Stimulated plasma emission at the second harmonic of the pump wave

Yuri Yampolski[1], Andriy Zalizovski[1], Alexander Koloskov[1], Cesar La Hoz[2], Michael Rietveld[3]

[1]Institute of Radio Astronomy, National Academy of Sciences of Ukraine
4, Chervonopraporna str.
Kharkiv, 61002
Ukraine

[2]The Arctic University of Norway, Tromsø
Hansine Hansens veg 18
9019 Tromsø
Norway

[3]The EISCAT Scientific Association
Ramfjordmoen
N-9027 Ramfjordbotn
Norway

ABSTRACT

The possibility of generating of electromagnetic radiation at harmonics of the pump wave in the ionospheric plasma is still open because of complexity of the experiments on its detection. The fact is that the parasitic generation of harmonics can occur in the output circuit of the transmitter, and to separate it from the possible ionospheric effects is very difficult. To solve the problem of detecting the 2nd harmonic which is excited in the ionosphere, the special scheme of the experiment was proposed that is based on using the stable low-power probe wave on the frequency near the second harmonic of the pump wave for inspecting the propagation conditions of parasitic radiation. The conclusion about the ionospheric generation of the 2nd harmonic was done by comparing its parameters with those of the probe signal.

1. INTRODUCTION

The nonlinear wave-plasma interaction is an important problem of modern physics. The impact of the controlled electromagnetic emission produced by the heating facilities on the ionospheric plasma is a convenient technique for experimental investigations of nonlinear effects [*Gurevich and Shvartsburg*, 1973]. Currently the most powerful heating facilities are HAARP (Alaska, USA), EISCAT (Tromso, Norway) [*Stubbe et al.*, 1982], and SURA (Vasilsursk, Russia). The heating experiments are used to study the excitation of the artificial ionospheric turbulence of different scale-sizes [*Erukhimov et al.*, 1987] and its effect on wave propagation [*Zalizovski et al.*, 2009], artificial aurora activations [*Mishin et al.*, 2004], generation of the stimulated electromagnetic emission (SEE) [*Thide et al.*, 1982; *Bernhard et al.*, 2009], artificial excitation of the atmospheric gravity waves (AGW) [*Chernogor and Frolov*, 2012] and MHD waves [*Yampolski*, 1989], and different natural phenomena in the Earth's ionosphere [*Beley et al.*, 1997; *Sinitsin et al.*, 1999].

One possible nonlinear effect, which can be produced during the ionospheric heating, is the excitation of the 2^{nd} harmonic of the pump wave. However, the question about the possibility of generation of the 2^{nd} harmonic of the heater emission in the ionosphere remains unanswered yet because of difficulties in separation of the ionospheric excitation from the appearance of the parasitic harmonic in the output stage of the transmitter.

This paper presents the results of the heating experiments specially designed to detect the second harmonic of the pump signal, analyze its features and select the source of this effect: stimulated emission of the ionospheric plasma or parasitic harmonic in transmitter. To do this we use the stable low-power probe signal with frequency near the 2^{nd} harmonic of the pump wave produced by the same heater. It is possible to select the source of the second harmonic signal by comparison of its features with the behavior of the probe radiation.

