The *Lenkurt* Demodulator

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Methods for TRANSMITTING DATA FASTER

Increased use of data transmission between distant business machines, computers, and other information-handling devices is focusing attention on the need for reliable data transmission at higher speeds. This article discusses some of the methods being developed to increase the speed of reliable data transmission over telephone circuits.

High speed data transmission presents no problem if there are no restrictions on the cost of the system or the kind of transmission to be used. The great bandwidth of microwave radio links, for instance, permits millions of bits per second to be transmitted. Such means of transmission may be relatively expensive, however.

Although many special applications require high-capacity data transmission channels, most needs may be satisfied by systems operating within the capacity of a standard telephone voice circuit. These telephone circuits are available throughout the inhabited world. Standard communications facilities are usually divided into such channels, and these channels almost always have a useful bandwidth of 3000 cycles or more. In some cases, inductive loading or other physical characteristics of the transmission line may reduce its ability to handle high speed data, but this quality of circuit is becoming more the exception than the rule.

It is only logical, therefore, that communications engineers have concentrated on data transmission systems designed for voice circuits. The prob-

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lem is to make the most efficient use of existing facilities.

Transmission Methods

Information has to be converted into some sort of code or set of symbols for transmission. These may be letters, words, or numbers — or they may be the dots which make up a television or facsimile image. The symbols must undergo further transformation in the form of modulation to adapt them to the transmission medium. For instance, a tone or a direct current may be keyed to convey code symbols; a subcarrier frequency may be shifted in phase or frequency in a systematic manner. The choice of modulation method is very important in determining the actual performance of a high speed transmission system. There are advantages and disadvantages to nearly all the methods now being used or seriously considered.

Amplitude Modulation

Amplitude modulation (AM) methods are historically related to direct-current telegraphy. In d-c telegraphy, a battery or other source of direct current is keyed on and off. At the receiving end, the signals are detected by some sort of magnetic receiving device. In AM telegraphy, the process is similar. Instead of direct current, a tone or subcarrier is keyed, so that the two binary states, "mark" and "space", are indicated by the presence or absence of the tone.

This method has several disadvantages: it does not use bandwidth efficiently, since two sidebands of the carrier are produced. Unlike single-sideband voice communications methods, the carrier and one sideband can not be completely eliminated and still do a satisfactory job.

Sidebands are produced when the modulating wave causes the carrier to change from one value or state to another. In the case of voice communications, the modulating waveform is continuous, thus causing modulation products (sidebands) to be formed continuously. If the carrier and one sideband are eliminated, the other sideband remains to convey the modulating intelligence.

In the case of telegraphy, where on-off pulses are the modulating signal, modulation products are formed only during the transition from "on" to "off", and from "off" to "on." These modulation products are transients whose bandwidth is a function of the keying or switching rate. Except when a pulse is started or ended, no modulation products can appear in the transmission path. Thus, it would be impossible to continuously transmit a steady mark or space. It is possible to design a system with "memory" so that only changes are transmitted. In such a system, after receiving a mark, the receiver holds a marking condition until a signal is received indicating a space. Such systems usually must be quite complex to offset the problems of ambiguity and errors due to interference.

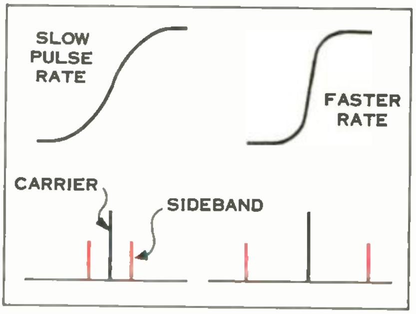

Figure 1. Sidebands are farther from carrier at high keying rates. Round-cornered pulses require less bandwidth than square-cornered pulses.

The information-carrying characteristic of an AM signal is its amplitude. For this reason, AM is particularly vulnerable to impulse noise and changes in transmission level. Impulse noise is particularly disturbing. Noise pulses caused by electrical storms, switching transients, and similar disturbances, may equal or exceed the information pulses in amplitude and duration. Under severe conditions, impulse noise may completely obliterate an AM information pulse.

