SSB SIGNALS WITH CONTROLLED PILOT LEVEL

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An approach to the formation of single-sideband modulation signals based on quadrature synthesis is considered. The relevance of the use of single-sideband modulation signals for decameter radio communication systems is demonstrated. The analytical generality of the signals of amplitude and single-sideband modulation is shown in the transition to the analytical form of their representation. An analysis of the known methods for generating signals of single-sideband modulation with a suppressed carrier has been carried out. Their advantages and disadvantages are shown. The structural commonality of amplitude modulation signals and single-sideband modulation signals with a preserved carrier wave is demonstrated. The introduction of an additional parameter is justified, which makes it possible to adjust the level of the stored pilot signal in single-sideband modulation signals. The developed analytical model of the single-sideband modulation signal is presented, in which, unlike the known models, the pilot signal level can be adjusted at the stage of its formation. The results obtained open up new possibilities for redistributing the output power between the pilot signal and sideband information components depending on the level of interference in the channel. It is shown that the developed approach based on quadrature synthesis makes it possible to form single-sideband modulation signals with a stored pilot signal without additional filtering procedures. The gain in noise immunity of reception during the transition from amplitude modulation to single-sideband is demonstrated. A block diagram of the formation of single-sideband modulation signals with a given pilot signal level has been developed. The results of analytical modeling are demonstrated.

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Introduction

Single-sideband modulation (SSB), in the English version single-sideband modulation (SSB), was developed thanks to the work of J.R. Carson, who received a patent for a signal transmission method with efficient use of the channel spectrum [1]. In the general case, the use of SSB signals allows minimizing the frequency band while maintaining the information transfer rate with respect to amplitude modulation (AM) signals [2, 3]. The theoretical foundations for the synthesis and processing of SSB signals are well developed, which made it possible to obtain their wide practical approbation [4, 5].

Currently, OM signals are mainly used on shortwave communication lines [6, 7], as well as in frequency division multiplexing (FDM) technology [8, 9], in optical and wired communication systems for voice traffic transmission [10, 11]. Since the mid-1950s, single-sideband modulation has been used as the main standard for communication with aircraft in the air.

At the same time, the analysis of publication activity related to the study of SSB technology showed that SSB signals still arouse a certain interest among a wide range of specialists in the field of telecommunications and radio engineering, which indicates the relevance of this direction [12-15].

Given this fact, this article presents the results of the development of a modulator that allows you to adjust the level of the carrier wave. This technology is called single-sideband suppressed-carrier modulation (SSB-SC).

Theoretical foundations of the synthesis of SSB signals

In analog systems, SSB signals were formed by filtering the AM signal spectrum, which resulted in complete suppression of the upper or lower sideband [16]. However, this approach is quite difficult to physically implement, since it requires a filter with a rather narrow transition band and a very low level of side lobes [17, 18].

Currently, the synthesis of SSB signals is carried out in accordance with the concept of transition to the analytical form of representation of the processed signal [19, 20]. It should be noted that the procedures for generating SSB signals are based on the technology of quadrature synthesis of amplitude modulation signals [3, 4].

$$s_{AM}(t) = [1 + m_{AM} s(t)]\cos(\omega_0 t) + [1 + m_{AM} s(t)]\sin(\omega_0 t) \quad (1)$$

where m_{AM} – amplitude modulation index; $s(t)$ – modulating signal; $\omega_0 = 2\pi f_0$; f_0 – carrier frequency.

In the interests of substantiating this thesis, let us consider the synthesis of an SSB signal modulated by a low-frequency harmonic.

In the general case, they can be considered as a special case in which, instead of addition, the quadrature components are subtracted

$$s_{SSB}(t) = s(t)\cos(\omega_0 t) - s^*(t)\sin(\omega_0 t), \quad (2)$$

where $s(t)$ – modulating signal; * – Hilbert complex conjugation sign; $\omega_0 = 2\pi f_0$; f_0 – carrier frequency.

