Observations of Stimulated Scattering of a Strong High-Frequency Radio Wave in the Ionosphere

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Electromagnetic sideband spectra induced by a strong monochromatic high-frequency radio wave in an overdense ionosphere have been observed for the first time by means of a new direct observational technique. The observed asymmetry of the spectra, a characteristic feature of stimulated scattering, is tentatively attributed to parametric and linear-mode-conversion processes occurring in the irradiated ionospheric-plasma volume.

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We wish to report what appear to be the first direct observations of typical stimulated scattering spectra obtained as a result of the interaction between a vertically incident strong monochromatic high-frequency radio wave and an overdense ionospheric plasma. The observations were direct in the sense that the emitted and ionospherically reflected signals, including the induced sidebands, were monitored directly on the ground with a spectrum analyzer connected to a receiving antenna and, hence, no diagnostic radar with its Bragg-condition constraints was utilized. The strong radio wave in question was transmitted from the powerful ionospheric modification facility HEATING at Ramfjordmoen near Tromsø, Norway (geographical coordinates 69.58° N, 19.21° E), which has been built by the Max-Planck-Institut für Aeronomie, Federal Republic of Germany, in cooperation with the University of Tromsø. The HEATING transmitters and antenna arrays are designed to operate in the 2.5–8 MHz range with a maximum effective radiated power (ERP) of 360 MW, yielding a maximum electric field strength of roughly 1 V/m at 100 km height; for a more detailed description of the HEATING facility see Stubbe and Kopka.[1]

During the experimental period (31 August–6 September 1981) the monitoring equipment was moved and set up at three different geographical locations, viz., Lavangsdalen (≅15 km SSW of the HEATING site), Skibotn (≅50 km SE), and Kiruna (≅200 km SSE), where the received spectra were analyzed and recorded on photographs. Some of these photographs are shown in Figs. 2–5. For reference purposes, the transmitter output was spectrum analyzed at the HEATING site by connecting the analyzer to a very short pickup antenna a few hundred meters away from the transmitting antenna array where the ground wave dominates. The spectrum displayed in Fig. 1, which was obtained with ≅280 MW ERP, shows that the transmitted strong radio wave has a very high spectral purity.

Figure 2 shows the signal received at Lavangsdalen, where the ionospherically reflected sky wave dominates, on 31 August when transmission was at a frequency that was lower than critical. A broad, skewed noise spectrum extending from ≅−15 to ≅+10 kHz relative to the HEATING carrier (center peak) is clearly seen to emerge from the ubiquitous background noise, the narrow peaks at ≅−18 and ≅+16 kHz being interfering short-wave radio stations. Beyond any doubt this

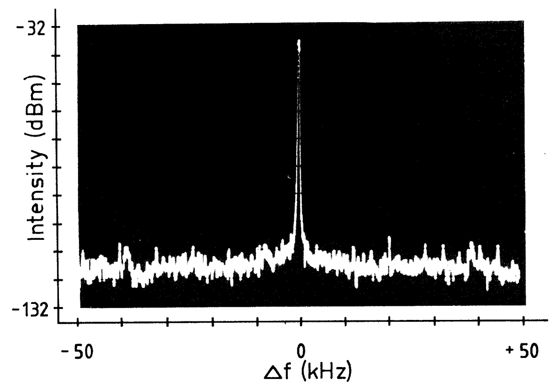

FIG. 1. Transmitter output reference spectrum for ≅ 280 MW ERP in ordinary (*O*) wave polarization mode. HEATING frequency (center frequency): $\omega_0/2\pi = 5423$ kHz. Frequency span: $2|\Delta f| = 100$ kHz. Amplitude resolution: 10 dB/division. The intensity is given in dBm (0 dBm = 1 mW at 50 Ω).

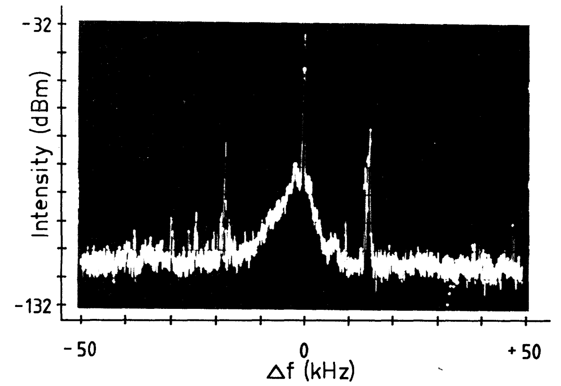

FIG. 2. Received spectrum at Lavangsdalen for ≅ 280 MW ERP in O mode. HEATING frequency (center frequency): 4040 kHz. Frequency span: 100 kHz. Note the strong, induced asymmetric noise spectrum from $\Delta f \cong -20$ kHz to $\Delta f \cong +10$ kHz from the HEATING carrier reaching a maximum close-in intensity almost 40 dB above the background noise level. The two narrow sideband spikes are interfering radio stations.

