The Lenkurt® Demodulator

NEWS FROM LENKURT ELECTRIC

Vol. 8 NO. 12 DECEMBER, 1959

The Very Important Klystron

Almost single-handedly, the klystron has revolutionized much of the technology and even the economics of communication. By expanding the usable radio frequency spectrum hundreds of times beyond its previous maximum limits, the klystron has proved to be one of the most important inventions since DeForest invented the vacuum tube amplifier. This article traces some of the progress made in klystron technology since the device was first conceived 22 years ago.

The klystron, like many other developments that have become important to our economy and way of life, resulted not from "practical" research, nor from the search for a good commercial product, but as a by-product of pure academic research into the nature of matter.

In 1933, Professors Russell Varian and W. W. Hansen of Stanford University were seeking economical ways of obtaining higher energy X-rays to support work in nuclear physics. The large high-voltage "atom-smashers" which were the subject of so many jokes and cartoons at that time, were not available, primarily due to budget limitations. Very high voltages were required to produce X-rays of the desired energy, but the means of achieving these voltages were too expensive.

Dr. Hansen believed that the desired high voltages might be achieved in a resonant circuit if the efficiency of the resonator could be improved sufficiently.

About this same time, Sigurd Varian, an airline pilot and brother of Russell Varian, was concerned about the alarming growth of Hitler's air force, and felt that electronics might provide a suitable defense against the growing threat. Other researchers had reported being able to detect the presence of ships offshore, using radio waves at a frequency of about 60 megacycles. After studying the problem, the Varians concluded that frequencies higher than any then possible would be required — primarily because frequencies large enough to concentrate low frequency radio energy into useful beams would require antennas of an impractical size.

By 1937, Dr. Hansen had developed the cavity resonator or "rhumbatron" and had gone on to prove mathematically that it could be far more efficient than any other resonant devices then known. The cavity resonator was the perfect starting point from which to begin a search for a new high frequency oscillator. Accordingly, the Varian brothers and Dr. Hansen teamed up to develop such a device.

In the conventional vacuum tubes of the day, the top limit of operating frequency was set by the time required for electrons to travel from the tube's cathode to its anode or plate. The tube could no longer amplify or oscillate at frequencies where one cycle required less time than required by electrons to go from cathode to plate. Accelerating the electrons by increasing the voltage on the plate interfered with the tube's functioning. Narrowing the distance between tube elements increased capacitance — also interfering with the tube's high-frequency performance. Furthermore, reducing the tube's physical size was limited by the difficulty of manufacturing the microscopic structures that would be required.

Obviously, some method of controlling the flow of electrons had to be devised that would not be penalized by the relatively long transit time of the electrons between tube elements.

The solution to the problem occurred to Dr. Varian while he was attempting to systematically classify all known methods of controlling electrons. His solution was to allow the characteristics of the cavity resonator itself to control the electrons as they flowed toward the tube anode. He reasoned that an alternating field on a short portion of the electron stream would retard some electrons and accelerate others. The different electron velocities would cause the electrons to gather in groups or "bunches." The speed of the electron stream and the time interval between bunches would determine the frequency of oscillation. Instead of requiring ever-shorter transit times between cathode and anode for higher frequencies, this scheme actually worked better if the transit time was increased!

The team's first design consisted of two resonators linked by a "drift" tube, and suitably equipped with an electron gun and grids for forming a beam. The "drift" tube was to allow sufficient time for electrons to group in bunches.

Before the researchers could be sure that their device worked, they had to solve the basic problem of detecting the high-frequency oscillations. No detector known at the time would be able to function at microwave frequencies. Without a detector it was very unlikely that anyone would know if the machine operated successfully. This problem was solved by providing a small hole in the last resonator so that during oscillation, a portion of the electron beam used to drive the klystron would be deflected through the hole and hit a fluorescent screen. If oscillations were produced, the screen would glow. This detection method was easy to incorporate in the experimental model because the entire device was operated in an evacuated bell jar. The third model constructed, shown in Figure 1, provided reproducible oscillations at a frequency of about 2300 megacycles.