The use of the complex conjugation procedure in expression (1) provides a transition to the analytical form of the signal representation $s_a(t)$, according to which in the resulting spectrum $S_a(f)$ only positive components are observed

$$S_a(f) = \begin{cases} 2S(f), & f > 0; \\ S(f), & f = 0; \\ 0, & f < 0, \end{cases} \quad (3)$$

where $S_a(f)$ and $S(f)$ – respectively, the spectral representations of the signals $s_a(t)$ and $s(t)$, obtained as a result of the Fourier transform.

Considering that the spectrum of the analytical signal contains only positive components, then, accordingly, the Fourier transform of the shift function $S_a(f - f_0)$ will contain only one of the frequency bands (components in the harmonic oscillation) of the spectrum $S(f)$ [21, 22].

$$s_{SSB}(t) + js^*_{SSB}(t) = \Phi^{-1}\{S_a(f - f_0)\} = s_a(t)\exp(j2\pi f_0 t). \quad (4)$$

In the formula (4) Φ^{-1} – inverse Fourier transform procedure; j – imaginary unit sign [23].

For a detailed disclosure of the essence of the considered procedures, in fig. 1 shows a temporal representation of AM signals (AM signal received at $m_{AM} = 1$) and SSB signal modulated by low-frequency harmonics.

The legitimacy of the procedures defined by formula (4) is confirmed by the following transformations.

$$\begin{aligned} s_{SSB}(t) &= \mathrm{Re}\{s_a(t)\exp(j2\pi f_0 t)\} = \\ &= \mathrm{Re}\{[s(t) + js^*(t)][\cos(2\pi f_0 t) + j\sin(2\pi f_0 t)\} = \\ &= s(t)\cos(2\pi f_0 t) - s^*(t)\sin(2\pi f_0 t). \end{aligned} \quad (5)$$

Fig. 1. Time representation of AM $s_{AM}(t)$ and SSB $s_{SSB}(t)$ signals

And in figure 2 – modules of their spectral representations $S_{AM}(f)$ and $S_{SSB}(f)$.

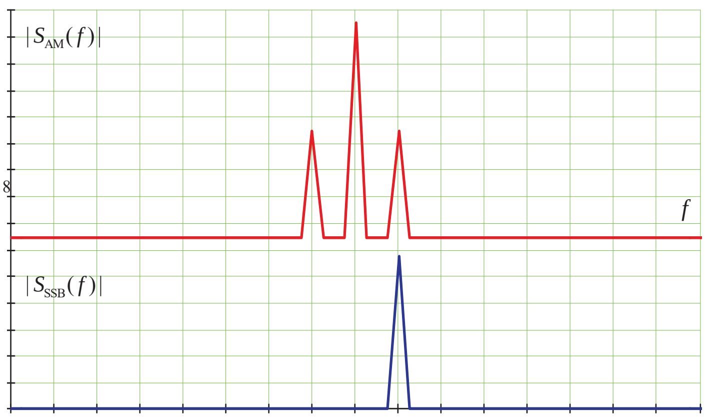

Fig. 2. Spectral representation of AM $s_{AM}(t)$ and SSB $s_{SSB}(t)$ signals

It should be noted that, with the initial energy being equal, the AM and SSB signals, as well as their spectral representations, have a rather different structure. Thus, the limits of change in the amplitude of the AM signal are almost three times higher than those for the SSB signal. At the same time, the energy of the spectral component of the SSB signal is twice the energy of one of the side bands of the AM signal.

For a more detailed understanding of the features of the spectral representation of the SSB signal, consider its synthesis when using as a modulating signal s(t) a low-frequency harmonic oscillation with a zero value of the initial phase $s(t) = A\cos(\Omega t)$, where A is the oscillation amplitude. Then, substituting this value into formula (2), and assuming that the amplitude of the carrier oscillation is equal to U_0, and $s^*(t) = A\sin(\Omega t)$, we obtain, taking into account the well-known trigonometric transformation $\cos(\alpha+\beta) = \cos\alpha\cos\beta - \sin\alpha\sin\beta$

$$\begin{aligned} s_{SSB}(t) &= s(t)\cos(\omega_0 t) - s^*(t)\sin(\omega_0 t) = \\ &= A\cos(\Omega t)U_0\cos(\omega_0 t) - A\sin(\Omega t)U_0\sin(\omega_0 t) = \\ &= AU_0\cos([\omega_0 + \Omega]t). \end{aligned} \quad (6)$$

According to expression (6), the resulting SSB signal contains only one cosine component with a frequency equal to the sum of the frequencies of the modulating and modulated oscillations, and an amplitude equal to the product of the amplitudes of the modulating and modulated oscillations, which is confirmed by the result shown in figure 2.

