing aspect about the BUM is the fact that its frequency spectrum lies entirely on the up-shifted side. Wave interaction processes preferentially lead to frequency down-conversion, with only a small, or at best equally strong, up-shifted mirror image. The entirely up-shifted nature of the BUM, therefore, represents a major theoretical challenge. By now a few theoretical models for the BUM generation have been suggested [2,9,10]. Huang and Kuo [11] reviewed the previously considered mechanisms, showed their limitations and contradictions with experimental data, and proposed a new second-order four-wave interaction process. However, none of these theoretical mechanisms can explain the complete set of observational properties, especially the existence of a frequency range with a weaker dependence of Δf_{BUM} on f_0 when the pump frequency is slightly above a gyroharmonic frequency [6–8]. The demand on the theoretical side would be altered if the properties attached to the BUM as a uniform feature would actually belong to different features with different physical causes.

Certain indications that two different BUM components may be distinguished can be found in some of the previous experimental material (e.g., Fig. 14 of Stubbe and Hagfors [12] and Fig. 1(a) of Frolov *et al.* [7]). To understand better the actual BUM structure, we have performed purposeful experiments with the Sura heating facility (56.13°N, 46.10°E, Nizhny Novgorod, Russia) in which the pump frequency has been changed in very small steps in the immediate vicinity of the fourth gyroharmonic frequency. This Letter gives experimental proof of the two-component nature of the BUM structure and presents the characteristics of each component.

The measurements were performed on 3 and 8 September 1997. An O-mode pump wave was transmitted continually, and f_0 was varied in steps of typically 5 kHz around $4f_{ce}$ ($\simeq$5450 kHz) and was kept fixed for a few minutes for each step during the time of measurements. The experimental results presented herein relate to steady-state SEE spectra. For the frequency range used, the maximum possible effective radiated power (ERP) of the Sura facility is $P = 150$ MW. An ionosonde is operated near the site of the heating transmitter, providing ionograms every 15 min. From the ionograms, the bottom side electron density profile, the critical frequency of the ionospheric F_2 region f_{0F_2} (which is the maximum plasma frequency of the medium), and the natural level of ionospheric disturbance are derived to support the observations.

In the measurements carried out around the fourth cyclotron harmonic, the precise value of $4f_{ce}$ was determined by using the effect of DM quenching. Figure 1 displays a sequence of SEE spectra for pump frequencies in the range 5390–5510 kHz (here, $4f_{ce} \simeq 5450$ kHz). The experiments were carried out under daytime conditions. The heater was operated with an ERP of 150 MW. The spectra presented in Fig. 1 were produced by averaging over four to six successive single spectra to reduce the noise. For each measurement two spectra, differing with respect to their frequency span, are shown in order to highlight different spectral portions. In each spectrum, the intensity level covers the interval from -120 to -60 dBm, and successive panels are separated by 30 dB.

In Fig. 1 we see that maximum DM suppression occurs at $f_0 \simeq 5450$ kHz which implies $4f_{ce} \simeq 5450$ kHz. It is clearly seen from the spectra at $f_0 = 5430$, 5440, and 5445 kHz that the BUM excitation is not restricted to the case $f_0 \geq 4f_{ce}$ but extends down to 20 kHz below $4f_{ce}$. For $f_0 - 4f_{ce} \equiv \delta f \leq 0$ it is seen (1) that the BUM peak frequency Δf_{BUM} is almost independent of the pump frequency f_0, settling at about 14–15 kHz, and (2) that the BUM peak intensity decreases significantly with decreasing f_0. At the lower pump frequencies (see the spectra for $f_0 = 5390$ and 5410 kHz), we have a low intensity wedge-shaped emission occurring in the upper sideband of the pump over a rather wide frequency range. This emission, however, is not likely to be an integral part of the BUM feature. Further detailed experimental studies appear necessary to clarify this aspect.

