The Virtues of Nonlinearity—Detection, Frequency Conversion, Parametric Amplification and Harmonic Generation

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I. Detection

IN THE LATE 1920's when I was 9 and my brother Laurence was 12, he spent his life savings to buy a "crystal set." This was an exceedingly simple radio receiver. It had no tubes, it required no battery, and it had no power cord. It was a black box about 6×6×2 in. On its top were two tuning knobs, a number of binding posts, and a "crystal." Following instructions, we connected an "aerial," a ground wire, and a pair of earphones. The crystal itself was a piece of rock-like mineral; galena, I believe. It had a polycrystaline multifaceted surface. It was clamped in a metal cup. Facing the crystal was a pointed spring wire mounted in a ball-joint holder, designed so that the point could be placed anywhere on the surface of the crystal and be set to remain there under spring pressure. This was known as the "cat whisker." Again, following instructions, with the earphones in place, Laurence searched for and found a sensitive spot, after many tries. Eureka! He could hear the nearest local radio station, faintly but clearly. We spent many hours with this receiver, not all happy. The crystal contact was erratic and the sound was always faint. We would lose the signal quite frequently, necessitating a search for a new sensitive spot on the crystal.

At that late date, Laurence and I were already far behind the times. Powerful broadcast stations had sprung up in every American city. Millions of highly sophisticated, multitube, superheterodyne receivers were being sold to a public rapidly becoming addicted to Lucky Strikes, Ipana toothpaste, Lifebouy soap, and Amos n' Andy. The only virtue of the crystal set was its low price, affordable by young boys. For those who could afford the latest in high technology, the unreliable solid-state crystal rectifier had been replaced by the vacuum tube! Looking back, with 20–20 hindsight, we can recognize that our crystal was an example of the earliest solid-state semiconductor electronic device, a precursor of the transistor revolution that was to come a few decades later.

I have not discovered who first reported that rectification and RF detection could occur at contacts between metals and certain nonmetallic substances, now called semiconductors. Southworth [3] indicates that the earliest reports preceded the discovery of radio. In the first part of this century, these detectors were receiving serious study. One report from 1909 [4] and another from 1916 [5] describe experiments with crystal detectors using various materials, including silicon, galena, carborundum, and "Perikon," the last being a 2-crystal type of detector (p-n junction?).

At Bell Laboratories in the 1930's, G. C. Southworth was exploring the propagation of ultra-high-frequency radio waves, particularly the way that those waves could be transmitted by transmission lines and waveguides. He was able to obtain sources of UHF and microwave energy in magnetrons and Barkausen tubes, but there was no satisfactory detector. The available diode and triode tubes were not capable of responding to these frequencies. To solve this problem, he resurrected the crystal rectifier, going back to earlier work, some of his own and some of others. Two of his colleagues, A. P. King and R. S. Ohl, set out to develop a reliable and sensitive detector. First, they devised a rugged miniature cartridge mount which could withstand being thrown to the ceiling and allowed to bounce on the floor! Ohl subsequently carried out a program to improve the performance of this device as a detector. At one point, he discovered a silicon ingot which exhibited one direction of a rectification when contacted at the bottom, the opposite direction on the top, and which performed as an optical detector in the middle! Some of these effects had been observed and reported in 1909 [3], [4]. These observations were among the earliest evidences of the dual nature of hole and electron conduction in a semiconductor, showing the effects of sparse impurities and their segregation on cooling from the melt. According to Southworth, "It was Mr. Ohl who first triggered the chain reaction that led not only to the modern microwave rectifier, but to the solar battery, the transistor, and finally to the broader field now generally known as solid-state physics."

In their device, a sharp metal point was held against a polished piece of silicon with simple spring pressure, no different in principle from Laurence's "crystal." With improved materials and packaging, it had become a reliable and useful device. Laurence and I would have been happier if we could have had one of their detectors. Without a reliable detector, Southworth would have had a much more difficult time, and the development of microwave technology might have been long delayed. There is no doubt in my

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mind that the crystal rectifier was, and remains, the most important, the most indispensible, and perhaps the least appreciated of microwave devices. In concept, it has changed but little over the years. The modern Schottky-barrier junction, which is now used in microwave detectors, FET's and in many other devices, does not differ in principal from Laurence's crystal or from Ohl's.