Vestigial Sideband Transmission

Vestigial sideband systems result from an effort to reduce the bandwidth requirements of AM transmission. As we saw above, it isn't practical to eliminate one entire sideband from a telegraph or data transmission channel, despite the reduction in bandwidth. Instead, one entire sideband and only a vestige (10% to 15%) of the other sideband are transmitted. This is done by filtering the telegraph channel so that the output signal barely includes the edge of the sideband to be reduced, as shown in Figure 2. Although this reduces the total bandwidth to be transmitted, another difficulty appears immediately. Because of the lack of symmetry of the signal obtained from the filter, a *quadrature component* — a wave component 90° out of phase with the basic signal — is produced and combined with the signal. This distorts the pulse, making it more difficult to identify or reconstruct at the receiving end, if normal envelope detection is used. This difficulty adds to the inherent AM vulnerability to changes in level, and makes such a system even more sensitive to interference.

To reduce quadrature component effects, the transmitting modulation index is reduced. The amplitude of the "space" may be increased from the normal value of zero to 30% or 40% of the amplitude of the "mark." In other words, the *difference* in amplitude between the mark and the space is reduced, thus making vestigial sideband transmission even more sensitive to noise.

The sensitivity of vestigial sideband transmission to noise has been confirmed by extensive experience in the SAGE data systems. Since most SAGE channels are operated through regular telephone offices, impulse noise caused by dialing pulses and other switching transients normally found on telephone circuits are present in large amounts. All of these types of impulse noise reduce the accuracy or reliability of vestigial sideband transmission. In addition, vestigial sideband is so sensitive to disturbance that in SAGE systems many errors occur which have no readily apparent cause. The actual cause is probably a combination of minor line disturbances, each of which is too small to be very noticeable.

On the good side, vestigial sideband methods are believed to require less

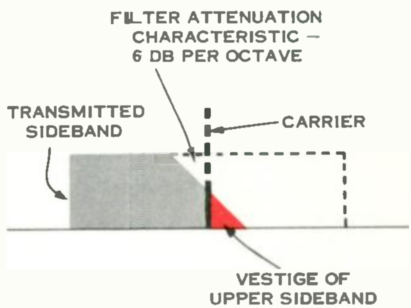

Figure 2. Vestigial Sideband is produced by special filter which attenuates carrier and second sideband at 6 db-per-octave rate.

correction for delay distortion than most other approaches to high speed transmission. Also, it is relatively uncomplicated and easy to maintain.

Phase Modulation Methods

From a *theoretical* viewpoint, phase modulation (PM) is perhaps the most attractive approach to higher speed data transmission. In this method, the *phase* of a carrier is shifted a certain number of degrees ahead of or behind the normal sine wave of the carrier. For instance, "mark" might be signified by momentarily advancing the phase of the carrier by 90° or 180°. A "space" might be represented by retarding the carrier phase a like amount.

In practical PM systems, as much phase difference as possible is used between channels (or between mark and space conditions of one channel) by employing as few phases of a single carrier as possible. The most rudimentary form of phase modulation uses the unmodulated carrier to signify a space, and reverses the phase of the carrier (shifts it 180°) to signify each mark. Thus, a series of consecutive marks would be indicated by continuous phase reversals, such as shown in Figure 4.

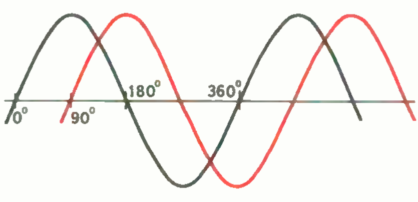

Figure 3. Phase Modulation systems are based on shifting the phase of a carrier from the normal or "zero" phase. Red waveform is shown advanced 90° in phase.

Phase modulation has the advantage of being insensitive to level variations, and being able to transmit low modulating frequencies, including zero frequency (a continuous steady-state condition). Theoretically, PM makes the best use of bandwidth for a given transmission speed.