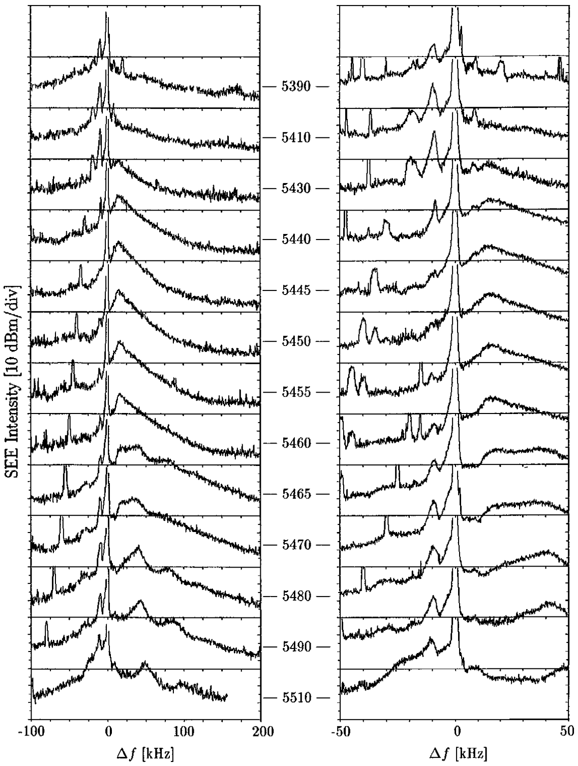

FIG. 1. Experimental results obtained on 3 September 1997 from 13:10 to 13:50 LT for pump frequencies around the fourth gyroharmonic. The heater is operated in the O mode with an effective radiated power of 150 MW. Shown in the SEE strength in relative units (10 dB/division) versus frequency offset $\Delta f = f - f_0$. The strong narrow maximum at $\Delta f = 0$ corresponds to the pump wave reflected signal. Two spectra are presented for each of the selected pump frequencies (which cover the range from 5390 to 5510 kHz), differing with regard to the frequency span. The spiky peaks in the spectra are due to interfering radio stations.

The spectrum for $f_0 = 5465$ kHz ($\delta f \simeq 15$ kHz) deserves special attention. Two different spectral maxima (BUM_1 and BUM_2), up-shifted by approximately 19 and 37 kHz from f_0, can be distinguished in the BUM spectrum. After having identified these two separate maxima, we can state that the BUM here is identical with the BUM_1 for 5430 kHz $\leq f_0 \leq$ 5460 kHz, and with the BUM_2 for $f_0 \geq 5490$ kHz. In between, there is a narrow pump frequency range in which the BUM_1 and BUM_2 coexist. In its range of existence (-20 kHz $\leq \delta f \leq$ 30 kHz), the peak frequency of the BUM_1, $\Delta f_{\mathrm{BUM}_1}$, shows only a moderate increase with f_0. The BUM_2 peak frequency is nearly constant ($\Delta f_{\mathrm{BUM}_2} = 35$ to 40 kHz) over the frequency range $15 \leq \delta f \leq 30$ kHz and goes over to a stronger f_0 dependence for $\delta f \geq 40$ kHz.

Starting at $\delta f \simeq 20$–30 kHz, the BUM$_2$ dominates in the BUM spectrum. It should be noted that the width of the BUM$_1$ spectrum, measured 3 dB below its peak intensity, is approximately 10–12 kHz, independent of f_0. The width of the BUM$_2$ increases slightly from 15 to 25 kHz with increasing f_0.

A summary of the experimental results is given in Fig. 2. Panels (a) and (b) show the DM, BUM$_1$, and BUM$_2$ peak intensities versus δf for two separate experimental sessions, and panel (c) shows the corresponding values of $\Delta f_{\mathrm{BUM}_1}$ and $\Delta f_{\mathrm{BUM}_2}$ (i.e., the frequency offsets of the BUM$_1$ and BUM$_2$ peaks from f_0) for both sessions, marked by circles and triangles, respectively. It is seen in panels (a) and (b) that the DM peak intensity has a deep minimum of more than 20 dB in the gyroresonance region at $\delta f \simeq 0$. This minimum coincides with a maximum of the BUM$_1$ peak intensity. The maximum of the BUM$_2$ peak intensity, on the other hand, occurs at $\delta f \simeq 20$–40 kHz, which is outside the gyroresonance frequency range. The difference between the experiments shown in panels (a) and (b) lies in the pump power which is 150 MW ERP in (a) and 20 MW ERP in (b). We notice that the range of existence of the BUM$_1$ extends to larger negative values of δf for the higher pump power.