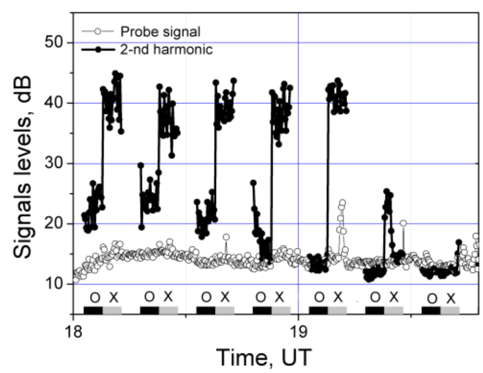
2. OBSERVATIONS

Two special measuring campaigns were organized jointly by the Institute of Radio Astronomy, NASU, and the EISCAT scientific association on 29-31 October 2013, and 17-18 November 2014. The EISCAT heating facility, UHF incoherent scatter radar, and coherent HF receiving systems of IRA NASU located in Tromso, Svalbard (KHO observatory) and Radio Astronomical observatory (RAO, Kharkiv region, Ukraine) at the distances about 15 km, 1000 km and 2400 km from the heating facility respectively were used. The carrier frequency of the CW pump wave f_p was constant and equal to 3989942 Hz during all experiments. In addition to the pump emission, the heater radiated the probe pulsed signal with power of about 100 kW at the carrier frequency $2 \cdot f_p + 500$ Hz. Pulse repetition period was 25 ms, pulse width – 10 ms. All receiving sites registered the signals on the frequencies of heating, probe signal, and 2^{nd} harmonic of the heating. As mentioned earlier, the probe signal was used for localization of the source of the excitation of the 2^{nd} harmonic of the pump wave. If the 2^{nd} harmonic emission is generated in the transmitter chains, then its parameters should be well correlated with the parameters of the probe signal radiated by the same heater facility at a very close frequency. If the 2^{nd} harmonic radiation is produced in the ionosphere, then the correlation with the probe signal should be absent, but dependence on the characteristics of ionospheric plasma modified by the heater pump wave should appear.

Let us consider the variations of 2^{nd} harmonic emission and probe signal levels together with the ionospheric parameters measured synchronously by EISCAT UHF IS radar on 31 October 2013 (Fig. 1). As can be seen, a clear response of the 2^{nd} harmonic level on the ionospheric conditions and heating efficiency are observed when the critical frequency of *F2* layer was higher than carrier frequency of the pump wave (Fig 1, 18:00-19:15 UT). Between 18:00 and 19:15 UT during O-mode heating the IS radar data demonstrated an increase of the electron temperature in the ionosphere (Fig. 1 b). For this period all O-mode heating cycles were accompanied by high-level emission at the frequency of 2^{nd} harmonic of pump wave (Fig. 1 a). During X-mode operation IS radar data demonstrated no noticeable increasing of electron temperature (Fig. 1 b) while the level of the second harmonic of pump wave increased on 15-20 dB in comparison with O-mode heating. The level of the probe signal slightly exceeded the noise level, but did not changed during "ON" and "OFF" period and did not respond to the heating-mode (Fig 1 a).

Both the ionospheric heating effect and the emission at 2^{nd} harmonic of pump wave disappeared synchronously after 19:30 UT when the critical frequency became lower than the heater frequency (Fig 1 a). Therefore, the emission at the frequency of second harmonic was registered at Tromso site only during the time of effective wave-plasma interaction. This is a serious argument in favor of ionospheric mechanism of generation of the 2nd harmonic of pump wave. Alternatively, in the hypothesis of generation of the 2nd harmonic radiation by output stages of transmitter it is impossible to explain huge variations of the signal level which agreed with ionospheric conditions and simultaneously the absence of variation of probe emission amplitude at almost the same frequency.

From 18:00 till 19:15 UT the signal at the 2nd harmonic of the pump frequency was observed at about 30 dB over the noise level. The probe signal was registered just above the level of atmospheric noise. From 19:15 to 19:45 UT when the critical frequency of F2 layer became lower than the pump



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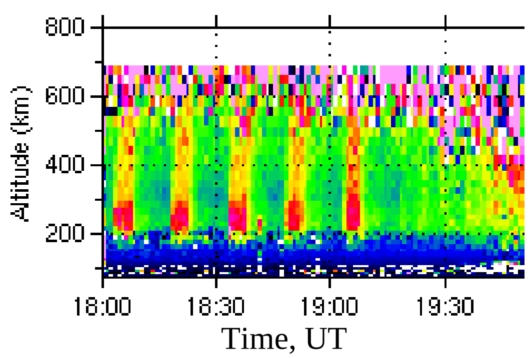

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Figure 1. Variations of the 2nd harmonic and probe signal levels in Tromso (a), and electron temperature variations according to UHF EISCAT IS radar (b) 31 October 2013.

wave carrier frequency and ionospheric conditions were quiet, both 2nd harmonic and probe signals were not registered at Tromso. After 19:55 UT, when natural ionospheric disturbances appeared, both signals reappeared. The spectra of the signals were wide, which are typical for the scattered emission, with quick variations of the Doppler frequency shifts. It should be noted that during the presence of natural ionospheric disturbances the levels of pump wave and its 2nd harmonic demonstrate much more consistent behavior than the variations of the pump wave and probe signal amplitudes.