It should be noted that the presented results are aimed at synthesizing the OM signal with the upper sideband.

Synthesis of an OM signal with a lower sideband is possible upon transition to a modulating oscillation of the form $s(t) = A\sin(\Omega t)$ and correspondingly, $s^*(t) = A\cos(\Omega t)$. Then, using the trigonometric transformation of the form $\cos(\alpha - \beta + \pi/2) = \sin\alpha\cos\beta - \cos\alpha\sin\beta$.

Suppressed carrier signals

At the same time, despite the obvious simplicity of implementing the considered approach, OM signals have not been widely used due to the fact that the reception of such signals is associated with certain difficulties. So, in order to ensure the transmission of messages without distortion, the receiver must be accurately tuned to the frequency of the transmitter. However, due to the instability of reference oscillators and channel distortions, this is actually an unsolvable problem [24, 25]. As a result, OM-based transmissions can sound very unnatural with poor intelligibility.

To reduce the negative consequences of this effect, in practice, OM signals with a partially retained (suppressed) carrier (SSB-SC) are used [26]. The presence of a carrier oscillation provides at the reception the possibility of frequency adjustment of the reference oscillator of the receiver. At its core, SSB-SC transmissions are similar to AM transmissions, but use a frequency band that is twice as narrow. Therefore, the mode of operation with a full or partially suppressed carrier is called the amplitude modulation equivalent (AME) mode [27].

Technologically, the AME mode is not efficient, although its use just makes it possible to maintain the required quality and high speech intelligibility, since its implementation leads to harmonic distortions that can reach a value of the order of 25% [16], and the resulting intermodulation distortions are much higher than in traditional modes with AM.

In theory and practice, two transmission methods are widely used.

The first method is based on the joint use of amplitude and phase modulation, called compatible single sideband (CSSB) [27]. This approach provides for the presence of a phase converter with a highly stable phase response at all passband frequencies. The disadvantage of such a system is the high level of second-order intermodulation components, which, with a modulation index $m_{AM} < 100\%$, the fight against which leads to asymmetry of the sideband structure. As a result of the resulting asymmetry, the signal is shifted and its spectrum occupies only about half of the usual frequency band. This leads to the fact that during speech transmission, the high-frequency components of the spectrum in the 3 kHz band are suppressed by almost 20 dB in relation to the low-frequency ones.

Another feature of this method is that a logarithmic function is used for phase modulation, the nature of which depends significantly on the carrier level. Therefore, with a very small modulation index, the CSSB signal becomes close in structure to the SSB signals, which leads to loss of synchronization at the reception.

The second method was developed by Leonard R. Kahn [26], who suggested using pre-distortion procedures in order to reduce the level of second-order intermodulation components. To do this, he proposed a modulator based on arcsin functions. But such an implementation is quite technically complicated, since in order to generate an accurate arcsin waveform, it is necessary to use multiple feedback loops in both the modulator when the signal is generated, and in the demodulator when it is received. Despite this, this technology has been developed as the STR-84 method [27].

At the same time, the analysis of expression (1) suggests that the change of sign, similarly in expression (2), will lead to the synthesis of the signal

$$s_{SSBC}(t) = [1 + m_{AM}s(t)]\cos(\omega_0 t) + [1 + m_{AM}s^*(t)]\sin(\omega_0 t). \quad (7)$$

On figure 3 shows diagrams of the AM signal and the SSBC signal synthesized in accordance with formula (7), which we define as a single-sideband modulation signal with a carrier (CSSB).

