FREQUENCY STABILITY

In the modulation system which has been described in this paper, three separate quartz-controlled oscillators were employed. The over-all frequency stability obtainable in this way will now be discussed.

The maximum over-all frequency departure contains the effects of deviations in all three oscillator frequencies. If f_1, f_2, and f_3 are the conversion frequencies obtained from the three oscillators, and t_1, t_2 and t_3 are the tolerance factors of the quartz plates of the three oscillators, then the maximum frequency departure of the output carrier is

$$\text{max frequency departure} = \frac{t_1 f_1 + t_2 f_2 + t_3 f_3}{\text{output carrier freq}}.$$

Studies have shown that this departure figure is greatest at the lowest transmitted carrier frequency. Assuming $f_1 = 100$ kc, $f_2 = 2.7$ mc, and $f_3 = 6.8$ mc, while $t_1 = 0.007$ per cent, $t_2 = 0.001$ per cent and $t_3 = 0.001$ per cent, and letting the final carrier frequency be 4 mc, we find that

$$\text{max departure} = \frac{7 + 27 + 68}{4 \times 10^6} = 25.5 \times 10^{-6}$$

or

$$= 0.00255 \text{ per cent.}$$

Obviously, it is the high-frequency oscillator whose stability is the most important because it contributes most of the departure. The improvement to be gained by greater stability of the first oscillator is small.

CONCLUSION

It can be seen from the foregoing discussion that the design of single-sideband generators involves a great many considerations. The existing practices and the receivers in the field must be considered. The availability of component parts and the economic factors in the design of such things as varistors, filters, and transformers affect the choice of circuits and the details of fitting them into a system. Experience over many years, by a great number of people, has had immeasurable influence on the present art. The author wishes to express his appreciation to numerous colleagues who have contributed to the collection of ideas presented here.

Single-Sideband Transmission by Envelope Elimination and Restoration[*]

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Summary—**A new type of single-sideband transmitter is described which does not require the use of linear radio-frequency amplifiers. Amplification is accomplished by a process in which the phase-modulation component of the single-sideband wave is amplified by means of Class-C amplifiers, and the amplitude envelope is restored at the final amplifier. Experimental results show performance equal to or better than conventional linear radio-frequency amplifier practices. The over-all efficiency is approximately the same as that of a double-sideband amplitude-modulated transmitter. This system is especially suitable for high-power operation.**

INTRODUCTION

THIS PAPER DISCUSSES a new method of amplifying single-sideband signals and other forms of hybrid modulated waves.[1] The power and spectrum efficiency of single-sideband transmission is well known, and the reader has many fine papers[2,3] at his disposal. The main problem associated with single-sideband operation is the complexity and cost of the equipment involved.

The conventional system generates the desired single-sideband wave at very low power levels (a few watts) and amplifies this wave in a series of cascaded linear rf amplifiers. Linear rf amplifiers have comparatively low efficiency and are critical in adjustment. Due to their low efficiency, the cost of these transmitters is quite high.

Another characteristic of the conventional system is that each additional amplifier introduces its own distortion and attendant spurious output. Therefore, the higher the power output desired, the more difficult it is to maintain low spurious output.

There have been a few alternate systems proposed[4,5] which do not require linear radio-frequency amplifiers. These systems, however, require wide-band phase-rotation networks. The system to be proposed is a different approach to the problem.

The advantages of the proposed system are:

(a) High efficiency is obtained (comparable with standard double-sideband amplitude-modulation transmitters).
(b) Conventional telephone transmitters can be used for single-sideband operation. Auxiliary equipment and its installation are relatively inexpensive.
(c) Distortion and its accompanying spurious fre-

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[†] Crosby Laboratories, Inc., Mineola, N. Y.

[1] A hybrid modulated wave has both amplitude and angular velocity modulation components. Examples of hybrid modulated waves are: carrier-suppressed-double-sideband, single-sideband, vestigial sideband, and quadrature-modulated.

[2] A. H. Reeves, "Single-sideband system applied to short wave telephone links," *Jour. IEE* (London), vol. 73, pp. 245–279; September, 1933.

[3] F. A Polkinghorn and N. F. Schlaack, "A single-sideband short wave system for transatlantic telephony," PROC. I.R.E., vol. 23, pp. 701–718; July, 1935.

[4] E. S. Purington, U. S. Patent No. 1,994,048; filed September 6, 1930.

[5] O. G. Villard, Jr., "Composite amplitude and phase modulation," *Electronics*, vol. 21, pp. 86–89; November, 1948.

quency generation is independent of the transmitted power level. This is so because linear radio-frequency amplifiers are not required; therefore, the difficulty of maintaining low spurious output is not multiplied by each additional stage.