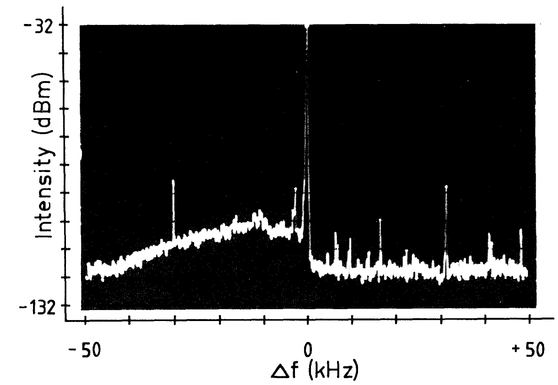

FIG. 3. Received spectrum at Kiruna for ≅ 280 MW ERP in O mode. HEATING frequency (center frequency): 5423 kHz. Frequency span: 100 kHz. Note the strongly asymmetric spectrum from $\Delta f \cong -50$ kHz to $\Delta f \cong +5$ kHz with a maximum intensity of ≅20 dB above the noise level at $\Delta f \cong -12$ kHz.

skewed spectrum of electromagnetic type is induced by the strong radio wave in the ionospheric plasma. As is seen in Fig. 2 the spectrum is quite strong, the maximum of the received power at −80 dBm being only 50 dB lower than the ordinarily reflected HEATING signal itself. Estimating the effective length of our (uncalibrated) receiving antenna to 50 m, we find that the stimulated sideband emission produces a maximum electric field strength on the ground of the order of 10^{-6} V/m. Hence, the effect is strong and easy to detect.

At Kiruna the spectra observed were consistently more asymmetric in shape and wider in frequency to the lower-sideband side. Figure 3 shows such a spectrum obtained on 2 September. Later that day the analyzer sweep shown in Fig. 4 was recorded. During this sweep, which took 93.8 s to run, the mode of wave polarization of HEATING was changed from ordinary (O) to (almost) extraordinary (X) after ≅38 s, corresponding to a frequency offset of ≅ −10 kHz. The almost complete disappearance of the induced broad sideband spectrum at this changeover point is clearly seen (cf. Fig. 3), despite the large number of interfering radio stations. Figure 5

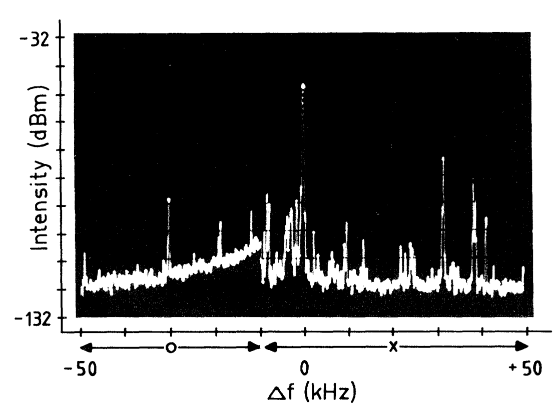

FIG. 4. Same as Fig. 3 but with a change from O to X mode at $\Delta f \cong -10$ kHz. At this changeover point the intensity of the induced spectrum immediately drops by ≅ 15 dB.

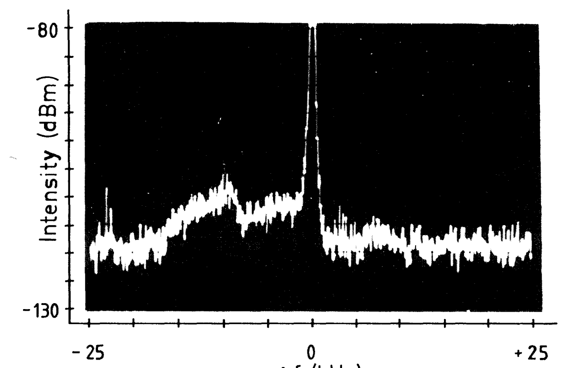

FIG. 5. Higher-resolution spectrum at Kiruna for ≅ 280 MW ERP in O mode. HEATING frequency (center frequency): 5423 kHz. Frequency span: 50 kHz. Amplitude resolution: 5 dB/division. The induced asymmetric spectrum from $\Delta f \cong -20$ kHz to $\Delta f \cong +10$ kHz shows some peak structure with the strongest peak at $\Delta f \cong -10$ kHz being almost 15 dB stronger than the background noise.