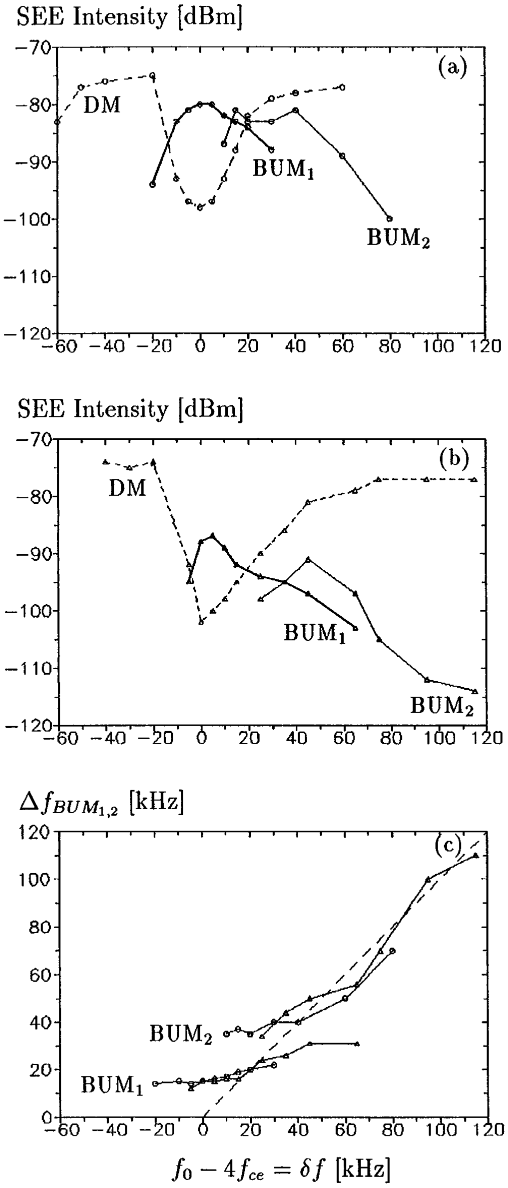

FIG. 2. Dependence of the SEE strength for the DM, BUM$_1$, and BUM$_2$ on the offset of the pump frequency from the fourth electron cyclotron harmonic frequency δf for the experimental results obtained (a) on 3 September 1997 ($P = 150$ MW ERP) and (b) on 8 September 1997 ($P = 20$ MW ERP). Panel (c) represents the δf dependence of both $\Delta f_{\mathrm{BUM}_1}$ and $\Delta f_{\mathrm{BUM}_2}$, marked by circles for $P = 150$ MW ERP (3 September 1997) and by triangles for $P = 20$ MW ERP (8 September 1997). The dashed line is a plot of the relation $f_{\mathrm{BUM}} = 2f_0 - 4f_{ce}$.

Panel (c) shows that $\Delta f_{\mathrm{BUM}_1}$ is almost independent of the pump frequency for δf in the range -5 to 15 kHz, amounting to about 15 kHz for both $P = 150$ MW and $P = 20$ MW ERP. For higher values of δf, an increase of $\Delta f_{\mathrm{BUM}_1}$ up to about 30 kHz is observed. For the lower pump power, $P = 20$ MW ERP, the magnitude of $\Delta f_{\mathrm{BUM}_2}$ is well represented by the relation $\Delta f_{\mathrm{BUM}_2} = \delta f$, or $f_{\mathrm{BUM}} = 2f_0 - nf_{ce}$, as found in [2] [the dashed line in Fig. 2(c)]. For the higher pump power $P = 150$ MW ERP, we notice that for $\delta f \leq 40$ kHz the situation is changed in that the curve $\Delta f_{\mathrm{BUM}_2}$ versus δf now has a much smaller slope. We also see that $\Delta f_{\mathrm{BUM}_2}$ is approximately given by $\Delta f_{\mathrm{BUM}_2} \simeq 2\Delta f_{\mathrm{BUM}_1}$ for $\delta f \leq 20$ kHz. However, additional experiments should be performed in order to investigate whether the BUM$_2$ maximum at low δf values should be interpreted as a second BUM$_1$ maximum.

Another experimental finding that should be noted is the occurrence of multiple BUM$_2$ maxima (see also [3,7]). We see in Fig. 1 that multiple BUM$_2$ maxima exist when $\delta f \simeq 30$–40 kHz, which is the frequency range of maximum BUM$_2$ intensity. Three maxima are seen in Fig. 1 for $f_0 = 5480$ and 5490 kHz. The frequency shifts of these maxima are given by $\Delta f_{1,2,3} \simeq 36$, 75, and 110 kHz for the case $f_0 = 5480$ kHz.

