Application of a Backward-Wave Amplifier to Microwave Autodyne Reception*

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Summary—**A microwave receiver using a single-circuit backward-wave amplifier as a combination radio-frequency amplifier and homodyne local oscillator is described. The amplifier tube is operated at a value of beam current just above that required to maintain oscillation. It is shown that in this way, the high gain and narrow bandwidth of the single-circuit backward-wave amplifier may be utilized in an electronically tunable microwave receiver. The resultant sensitivity is 10 to 15 db worse than that obtainable from a good superheterodyne. The loss in sensitivity is due entirely to the high noise figure of the backward-wave amplifier, which can theoretically be reduced to a value comparable with that of a superheterodyne. The advantages of the receiver are its simplicity and its lack of image difficulties. Rejection of off-frequency signals is such that they are attenuated by at least 50 db.**

Introduction

In many fields, a microwave spectrum analyzer is desirable which can display a band of frequencies of 25 to 50 per cent while at the same time maintaining a resolution of one in 10,000 or better. The resolution can easily be obtained by using a superheterodyne system, but the wide display bandwidth requires either a high first intermediate frequency or a zero intermediate frequency (homodyne) system in order to avoid images.

In principle the microwave homodyne receiver is simple and straightforward. The image problem inherent in superheterodyne receivers is no longer present. In attempting to build a practical receiver, however, one encounters the following difficulties:

1) The noise output from the mixer, which usually limits the sensitivity of the homodyne, is inversely proportional to frequency in the video range, and so is much larger for homodyne than superheterodyne operation.

2) The noise output of the local oscillator is also concentrated in a narrow spectrum around the oscillator frequency, and may contribute to the overall receiver noise figure.

3) Very high gain broadband video amplifiers are subject to hum, stray pickup, and microphonics, and so must have a limited lower-cutoff frequency.

4) For the video bandwidths usually required, the observable minimum signal for homodyne detection is usually only 20 to 25 db less than that for direct video detection, so that unless some filtering is included ahead of the detector, off-frequency signal rejection is very poor.

* Received by the PGMTT, January 21, 1959.
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Backward-Wave Amplifier Autodyne

It is evident that many of the disadvantages of the homodyne system would be removed by providing a high-gain narrow-band filter ahead of the mixer. This would eliminate the mixer as a source of noise, reduce the effects of local oscillator noise, hum, and microphonics, and improve off-frequency signal rejection. It raises the further problem, however, of keeping the filter and the local oscillator tracking in frequency.

The autodyne detector[1] used in the early days of radio consisted of a triode regenerative amplifier operating just above the oscillation threshold resulting in very high gain and coherent detection for a Morse code CW signal.

In the system to be described, a single-circuit backward-wave amplifier (BWA), which behaves as a high-gain narrow-band electronically-tunable filter, is allowed to oscillate. The filter and the local oscillator, therefore, track automatically in frequency, and can be tuned electronically. As in the conventional triode autodyne detector, simultaneous amplification and oscillation occur in the tube just above starting current. The output of the backward-wave tube is then fed into a crystal detector at high level, and thence to a video amplifier. It is also possible to recover the video voltage directly from the electron beam by means of a suitable collector. With presently available tubes, the latter method has not been too successful.

In order to understand the operation of the BWA Autodyne properly, it is necessary to study the effect of simultaneous application of two signals to a backward-wave amplifier.

In a recent publication, Laico, McDowell, and Moster[2] have shown that saturation of the beam in a conventional forward-wave traveling wave tube results in reduction of amplitude variations in the sum of two simultaneously applied signals, while preserving the phase changes. Behavior of signals in a backward-wave amplifier is similar provided that they are sufficiently close in frequency to be amplified simultaneously.

Results and Discussion

The above reasoning has been verified by measurements on an experimental homodyne receiver constructed from a Varian VAD-161 backward-wave am-

[1] F. E. Terman, "Radio Engineering," 2nd ed., McGraw-Hill Book Co., New York, N. Y., p. 453; 1937.