During this period and in the years thereafter, the crystal detector evolved through many changes: by obtaining better materials, by numerous package variations and by the introduction of various forms of coaxial and waveguide mounts. It was not until the 1960's that metallic deposition methods were developed which were superior to the simple unbonded spring contact. When these new techniques appeared, the diodes were given new names, like "Schottky-barrier" or "hot-carrier," but the basic principles remained the same. The essential features were: 1) a high-conductivity material in the body of the semiconductor, 2) an optimum choice of materials and surface treatment to provide a thin rectifying barrier, and 3) a tiny contact to minimize the reverse-bias capacitance across the barrier. The original applications for these crystal detectors involved direct detection of RF waves by rectification, converting some of the high-frequency energy into dc. If the RF was modulated in amplitude, the rectified dc became similarly modulated, generating audio waves which followed the envelope of the RF wave. For Laurence, this became audible speech and music when passed through the earphones. For Ohl, the dc magnitude became a measure of microwave signal strength. Direct detectors are still widely used for instrumentation and for many other miscellaneous applications, but rarely for direct radio reception. However, some few uses of this technique persist, largely because they have much lower cost than superheterodyne receivers. One of the most interesting of these is the inexpensive radar detector, which speeders buy to warn them when they approach a police radar speed trap. The best of these devices can respond reliably to waves of power less than 10^{-10} W. Of course, the superheterodyne type of receiver is much more sensitive than this.

II. Frequency Conversion

The principles of double-detection or superheterodyne receivers were developed in the 1920's. It was realized early in WW II that Ohl's crystal detector could be used as a nonlinear mixer to provide frequency conversion of microwave signals into lower frequencies in the same way that vacuum tubes were being used for radio frequencies.

When two RF waves were applied to the crystal detector simultaneously, the nonlinearity induced a conversion of some of the wave energy into new frequencies. These appeared at the sum of the two input frequencies, at the difference, and at the sum or difference between higher harmonics of the two applied frequencies.

For superheterodyne receivers, the difference frequency was most commonly used. To convert a weak signal in this way at a frequency such as 3000 MHz, it was necessary to apply it to a crystal detector along with a relatively strong wave from a microwave local oscillator at nearby frequency, such as 3030 MHz. In a properly designed mixer, this caused the radar signal to be converted to 30 MHz with only a few decibels loss. Using a vacuum-tube amplifier designed for 30 MHz, this weak signal could then be amplified to the point where it could be directly detected by a vacuum tube and presented for display. Much greater sensitivity was achieved in this way than by direct detection of the input microwave signal. Until recently, most microwave receivers used a crystal rectifier mixer as the first-stage electronic device. Low-noise microwave amplifiers are now becoming available at reasonable cost, and are being used as preamplifiers. Nevertheless, the crystal mixer remains with us, almost as indispensible as ever.

The application as a frequency converter or mixer soon became the dominant one for the crystal rectifier. Applications as direct detectors continued to be important, but of lesser significance. As technology advanced, it was realized that, for long-range radars, the sensitivity of the receiver was just as important as the power of the transmitter, and the crystal mixer was one of the key components which determined and limited this sensitivity. The WW-II story about the development of these devices and their effect on radar is told by Torrey and Whitmer [6] in Volume 15 of the famous Radiation Laboratory Series.

The concepts and theoretical background of our present understanding of radio receiver sensitivity took a long time to solidify. It was not until 1944 that H. T. Friis put it together in his classical paper "Noise Figures of Radio Receivers" [7]. This was based upon earlier work of his own, plus fundamental work by Johnson [8] and Nyquist [9] on thermal noise, Schottky on tube noise [10], and experimental contributions from W. W. Mumford and many others. Friis gave us a quantitative theory, showing the limits to sensitivity which are imposed by signal losses, by external thermal noise, and by noise generated in the receiver.

To maximize the sensitivity, we must not attenuate the input signal any more than necessary in frequency conversion in the mixer or in any other part of the input path up to the first amplification stage, and we must introduce as little noise as possible before or in the first stages of amplification. Torrey and Whitmer devote most of their book to the work done during WW II to obtain an understanding of the crystal rectifier, to the study of means for reducing the loss in frequency conversion, and to the minimization of additive noise in the frequency conversion process.