Simultaneous measurements of the DM and BUM features have been performed during sunset when the critical frequency f_{0F_2} undergoes a successive decrease. We find that, once f_{0F_2} falls below f_0, both the DM and BUM$_2$ intensities decrease by about 15–20 dB and continue to be observed down to critical frequencies 150 kHz below the pump frequency. This suggests that the BUM$_2$ generation occurs in the vicinity of the upper hybrid resonance level, that is, where the local upper hybrid frequency $f_{\mathrm{uh}} = (f_{pe}^2 + f_{ce}^2)^{1/2}$ equals the pump frequency f_0. Observations of the DM for such underdense plasma conditions have been previously reported by Leyser *et al.* [3].

An important point is the influence of small-scale magnetic field-aligned striations on the BUM generation. It has been shown in [6] that the occurrence of the DM intensity minimum in the gyroresonance frequency range is accompanied by a minimum in the anomalous absorption rate of a hf diagnostic wave, which is an indication of a corresponding minimum in the striation excitation level. This then means that the BUM$_1$ maximum at gyroresonance should be linked to the reduced absorption rate, i.e., to an enhanced pump energy flux reaching the resonance region. This implies that a theory aiming at an explanation of the BUM$_1$ should not depend on the presence of striations. The same cannot be said with respect to the BUM$_2$ which exists in a frequency range where the anomalous absorption rate is back to normal values and which is produced near the upper hybrid resonance level where upper hybrid waves and striations are important for wave-plasma interaction. However, according to [7], there is reason to believe that the temporal evolution of the BUM$_2$ is determined, first of all, by the presence of low frequency turbulence which is immediately involved in the BUM$_2$ generation process. Based on the available data, we can state that this turbulence has a decay time of a few tens of milliseconds and a growth time to saturation longer than the growth time of striations. In order to clarify the properties of the low frequency turbulence, as well as the role of striations in the BUM$_2$ generation process, further detailed experimental investigations are needed.

In summary, we may conclude that the BUM is a composition of two different emission components. The first, dominating in the BUM spectrum for $\delta f \leq$ 10 kHz, is generated in the immediate vicinity of the electron cyclotron harmonic frequency and shows a weak dependence of its peak frequency, $\Delta f_{\mathrm{BUM}_1}$, on the pump frequency f_0. Its intensity is greatest for $\delta f \simeq 0$. Up to now, a mechanism for its generation has not yet been considered. The second component, to which all existing theoretical models can be related, is generated when $\delta f > 0$ and prevails in the BUM spectrum for $\delta f \geq$ 20 kHz, showing a stronger f_0 dependence of its peak frequency than the BUM$_1$. For $\delta f \geq 40$ kHz, $\Delta f_{\mathrm{BUM}_2}$ may be approximated by $\Delta f_{\mathrm{BUM}_2} = \delta f$. The BUM$_2$ peak intensity has its largest value for $\delta f \simeq 30-40$ kHz, where the occurrence of multiple maxima (up to three, as a rule) is observed in the spectra.

Some of the BUM$_2$ features can be compared with theoretical predictions (Huang and Kuo [11]). First, the BUM$_2$ is generated near the upper hybrid resonance level when the pump frequency is close to, but larger than, a harmonic of the electron cyclotron frequency here. The frequency of the BUM$_2$ peak, f_{BUM_2}, versus the pump frequency f_0 follows the relation $f_{\mathrm{BUM}_2} = 2f_0 - nf_{ce}$ ($n = 4$ in our measurements), at least for $f_0 - 4f_{ce} \geq$ 20 kHz. According to [7], BUM$_2$ starts to be detectable when the pump power is higher than $P \simeq 5$ MW ERP ($E \simeq 120$ mV/m in the vicinity of the upper hybrid resonance level). This value is to be compared with the calculated magnitude $E_{th} \simeq 250$ mV/m. The decrease of the BUM$_2$ intensity as the pump frequency approaches a harmonic of the electron cyclotron frequency can be explained by a decrease of the striation intensity. The proposed mechanism [11] explains also the existence of the low-end cutoff frequency of the BUM$_2$ [4], the occurrence of the second BUM feature (but not of the third), and the generation of the emission preferentially in the up-shifted sideband of the pump wave. On the whole, this theory has explained some of the important characteristics of the observed BUM$_2$ features but not the existence of a frequency range with a weaker dependence of Δf_{BUM} on f_0 when $f_0 - nf_{ce} \leq 20-30$ kHz.

The experimental results presented here will require a revision of the theoretical views on the physical nature of the BUM emission in the SEE spectra, taking into account its double structure.

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