Figure 2 shows the Doppler spectrograms of the signals registered at Tromso at 19:06-19:09 on 31 October 2013 and calculated for different frequency bands. The ionosphere was quiet during that time. When the electron temperature was increased during O-mode heating (09:06-09:08 UT) relatively narrowband signals at the heating frequency (Fig 2 a,d,g) and its 2nd harmonic (Fig 2 b,e,h) have been observed. As can be seen, the levels of both the pump wave and 2nd harmonic were increased after the switching of polarization from O- to X-mode at 19:08 (Fig. 2 a-b, d-e, g-h).

During the experiments of November 17, 2014, effects similar to those observed on October 31, 2013 were registered (Fig. 3). In contrast to the 2013 observations, this experiment was conducted in the morning when the ionospheric critical frequency was increasing. According to the results of the EISCAT UHF IS radar, during the first hour of the experiment the increase of the electron temperature (heating effect) was absent or very weak. The signal at the 2nd harmonic of the pump wave was detected for the first time at 6:36, and later at a higher level at 6:41-6:45 during the X-mode emission (Fig. 3). Because of the increase of the electron density, the heating effects accompanied by the growth of the level of 2nd harmonic was stably observed after 7:00 UT during the O-mode heating.

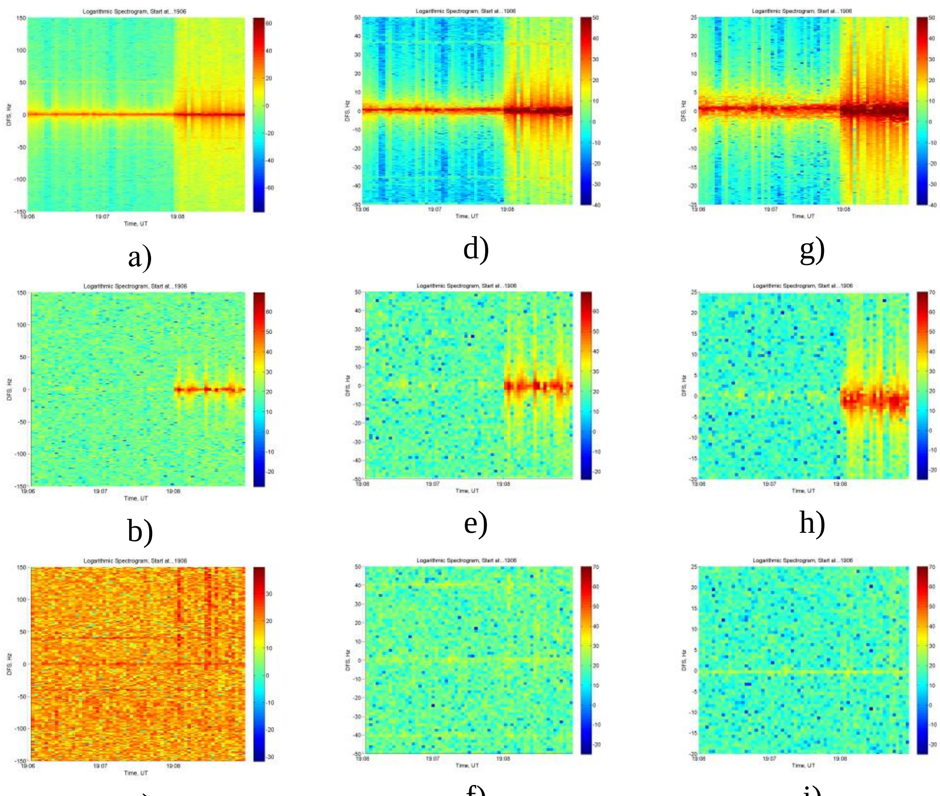
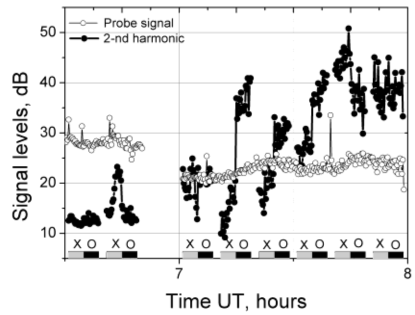


Figure 2. The spectrograms of pump wave (a, d, g), signal at the 2nd harmonics of heating (b, e, h), and probe signal (c, f, i) that were received October 31, 2013 19:06-19:09 UT at Tromso receiving site in frequency bands of 300 Hz (a-c), 100 Hz (d-f), and 50 Hz (g-i) respectively.