Another classical paper on this subject is that of Peterson and Llewellyn [11]. They provided a theoretical basis for understanding the process of small-signal frequency conversion in nonlinear devices. For its use in a receiver, a mixer requires a "strong" applied wave from a local oscillator to be mixed with the "weak" signal wave received from the antenna. They provided a multifrequency technique of analysis using matrix methods similar to those which had been developed for single-frequency analysis of multiport linear networks. In the mixer diode, the currents and voltages at the various frequencies interact with one another in a manner closely analogous to the way the current and voltages at the various ports interact with one another in a linear, passive multiport network. In this way, they could analyze the device as a linear small-signal transducer. They showed how the coefficients of the interaction matrix can be determined if we have knowledge of the harmonic content of the periodic time variation of the diode's conductance as it is being driven nonlinearly by the local oscillator wave. Although it is difficult to determine these coefficients with accuracy, their theory provided the basis for a sound physical understanding of the frequency transfer properties of a nonlinear-resistance diode mixer.

Over the years, Peterson's and Llewellyn's theory has been expanded and extended by many authors. As applied to mixers, Saleh [12] presents a comprehensive treatment of many mixer configurations and provides the techniques of analysis for various methods of suppressing the unused responses. For the millimeter-wave range, low-loss, low-noise mixers continue to be important. Suppressing the unwanted responses of a mixer has a significant desirable effects. I explored the limits of these techniques in a recent paper [13].

III. Low-Noise and the Parametric Amplifier

In the mid-fifties, there was a concerted search in many laboratories for a method of breaking the noise barrier. Radio engineers knew that their receivers were not nearly as sensitive as they should be. The fundamental limits imposed by quantum effects and thermodynamics were orders of magnitude better than had ever been achieved in practice. The problem was noise. Noise in a microwave radio consists of random waves which become mixed with the signal being received. Some of the noise is picked up by the antenna along with the signal and some is generated in the first stages of amplification and/or frequency conversion. This noise appears in the signal channel and is amplified whether or not a signal is present. If the signal is too weak, it is masked by the noise and becomes uninterpretable. In the conventional microwave receiver, the first-stage device was the mixer, converting the signal to an intermediate frequency. This resulted in 6 dB or more of signal loss in most cases, and some "shot noise" was added. The vacuum-tube IF amplifiers added still more shot noise. Shot noise (or Schottky noise) is produced in all vacuum-tube and semiconductor devices [10]. It is a result of the discrete nature of the electronic charge and the random statistical fluctuations in their numbers which pass between the device electrodes.

Another, and more fundamental, noise source is thermal or Johnson noise [8], [9]. It results from thermal agitation of mobile electrons in various natural or man-made substances. It is simply electromagnetic radiation, of the same nature as radiant heat from a stove or optical radiation from an incandescent lamp. At radio and microwave frequencies, at ordinary temperatures, this radiation is very weak, but is nevertheless measurable and important. An antenna coupled to the earth will pick up thermal noise appropriate to the earth's temperature. A beam antenna pointed at the empty, cold sky will pick up very little noise. A resistor also produces thermal noise. The maximum thermal noise power available from the terminals of an antenna, or of a resistor, or of a long lossy transmission line, is given by the formula: $N = kTB$, where k is Boltzman's constant, T is the absolute temperature of the radiating object in degrees Kelvin, and B is the bandwidth of the receiver which detects that power. This is the "black body" value, obtained by "matching the impedance" of that object. Thermal noise forms a useful standard for comparison in evaluating the sensitivity of receivers. The IEEE has set 290° K as the standard temperature for such comparisons. This standard level of noise is about 4×10^{-21} W in each hertz of bandwidth (-204 dBW/Hz) and is uniformly distributed over the useful radio spectrum. Using the above formula, we can describe the noisiness of any device or source by specifying its effective temperature. The empty sky, for example, is said to have a temperature on the order of 4° K, even though no one has been to the far reaches of space to measure that temperature. A radio receiver can also be said to have a noise temperature, and a modern, low-noise highly sensitive receiver is very cold indeed, in the range of 10–30° K. In 1955, however, a temperature of 3000° K was considered to be good for a microwave receiver.

To understand the meaning and the effect of a receiver's noise temperature, we pretend that all of its internal noise sources are lumped together at the input and the total effect is added into any signal wave or external noise waves arising from the antenna. This effective noise generator can be assigned a temperature according to the formula above. Noise temperature is often used today to describe the sensitivity of receivers. More commonly, we use Friis' term noise figure or noise factor, which can be expressed as $F = 1 + T_r/T_0$, where T_0 is the standard value of 290° K and T_r is the temperature of the receiver alone. In 1955, we were happy to achieve a noise figure of 10–15 or 10–12 dB. Today, we can achieve a small fraction of 1 dB. A receiver with a noise temperature of 30° can detect a signal that is about 20-dB weaker than a 3000° receiver. To do so, however, the antenna must also seem to be very cold, and it can be when it is pointed at a satellite or deep-space probe or when used for radio astronomy.

