# Some Notes on the History of Parametric Transducers*

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**Summary—This paper summarizes briefly the chronology of the development of parametric transducers. The early works of Michael Faraday (1831), F. Melde (1859), and Lord Rayleigh (1883) are cited as mechanical examples and the pioneering work of L. Kühn, J. Zenneck, E. F. W. Alexanderson and R. V. L. Hartley are cited as electrical examples. A very brief résumé of selected contributions follows, dating from the work on H. Q. North's diodes in 1945 to the present flurry of excitement beginning in 1954, created by the development of the Signal Corps-Bell Laboratories Task 8 varactor diodes. A list of 200 selected references is included.**

THE recent interest in amplifiers which derive their gain from variable reactance circuit elements stems chiefly from the development of low-loss variable-capacitance diodes. There are two reasons for this interest. One reason is the fact that such amplifiers have low noise and the other is that the diodes are expected to have extremely long life. Either one of these properties is adequate justification for the excitement currently rampant throughout the world concerning the exploitation of this "new" type of amplifier, but, with two good reasons readily apparent, this excitation is doubled.

Mystery seemed to invade the thoughts of people when the scientists announced this new type of amplifier which was called a variety of names, such as: "Parametric Amplifier," "Reactance Amplifier" and "MAVAR" (Modulator Amplifier by Variable Reactance).[1] Some of this mystery could have been avoided had the modern men known or mentioned that the principle underlying the mechanism whereby electrical amplification was effected was an old principle. This principle may be broadly stated thus: *The energy of an oscillating system may be increased by supplying energy at a frequency which differs from the fundamental frequency of the oscillator.* One mechanical illustration of this principle is the simple pendulum. The child in the swing learns that he can "pump up" the amplitude of the oscillation of the swing by lowering his center of gravity on the down swing and raising it on the up swing. He thus "pumps" at twice the frequency of the swing. Who knows when this was invented? Could it have been in prehistoric times by a monkey swinging by his tail from the branch of a tree?

Faraday, Melde and Lord Rayleigh have published observations and calculations concerning this principle. Quoting Lord Rayleigh, "Faraday, . . . with great ingenuity and success (upon examining) . . . the crispations upon the surface of water which oscillates vertically, arrived at the conclusion experimentally that there were two complete vibrations of the support for each complete vibration of the liquid. Crispations (may be) observed upon the surface of liquid in a large wine glass or finger glass which is caused to vibrate in the usual manner by carrying the moistened finger round the circumference. All that is essential to the production of crispations is that the body of liquid with a free surface be constrained to execute a vertical vibration. Faraday's assertion that the waves have a period double that of the support has been disputed, but it may be verified in various ways." Faraday's work was published in 1831 and Lord Rayleigh verified his conclusions sixty years later, also with considerable ingenuity. The double period oscillation of the water is not readily proven by casual observation.

The following example of the principle, reported by Melde in 1859, is, however, readily observed and understood. Quoting again from Lord Rayleigh, "Perhaps the best known example is that form of Melde's experiment in which a fine string is maintained in transverse vibration by connecting one of its extremities with a vibrating prong of a massive tuning fork, *the direction of motion of the point of attachment being parallel to the length of the string.* Under these circumstances . . . the string may settle down into a permanent and vigorous vibration, whose period is the *double* of that of the fork." Lord Rayleigh analyzed and experimented with this and other similar mechanical phenomena in 1887. This led to analogous experiments with electrical circuits.

The electrical principle is readily understood by the following simple explanation. Suppose that we have a capacitor formed by two metal plates separated by air. Assume that a charge exists on the capacitor. The plates will be attracted to each other because of the equal and opposite charges so that to separate the plates requires work. Upon separating the plates, say to twice the original distance, the capacitance will be reduced to half its original value and, hence, the voltage must be twice the original value, since the charge upon the plates remains the same. The electrostatic energy, however, has been doubled, since it is proportional to the square of the voltage and directly proportional to the capacitance. The energy required to separate the plates now appears as electrostatic energy in the capacitor.

Now suppose that the capacitor is combined with an inductor to form an oscillating circuit. The voltage on the capacitor will reach a maximum value twice each cycle. Now if, on each half cycle, the capacitance is decreased when the voltage is maximum and increased when the voltage is zero, net energy will be imparted to the oscillations since no electrical energy is used to restore the capacitor to its original value when the voltage is zero.

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[1] These three names are considered herein to be synonymous and to apply to any device which derives its gain from the pumping of a variable reactance.