[2] J. P. Laico, H. L. McDowell, and C. R. Moster, "Medium power traveling wave tube for 6000 mc radio relay," *Bell Sys. Tech. J.*, vol. 35, pp. 1285–1346; November, 1956.

plifier.[3] The VAD-161 is a modification of the VA-161 oscillator in which the collector end of the helix is brought out to allow insertion of radio-frequency signals. The frequency range is 8.0 to 12.4 kmc.

A block diagram of the receiver and measuring equipment is given in Fig. 1. Two types of display were used. A spectrum analyzer was used with a CW signal generator to determine the frequency response of the amplifier. To measure signal discernibility, a pulsed input signal from 1 to 10 μsec long was used, and the output displayed on an oscilloscope.

Measurements were made at a fixed frequency of 10.4 kmc (approximately the center of the band). Attenuators were placed in both the input and output circuits of the amplifier to avoid any errors caused by external reflections.

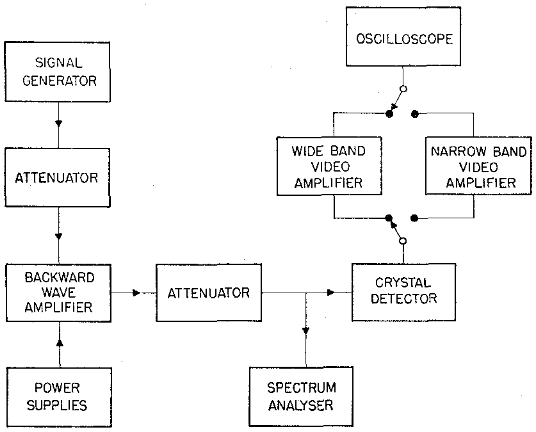
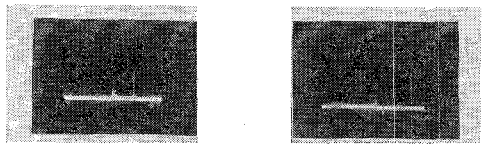
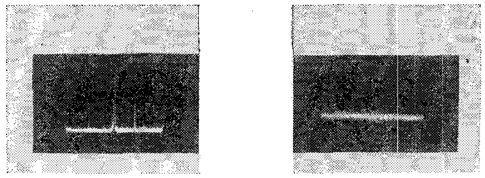


Fig. 1—Block diagram of the experimental receiver and measuring equipment.



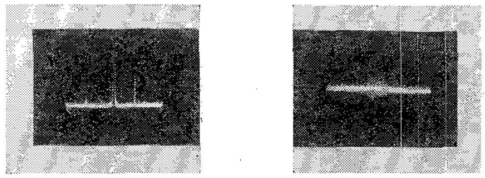
(a) (b)

Fig. 2—Amplifier and detector output when beam current is 99.5 per cent of starting current.



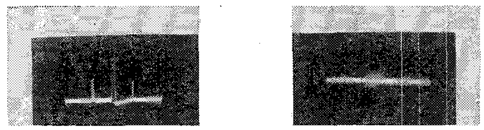
(a) (b)

Fig. 3—Amplifier and detector output for a beam current 100.3 per cent of starting current.



(a) (b)

Fig. 4—Amplifier and detector output for a beam current 100.6 per cent of starting current.



(a) (b)

Fig. 5—Amplifier and detector output for a beam current 107 per cent of starting current.

Operation of the receiver is best illustrated by Figs. 2–5. These show both the output spectra of the backward-wave tube for CW input, and the corresponding video output pulse (10 μsec long), for values of beam current of the backward-wave oscillator near starting current. The center frequency of the backward-wave amplifier response is on the center of the spectrum in Fig. 2(a). The width of the display is 4 mc and a CW signal at −80 dbm and 1 mc from the center frequency has resulted in a "pip" on the right-hand side of the spectrum. Fig. 2(a) illustrates the case where the beam current is just 99.5 per cent of starting current. The noise output from the amplifier can be seen at the center of the spectrum. The corresponding video output for a 10-μsec pulsed signal is shown in Fig. 2(b). As the lower cutoff frequency of the video amplifier was 20 kc, the pulse has been differentiated.

In Fig. 3(a) the beam current has been increased to 100.3 per cent of starting current, and the oscillator output occupies the center of the spectrum. There has been no significant change in the amplified signal at 1 mc away from the frequency of oscillation. The pulsed video output as displayed in Fig. 3(b) has become bipolar, and so is passed by the video amplifier.