This great improvement was achieved by the development of low-noise microwave preamplifiers which are used as first-stage devices prior to frequency conversion. They generate little noise of their own, and boost the input signal to a higher level, sufficient to overcome the mixer's conversion loss and overpower the shot noise of the mixer and IF amplifier. Four new and different lower noise microwave preamplifier devices were developed in the 1950's. The first was a low-noise traveling-wave tube using a special type of electron gun invented by Dean Watkins, working at Stanford University. Subsequent developments and improvements by Rolf Peter at RCA and Grant St. John at Bell Laboratories ultimately resulted in TWT devices whose best noise temperatures were in the general range of 1000° K. Unfortunately, these tubes and their focusing magnets were heavy, large, and expensive. They found extensive use only in fixed military radar applications.

Another device which appeared in the late 1950's was the tunnel diode amplifier. This also gave noise temperatures in the 1000° range. Low-noise microwave tunnel diode amplifiers were very delicate and could withstand very little RF power. They never achieved great popularity.

A major breakthrough was achieved with the development of the MASER. This device was based upon physical concepts proposed by Townes and Schawlow [14] and Bloembergen [15]. Amplification was obtained as a negative-resistance effect through certain quantum mechanical energy interchanges at microwave frequencies in a magnetized paramagnetic crystal. MASER is an acronym for Microwave Amplification by Stimulated Emission of Radiation. (Any deeper explanation of this device is beyond the scope of this paper and beyond my own scope as well.) A practical MASER amplifier was first developed by Schulz-DuBois, Scovil, and DeGrasse [16]. It achieved 23-dB gain and had a noise temperature of 10.7° K. At one blow, the sensitivity of microwave receivers had been improved by more than 20 dB!

Unfortunately, the MASER did not answer all of the prayers of the designers of receivers. It was very expensive and very large, because it required a liquid helium croyostat to maintain the paramagnetic crystal cooled to ~ 4° K. Not many users could afford the luxury, but, for the earliest satellite communications systems, it was an essential and practical device. It is still used for the ultimate in sensitivity. But, for the great majority of applications which required low noise, we needed something less costly and more convenient. A second breakthrough came with the development of the parametric amplifier or PARAMP.

I had nothing to do with the development of the early detectors, mixers, or MASERS. While at Bell Laboratories in the 1950's, I did participate in developing the PARAMP, and I'll try to present the story as I can best remember it. I have recently talked with some of the other early participants and they have helped to refresh my memory and provide some additional details. Much of this early history was summarized 23 years ago by W. W. Mumford [2], who also participated. Some of what I have to say has been paraphrased from his history, and my job has been made easier by reference to his extensive bibliography and that of Mount and Begg [1]. The microwave PARAMP operates through a nonlinear process of mixing and frequency conversion in a nonlinear reactor, the varactor diode. It had been known for years that spontaneous oscillations, negative-resistance effects, and signal amplification could be induced in electrical or mechanical systems in which an elastic or reactive device was stressed periodically into a regime of nonlinear response. Mumford cites publications of Faraday in 1831 and Lord Rayleigh in 1887 in which some of these effects were observed and analyzed. One of the first practical applications of the principle was the "magnetic amplifier" of Alexandersen [17], used for radio telephony in 1916. He used a saturable-core inductor whose effective reactance could be altered at audio rates to modulate a high-power radio-frequency transmitter. He found that a modulated wave could be produced to carry much more power in its modulation sidebands than the audio power required to produce them. Magnetic amplifiers have found wide use over the intervening years, sometimes for electronic communication, and sometimes as a means of controlling ac power levels for many other purposes.

In 1934, Jack Manley, at BTL, was working with E. Petersen and W. R. Bennet on the use of the magnetic amplifier as a modulator for carrier telephone service. He developed a number of fundamental equations concerning the energy flow in frequency conversions among the many different frequencies which appear when a saturable reactor or a nonlinear capacitor is driven by two separate sources. These results were not published at the time and remained buried for 20 years in Manley's notes and memoranda. He published a portion of it, however, in 1951 [27].