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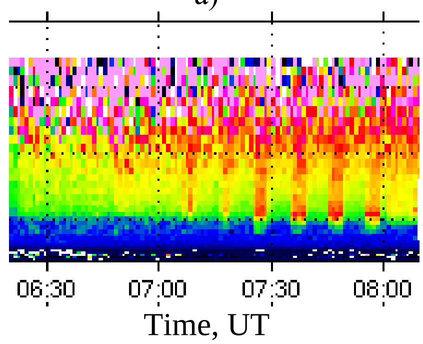

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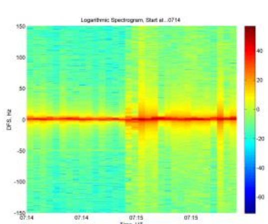
Figure 3. Variations of the 2nd harmonic and probe signal levels in Tromso (a), and electron temperature according UHF EISCAT radar (b) on 17 November 2014.

At the other receiving sites the 2nd harmonic was not detected. The level of 2nd harmonic signal generally was higher during the O-mode heating, in comparison with X-polarization emission (Fig. 3). The exceptions are the sessions which started at 7:41 and 7:51 UT, when levels of signals at the 2nd harmonic were similar for both X- and O-mode heating. The Figure 4 shows the typical spectrograms of heating radiation, 2nd harmonic and probe signals observed on November 17, 2014 at 7:14-7:16 UT. It is worth to note that the quick fluctuations of 2nd harmonic amplitude (Fig. 4 b, e, h) were accompanied by a nearly constant level of the probe signal (Fig. 4 c, f, i). At 7:15 UT when the polarization of the heating signal was switched from X- to O-mode, the levels of heating signal and its 2nd harmonic were increased, while the amplitude of the probe signal did not change.

On the next day on November 18, 2014 the same scheme of experiment was implemented, but the ionospheric conditions were dramatically different. Abnormal absorption in the low ionosphere significantly decreased the effectiveness of the ionosphere heating. As a result, both the heating effect and the 2nd harmonic of pump wave were not observed.



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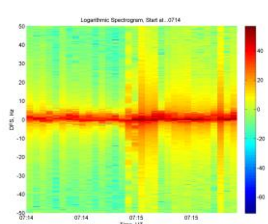

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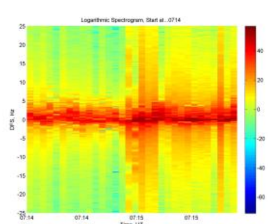

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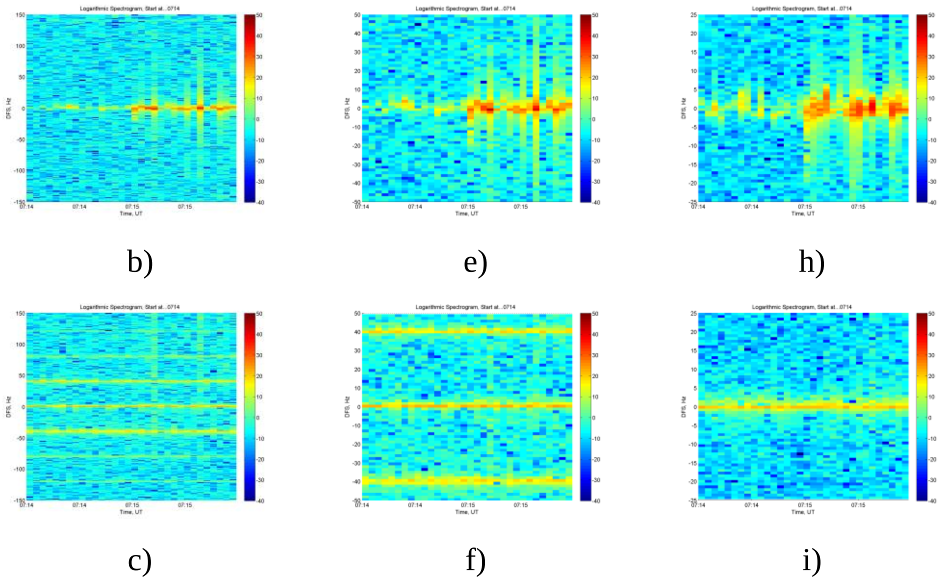