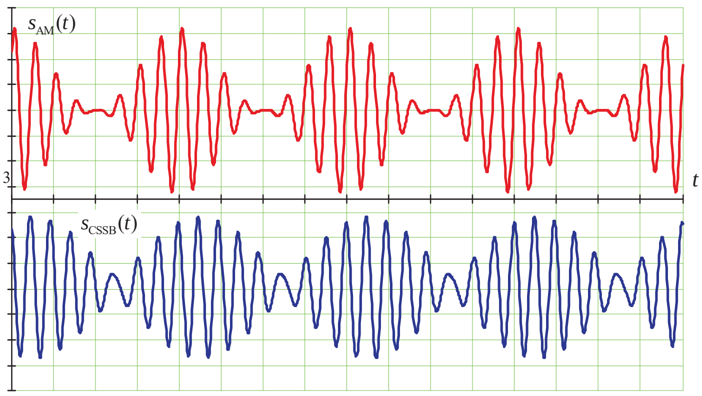

Fig. 3. Time representation of AM $s_{AM}(t)$ and SSBC $s_{CSSB}(t)$ signals

Analysis of the results presented in fig. 3 shows that externally the AM and CSSB signals have a similar structure. But if the AM signal has a phase inversion when the modulating signal changes, then the CSSB signals do not have a phase break. On figure 4 – modules of their spectral representations $S_{AM}(f)$ и $S_{CSSB}(f)$.

The signal $s_{SSBC}(t)$, judging by the results of Fig. 5 has a pronounced unsuppressed carrier, which in its structure fully corresponds to the carrier of the AM signal.

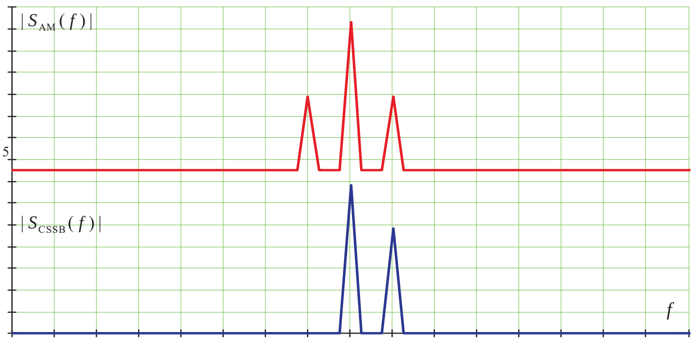

Fig. 4. Spectral representation of AM $s_{AM}(t)$ and SSBC $s_{CSSB}(t)$ signals

Obviously, the presence of a powerful carrier significantly reduces the noise immunity of reception. Therefore, it is necessary to search for the possibility of controlling its energy parameters. The conducted studies have shown that the desired effect can be achieved by introducing an additional m_{SSB} parameter. As a result of its introduction, expression (7) is transformed to the form

$$s_{SSBC}(t)=[m_{SSB}+m_{AM}s(t)]\cos(\omega_0 t)+[m_{SSB}+m_{AM}s^*(t)]\sin(\omega_0 t). \quad (8)$$

The control of the m_{SSB} parameter allows, while maintaining the energy allocated to the sideband, to control the level of the carrier wave. Given that

$$m_{SSB}\in[0;1] \quad (9)$$

The signal synthesized by formula (8) is defined as a single-sideband signal with an adjustable pilot signal level (SSBC). Carrier level control is provided from zero, at $m_{SSB}=0$, to its maximum value, at $m_{SSB}=1$. As an example, in fig. 5 and 6 show the temporal and spectral representations of the $s_{SSBC}(t)$ signal at $m_{SSB}=0.5$ against the background of $s_{CSSB}(t)$ signal at $m_{SSB}=1$.

