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ELF Chirp Communication based on Modulated Heating Low Ionosphere

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Abstract. ELF can be generated by HF heating the low ionosphere for submarine communication. QPSK has been used on ELF carried generated via modulated ionosphere heating to transmit digital data. However, ELF band is disturbed frequently by the power frequency harmonic interference, and QPSK modulation can't effectively suppress interference. In this paper, the Chirp-BOK(Binary Orthogonal keying) modulation method for ELF communication based on ionosphere heating is proposed. The up-chirp and the down-chirp modulation waveforms are designed to transmit the symbols "0" and "1" respectively. Simulation results show that the variation of electron temperature and conductivity in the ionosphere is basically consistent with the frequency modulation characteristics of power modulation when the ionosphere is heated by Chirp-BOK power modulation high frequency wave. The performance of Chirp-BOK and QPSK under harmonic interference is compared, and the simulation results show that Chirp-BOK has better anti-interference performance.

1. Introduction

Extremely low frequency (ELF: 0.3-3khz) communication has a wide range of applications, such as navigation, geophysical exploration, remote sensing and so on. When the ionosphere is periodically heated by the AM(amplitude modulation) modulated high frequency waves, it will lead to periodic oscillation of the currents to radiate ELF waves, and the "virtual antenna" is formed in the ionosphere[1]. Comparing to the traditional method which is directly radiating the ELF waves with ground antennas; it is small in size, flexible and not vulnerable to attack.

However, there are few reports on the scheme to realize the whole ELF communication by heating the ionosphere. In [2], Jin et al examined the experimental results of using quaternion phase shift keying (QPSK) to transmit digital data on ELF carriers generated by heating the ionosphere through modulation, and achieved the communication rates of 100bps,400bps,800bps. Whereas, the ELF band is always disturbed by the power frequency harmonic, and the BER performance of QPSK communication will be decreased sharply under harmonic interference. The chirp communication system has strong anti-jamming ability, narrowband anti-jamming ability and multipath anti-jamming ability [3]. Therefore, this paper propose a a chirp-bok waveform modulation method by combining chirp modulation method with AM(amplitude modulation) to heat the ionosphere. Finally, the feasibility of the proposed scheme is verified and its anti-interference performance is compared.

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2. System Model

2.1. Theoretical Model of Heating Ionosphere

Current modulation theory is the basis of ELF generated by periodic heating of ionosphere by high frequency waves. When the high power high frequency transmitter is started, the ionosphere begins to absorb high frequency energy and the temperature rises. When the transmitter is turned off, the ionosphere cools to its ambient temperature and the conductivity returns to its ambient value. Therefore, by changing the power of the transmitter at ELF frequency, ionospheric conductivity and current radiate ELF waves at the same frequency. Therefore, the virtual antenna is formed in the low ionosphere, as shown in figure 1.