In Fig. 4(a) the beam current has been increased to 100.6 per cent of starting current. At this point, the oscillator output has increased to a level which results in almost complete bunching of the electron beam. The tendency to saturation which results produces a third spectral component separated from the signal by 2 mc and on the opposite side of the oscillator frequency. As can be seen from the corresponding pulsed output displayed in Fig. 4(b) saturation of the beam current has not reduced the output pulse a significant amount.

In order to produce a noticeable change in the output the beam current was increased to 107 per cent of starting current giving the results illustrated in Fig. 5. Since the oscillator output was much greater than the signal at this beam current, almost complete saturation has taken place, and the two sidebands corresponding to the signal and its image reflected in the oscillator are approximately equal in amplitude. The resultant suppression also produces a reduction of amplitude of the output pulse as in Fig. 5(b).

[3] This tube was developed by Varian of Canada Ltd., Georgetown, Ont., under the auspices of the Defence Research Board, Can. (Electronic Components Res. and Dev. Committee).

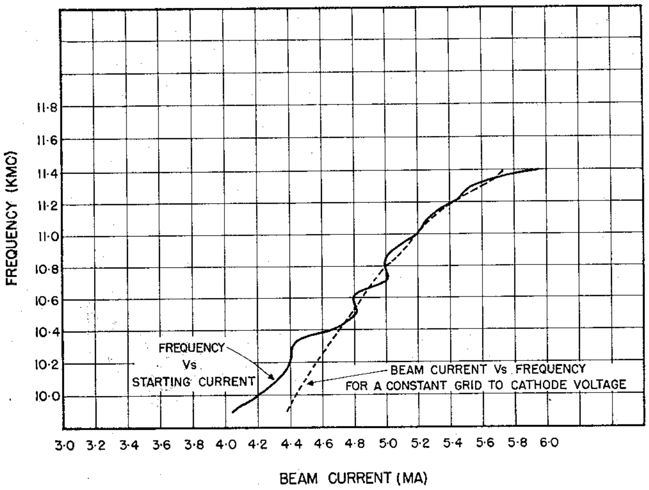


Fig. 6—Graph of frequency vs starting current, compared with frequency vs beam current at a constant grid voltage.

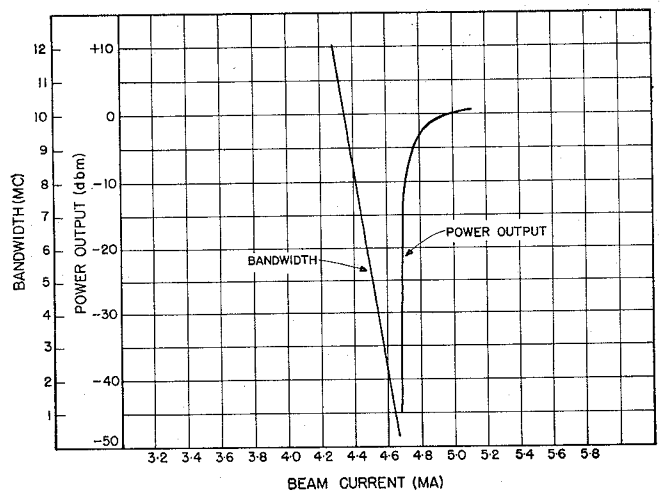


Fig. 7—Graph illustrating the variation of amplifier bandwidth and oscillator output with beam current in the vicinity of starting current.

It can be seen, therefore, that ratio of beam current to starting current must be maintained between 1 and 1.01 for maximum gain. This is not as difficult as would first appear, since a small change in beam current results in a relatively large change in oscillator output which may be regulated by a feedback system. Another factor which should be considered is the change of beam current, as frequency is changed (by varying the delay line voltage). Fig. 6 shows a plot of starting current vs frequency, and also a plot of beam current vs frequency for a constant grid voltage. It can be seen that operation over the entire range from 10.4 to 11.4 kmc results in a variation of only ± 2 per cent of beam current relative to starting current.