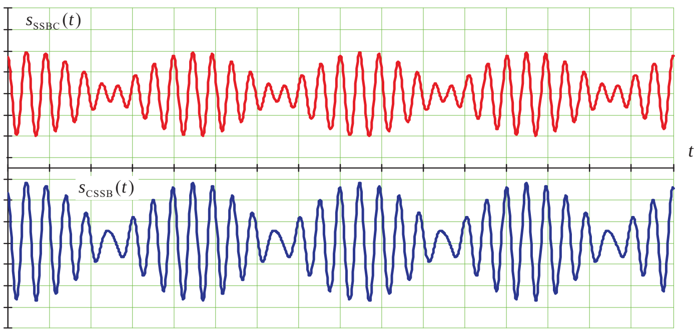

Fig. 5. Time representation of SSBC $s_{SSBC}(t)$ and CSSB $s_{CSSB}(t)$ signals

An analysis of the time representation diagrams shows that a decrease in the m_{SSB} value does not lead to a redistribution of the total signal energy between the side component and the carrier wave. Due to quadrature synthesis, the energy of the in-phase and quadrature components is mutually compensated. And when $m_{SSB}=0$, the signal $s_{SSBC}(t)$ will degenerate into the signal $s_{SSB}(t)$. On fig. 6 shows the spectra of the $s_{SSBC}(t)$ signals at $m_{SSB}=1$ and $m_{SSB}=0.5$, where a decrease in the energy of the carrier vibration is demonstrated while the side component is retained.

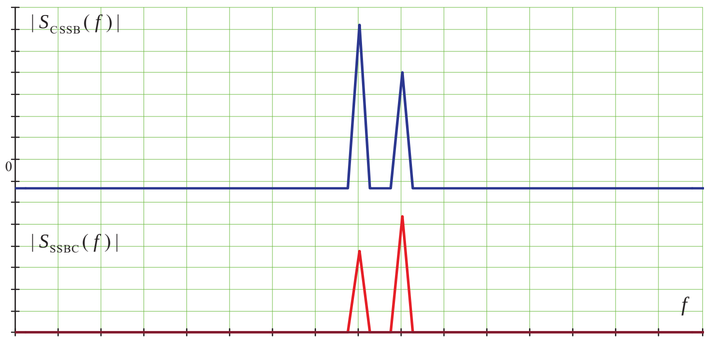

Fig. 6. Spectral representation of SSB $s_{CSSB}(t)$ and SSBC $s_{SSBC}(t)$ signals

SSBC and SSB signals modulator

From the standpoint of the methodology of quadrature synthesis, the modulator of SSB signals generated in accordance with formula (2) can be represented as a block diagram in Figure 7.

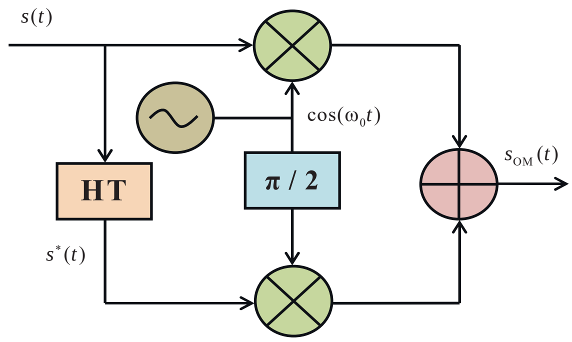

Fig. 7. Block diagram of the SSB signal modulator $s_{SSB}(t)$

In accordance with the presented structure, the basis of the modulator is the Hilbert Transformer (HT), which provides the formation of the complex conjugate form $s^*(t)$ of the modulating signal $s(t)$. The quality of the SSB signal depends on the conversion to HT. The OM modulator itself is built according to the classical technology of quadrature synthesis [28, 29].

Given that the structure of the SSB modulator is determined by an analytical expression, it is proposed, taking formula (8) as a basis, to represent the SSBC modulator in the following form, see Figure 8.

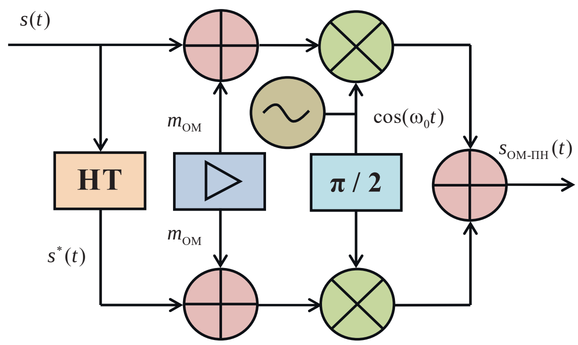

Fig. 8. Block diagram of the SSBC signal modulator $s_{SSBC}(t)$

A distinctive feature of the structure of the SSBC modulator is the use of additional adders in the signal paths $s(t)$ and $s^*(t)$ to the second inputs of which the voltage of the DC voltage amplifier is applied, which ensures the formation of a level corresponding to a given value m_{SSB}. Shown in Fig. 8, the modulator generates *SSBC* signals at a value of $m_{AM} = 1$.