Torrey and Whitmer [6] describe some closely related microwave work which occurred during WW II. H. Q. North [18] was attempting to find a better mixer crystal. One of his efforts was a "welded contact" germanium diode. M. C. Waltz obtained some remarkable results with these diodes, which aroused considerable interest at the time. He discovered that gain could be obtained in down-conversion from a microwave frequency to a much lower intermediate frequency, and sometimes, spontaneous oscillation would occur. Torrey explained these effects quite correctly with a set of multifrequency equations interpreted as an interaction matrix, which was an extension of the one developed by Peterson ad Llewellyn for nonlinear resistive diode mixers [11]. Torrey's equations included the effects of a periodically varying capacitance, as well as a varying resistance. Both effects were known to exist in semiconductor diodes when "pumped" by a microwave local oscillator. It was found that North's diodes did not provide low-noise frequency conversion in the receiver application for which they were intended. The full implications of Torrey's equations were not apparent at that time. The matter slept again. In 1948, van der Ziel published a paper [29] which predicted that low-noise amplification could be obtained with a nonlinear capacitance mixer. No one paid attention. To quote an old mentor, John Pierce, "The truth had reared its head, only to subside again."

In 1952, at BTL, C. F. Edwards was working with an up-conversion mixer to generate a microwave FM signal for radio-relay communications. He was using crystal rectifier diodes. When he tried a special "bombarded silicon" diode made by his friend R. S. Ohl, he observed gain in his up-converter. He was "pumping" the diode at a microwave frequency and applying the FM message signal at an intermediate frequency. He obtained modulation sidebands at the sum and difference frequencies which were larger than the input signal at IF. This gain was quite mysterious at first. John Pierce [19] had a suspicion that this was an effect of nonlinear junction capacitance. Somehow, he was led back to Manley's early work. The story is told that he acquired a large stack of Manley's notes and memoranda and dropped them on Harrison Rowe's desk with the suggestion that he look there for an explanation of Edwards' mystery. The search was successful. Rowe found that it was all there. He and Manley then got together and reworked, recast, expanded, and generalized. The result was an elegant and beautiful theory which they published in that widely distributed underground journal known as the BTL *Memorandum for File*. At first, they encountered a certain amount of disbelief and opposition, but when the dust settled, it was discovered that they had made an important contribution which has since been widely recognized as a landmark in the field of parametric interactions. After much delay in the internal BTL review procedures, the paper appeared in the *IRE Proceedings* in 1956 [20]. The Manley-Rowe equations delineate the special laws of conservation of energy in the interactions of multiple frequencies in any type of lossless nonlinear reactor. It was found that the experimental work of Alexanderson, Manley, Waltz, Edwards, and many who followed could all be recognized as special cases. For reasons which I am not qualified to discuss, the Manley-Rowe equations also appear to apply to the multifrequency quantum-mechanical interactions in MASERS and LASERS [26].

Meanwhile, Arthur Uhlir and Al Bakanowski, in the semiconductor device department at Murray Hill, had undertaken the task of developing an improved microwave diode to provide the same up-converting mixer function which Edwards had seen, but at the higher power levels needed for a communications transmitter. They were also under contract with the U.S. Army Signal Corps, working on the now famous "Task 8," whose objective was to find improved microwave mixer diodes. The results of these assignments were published in a series of unclassified military reports [21]. One of their most important and revolutionary results was the development of a class of microwave diodes specifically designed to exhibit nonlinear capacitance effects in the reverse-bias nonconducting regime. These were later to be named Varactor diodes. Their first useful application was to be that of a power up-converter in a microwave radio relay system. A wide-band FM wave, generated in the 70-MHz range, was applied to the Varactor, along with a strong local oscillator signal in the 6-GHz range. This modulated the 6-GHz wave, and one of the sidebands was separated out by a filter. That sideband was then amplified by a traveling-wave tube for broadcast. This device was successfully developed by Uhlir, and it was used to obtain 10-dB gain as an up-converter into the 6-GHz band.

It was about this time in 1956 when I got into the act, and for me, it was an exciting time. I had responsibility at the Allentown laboratory for the final development of microwave tubes and semiconductors to be manufactured by the Western Electric Company. All of my earlier work at BTL had been in tube development, and now I was attempting to learn as much as I could about these newfangled semiconductor devices. One of my projects was to develop an improved down-converter mixer diode for radio relay. I made numerous trips to Murray Hill and Holmdel. I was working closely with Uhlir's group on microwave diode development. The new MASER was being developed and widely discussed. H. Suhl had just invented, on paper, a magnetic microwave amplifier using a ferrite as a nonlinear reactance element. (M. T. Weiss built one, but it didn't work out very well.) There was also much talk about the possibility of a LASER.