Figure 4. Spectrograms of signals at the heating frequency $f_p = 3989942$ Hz, (a, d, g), 2nd harmonics of the heating $2 \cdot f_p$ (b, e, h), and probe signal at the frequency $2 \cdot f_p + 500$ (в, e, i), that were received in Tromso on November 17, 2014 at 7:14-7:16 in the frequency bands of 300 Hz (a-c), 100 Hz (d-f), and 50 Hz (g-i), respectively.

3. DISCUSSION

The ionospheric excitation of the 2nd harmonic of powerful electromagnetic emission has been confidently registered during two heating experiments on October 31, 2013 and on November 17, 2014. This conclusion is based on the results of comparative analysis of the behavior of the signals at the 2nd harmonic of the pump wave and probe radiation at a frequency which was very close to the second harmonic. The variations of the levels of these signals were absolutely different. The signal at the 2nd harmonic of the pump wave was detected during the time intervals when the effective wave-plasma interaction was observed according to the data of EISCAT UHF IS radar. At the same time, it is obvious, that the excitation of the harmonic emission is not directly related to the increasing of the electron temperature through heating, because during the X-mode operation the electron temperature was not changed, but the effect was observed. The signal at the 2nd harmonic of pump wave has been detected at Tromso in the close vicinity of the heater. The 2nd harmonic was never detected at the remote receiving sites in Svalbard and Ukraine. Excitation of the 2nd harmonic wave was detected for both for O- and X-mode heating.

The efficiency of generation was changed for different periods of experiments. Effects during the X-mode heating were stronger on October 31, 2013. On the contrary, on November 17, 2014 the excitation of the harmonic was stronger during the O-mode heating for the most part of the sessions.

The effect was more pronounced for the polarization where the better conditions for reflection from the ionosphere are realized. Consider in more detail the ionospheric situation at the time of the experiments. On October 31, 2013 at 18:00-19:15 UT the critical frequency was changing near the heating frequency ($f_p = 3989942$ Hz). Under these conditions, the pump wave of O-polarization was reflected uncertainly from the ionosphere and scattered noticeably. (Fig. 5). Nevertheless, the interaction with plasma was detected for a wide range of heights (Fig. 1 b). The excitation of the 2nd harmonic was much stronger under influence of X-mode that reflected from the ionosphere more constantly (Fig. 5). At 6:00-6:45 UT November 17, 2014 the critical frequency was substantially less than the pump frequency. Consequently, neither heating effects nor excitation of 2nd harmonic emission were observed during this time. Near 6:45 UT the very weak signal at the frequency of 2nd harmonic was detected during X-mode operation. At that time, the critical frequency for X-mode was approaching the heating frequency (Fig. 6). Both heating effects and 2nd harmonic appeared just after 7:00 UT. After that, for the sessions of 7:01-7:05 UT (X-mode) and 7:05-7:09 UT (O-mode) the levels of 2nd harmonics were commensurate. At that time, the critical frequency of the ionosphere increased and went through the value of the pump wave frequency (Fig. 6 b). Already at 7:15 UT the critical frequency became much higher than the pump frequency (Fig. 6 c, foF2 = 4.75 MHz). Since that time, the reflections of X-waves were detected on the ionograms.

In that situation, during the O-mode operation the 2nd harmonic emission was observed at the level of 35 dB higher than the noise, and only 10 dB over the noise during the X-mode pumping. As one can see on the ionogram (Fig. 6 b), the reflection conditions at 4 MHz for O-polarization were much better than for X-mode. After 7:40 UT the effects on 2nd harmonic on O- and X-modes are aligned at level around 35-40 dB above the noise (Fig. 3 a). The reflection conditions for both polarizations at the 4 MHz were approximately the same (Fig. 6 g).