shows, with higher resolution, one of several similar spectra obtained at Kiruna on 5 September. A general feature of these spectra is the occurrence of a pronounced peak structure, especially in the lower sideband some 8–10 kHz below the HEATING frequency.

In earlier ionospheric modification experiments[2-6] incoherent radar has been used as a diagnostic tool. For a modifier wave of (angular) frequency ω_0, below the ionospheric critical frequency, ion and plasma line enhancement have been observed. The plasma line enhancement, with a spectral width of $\lesssim 40$ kHz, was partly attributed to a parametric decay instability[7,8] where the pump wave decays into an ion acoustic wave of low frequency ω_i and an electron plasma (Langmuir) wave with a downshifted frequency ω_e satisfying the condition $\omega_e = \omega_0 - \omega_i$ and the corresponding wave-vector–matching condition $\vec{k}_e = \vec{k}_0 - \vec{k}_i$, with $|\vec{k}_0| \ll |\vec{k}_i| \simeq |\vec{k}_e|$. Recently, Fejer and Kopka[9] performed an experiment in which the time history of the amplitude of the ionospherically reflected HEATING wave was recorded at Lavangsdalen. Their results also lend support to the idea that in the case of an overdense ionosphere the parametric decay instability comes into play.

As is seen from Figs. 2–5 a prominent feature of our spectra is an asymmetry in the induced sidebands with a clear tendency for the lower sideband to contain more energy than the upper one. In the present Letter we shall not try to give a detailed theoretical interpretation of this observational fact. We find it tempting, however, to tentatively attribute this asymmetry to parametric processes taking place in the ionosphere. The above-described parametric decay instability, with the strong HEATING wave acting as pump, would result in a Langmuir wave that is downshifted by the ion acoustic frequency. The Langmuir wave can propagate only in a comparatively narrow height range near the critical point. However, it is a well-known fact that in a plasma containing inhomogeneities, Langmuir waves may undergo a linear (direct) mode conversion into radio waves which may escape from the plasma.[10] The reverse process may also be at work, yielding Langmuir waves from radio waves incident on plasma inhomogeneities.[11] If sufficiently strong, such a Langmuir wave will act as a pump in a modified parametric instability.[12] The result of these parametric and linear-mode-conversion processes would be a generation of an asymmetric Langmuir wave spectrum which, because of scattering by stationary (zero-frequency) inhomogeneities and/or striations, would yield an induced lower sideband of the monochromatic HEATING wave. Scattering by damped ion acoustic waves of nonzero frequency would result in a mixing in of weak spectral components also in the upper sideband. The shape of such induced electromagnetic sideband spectra would thus be in agreement with the ones actually observed. Crude theoretical estimates of sideband intensities were made and provide a semiquantitative support to our tentative conjectures; the result of the theoretical analysis will be published elsewhere.[13]

Assuming for simplicity that the electron Langmuir waves $(\omega_e, \vec{k}_e)$ satisfy the Bohm-Gross dispersion law $\omega_e^2 \cong (1 + 3k_e^2/k_D^2)\,\omega_{pe}^2$, where k_D is the inverse electron Debye length, and that the ion acoustic waves $(\omega_i, \vec{k}_i)$ satisfy the dispersion law $\omega_i^2 \cong \omega_{pi}^2 k_i^2/k_D^2$ (ω_{pe} and ω_{pi} denote the electron and ion plasma frequencies, respectively), and recalling the fact that $k_e^2/k_D^2 \simeq k_i^2/k_D^2 < 1$, one finds values of the width of the induced Langmuir and electromagnetic sideband spectra (a few tens of kilohertz or less) that compare rather nicely to those observed in incoherent radar measurements[3-6] and in our experiments. Another feature that also speaks in favor of our conjectures is the O/X mode dependence (Fig. 4) which is in agreement with theory.[7] Furthermore, the more asymmetric shape of the spectra obtained when looking at the modified volume under larger angles to the vertical[14] could be related to the spectral differences exhibited by Langmuir waves propagating at different angles to the magnetic field.[8] Other processes than the parametric decay instability, including higher-order parametric and nonlinear ones, may very well account for the finer details of the observed spectra.