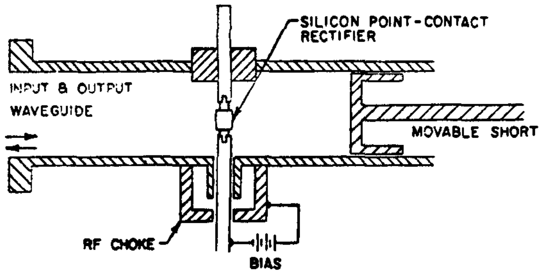

Fig. 1. This schematic sketch is taken from my original technical memorandum describing negative-resistance parametric amplification. It is simply a 6-GHz diode mount in 6-Ghz waveguide, "pumped" with a local oscillator at 12 GHz. Negative-resistance-type reflection gain occurred near 1/2 the pumping frequency.

I was particularly fascinated by nonlinear reactance effects. Bakanowski [21] had resurrected Torrey's matrix for the small-signal theory of the pumped nonlinear capacitor. This time, the proper inferences were drawn, and a more complete theory of the PARAMP was presented. These matters were being widely discussed at BTL at the time, and I'm not sure how I got the idea, but I decided that I could easily make a negative resistance microwave amplifier with existing devices. At BTL, we weren't supposed to do research in a development department, least of all in the basement of the Western Electric factory at Allentown. I was unable to resist the temptation. I'll quote now from my old BTL memorandum, which contained a 3-frequency analysis and the following descriptive material and discussion:

> It seems appropriate at this time to coin a new work for this type of device. For the sake of brevity, it is suggested that the name VARACTOR be used to represent a nonlinear reactor of either the inductive or capacitive type. This word is intended to combine the words variable and reactor. An amplifier or modulator using a varactor may be called a varactor amplifier or varactor modulator.
>
> AN EXPERIMENT WITH LOWER SIDEBAND OPERATION
>
> Recently, Mr. H. E. Elder of the Bell Telephone Laboratories, together with the author, set up a simple microwave mixer circuit of entirely conventional design, incorporating a conventional type of silicon point-contact rectifier crystal. The mixer mount is sketched in Fig. 1.
>
> The waveguide is of dimensions suitable for 6000 Mc service. A local oscillator of 12350 Mc was applied through the 6000 Mc waveguide along with a very weak signal of roughly 6175 Mc. The signal frequency could be varied ± 20 Mc.
>
> With proper adjustment of the waveguide short so that the crystal was activated by both the signal and the local oscillator, strong mixing effects occurred. If the signal were set at 6165 Mc, a frequency of 6185 Mc would emerge from the waveguide along with a 6165 Mc reflected wave. When the crystal bias was set to approximately 1/2 V in the nonconducting direction and the local oscillator drive increased to about 1 MW, the circuit would break into oscillation at

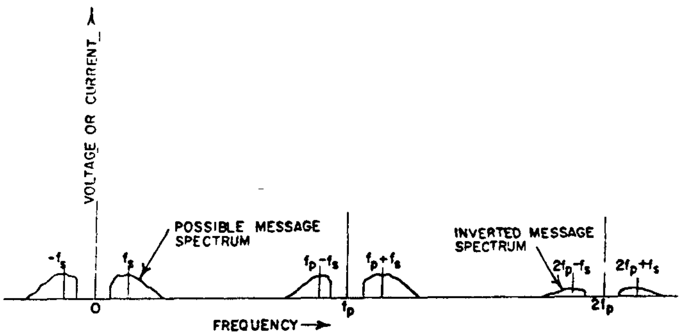

Fig. 2. This, like Fig. 1, is taken from my old BTL manuscript. It shows how the parametric modulation products are distributed over the entire RF band. The device is to be pumped strongly at f_p. A weak message may be injected at f_s, resulting in the generation of frequency-shifted signals at $f_p - f_s, f_p + f_s, 2f_p - f_s$, etc.

For stable up-conversion-type amplification, the signal is tuned at f_s and $f_p + f_s$, and up-conversion gain may be observed. If tuned at f_s and $f_p - f_s$, negative resistance can be found at both frequencies. For the experiment of Fig. 1, the bands for f_s and $f_p - f_s$ were tuned to overlap around the frequency $f_p/2$, giving "degenerate" amplification. In the most common useful type of nondegenerate PARAMP, the frequencies are distributed as shown above.

exactly 1/2 the local oscillator frequency (6175 Mc). At slightly lower oscillator drive, negative-resistance gain occurred in the vicinity of 6175 Mc. Reflected waves emerged with greater power than the incident wave. The second wave was also stronger than the incident wave.