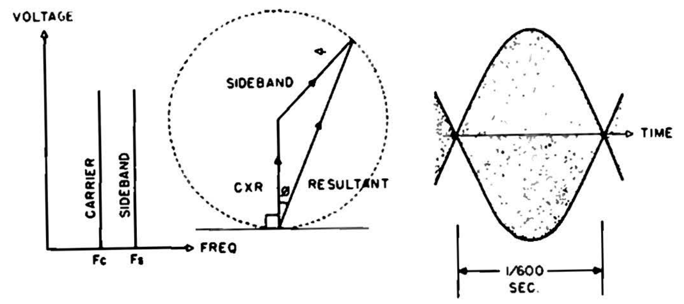
Before describing the new system, it may prove helpful to examine the structure of a single-sideband wave as shown on Fig. 1.

Fig. 1(a) shows a spectrum figure of a single-sideband wave having equal carrier and sideband amplitudes. The upper sideband is shown selected in this figure and it represents a signal frequency of 600 cycles.

Fig. 1(b) is the vector representation of the single-sideband wave shown in Fig. 1(a). The carrier frequency is the reference vector. The sideband revolves past the reference vector at a velocity equal to the tonal frequency of the signal. The resultant of the two frequency components varies both in amplitude and angular velocity. *Therefore, a single-sideband wave has both amplitude- and phase-modulation components.*

Fig. 1(c) shows the amplitude-modulation envelope of the wave. This envelope is identical with the wave shape derived from a full-wave resistance-loaded rectifier when fed a sine wave.

Figs. 1(a), 1(b), and 1(c) would also be obtained if a suppressed carrier single-sideband signal, modulated by two equal tones, was considered.



(a) (b) (c)

Fig. 1—(a) Spectrum diagram of single-sideband wave. (b) Revolving vector representation of single-sideband wave. (c) Envelope waveform of single-sideband wave.

BASIC CONCEPTS OF SYSTEM

The steps of the proposed system are:

(a) A portion of the single-sideband wave to be amplified is limited, thereby producing a pure phase-modulation signal.

(b) This phase-modulated wave is amplified to the desired output level by efficient, noncritical Class-C amplifiers.

(c) A portion of the original single-sideband wave amplitude envelope is detected and the resultant audio-frequency wave is amplified.

(d) The amplified detected, amplitude-modulated component remodulates the amplified phase-modulation component, resulting in an amplified copy of the original single-sideband wave.

Fig. 2 is a simplified block diagram which will be used to describe the fundamentals of this system. Waveforms at various points in the diagram are given in order to make this explanation more easily understood. Let us consider the case where two equal amplitude tones are fed to the input of the "single-sideband generator"[6] and the carrier is suppressed. The "single-sideband generator" produces a low-power (a few watts), single-sideband signal identical with the wave shown in Figs. 1(a), 1(b), and 1(c). This signal is represented at point *a* by a wave shape having an envelope corresponding to a full-wave rectified sine wave. This low-power single-sideband signal is fed to the "limiter." The "limiter" removes the amplitude-modulation component from the wave, so that the output is a pure phase-modulated wave. This phase-modulated signal can be conveniently amplified by the highly efficient "class-C amplifier." The "class-C amplifier" provides the phase-modulated driving power for the "modulated stage."

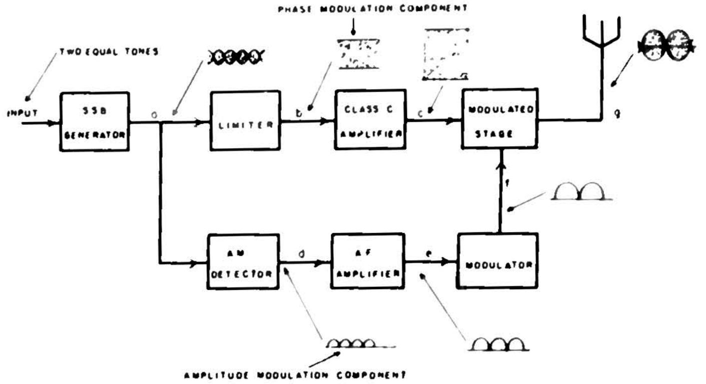


Fig. 2—Simplified block diagram of system.

The amplitude-modulation component is detected and isolated from the phase-modulation component by the "AM detector." The output of the "AM detector" corresponds to the envelope wave shape of the single-sideband wave at point *a*; therefore, the wave shape at point *d* is the same as a full-wave rectified sine wave. This audio-frequency wave is amplified by the "af amplifier." The "modulator" modulates the phase-modulated signal in the "modulated stage." Hence, the envelope wave shape of the signal at point *g* is the same as the envelope wave shape at point *a*. Furthermore, the phase-modulation component at point *g* is identical with the phase-modulation component at point *a*. If time relationships between the phase- and amplitude-modulation components are properly maintained, the signal at point *g* will be a pure, high-power, single-sideband wave.