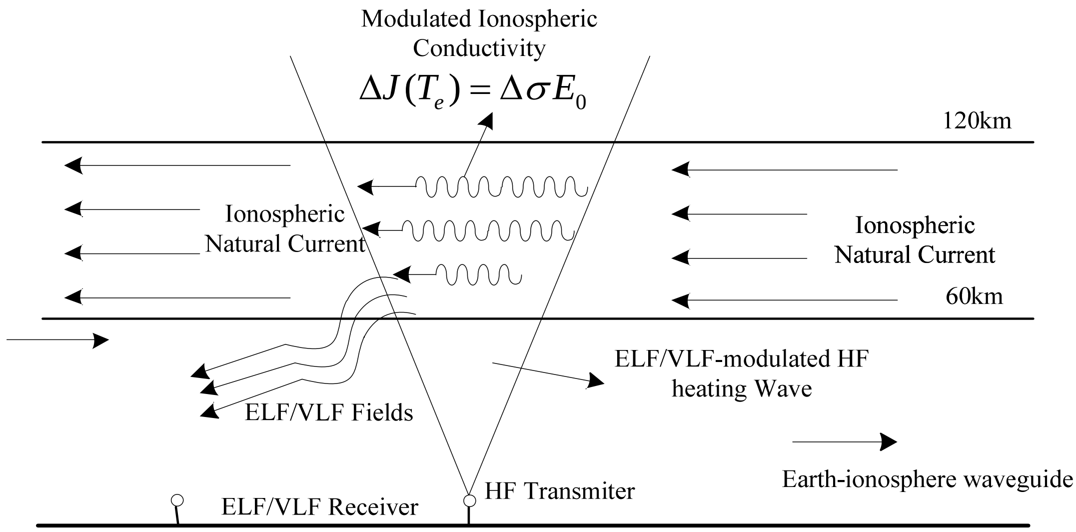

Figure 1. Cartoon depicting ELF/VLF waves generated via modulated ionospheric heating

Current modulation theory is the basis of ELF generated by periodic heating of ionosphere by high frequency waves. In the process of high frequency heating, the electron temperature distribution is controlled by the ionospheric energy balance equation, ignoring the influence of electron thermal conductivity and plasma transport. The energy balance equation is:

$$\frac{3}{2}N_e k_B \frac{dT_e}{dt} = 2k\chi(T_e)S - L\left(T_e, T_0\right) \tag{1}$$

Where, k_B, N_e, T_e and k are the Boltzmann's constant, the electron density, the heated electron temperature and the wave number respectively. S is the high frequency power density. χ is the imaginary part of the refractive index, calculated by the Appleton-Hartree equation, and L is the rate of electron energy loss, which is a function of the ambient electron temperature T_0 [4] and T_e. In [5], the formula of AM heating the low ionosphere were given.

2.2. Chirp-BOK Waveform Modulation Method

The square wave amplitude modulation efficiency of heating ionosphere is the highest, and the square wave amplitude modulation and power modulation functions are as follows:

$$\begin{aligned} M_r(t) = A_r(t) &= \frac{1}{2}\sum_n P_{T/2}(t - \frac{T}{2} - nT_1) \\ &= \frac{1}{2}[1 + 2\sum_{k=1} sinc(\frac{k\pi}{2})cosk\omega_1 t] \end{aligned} \tag{2}$$

Where $P_a(x)=1$ for $|x|<a$ and 0 for $|x|>a$ is square pulse function, T_1 is the period of modulation, $\omega_1 = 2\pi / T_1$. Combining the Chirp modulation technology with square wave AM, ionospheric heating adopts Chirp-BOK waveform modulation, and its amplitude and power modulation functions are as follows:

$$\begin{aligned} M_r(t) &= A_r(t) \\ &= \frac{1}{2}[1+2\sum_{k=1} sinc(\frac{k\pi}{2})\cos k(\omega_1 t+\pi\mu t^2)] \end{aligned} \tag{3}$$

Where, ω_1 is the center frequency of the signal, μ is the rate of the linear frequency. The bandwidth of chirp signal is $B=|\mu|t$. If the symbol time T_1 is fixed, the bandwidth increases with the increase of μ. As shown in Eq.(3), when $\mu>0$, the signal of chirp is up-chirp, and when $\mu<0$, the signal of chirp is down-chirp. Due to the up-chirp and the down-chirp have good autocorrelation and cross-correlation, we can use up-chirp and the down-chirp to transmit information. The symbol '0' and '1' are denoted by up-chirp and down-chirp respectively, and the two signals are given as follows:

$$\begin{cases} S_0(t)=\frac{1}{2}[1+2\sum_{k=1} sinc(\frac{k\pi}{2})\cos k(\omega_1 t+\pi\mu t^2)], -\frac{T_1}{2}<t<\frac{T_1}{2} \\ S_1(t)=\frac{1}{2}[1+2\sum_{k=1} sinc(\frac{k\pi}{2})\cos k(\omega_1 t-\pi\mu t^2)], \frac{T_1}{2}<t<\frac{T_1}{2} \end{cases} \tag{4}$$

3. Numerical Analysis

3.1. Feasibility Test

The background of simulation was at local time 12:00 on 15 August 2016 at Nanjing, China($31.1°N$, $118.2°E$). Frequency of pump wave: 6MHz; ERP: 200MW; Modulation scheme: Chirp-BOK. Direction of high frequency heating beam: vertical; As shown in Fig.2, the chirp square wave AM is used to heat the ionosphere, and the electron temperature varies with time at an altitude of 75 km.