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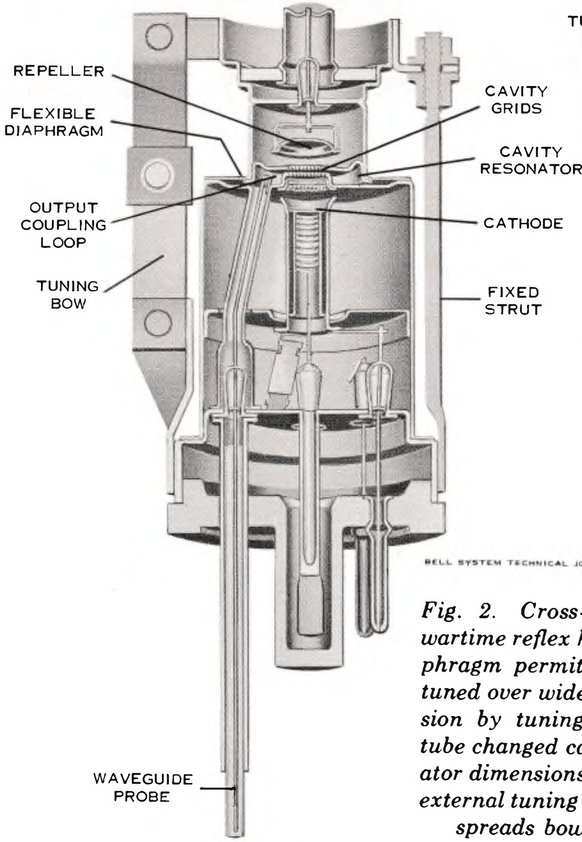
Fig. 1. First successful klystron produced microwave oscillations at about 2300 megacycles. Device incorporated water cooling and an ingenious fluorescent radio frequency detector. Shafts on front are micrometer controls for adjusting resonator positions and coupling between resonators during operation.

Wartime Urgency

The growing power of the German Luftwaffe, and the beginning of the European war in 1939, stimulated urgent research on the klystron in America, Britain, and France. Working under wartime pressure, the Bell Telephone Laboratories developed a line of klystrons which included prototypes of some still used today. The famous type 2K25 solved the problem of tuning the device over a wide frequency range.

Tuning had become a serious problem. Electrical tuning was possible by varying the voltage on tube elements. However, this permitted tuning ranges of only a few megacycles. Slight variations in the size of the resonator gap produced large changes in frequency, but were very difficult to control. Frequency changed 200 megacycles for every thousandth of an inch change in spacing between cavity grids. Since it was necessary to adjust frequency to within a megacycle, the tuning mechanism had to be able to position the grids accurately within five-millionths of an inch!

The Bell design is shown in Figure 2. Changes in gap spacing and cavity dimensions were made possible by a flexible diaphragm. This diaphragm, functioning like a bellows, permitted the upper portion of the tube to be moved in relation to the main body. The tuning device consisted of a fixed strut on one side of the tube, and an adjustable tuning bow on the other. The fixed strut provided enough hinge action to allow the diaphragm to flex,



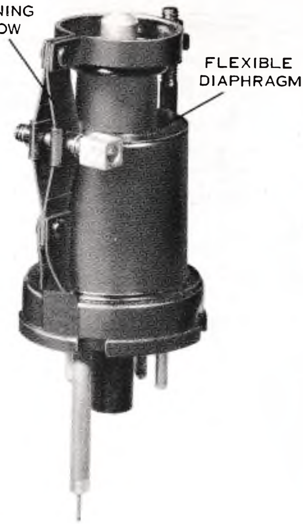


Fig. 2. Cross-section view of successful wartime reflex klystron design. Flexible diaphragm permitted output frequency to be tuned over wide range. Tension or compression by tuning bow on upper portion of tube changed cavity grid spacing and resonator dimensions. Photograph on right shows external tuning mechanism. Threaded screw spreads bow, thus compressing tube.

and the tuning bow provided tension. When the two members of the tuning bow were spread, the bow was shortened, thus reducing the gap between the cavity grids. This arrangement provided the very high leverage required to hold the grids to the desired spacing, and permitted slow motion tuning.