Similarly, it is apparent that energy could be imparted to the circuit had the *inductance* been varied in the appropriate phase. This electrical principle was expanded to include frequencies other than the two-to-one ratio and the resulting device was used successfully in radio telephone communication between Berlin and Vienna prior to World War I. This was described by L. Kühn in 1915. Prof. J. Zenneck, E. F. W. Alexanderson and R. V. L. Hartley pioneered with theoretical and experimental contributions within the next few years. Alexanderson called these devices "Magnetic Amplifiers," a name which remains with us today. The objective then was to modulate a continuous wave arc transmitter by means of a nonlinear inductance or saturable reactance. Here the voice currents constituted the signal, and the carrier was the pump. The resulting sidebands were radiated, together with the pump (or its harmonic in some cases).

I quote the following from a paper delivered by E. F. W. Alexanderson at an IRE meeting in New York City on February 2, 1916:

> The name "Magnetic Amplifier" has been given to a device for controlling the flow of radio frequency currents because this name seems to describe its function when it is used for radio telephony better than would any other. As the same device can be used for a variety of other purposes, the above name may in some cases not seem too appropriate. However, the essential part of the theory that will be given refers to the amount of amplification which is possible of attainment and the methods of securing a higher ratio of amplification than would be given by the device in its simplest form. . . .
>
> The ratio of amplification is proportional to the ratio between the frequency of the radio current and that of the controlling current.

(This conclusion was verified by R. V. L. Hartley and subsequently by Manley and Rowe.)

Alexanderson, in the discussion, also suggested amplification of incoming signals by cascaded stages of up-conversion, rectification and up-conversion, etc. The name of Alexanderson's device withstood the rigors of time. Currently, however, we recognize its radio frequency version as a type of parametric amplifier, reactance amplifier, or MAVAR.

In Alexanderson's magnetic amplifier, the chief interest resided in the mode of operation in which the input signal was in the voice frequency band and the useful output power was taken in some radio frequency band. Thus it was a modulator or up-converter.

Alexanderson presented curves to show that negative resistance effects could exist. Quoting again from his 1916 paper: Under some conditions "instability and generation of self-excited oscillations" can exist. "This is a condition that must be avoided for telephone control; whereas it may have useful applications for other purposes." (One useful application, pointed out by Eugene Peterson in 1930, was the negative resistance straight-through amplifier, in which the negative resistance effect was enhanced by the suppression of frequencies higher than the pumping frequency.)

Louis Cohen, in a communicated discussion of the paper, said:

> It appears to me that the fundamental principle . . . will find its application to other problems in connection with radio frequency circuits. One that suggests itself immediately is the amplification of incoming signals.

Alfred N. Goldsmith pointed out the advantages of Alexanderson's magnetic amplifier over the direct-current-controlled frequency doubler employed by Kühn.

Lee De Forest commented that the magnetic amplifier was far more practical as a high-power modulator than the ensemble of over 500 audion amplifiers used to obtain 11 kw at Arlington by the Western Electric Company. "No one can say, however, that the situation will not be altered very materially in one, two or three years after we learn how to build oscillions for large power outputs, say 5 or 10 kw each. That will create a very different situation."

Thus, there appears to be very old prior art on MAVAR, both as modulator and amplifier. However, the interest in magnetic amplifiers as radio frequency modulators subsided quickly with the advent of the high-power vacuum tube modulators. The "different situation" predicted by Lee De Forest in February, 1916, did, indeed, come to pass.

In the 1920's and '30's, interest developed in subharmonic oscillations in electrical circuits containing a variable reactance. These "parametric" oscillations could exist at any one of $f/n$ frequencies, where $n$ is the subharmonic fraction of the fundamental frequency. In 1954 Von Neumann and Goto independently recognized that a phase ambiguity existed in the subharmonic oscillations and that this ambiguity could be utilized in logic circuits. Goto calls this device a "parametron."

About thirty years after the pioneering work of Kühn, Zenneck, Alexanderson, and Hartley on inductive reactance modulators, interest developed in capacitance reactance modulators at microwave frequencies. The failure of reciprocity in some crystal converters observed in the middle 1940's by L. Apker of General Electric Co., Schenectady, N. Y., and R. N. Smith of Purdue University, Lafayette, Inc., and the peculiar behavior of welded contact germanium diodes made by H. Q. North of General Electric Co., Schenectady, N. Y., was interpreted to mean that the contact capacity varied with bias. H. C. Torrey of the Massachusetts Institute of Technology Radiation Laboratory, Cambridge, Mass., gave a thorough discussion of the theory of nonlinear capacity converters.