In conclusion, we have discovered experimentally that electromagnetic spectra induced by a strong monochromatic electromagnetic wave in an overdense ionospheric plasma may be received and analyzed with good frequency and intensity resolution directly on the ground, and that their skewness may tentatively be attributed to parametric processes hitherto only observed by means of diagnostic radars. Further investigations of directly observed sideband spectra are in progress.

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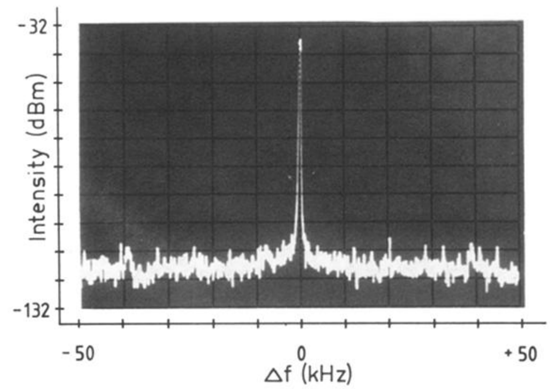
[14]The limited number of spectra observed at Skibotn were somewhat intermediate in asymmetry. As a result of technical reasons none of these spectra are presented.



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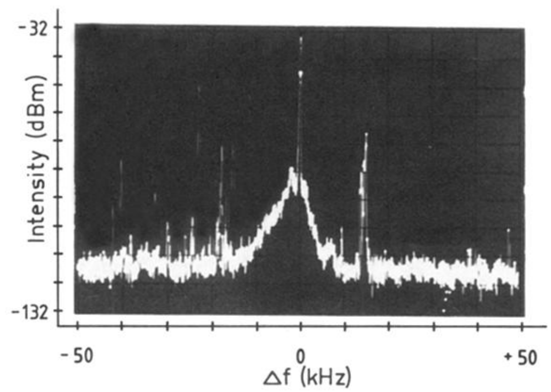

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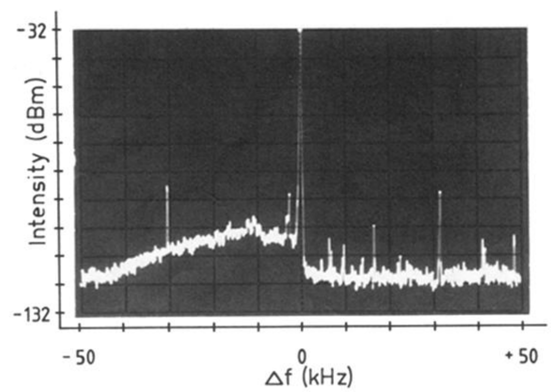

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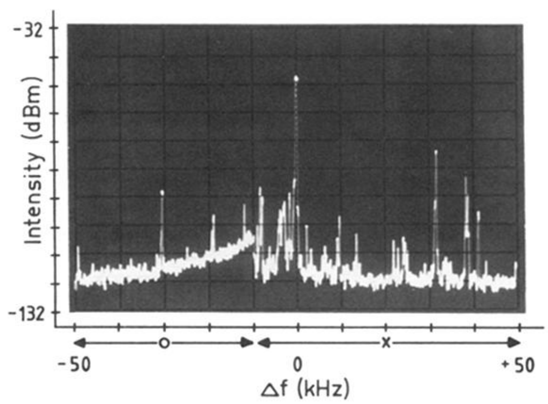

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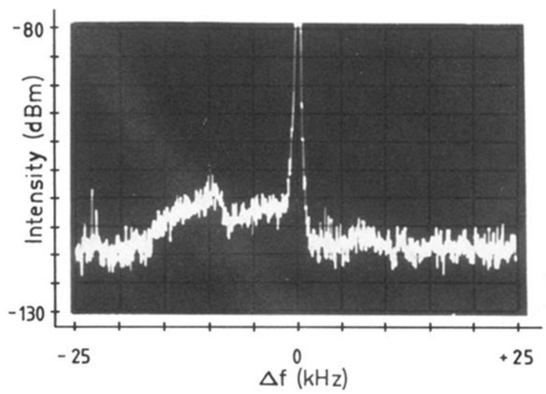

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