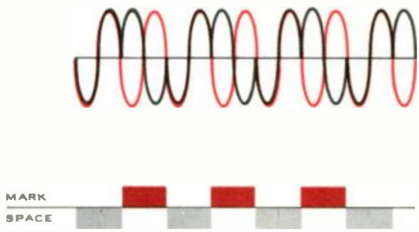

Figure 4. Phase reversal indicates marking condition. Red waveform indicates zero phase.

On the negative side, phase modulation methods have very great difficulty achieving or approaching their theoretical superiority over other methods except at the cost of extremely complex and sophisticated methods. Since the information-bearing characteristic of the received signal is its phase, the quality of any phase-modulated transmission depends on the accuracy with which the phase shift of the transmission path is stabilized. All actual communications paths show some phase drift. This is caused by temperature changes in cable or wire, atmospheric effects on radio paths, momentary variations in transmission equipment performance, and so forth.

Another major problem of phase modulation methods is *phase ambiguity.* Actual transmission paths are subject to many kinds of disturbance, both major and minor. Impulse noise may occur because of man-made disturbances, or because of electrical storms. If the signal is momentarily interrupted by any cause, the receiver has no way of knowing whether the first data pulse received after the interruption is the reference (or zero) phase, or whether it represents a mark or a space. If the receiver makes the wrong decision, a mark or space might be interpreted as the reference phase. All other signals transmitted after the interruption would then be misinterpreted, resulting in a thoroughly garbled message.

Most approaches to solving this ambiguity problem require the transmission of a pilot tone or other signal which carriers no message information. Some systems transmit timing pulses in addition to the pilot tone, to make sure that there is no ambiguity. Such techniques, while quite necessary for reliable performance, reduce the efficiency of the system. Although the ideal phase modulation system should enjoy about a 2-db advantage over FM, 7 db over AM, and 16 db over vestigial sideband transmission, much of the advantage is lost in preventing phase ambiguity. Like vestigial sideband transmission (which reduces modulation index to minimize quadrature component distortion of the transmitted wave), phase modulation methods sacrifice some of their basic advantage in solving related problems.

Any data transmission system that achieves the full theoretical advantage offered by phase modulation must do so at the cost of extreme complexity — with attendant high cost and difficulty of maintenance and adjustment — unless the signal path is very short or the signal power is unusually high.

Frequency Modulation

Frequency modulation, sometimes called *frequency shift keying* when applied to telegraphy or data transmission, has long been used for transmission of telegraph signals by radio or carrier systems. Like phase modulation, FM is insensitive to variations in level, and has a six-to-sixteen db signal-to-noise advantage over amplitude modulation methods. Because of the way in which FM trades bandwidth for freedom from interference, it doesn't enjoy as much freedom from noise interference as PM, for the same bandwidth.

In normal practice, binary signals are transmitted by allowing one frequency within the transmission passband to represent mark and another frequency to represent the space. Since the mark and space signals are represented by different frequencies of equal strength, amplitude variations have no effect on the signal unless the signal has the same or less amplitude than the noise. This contrasts strongly with amplitude modulation where a mark is represented by the presence of carrier and a space is indicated by a lack of carrier. Level changes due to fading, noise, and other interference have a strong effect on AM signals. FM systems can tolerate level changes of about 40 to 50 db, and are

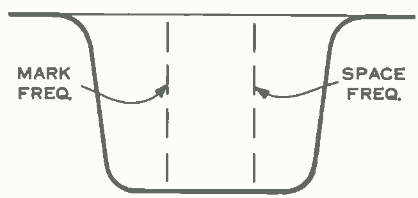

Figure 5. Single oscillator alternates between two frequencies to indicate binary mark and space in FM data system. Sidebands occupy remaining bandwidth.

about 12 db less sensitive to impulse noise than AM systems.

Conventional FM telegraphy is accomplished by alternately transmitting two frequencies representing mark and space. A diode keyer in the tank circuit of an oscillator changes the tank circuit so as to shift the tone back and forth between the two frequencies. Such frequency shifting does not occur instantaneously, however. The inherent resonance of the tank circuit causes the resulting waveform to change smoothly from one frequency to the other.