M. C. Waltz and R. V. Pound at the MIT Radiation Laboratory observed negative IF conductance when units like North's were used. Pound gave many interesting details about measured power and gain and also measured negative IF conductance. He obtained a 10-db gain and reasoned that such a receiver should have a better noise figure than that of a conventional converter which has conversion loss. He was unable, however, to achieve this.

In 1948, A. van der Ziel and, in 1949, V. D. Landon also derived the MAVAR gain relationships; the former also pointed out the low-noise figure possibilities.

In 1952, C. F. Edwards observed nonreciprocal behavior in converters when he used R. S. Ohl's bombarded silicon diodes which exhibited variable capacitance as well as variable resistance characteristics. This observation again triggered a sequence reminiscent of the North diode sequence of the 1940's in which Apker, Smith, Pound, and Waltz reported the experimental results and Torrey, van der Ziel, and Landon derived the theory. Corresponding names for the early 1950 sequence are Ohl, Edwards, Manley, and Rowe.

However, in neither of these sequences was a very low-loss variable capacitance diode available and hence the gain was limited and the noise figure was not especially good.

In 1954, the United States Signal Corps sponsored a project at Bell Telephone Laboratories, Murray Hill, N. J., to develop semiconductor devices. In the second interim report of this now famous "Task 8," A. E. Bakanowski published his derivation of the nonlinear capacitor as a mixer. The work of Bakanowski, Cranna and Uhlir led to the discovery of a technique for making low-loss units.

The technique of making low-loss silicon diode varactors or varicaps advanced rapidly and interest in these new units began to expand.

In the meantime, H. Suhl discovered that variable reactance in the microwave range was obtained in ferrite materials when properly excited by a pumping frequency. He proposed using this effect to obtain parametric amplification and discussed suitable materials in the paper published in 1957. M. T. Weiss verified Suhl's proposal experimentally.

M. E. Hines and H. E. Elder succeeded in demonstrating gain and oscillations in a reactance amplifier which used silicon varactors and suggested several microwave circuits for up-converters and negative resistance amplifiers. Their work stimulated activity in microwave applications of "varactor" diodes.[2]

In 1957, Heffner and Wade considered theoretically the noise, gain and bandwidth of parametric amplifiers.

Early in 1958, the low-noise properties predicted by theory were verified experimentally at the Bell Telephone Laboratories at 6000 mc by Uenohara and at 380 mc by Engelbrecht. Salzberg at Airborne Instruments Laboratory, Mineola, N. Y., and Heffner and Kotzebue at Stanford University, Stanford, Calif., also achieved low-noise performance working at 1 mc and 1200 mc, respectively.

Miyakawa in Japan, Cullen in England and Tien and Suhl in America considered the amplification and frequency conversion in propagating circuits in which the variable reactors were distributed along a transmission line while Bloom, Chang and Wittke of RCA Laboratories, Princeton, N. J., took up the theory of parametric amplification and discussed the new approaches to amplification of microwaves. Bloom and Chang also discussed the case of low frequency pumping.

R. S. Engelbrecht at Bell Telephone Laboratories designed a traveling wave UHF parametric amplifier using varactor diodes and achieved over 200-mc bandwidth at UHF with 8 to 10 gain. Measurements indicated an "astronomy" noise figure of one db, corresponding to a "radar" noise figure of about 3.5 db. (This compares favorably with the best commercially available vacuum tube, whose noise figure is about 5 db.)

In the meantime, Adler of Zenith, Chicago, Ill. (in June, 1957), suggested a novel principle of signal amplification using a pumped electron beam, and Bridges (in February, 1958) suggested and constructed a parametric amplifier using the variable reactance of a floating drift tube klystron. Louisell and Quate discussed the capabilities of this type of amplifier, and Adler demonstrated that the conclusions concerning the low-noise capabilities were indeed correct. He achieved a noise figure capability of 1.4 db, of which 0.4 db represented the loss in the input coupler.

The development of the vacuum tube in Alexanderson's time curtailed the interest in radio frequency parametric transducers. Thirty or so years later, the invention of the transistor then diminished the interest in vacuum tubes. But the interest in radio frequency parametric transducers was resurrected by the development of the low-noise variable capacitance diode, and this resurrection, in turn, has stimulated the interest in vacuum tubes as parametric transducers.

What is the next cycle in this see-saw pattern?

[2] It should be pointed out that, unknown to Hines and Elder, Kita and Fujii in Japan had been successful in demonstrating gain and oscillations at microwave frequencies independently while working with variable capacitance diodes in 1954.

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