Thus, the effectiveness of the 2nd harmonic excitation depends on the reflection conditions from the ionosphere of the waves with corresponding polarizations. Comparison of the levels of the received signals for the moment of switching the polarization confirms this conclusion: excitation of the 2nd harmonic is stronger on that polarization which more effectively reflects from the ionosphere (Figs. 2, 4). Obviously, the presence of the reflected wave of sufficient energy is a necessary condition for the excitation in the ionosphere of the second harmonics recorded on the Earth surface. Hence, the second harmonic excitation occurs as a result of nonlinear interaction in presence of the reflected wave with the ionospheric plasma. If the 2nd harmonic generation took place on the upward trajectory, it could not be detected on the ground, as it could not be reflected from the ionosphere, because in all considered cases the critical frequency was significantly lower than the doubled frequency of the pump wave (Figs. 5, 6).

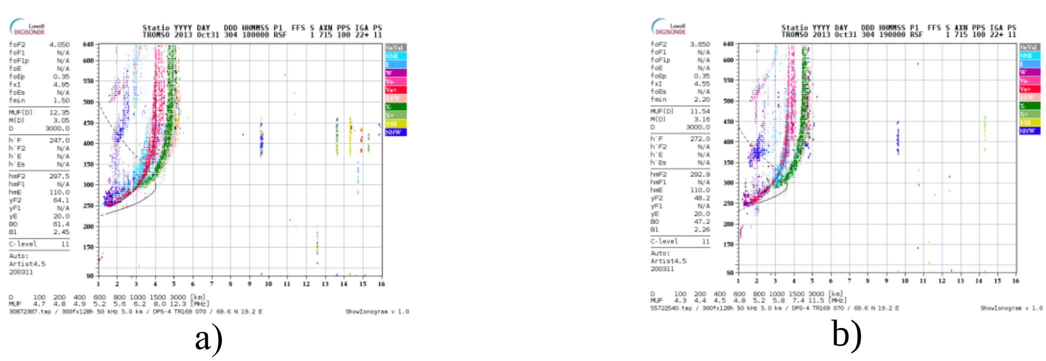
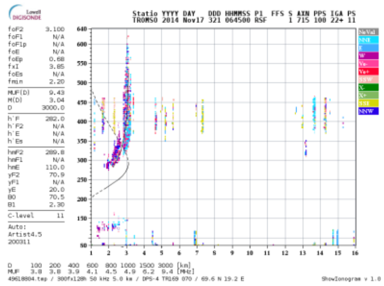


Figure 5. The ionograms registered at Tromso 31 October 2013 at 18:00 (a) and 19:00 (b)



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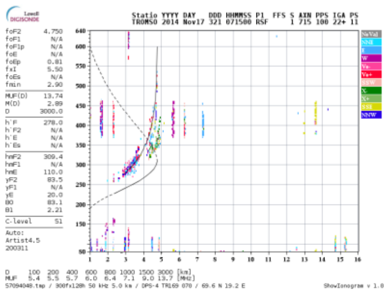

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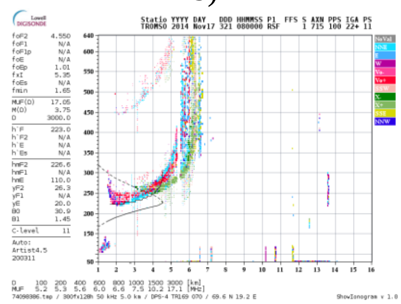

c)

Figure 6. The ionograms registered at Tromso on November 17, 2013 at 6:45 UT (a), 7:00 UT (b), 7:15 UT (c) и 8:00 UT (d)

Generation of the 2nd harmonic could appear in the case of excitation of nonlinear current by the pump wave. In that situation, harmonics should appear in the current, and as a result, this current should emit on harmonic frequencies.

4. CONCLUSIONS

Generation of electromagnetic waves at a frequency of the second harmonic appearing because of interaction of powerful electromagnetic radiation from heating facility with the ionospheric plasma has been discovered. The 2nd harmonic signal has been detected only in close vicinity of the heater. It was absent at the receiving sites located at a distance 1000 km and more from the heater. The 2nd harmonic emission is observed during both O- and X-mode heating. The effect is stronger on the polarization for which the better conditions of reflection from the ionosphere are realized. Hence, the 2nd harmonic signal that is recorded at the Earth surface is excited with participation of the pump wave specularly reflected from the ionosphere.

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