Noise immunity of SSBC signals reception

To assess the noise immunity of SSB signals, as a rule, a generalized gain indicator B is used, which characterizes the ratio of signal power to interference power at the output and input of the demodulator. Such an approach, in particular, was used in [16, 30] when evaluating analog signals.

Thus, for AM signal receivers, the generalized gain is defined as

$$B_{AM} = \frac{U_0^2 \Delta F_{in} \upsilon^2}{\upsilon_0^2 \Delta F_{out} (1+\Pi^2)} \approx \frac{1}{(1+\Pi^2)}, \qquad (10)$$

where υ^2 and υ_0^2 are the interference power at the output and input of the receiver; P is the crest factor of the signal; ΔF_{in} and ΔF_{out} are the bandwidth at the input and output of the receiver; U_0 is the carrier frequency voltage amplitude.

Accordingly, for receivers of SSB signals, the generalized gain will be equal to

$$B_{SSB} = \frac{\Delta F_{out} \upsilon^2}{\upsilon_0^2 \Delta F_{in}}. \qquad (11)$$

Since the ratio of the bandwidths at the input and output of the receiver is preserved for the SSB signal, then with the Gaussian nature of the noise, when the identity $\upsilon^2 = \upsilon_0^2$ is satisfied, the generalized gain will be equal to 1.

At the same time, taking into account the fact that the peak factor of speech is approximately equal to $\Pi \approx 3.3 ... 3.9$ [30], we get that $B_{SSB} \approx 0.084 ... 0.062$. That is, the noise immunity of SSB signal reception is 12 to 16 times higher in relation to the noise immunity of AM signal reception.

Conclusion

The study showed that the further development of technologies for generating SSB signals based on quadrature synthesis opens up new opportunities for their application in software and hardware systems and radio communication complexes.

According to the authors, the capabilities of the proposed SSBC modulator will be revealed to the greatest extent when it is used in decameter radio communication lines, which are characterized by fading.

The authors associate further research with the evaluation of the noise immunity of receiving SSBC signals.

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ОДНОПОЛОСНО МОДУЛИРОВАННЫЙ СИГНАЛ С КОНТРОЛИРОВАННЫМ УРОВНЕМ ОСТАТКА НЕСУЩЕЙ

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Аннотация

Рассмотрен подход к формированию сигналов однополосной модуляции, основанный на квадратурном синтезе. Показана актуальность использования сигналов однополосной модуляции для декаметровых систем радиосвязи. Аналитическая общность сигналов амплитудной и однополосной модуляции проявляется при переходе к аналитической форме их представления. Проведен анализ известных способов формирования сигналов однополосной модуляции с подавленной несущей. Показаны их преимущества и недостатки. Показана структурная общность сигналов амплитудной модуляции и сигналов однополосной модуляции с сохраненной несущей. Обосновано введение дополнительного параметра, позволяющего регулировать уровень сохраняемого пилот-сигнала в сигналах однополосной модуляции. Представлена разработанная аналитическая модель сигнала однополосной модуляции, в которой, в отличие от известных моделей, уровень пилот-сигнала может регулироваться на этапе его формирования. Полученные результаты открывают новые возможности для перераспределения выходной мощности между пилот-сигналом и информационными компонентами боковой полосы в зависимости от уровня помех в канале. Показано, что разработанный подход на основе квадратурного синтеза позволяет формировать сигналы однополосной модуляции с сохраненным пилот-сигналом без дополнительных процедур фильтрации. Продемонстрирован выигрыш в помехоустойчивости приема при переходе от амплитудной модуляции к однополосной. Разработана структурная схема формирования сигналов однополосной модуляции с заданным уровнем пилот-сигнала. Демонстрируются результаты аналитического моделирования.

Ключевые слова: *однополосная модуляция, регулируемый уровень пилот-сигнала, синтез сигнала однополосной модуляции, помехоустойчивость приема сигналов однополосной модуляции.*

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