The circuit used was not designed for this purpose nor was the crystal rectifier. Adjustments were somewhat critical in that both the 6-KMc and 12-KMc waves must be allowed to excite the crystal. This experiment could properly be classified as a "Baling Wire and Sealing Wax" type which showed feasibility of the principle only. Additional, more careful, experiments may be expected to yield a more practical type of varactor amplifier.

Noise

The theory has assumed that nonlinear reactances can be free of loss. If internal resistance effects occur, it is expected that these may contribute to a noise output. The power oscillator may be a source of noise in a spectrum near to its nominal frequency. If, indeed, there are no other sources of noise, it would appear that varactor amplifiers could be made with a very low noise figure if high-Q varactors can be made. There is, however, no experimental evidence to show whether or not this type of amplifier will be superior in this regard.

Summary

The important results of this theory and experiment are:

1) Modulators using nonlinear reactances can have gain if the frequency is shifted upward, and this gain will be increased if modulation product frequencies in inverted regions of the spectrum are loaded.

2) Negative-resistance gain may occur provided two mutually inverted regions of the spectrum are resistively loaded, and gain in a frequency shift can occur whether the shift is downward or upward.

3) Oscillations can be induced at two frequencies simultaneously or at single-frequency subharmonics.

4) Microwave amplification has been obtained experimentally using a semiconductor diode as a nonlinear reactance.

5) Varactor amplifiers give promise of low-noise amplification although this has not been proven experimentally.

Meanwhile, Uhlir had made a theoretical analysis which said that a varactor up-converter should have a low-noise figure. He and I each presented papers at the Solid State Devices Research Conference in 1957. Shortly thereafter, Uhlir did indeed find that his up-converter was a low-noise device. "Mickey" Uenohara at BTL, using Uhlir's newest diodes, quickly and easily duplicated my Allentown experiment, and proceeded to develop a more practical low-noise nondegenerate amplifier. The race was on, and many others were soon developing their own low-noise devices. The most successful PARAMPS required a tiny high-Q Varactor diode, pumped at a much higher frequency than that of the signal. The microwave circuit was made to resonate at three frequencies, one for the signal, one for the pump, and one for an idler." The sum of the signal and idler frequencies was equal to the pump frequency. For low noise, it was necessary that the idler frequency be much higher than the signal frequency. To obtain the lowest noise, it was necessary to use a varactor and circuit with the least possible resistive loss.

The varactor diode is a p-n junction device. Its useful voltage range is predominantly in the nonconducting direction. At the junction, there is a barrier region which is free of holes and electrons. On either side of the barrier, there are highly conductive zones in the p- and n-type materials. The barrier zone is much thinner near zero bias than it is at a large reverse bias, and this barrier acts as the dielectric zone of a capacitor. As this zone has a variable thickness, it also has a variable capacitance.

Many more PARAMPS were made and used than MASERS. Their noise levels were not as low, but they were much smaller and much less costly, and they did not require a liquid helium cryostat, although cooling has been helpful in obtaining the lowest noise levels.

The most complete design theory of the PARAMP was later published by Penfield and Rafuse [22]. They also treat, in full detail, the subject of Varactor harmonic generation, to which we turn next.

IV. Varactor Harmonic Generation

Nonlinear electronic devices have been used for a great many years to generate higher frequencies from lower frequencies by the process of harmonic generation or frequency multiplication. This was done with vacuum tubes, saturable inductors, semiconductor diodes, and transistors. The varactor diode, as a low-loss nonlinear reactive element, was quickly recognized to have a potential for highly efficient frequency multiplication. When driven with a sinusoidal current at one frequency, its voltage waveform becomes distorted and rich in harmonics, without a great loss in energy. This principle is illustrated in Fig. 3. Leenov and Uhlir [23] reported some early theory and experiments in 1959. T. Hyltin and K. Kotzebue at Texas Instruments [24] developed a multistage harmonic generator chain which began with a crystal-controlled transistor oscillator at 70