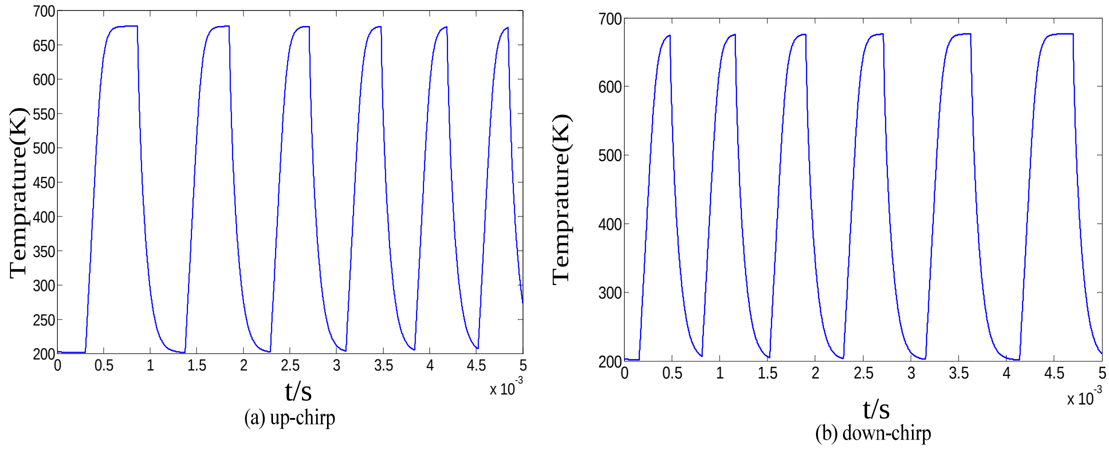

Figure 2. Electron temperature variations with time (75km height)

As can be seen from Fig.2, electron temperature frequency has the obvious frequency modulation characteristics, so does the Pedersen and Hall conductivity variations. The change of Pedersen and Hall conductivity with time at an altitude of 75 km is shown in Fig.3. The ionospheric electronic temperature rises from about 200K to 680K, with a change of about 480K. The Periodic perturbations of the electron temperature and Pedersen and Hall conductivity cause periodic perturbations of ionospheric currents. Then, ELF signals are obtained through Chirp-BOK ionospheric heating, and the up-chirp (symbol ’0’) and down-chirp (symbol ’1’) ELF/VLF signals are transmitted for practical communication.