The design was easy to produce, and by the end of the war, thousands of klystrons of this type were in use all over the world. Even today, some tubes of this type are still in use — a tribute to the excellence of the wartime engineering effort.

After the war, a new type of communication came into being. Point-to-point microwave circuits, using klystron oscillators as transmitting tubes, permitted interference-free radio circuits with enough bandwidth to carry hundreds of telephone channels. The high frequencies opened up by the klystron increased the efficiency of antennas to such a degree that transmitter powers of only a watt, or even less, could provide reliable communication across many miles.

Under the seemingly hum-drum peacetime conditions, certain characteristics of the wartime klystron became evident that hadn't mattered too much in the military applications where life expectancy of the equipment was short and maintenance was plentiful.

Small factors, such as temperature change, affected frequency stability. Because of the flexible diaphragm in the gap-tuned klystron, even changes in barometric pressure tended to shift operating frequency. Stresses on the diaphragm resulted in metal fatigue and "creep," thus producing a gradual shift in operating frequency which required periodic readjusting.

The biggest problem, however, proved to be temperature compensation. In this type of tube, cavity dimensions and gap spacing have a profound effect on operating frequency. Both the cavity itself and the external tuning mechanism require very careful temperature compensation. Since they are physically separated, long warm-up periods are required to stabilize operating frequency. Legal and practical requirements for frequency stability make it essential that this type of klystron be operated in some sort of temperature-controlled chamber or "oven." Al-