If the sensitivity of the backward-wave amplifier is constant over a wide band of frequencies, one other factor affects the wide-band operation of the over-all receiver. This is the variation in sensitivity of the crystal detector with frequency. It is difficult to find a video crystal mount with sensitivity constant within one or two db over a wide frequency range, particularly at frequencies above 10,000 mc. Usually the variation in crystal sensitivity at high level (-20 dbm or higher) is not as pronounced as the variation in minimum detectable signal, but can still be troublesome.

Fig. 7 illustrates the rate of change of amplifier bandwidth below oscillation starting current, and the way in which the output changes at currents above the starting current. Bandwidth measurements above the oscillation threshold are not possible because it is very difficult to measure the value of amplified signal at the center frequency in the presence of an oscillation at that frequency, which is much larger in magnitude. Some idea of the gains and signal levels involved in the operation of the amplifier can be obtained from Fig. 8. Curve (a) illustrates how the gain of the amplifier increases with beam current. This gain was measured by applying a CW signal to the amplifier and comparing the outputs at different values of beam current.

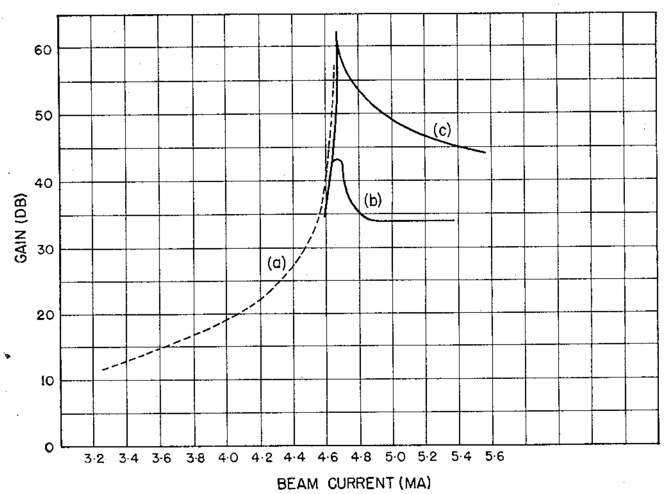


Fig. 8—Gain vs beam current for the type VAD-161-2 backward wave amplifier for three different input signals.

As the beam current reaches starting current, the regenerative gain increases indefinitely. Curve (b) illustrates gain at a frequency 1 mc higher than oscillation frequency.

Curve (c), which is a plot of sensitivity to a pulsed signal, shows that pulse sensitivity continues to fall well above the oscillation threshold, owing to saturation of the beam as described above.

In Fig. 9(a), a 1-μsec and a 10-μsec pulse at -70 dbm are illustrated. A wideband video amplifier was used, and the increased rise time of the pulses was caused by the narrow-band radio-frequency amplification. By using a pulse stretcher followed by a narrow-band video amplifier, the output can be made unipolar, and the sensitivity improved for longer pulses as illustrated in Fig. 9(b), where 1-μsec and 10-μsec pulses at -80 dbm are illustrated.

Fig. 10 is a typical plot of the sensitivity of the receiver vs frequency for a fixed delay line voltage. As can be seen, off-frequency signals are rejected by at least 50

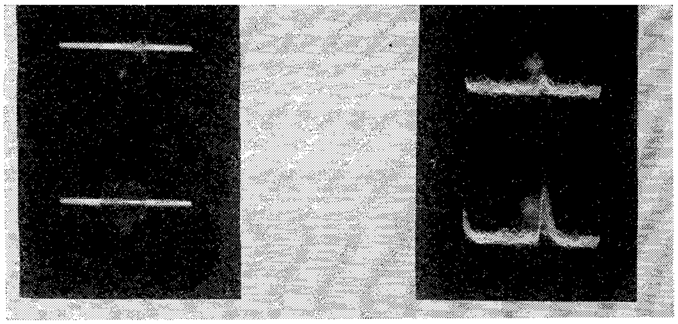


Fig. 9—(a) Output pulses from a 1.5 mc video amplifier for 1-μsec and 10-μsec inputs at a level of −70 dbm. (b) Output pulses from a 1 mc video amplifier and pulse stretcher for 1-μsec and 10-μsec inputs at −80 dbm.