PRACTICAL EMBODIMENT OF SYSTEM

Fig. 3 shows a possible working system. The additional blocks indicate circuitry required to produce a practical system from the theoretical system in Fig. 2.

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[6] The following phrases in quotes refer to blocks of the referenced diagram.

The blocks marked "xtal osc" and "mixer" are used to change the frequency of the "ssb generator" into any required output frequency. Mixers should be carefully designed to maintain low intermodulation distortion.

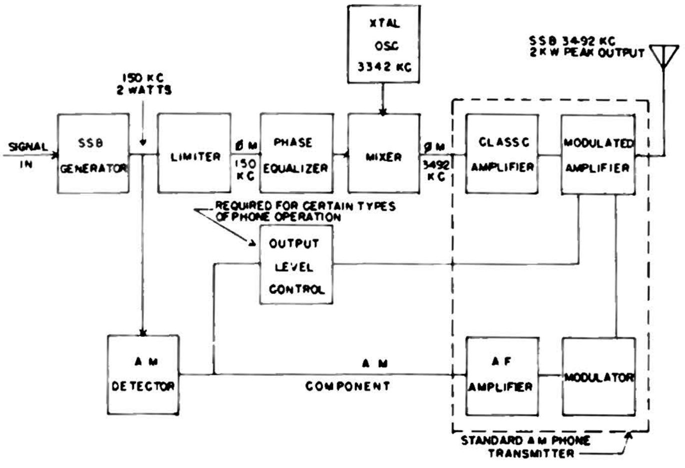

Fig. 3—Practical block diagram of system.

The "phase equalizer" is required to equalize the time delay between the phase-modulation channel and the amplitude-modulation channel. When the "phase equalizer" is correctly adjusted, the amplitude-modulation and the phase-modulation components retain the original phase relationship of the single-sideband wave.

The "output level control" is required in transmitting variable average amplitude signals. Since frequency-shifted, frequency-division multiplex signals are of constant amplitude, the "output level-control" circuit is not required. However, voice waves are not of constant average amplitude and the "output level control" will be required in this form of transmission. The "output level control" may be a series of dc amplifiers which control one of the electrode voltages of the "modulated stage."

There is, however, a different approach to this variable average amplitude problem which does not require the "output level control." This system would transform a single-sideband voice wave into a constant average amplitude wave, by varying the amount of suppression of the carrier. During silent periods the transmitter would produce large carrier levels. A squelch-operated carrier channel could be used in the receiving system to take advantage of these large-carrier level periods. In this manner, improved afc and avc operation may be obtained, and the entire receiver can be made less susceptible to jamming and other forms of interference.

MODULATOR REQUIREMENTS

In order to maintain good spurious-radiation suppression, it is necessary that the "modulator" used have certain qualities. The appendix shows a method for determining the modulator requirements. Two answers to the problem are: For 35 db or more spurious-radiation suppression, the modulator must have sufficient high-frequency response to amplify the third harmonic of the difference between the highest-frequency and lowest-frequency appreciable energy signals; for 25-db spurious-output suppression, only the second harmonic is required.

EXPERIMENTAL RESULTS

The quality of a single-sideband signal is dependent upon the amount of spurious output. The specification which is used by many companies is based on the amplitude of the third-order intermodulation distortion component. The ordinary test procedure is to feed two equal amplitude test tones into the transmitter, and then measure the amplitude of the spurious component $2f_1-f_2$ (third-order intermodulation product). The amplitude of this spurious component should be at least 25 db below one of the signal tones after the composite signal is detected in a linear detector.

Experiments were conducted at the Rocky Point Transmitter Laboratory, RCA Laboratories Division, with a one-kw telephone transmitter. A 2.5-kw peak-power single-sideband wave was produced utilizing the proposed system. The undesired sideband was reduced to 25 db below the desired test signal. These results meet current industry standards. At times, better than 30 db of spurious-radiation suppression were measured; and it appears that by careful design 35 db can be obtained. No negative feedback was used in these tests, and further improvement is possible by adding this expedient.

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APPENDIX

This analysis will attempt to answer the following questions: (1) What are the power relationships of the system? (2) What is the frequency response requirement of the modulator for a specified allowable spurious output?

In order to answer these questions, *the severe case of a single-sideband, carrier-suppressed transmitter with two equal amplitude tones applied will be considered.* The analysis will be based upon the fact that the AM envelope of this wave has a full-wave rectified sine-wave form.