In an FM system, information is conveyed by the instantaneous frequency of the waveform. This instantaneous frequency determines the exact time at which the waveform crosses zero. The shorter the time, the higher the frequency. The only way that impulse noise or interference can affect an FM transmission is to change the instantaneous frequency. The random pulses of energy which comprise impulse noise have relatively little effect on an FM signal except when they occur near a

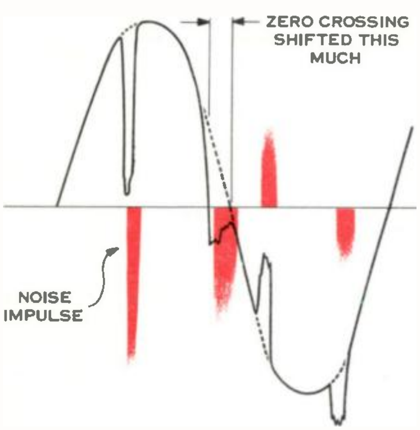

Figure 6. Impulse noise distorts received FM pulse only by speeding or delaying zero crossing of waveform.

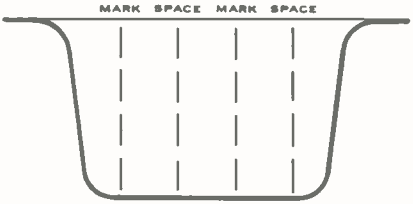

Figure 7. Four tones in channel bandwidth permit information rate to be doubled.

zero crossing. Where noise impulses combine with the signal to hasten or retard a zero crossing, pulse distortion results. This may or may not produce an error, depending on how much the pulse was distorted.

Band Compression

Phase modulation systems can transmit more information in a given band of frequencies by displacing a carrier fewer and fewer degrees of phase between channels. A similar increase in information rate can be obtained in AM systems by transmitting more levels. This is undesirable because noise sensitivity — which is already great — becomes much worse. An equivalent method of band compression is available to FM, based on the manner in which the modulating signal is encoded. To make the comparison clearer, let us first review the operations involved in phase modulation.

In a system where binary mark and space are indicated by 180 degrees phase separation, the voltage appears as "on" and "off." If an additional channel is obtained by displacing the mark and space conditions 90 degrees instead of 180 degrees, the phase detector output will consist of four different voltage levels — two for each channel. Since the amplitude difference between mark and space has been reduced to half its previous value, the system is 6 db more sensitive to noise interference.

In FM systems, the same type of band compression may be obtained by using an increased number of significant frequencies to obtain additional channels. To obtain two channels, four instead of two frequencies might be employed. A single oscillator could be deviated to one frequency to indicate a mark, and to another frequency to indicate a space. The remaining two frequencies could represent the mark and space of the other channel. If bandwidth were increased to keep the same frequency spacing as in ordinary binary telegraphy, there would be no noise disadvantage. Where bandwidth is limited, however, the frequencies must be more closely spaced. This is analogous to the more closely spaced phases used in the phase modulation method.

A Practical System

An interesting variation of this band compressed FM system was recently installed at Cape Canaveral to transmit data between a tracking radar and a computer at Patrick Air Force Base. The radar set transmits data concerning the position, velocity, and heading of missiles, to an impact prediction computer at the launching site. The computer constantly analyzes the data and predicts the point where the missile would land if thrust were cut off at any given instant. The radar information requires a transmission rate of 6720 bits per second. This is transmitted to the computer over two cable channels.

Each channel is supplied data at the rate of 3360 bits per second. Because the FM system is necessarily double sideband, a *quaternary* or four-tone system is used to double the information rate without requiring more bandwidth.