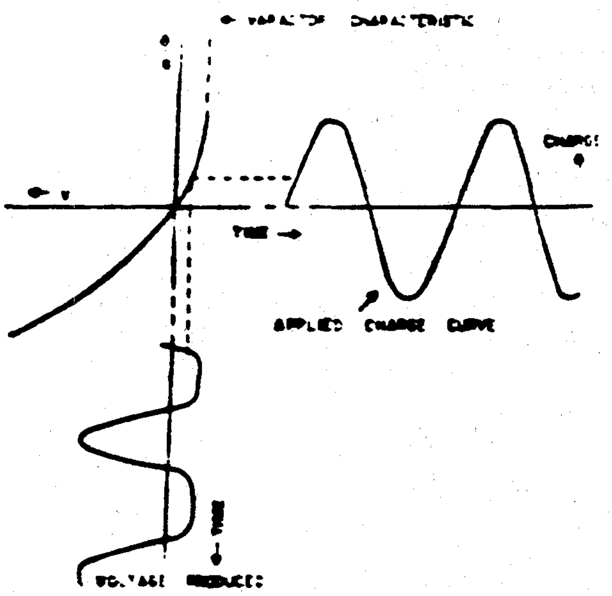

Fig. 3. Overall principle of varactor harmonic generation. A sinusoidal current or charge input generates a nonsinusoidal voltage wave, rich in harmonics (from ref. [25]).

MHz, followed by a transistor frequency doubler which gave 200 mW at 148 MHz. This drove a varactor frequency tripler, which drove a doubler, followed by another tripler. This sequence of tandem device stages provided a final output of 5–10 mW at 2520 MHz. This was a highly useful all-solid-state source providing a local oscillator signal with precise frequency control, suitable for microwave radio relay service.

In 1960, I left BTL and joined Microwave Associates. One of the first projects I worked on there was the development of a higher power all-solid-state source at *x*-band, under U.S. Air Force sponsorship. Using many stages also, starting with a transistor-powered amplifier at 64 MHz, my colleagues and I obtained over 200 mW at 8192 MHz [25]. This was enough for a useful transmitter in a microwave radio-relay link. F. Collins at Microwave Associates moved quickly to develop reliable and practical transmitters to exploit the commercial possibilities. His first radios were highly portable video-relay systems which we sold to television studios. During the next few years, the technology spread world-wide and there were thousands of all-solid-state radio-relay communications transmitters in the field, manufactured by many companies. Fig. 4 shows one of these devices featured on the cover of the *Microwave Journal* in 1963.

The technique continues to be used extensively, but, as power transistors became available at higher frequencies, the basic power generation stage moved first into UHF, then into *L*-band and then into *S*-band, requiring fewer subsequent stages of passive harmonic generation. Varactor harmonic generators continue to be employed to reach the highest frequencies at the highest power levels achieveable by solid-state devices.

Now that we have FET-type *X*-band power transistors, we don't need harmonic generation for bands up to 11 GHz. However, for the millimeter-wave bands, we are now,

Fig. 4. Cover of the *Microwave Journal* of April 1963. An *X*-band varactor-generator source is shown in the background. Various varactors are shown in the foreground. The block diagram across the lower part of the picture shows how these devices are organized.

once again, developing varactor harmonic generator-type transmitters, to be driven by FET's at *X*-band!

V. Epilogue

The stories I have told deal only with the relatively early history of microwave semiconductor devices. I have summarized the work of hundreds of people in many laboratories, and I regret that I could mention only a few. This is a subjective short history, no doubt colored by my own experiences. Although I was involved in their developments, I have not described the work on IMPATT, Gunn, and p-i-n diode devices, inasmuch as they are being treated by others in this issue. Nor have I discussed the steady advance of transistor technology from audio and radio frequencies into VHF, UHF, and microwave bands, finally, now entering the millimeter-wave range. I had little to do with that advance. Somewhat wistfully, I have come to realize that various types of transistors have become the dominant electron devices in microwave technology, and the exotic diodes, to which I devoted so much of my career, are gradually being relegated to supporting roles or to obsolescence!

In this paper, I have emphasized the importance of low-noise receivers and the profound implications in their time of the MASER and PARAMP. The gallium arsenide field effect transistor (FET) is now becoming a low-noise device to rival them. Although the noise temperature of the FET is not yet better than a MASER or the best PARAMP, its cost is very much less; low enough for use in consumer television sets to receive direct broadcast from satellite transmitters.

I've spent 37 years in microwave R&D, and it has been an enjoyable career. The fun isn't over yet. Now, we move into millimeter waves with a vengeance.

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