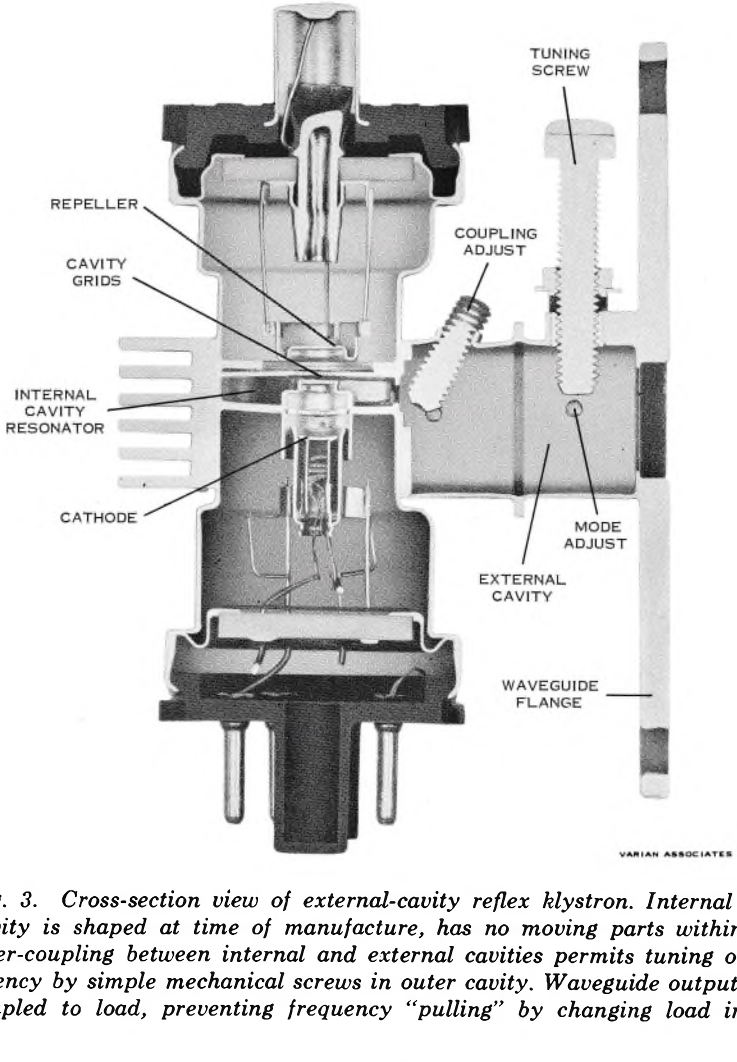


Fig. 3. Cross-section view of external-cavity reflex klystron. Internal resonator cavity is shaped at time of manufacture, has no moving parts within vacuum. Over-coupling between internal and external cavities permits tuning output frequency by simple mechanical screws in outer cavity. Waveguide output is under-coupled to load, preventing frequency "pulling" by changing load impedance.

though this helps the situation considerably, even a brief loss of power, or a malfunction of the thermostat or heater will throw the klystron off frequency for a considerable time.

To cope with these and other problems, many new types of klystrons have been devised. One type finding wide acceptance in microwave communications is shown in cut-away form in Figure 3. This tube avoids the troubles of the older design by having no variable or moving parts within the vacuum. Unlike the gap-tuned klystron, the shape and dimensions of the internal cavity are fixed at the time of manufacture and are not changed.

Tuning is provided by an external cavity electrically coupled to the internal cavity by means of an iris or window between the two. A vacuum seal of ceramic or mica preserves the vacuum in the inner cavity. The two cavities are strongly over-coupled so that changes in the electrical characteristics of the outer cavity will affect the fields set up in the internal resonator, thus permitting the tube to be tuned. Simple mechanical screws entering the outer cavity permit adjustment of coupling, frequency, and mode selection.

The output aperture for this type of klystron is designed to under-couple the tube to its waveguide load in order to prevent differences in load impedance from affecting the output frequency. This feature provides the additional benefit of holding output power constant in the face of reduced cathode emission as the tube ages. The "reserve against age" thus obtained reduces the amount of maintenance required, a valuable consideration in microwave communications systems where some stations are rather inaccessible.

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Fig. 4. Ballistic missile early warning radar at the Lincoln Laboratory of M.I.T. Using the klystron shown in Figure 5, this installation made radar contact with planet Venus.

Temperature compensation is achieved by a proper choice of materials used in the internal cavity. Because of the proximity of the cavity to the electron gun and the stream of electrons, this type of klystron achieves its final operating frequency only a few seconds after the filament reaches operating temperature and oscillation begins. Since a temperature-compensated oven is not required, the tube operates at lower temperatures, thus increasing life expectancy.

Not only is this new-found frequency stability useful in the communications industry, but it has permitted the klystron to enjoy greater usefulness in the missile and space development field. The external-cavity klystron has proved especially valuable where high levels of vibration and rapidly changing pressure

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Fig. 5. World's largest electron tube, this amplifier klystron was designed for ballistic missile early warning radar. Shown here without external resonators and focusing coils, this tube provides 1¼ million watts peak output power.

make the gap-tuned klystron undesirable or unsuitable.

In the early days of radar, the klystron was overshadowed by the magnetron as a source of high power radar energy. The klystron was relegated to use as the local oscillator in the radar receiver. At that time, frequency stability and the ability to amplify were not as desirable as high-efficiency and extreme compactness.

In recent years, the klystron has begun to displace the magnetron. Modern radar systems obtain considerable information from the phase characteristics of the returning echo, but require accurate phase control of the outgoing pulse. The magnetron, which is only an oscillator and cannot amplify, is generally unable to satisfy this criterion. The klystron, which can amplify, has no such limitation. Modern high-power klystron amplifiers are even approaching the magnetron in efficiency, often achieving 40 to 45% efficiency.

The klystron amplifier shown in Figure 5 is believed to be the world's largest electron tube. This tube was developed for use in a large early warning radar to detect ballistic missiles, and can deliver a peak power output of 1¼ million watts, or sustain a continuous power output of 100 kilowatts!