Four frequencies within the voice

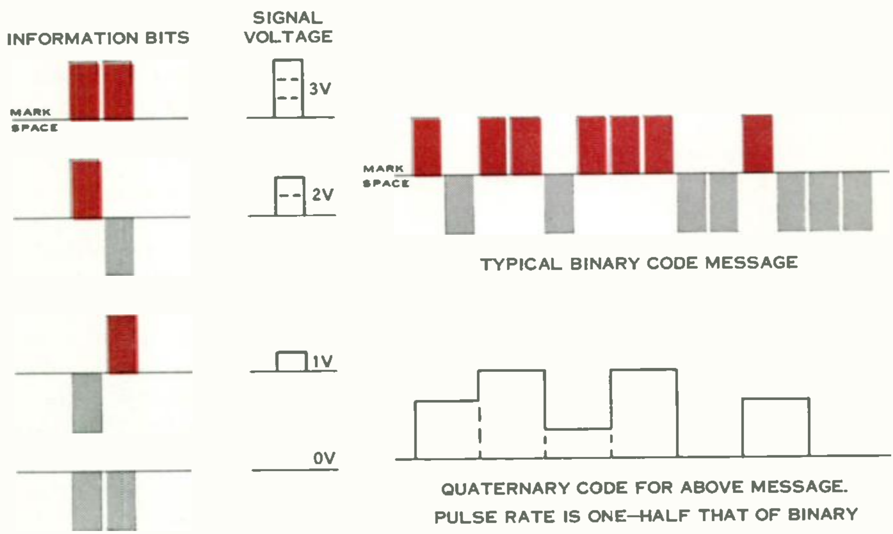

Figure 8. Quaternary (four-level) code adapts binary information for transmission by four tone system shown in Figure 7. Each pair of information bits is represented by one tone or level. System requires transmission system with good tolerance to noise and level changes.

band are used to convey the information. Instead of using two of the four tones for mark and two for space, thus yielding two channels, the data signal is encoded so that each transmitted pulse carries two bits of information. Since there are four possible combinations of mark and space taken two at a time, one tone is assigned to each of these combinations. Figure 8 shows the encoding scheme by which information rate is doubled. The actual transmitted pulse rate is 1680 pulses per second, and the information rate is 3360 bits per second. At the receiver, the tones representing the four combinations appear at the discriminator as four voltage levels — the same as in the phase modulation method. This straight-forward approach avoids many of the problems of complexity inherent in the more elaborate phase modulation methods.

Synchronization

Frequency modulation does not require synchronization, unlike phase modulation systems. In phase modulation, failure to maintain perfect synchronization between the two ends of a transmission path results in failure of the system, since information is carried only by the phase of the transmitted wave.

FM systems can achieve additional signal-to-noise advantage if they are operated synchronously. This makes it possible to mute the receiver until the exact moment when a signal pulse is strongest. Instead of receiving everything that comes over the line, including noise, the receiver samples the incoming signal at the optimum moment. Figure 9 shows a simplified block diagram of a typical synchronous detector which yields about 4 db signal-to-noise advantage, compared to non-synchronous detection.

Pulse Integration

A useful technique for obtaining even more signal-to-noise advantage is to integrate the received signal over a short period of time. Since background noise is perfectly random, there is no coherence to the integrated noise. Positive and negative pulses tend to offset each other on a statistical basis. Signal pulses, on the other hand, are coherent, and tend to build up by integration.

Extreme examples of this principle are the historic radar contacts made with the planet Venus in 1958, and with the Sun in 1959. In the case of

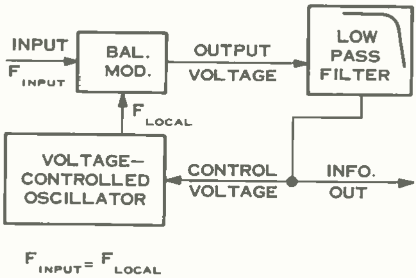

Figure 9. Block diagram of typical synchronous or homodyne detector. This is mandatory for PM, optional for FM.

the Venus contact, the planet was about 28 million miles away, requiring a round trip of about five minutes for the radar signals. The radar transmission consisted of a series of 2-millisecond pulses transmitted every 33.3 milliseconds. The transmitter was operated for about 4½ minutes, turned off, and the return signal was recorded on magnetic tape for five minutes. The estimated signal-to-noise ratio was -10 db. That is, background noise was 10 db greater than the radar echo.