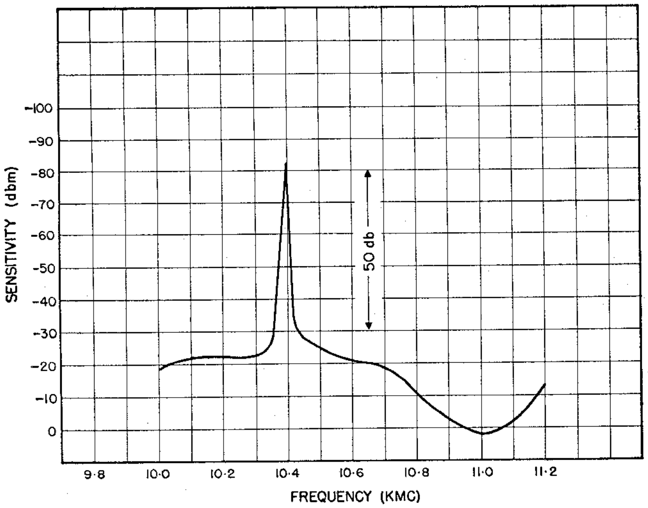


Fig. 10—Receiver sensitivity vs frequency for a fixed line voltage.

db. Bandwidth at the 3 db points is approximately 1 megacycle.

Where fixed frequency operation with good long-term stability is required, dc is used on the filaments, and a supply with a regulation of <.025 per cent is used for grid and cathode voltages. When the tube is used as a sweeping receiver for spectrum analysis, the requirements on power supply regulation, and ripple are an order less important.

Fig. 11 illustrates the over-all dynamic range of the receiver. This range is limited for large signals by saturation of the video amplifier and is not limited by the oscillator tube.

Minimum detectable 1-μsec pulsed signal is of the order of -90 dbm, with all voltages optimized. Minimum detectable CW signal is of the order of −105 dbm. If the output is fed to a pair of earphones, a 400-cycle square-wave modulated signal can be heard at −105

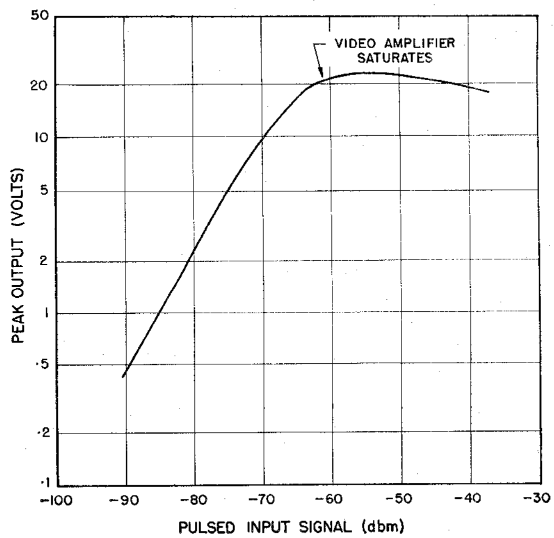


Fig. 11—Dynamic range of receiver.

dbm. These values of sensitivity correspond to an over-all noise figure of about 22 db. This noise is generated in the backward-wave amplifier and could possibly be reduced considerably by proper gun design.[4]

Conclusion

A receiver can be constructed using a single backward-wave amplifier, crystal detector, and video amplifier. While this receiver is not a true homodyne, it operates with a locally generated voltage mixing in a crystal with an incoming signal. The oscillation is essential to operation of the receiver since maximum gain occurs just above oscillation starting point. The receiver has the following advantages:

1) It can be tuned over relatively wide bands electronically without complicated circuitry and power supplies.

2) It does not have image difficulties, as does a superheterodyne.

3) The unwanted signal rejection is at least 50 db, which is considerably better than that of the homodyne.

4) Bandwidth may be increased if sensitivity can be sacrificed.

Acknowledgment

The author is indebted to H. W. Poapst, who constructed the experimental receiver and assisted with the measurements, and to many of his colleagues for helpful suggestions given during the experimental work and preparation of this report.

[4] M. R. Currie and D. C. Forster, "Low noise tunable preamplifiers for microwave receivers," Proc. IRE, vol. 46, pp. 570–579; March, 1958.