Impressive as these figures are, other klystrons have been developed which can deliver even greater peak power. At Stanford University, where the klystron was invented as a tool to help explore the atom, 21 extremely high power klystrons are used in the world's largest linear accelerator. These klystrons, each having a peak power capability of 30 million watts, provide the power for accelerating particles to speeds very close to the speed of light. Particles achieve energy levels approaching a billion electron volts, and reach velocities so close to the speed of light that their mass increases 2,000 times!

It is very fitting that the klystron has contributed so well to the basic research for which it was invented. Not only

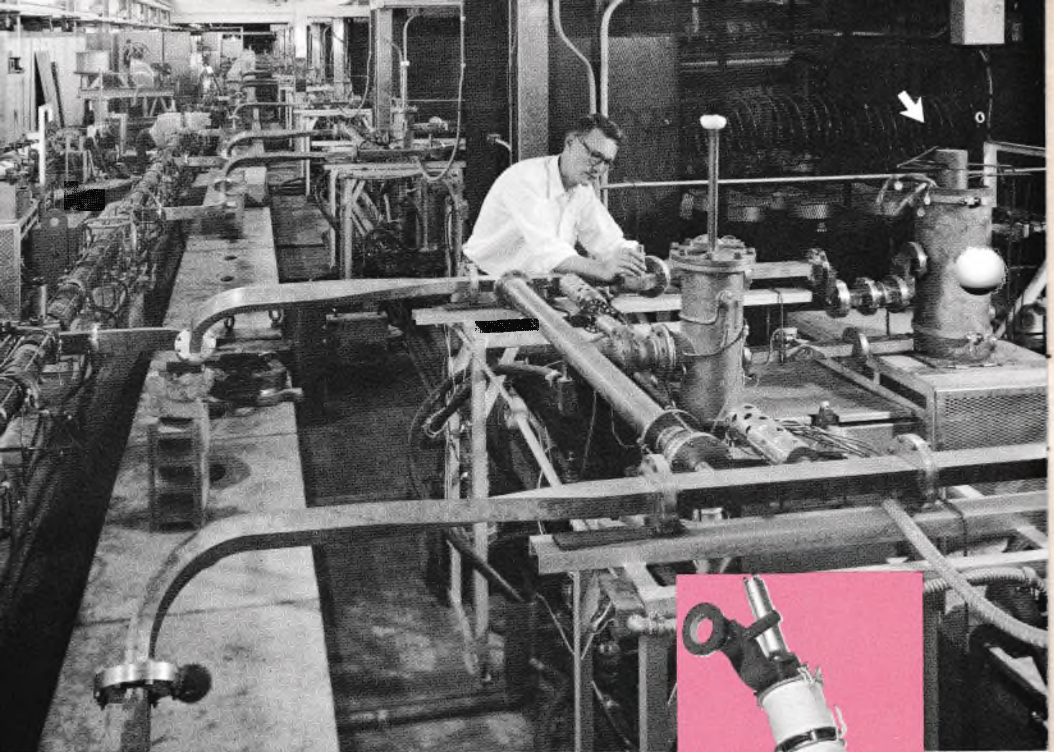

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Fig. 6. World's most powerful electron tube. Twenty-one of these klystrons are used in the Stanford linear accelerator. Researchers say that although tubes are each capable of 30 million watts peak power, they are usually operated at "only 20 million watts." Microwave energy from klystrons is used to accelerate particles in evacuated tube on left to speeds approaching that of light. Screened area in background contains pulse network for one klystron. Arrow indicates klystron.

has it fulfilled its original purpose, but has produced tremendous social and economic benefits as well. Large klystrons make possible tropospheric "scatter" communication sytsems which link remote communities, which never knew a telephone, to the rest of the world. Similar facilities enable early warning radar stations (which also depend on the klystron) to maintain constant communication with control centers in central locations. Tomorrow, a klystron may be the means of talking back to earth from outer space or the planets!

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Basic Measurement Techniques

Choosing a **Frequency-Selective Voltmeter**

One of the more useful pieces of test equipment finding increased application in communications is the *frequency-selective voltmeter* or *wave analyzer*. This device is a combination a-c voltmeter and superheterodyne radio receiver. Its principal purpose is to measure the voltage or level of a specific signal or tone in the presence of other signals.