Power Relationships

Consider that this two-tone carrier-suppressed single-sideband wave has a peak voltage of $2E$ and that it is applied to a load resistance R. The peak power is $4E^2/R$. Single-sideband transmitters are rated according to their peak-power output.

The power corresponding to average amplitude of the wave is 1.62 E^2/R or $(2/\pi)^2 \times 4E^2/R$. This average value is the same as the amount of dc power obtained from a full-wave rectifier in the analogous case. If the amplitude modulation were removed from the single-sideband wave, this would be the power remaining. Thus, it is the power in the phase-modulation component of the single-sideband wave. *The ratio of peak power to average amplitude power (phase-modulation component) is 4/1.62 or 2.47.* In comparison, a 100-per cent modulated amplitude-modulation wave has a ratio of 4. If a 2-kw peak-power single-sideband signal is desired, the radio-frequency stages of the transmitter must supply 810 watts of phase-modulated power.

The total or effective power is the sum of the power in the phase-modulation and amplitude-modulation components. In the analogous case of a rectified sine wave, the dc power is equivalent to the phase modulation, and the ripple currents represent the amplitude modulation of the single-sideband wave. The effective power is $(0.707)^2 \times 4E^2/R$ or $2E^2/R$ watts. This is the power that a load resistor R would be required to dissipate.

The total or effective power is $2E^2/R$, and the average amplitude derived from the radio-frequency section of the transmitter is 1.62 E^2/R. Therefore, the difference power of 0.38 E^2/R must be supplied by the amplitude modulator. *The ratio of peak power to amplitude-modulation component power is 4/.38 or 10.5.* For a 2-kw peak-power single-sideband transmitter, the modulator must supply 190 watts of power to the output signal.

Modulator Frequency Requirements

To determine approximately the frequency-response requirements of the amplitude modulator, use will be made of the Fourier series expansion of the envelope wave shape of the single-sideband signal. Tabulation will be given of the power in each amplitude-modulation component harmonic. The amount of power in all the higher amplitude-modulation component frequencies that are beyond the response of the modulator will be totalled. Most of this power represents the spurious content of the signal.

If this "above modulator response power" figure is used as a rating of spurious output, an approximate rating on the pessimistic side will be obtained. The rating is pessimistic because a portion of this power is allocated to the desired output component instead of to the spurious output. Furthermore, the amount of "above modulator response power" is divided between a number of spurious components, whereas present ratings specify the power in a single spurious component. The situation is analogous to the measuring of total harmonic distortion when a specification calls for a certain maximum second-harmonic distortion figure.

The following equation is the expansion of the envelope of a two-tone carrier suppressed single-sideband signal:

$$e = 0.636E(1 + 0.667 \cos Wt - 0.133 \cos 2Wt + 0.057 \cos 3Wt - 0.032 \cos 4Wt \cdots),$$

where W is 2π times the difference frequency of the two applied tones.

Realizing that the unit dc term (average amplitude value) is equivalent to the phase-modulation component of the wave, and that the cos Wt term gives the peak value of the fundamental amplitude-modulation component in the above equation, the following table can be constructed (in which a 2-kw peak single-sideband signal is considered).

The first column is a function of the fidelity of the amplitude-modulation path and of the separation of the two tones being transmitted. For example, an amplitude modulator equalized for phase and amplitude up to 15 kc will respond to the fifth harmonic of a 3-kc tone separation.

The second and third columns were calculated by summating the power in the harmonics that were too high in frequency for the modulator to pass. Since most of this "above modulator response power" would have been used to neutralize the spurious signals, it is evident that this column gives the maximum possible total spurious-power output.

Highest Harmonic Modulator Equalized For	Power Due to All Harmonics Above Modulator Response	
	Absolute Power	DB Relative to PM Component
cos $0Wt$ (dc) PM component	190 watts	− 6.3 db
cos Wt	9.16 "	−18.9 "
cos $2Wt$	1.94 "	−26.2 "
cos $3Wt$	0.61 "	−31.2 "
cos $4Wt$	0.20 "	−36.0 "
cos $5Wt$	0.04 "	−42.0 "
cos $6Wt$		

The chart gives a somewhat *pessimistic* figure for spurious amplitude as has been previously pointed out.

Because practical modulators do not faithfully reproduce frequencies up to a certain point and then reject all higher frequencies, it becomes a very difficult problem to determine the spurious content of the signal. If it is necessary to calculate the exact spurious content, the designer must know the phase and amplitude characteristics of the transmitter and associated equalizers. With this information, he can work out graphically or analytically the sideband distribution of the phase-modulation component, and then vectorially add the sideband distribution caused by the reinsertion of the amplitude-modulation component.[6]