The recorded signal was passed through a shaping filter and quantized to 64 values of amplitude. A digital

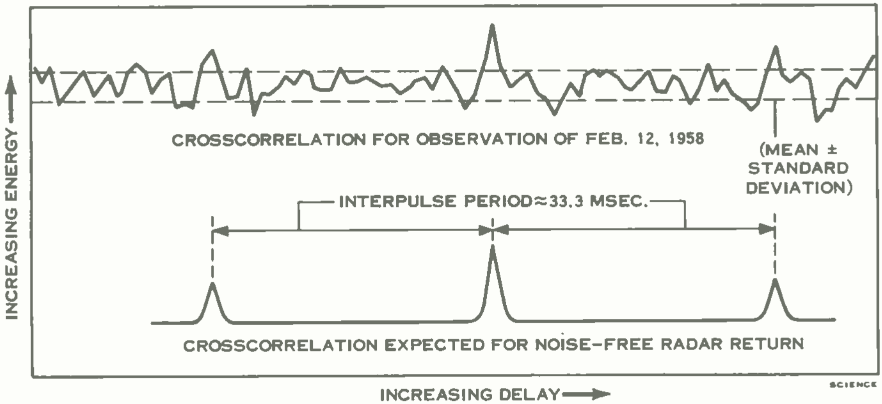

Figure 10. Use of pulse integration and statistical correlation techniques made possible radar contact with planet Venus and Sun. Similar technique can be used to improve high speed data transmission, particularly with longer pulses.

computer integrated each one-millisecond period of signal over a time span equal to several thousand pulses, in an attempt to obtain correlation between the transmitted pulses and the received signal. Figure 10 compares the cross-correlation that would be expected in the absence of noise, and that which was actually obtained.

In data transmission, each pulse may be integrated over its own length, and the integrated value sampled at the end of each pulse. This will normally yield about six db additional freedom from noise interference, but will also require synchronous operation. While such techniques are not mandatory in FM data systems, they are available when circuit conditions are noisy, or reliability requirements are so stringent as to justify the additional complexity and expense.

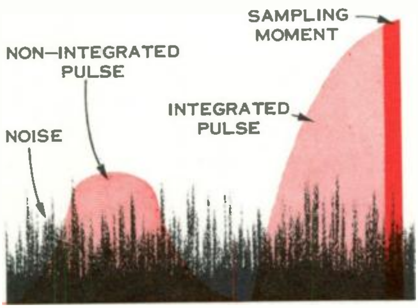

Figure 11. Bit integration builds up pulse amplitude. Noise fails to build up because of statistical cancellation of individual noise pulses.

At the present state of the art, how close a system comes to ideal performance seems to depend on how much the budget can stand. In practical terms, a very few decibels of signal-to-noise tolerance may cost a surprisingly large number of dollars. A review of various available methods of high speed data transmission would indicate that the cost of one terminal capable of transmitting 3000 bits per second in a 3000-cycle channel goes up at a rate which rapidly exceeds $1,000 for *each* db drop in signal-to-noise ratio! The choice of the methods available for higher transmission speeds might very well be decided on the basis of the quality of circuits available. •

IMPORTANT TRANSISTOR DISCOVERY

DR. V. W. VODICKA

A new mode of transistor operation that extends performance of certain kinds of transistors far beyond their ratings has been discovered at the Lenkurt research laboratory. In demonstrations of this new characteristic, ordinary MADT transistors rated at 500 mc alpha cutoff frequency (the frequency at which useful gain is reduced to zero) provided stable voltage gains between 40 and 60 db at 500 mc. In these experimental circuits, bandwidth of 2 mc was obtained at 40 db gain. In circuits where the bandwidth was reduced to 200 kc, 60 db gain was obtained. In one such circuit operated at a 400 mc detector, a signal-to-noise ratio of 14 db was obtained at an input level of one microvolt and produced a conversion gain of 60 db.

According to Dr. V. W. Vodicka, inventor of the circuits in which the effect was discovered, experiments and calculations indicate that the useful frequency of the transistors used in these experiments was extended from 500 mc to about 2500 mc!

This is in sharp contrast to conventional UHF and microwave detector performance. When using diode mixers, no gain is possible, there is always signal loss, and noise is inherently high. A separate local oscillator is required, usually a special, high-performance electron tube. The best previous transistorized mixer-oscillator circuits have required at least two expensive experimental transistors to obtain a maximum gain of 10 db at UHF frequencies and little or no gain at low microwave frequencies. Signal-to-noise ratio is always low, rendering such circuits of little value at low input levels.