The frequency-selective voltmeter is particularly valuable in maintaining carrier systems, especially where adjustments must be made while the equipment remains in service. A carrier system may have hundreds of voice or telegraph channels in operation, plus pilot tones. In such large systems, individual channels or groups of channels may require adjustment, while others perform normally. The frequency-selective voltmeter permits individual channels or tones to be measured, regardless of other frequencies that may be present.

Another application for the frequency-selective voltmeter is determining the performance of balanced modulators or demodulators. In such a modulator, the carrier frequency is normally balanced out by diode rectifiers. Should these become defective, however, excessive carrier frequency may be present. The frequency-selective voltmeter provides a convenient way of measuring such "carrier leak" without the measurement being influenced by the nearby sideband frequencies.

Wave analyzers of many types are available. Since the price range is fairly great, the selection of a meter should be based on the performance characteristics desired, and the characteristics of the equipment with which it will be used.

In communications work, the most important characteristic of a general purpose frequency-selective voltmeter is usually *selectivity*. Naturally, accuracy and stability are necessary, and are generally available in most instruments on the market. Figure 1 compares the

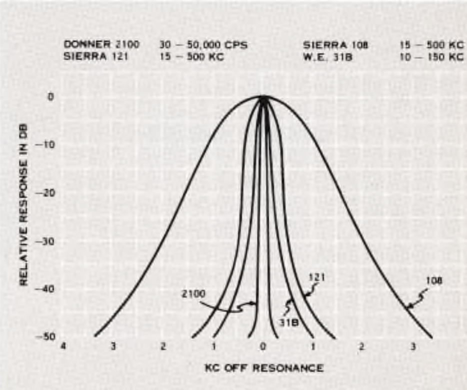

Fig. 1. Selectivity comparison of several typical frequency-selective voltmeters used in carrier communications.

selectivity of several frequency-selective voltmeters used in communications work.

In general, a frequency-selective voltmeter should exhibit at least 15 db rejection between the closest frequencies to be separated. Note that 15 db below the reference level, the Sierra 108 shows a bandwidth of 3500 cycles. This obviously would cause inaccurate readings of the level of a certain tone if another tone or signal was present only 500 cycles away. In some Lenkurt carrier equipment there is only a 450-cycle separation between pilot tones and the edge of a channel passband. In such a case, either the Donner 2100 or the Sierra 121 would prove adequate (the selection would be based on the frequency of the signals to be measured). The Sierra 108 would not be suitable for this application because both signals would be included within the passband of the equipment.

If we were measuring the levels of individual telegraph channels spaced a few hundred cycles apart, only the Donner, the Western Electric 31B, or other instrument having very sharp rejection characteristics would suffice.

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VOLUME 8 (1959)

Lenkurt Electric Co.
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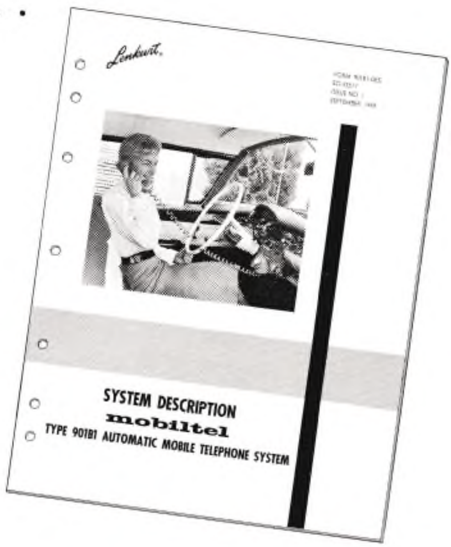

is described in this new publication now available from Lenkurt or Lenkurt distributors.

Bulletin 901B1-DES describes applications, design features, technical characteristics, and equipment options of the new Type 901B1 Automatic Mobile Telephone System. This new system features direct dialing in both directions between land and mobile telephones.

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