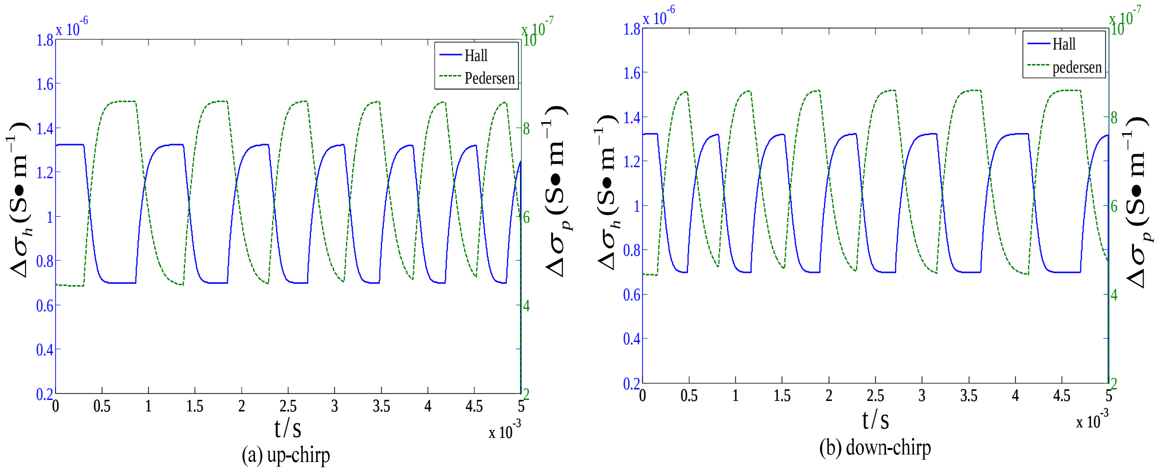

Figure 3. Pedersen and Hall conductivity variations with time (75km height)

3.2. *BER Analysis*

Broadband ELF channel noise is similar to gaussian noise, and the ELF band is often subject to power frequency harmonic interference, so the performance of QPSK, MSK and chirp-BOK under gaussian noise and harmonic interference are compared respectively. The simulation results are shown in Fig. 4.

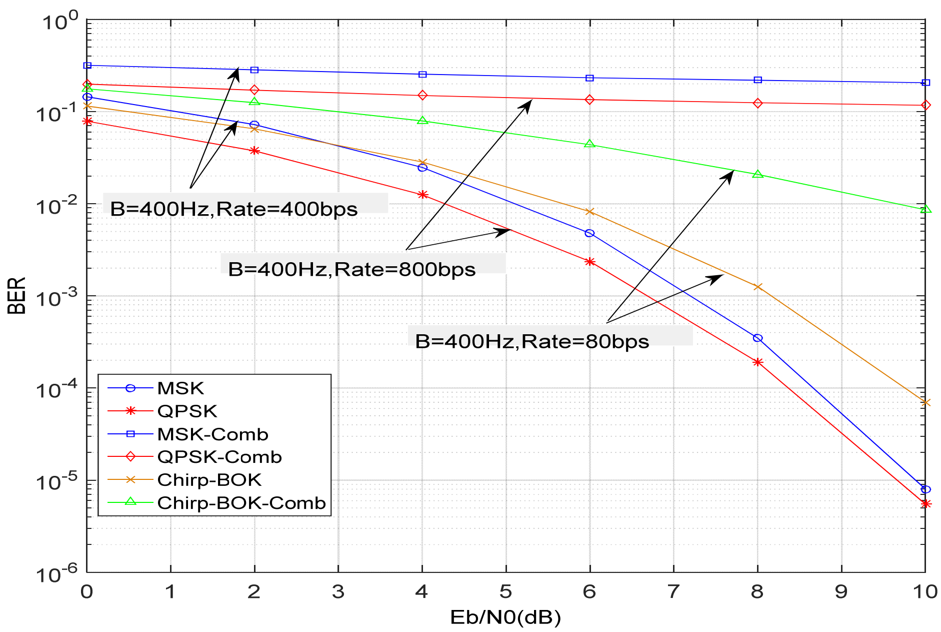

Figure 4. BER performance under gaussian noise and harmonic interference

It can be seen from the figure that MSK and QPSK are very sensitive to harmonic interference, and when using comb filter to filter the harmonic interference with bandwidth of 3Hz, the performance deteriorates sharply, while Chirp-BOK has the best BER performance under harmonic interference

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4. Conclusion

If the ionosphere is periodically heated by high frequency high-energy waves, the temperature and current of the ionosphere will oscillate periodically and emit ELF/VLF waves. The up-chirp (symbol "0") and the down-chirp (symbol "1") modulation waveforms are designed and verified respectively with the ionospheric heating model. In this paper, the proposed Chirp-BOK modulation scheme can be used in ionospheric heating to generate ELF waves. Due to the use of chirp signal, Chirp-BOK has a high time-bandwidth product, so it has a strong anti-interference ability. Compared with QPSK and MSK, Chirp-BOK has better anti-interference performance under harmonic interference.

5. References

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