The new effect is believed to result from a combination of semi-conductor "tunneling" and "avalanche" effects that occur at a very non-linear portion of the transistor operating characteristic. Certain conditions of impedance and bias must be present before the effect is produced. By modifying these conditions, several different modes of operation are possible:

- Conventional diode detection.
- One-transistor autodyne (self oscillating) mixer.
- High-gain negative impedance converter.

It is in this last mode, which combines several effects, that the most dra-

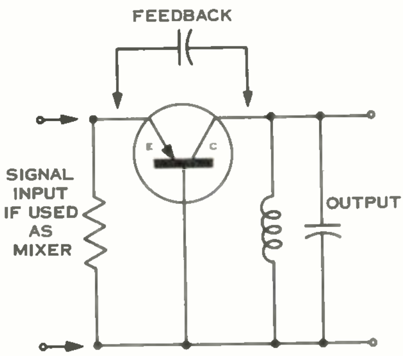

Figure 1. Basic grounded-base oscillator, showing possible feedback path for high frequency oscillation.

matic performance has been obtained.

Figure 1 shows a basic grounded-base transistor oscillator. In such a circuit, oscillation may be difficult to achieve at high frequencies because of insufficient feedback from collector to emitter. A capacitor will increase feedback, but hampers the use of the circuit as a mixer because of the regeneration that may occur at the demodulated frequency. If the feedback

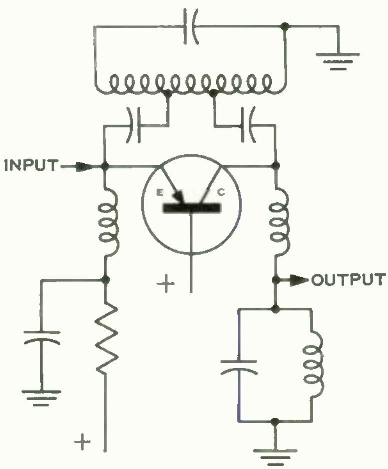

Figure 2. One variation of Vodicka converter which has provided useful gain at frequencies several times the transistor alpha cutoff frequency.

capacitor is split and a high-Q tuned element, such as a cavity resonator, is connected to the capacitors, it is possible to feed back harmonics of the input signal, harmonics of the self oscillating frequency, the demodulated signal, but little or none of the signal itself. Thus, the signal applied to the transistor emitter (input) may consist of the input signal and the second or higher harmonic of this signal. This harmonic acts as a parametric "pump" frequency for the input signal, thus increasing amplification.

If the input circuit is tuned to pro vide a high impedance to the demodu lated signal, this demodulated fre quency is amplified by the transistor Efficiency is increased by tuning the col lector to increase harmonic feedback.

Normally, this circuit should no work because of the transistor's in ability to produce harmonics at fre quencies beyond its rated alpha cutof frequency. However, because of th voltage and phase relationships appear ing at the three terminals of the tran sistor, the as-yet unexplained "tunnel avalanche" effect occurs in the tran sistor, extending its frequency capa bility significantly.

It is now believed that there are n inherent limits to the frequencies a which such performance can be ob tained. Even better performance than described above has been obtained under laboratory conditions. One con figuration, using a parametric diode in addition to the single transistor, ob tained 96 db gain at 400 mc, with bandwidth of 75 kc. At two megacycle bandwidth, 86 db gain was achieved and the signal-to-noise ratio for an input signal of 0.2 microvolt was bette than 6 db! Theoretical and practica investigations of these and related phe nomena are continuing.

Some of the practical benefits sug gested by this invention include Cheaper and more reliable microwav receivers; microwave repeaters requir ing neither IF amplifiers nor expensiv special purpose electron tubes such a traveling wave tubes or klystrons; mic rowave systems requiring no electron tubes at all; push-pull microwave am plifiers driven by independent antenna —these could simplify frequency o space diversity; tracking devices tha operate on the interferometer (phase difference) principle; encrypting o secrecy communications systems. ●

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