New Broadband Microwave Power Amplifiers Using Helix-Coupled TWT'S

THE Hewlett-Packard laboratories have developed several new broadband microwave power amplifiers which promise to be extremely important in furthering high-frequency development work of many kinds.

The importance of these amplifiers lies in the fact that they provide high gains, high power output, and very wide 2:1 bandwidths in the microwave region. The development of amplifiers with such characteristics at once solves several problems prevalent in high-frequency work. These problems include the need for signal powers much higher than those available from signal generators and the need for the wide-band amplification device necessary to development work in any frequency range.

Two of the amplifiers, those in production, operate from 2 to 4 kilomegacycles, provide maximum outputs of 1 watt and 10 milli-watts, respectively, into 50 ohms and have gains of 30 and 35 db. They can thus be operated directly from the 1 milliwatt drive available from the -hp- Model 616A 1.8-4 kmc signal generator to provide high level signal sources.

The 1-watt amplifier is designed as an unmodulated amplifier, while the 10-milliwatt unit is designed to be amplitude-modulated if desired. For modulating purposes very short pulses of about 25 millimicroseconds duration can be used. Both amplifiers will amplify even shorter r-f pulses of the order of 1 millimicrosecond in duration.

A third amplifier, soon to be in production, has been designed to operate from 4-8 kmc and provide an output of 10 milliwatts. Meantime, design work is progressing on higher frequency amplifiers.

Engineering-wise, these amplifiers are of special interest because they constitute what is probably the first economical application of the wide-band characteristics inherent in the traveling-wave tube. To make use of the potentially broadband capabilities of the basic traveling-wave tube, a new arrangement has been devised for coupling into and out of the tube helix. This coupling arrangement is such that a twt


Fig. 1. *New hp- Model 491A 2-4 kmc Traveling-Wave Tube Amplifier (center) used with -hp- 616A UHF Signal Generator to form 1 watt signal source. Ten milliwatt TWT amplifier is similar in appearance to 1 watt unit shown.*

structure can be manufactured with no means for coupling: the -hp- input and output couplers can then be slipped over the glass stem of an already evacuated and sealed tube. The arrangement leads to a simpler tube and less spoilage, which in turn leads to lower construction costs and better availability.
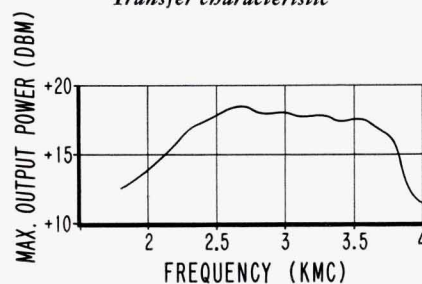
APPLICATION NOTES

Typical characteristic curves for the 2-4 kmc amplifiers are illustrated
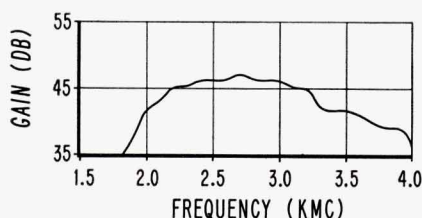
(a)
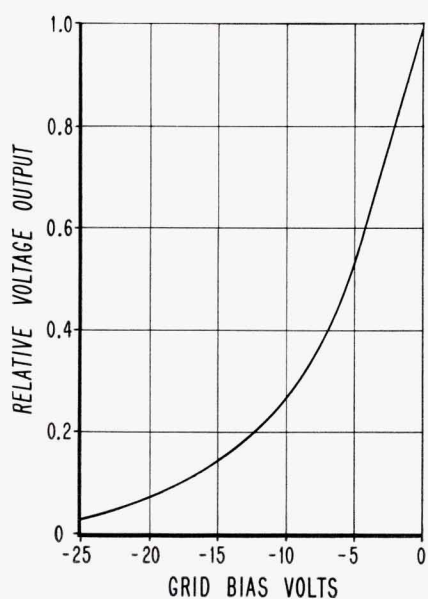*Small signal gain (−35 dbm input)*
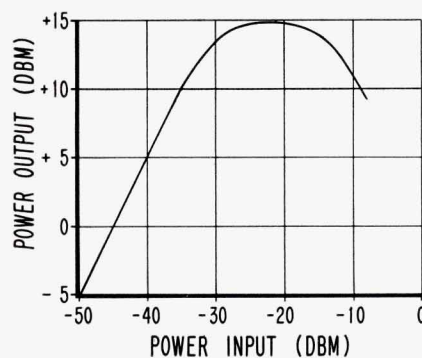
(b)
Transfer characteristic

(c)
Saturation level

(d)
Modulation characteristic

Fig. 2. *Characteristic curves for Model 490A 10-milliwatt amplifier.*

in Figs. 2 and 3. The heavy lines in the curves for the 1-watt amplifier show the performance obtained for a fixed setting of the anode and helix voltage controls. Point-by-point adjustment of the controls gives the responses shown by the dashed lines. It is of interest to note that for some applications the 1-watt amplifier can be used up to 5 kmc (Fig. 3(a)).

The bandwidth curves of Figs. 2 and 3 show the impressive speed of the amplifiers when used for amplifying r-f pulses. With 1 kilomegacycle or more separation between the 3 db points, the amplifiers have theoretical rise and decay times in the order of 1 millimicrosecond, a speed sufficient to enable the entries in Webster's Unabridged Dictionary to be transmitted in Morse Code in about 1/16 second. In other words the amplifiers represent the point where continuous amplification systems begin to outstrip systems using discrete circuit elements.

The 10-milliwatt amplifier, since

it is provided with a modulating electrode, is also provided with a panel control which adjusts the bias of the modulating electrode relative to the cathode over a range from −70 to 0 volts. This control permits the best compromise to be obtained between available modulation voltage, power output, and signal on-off ratio. The effect of bias control settings on voltage output from the amplifier is shown in Fig. 2(d). A 50-volt modulating pulse will give an on-off ratio of at least 40 db.

When fast video voltages are applied to the modulating electrode, the rise time of the output r-f voltage will vary, depending on the conditions of operation, from approximately 4 to 20 millimicroseconds. If a high-amplitude video modulating pulse is used to achieve a high on-off ratio, faster output r-f rise times will be obtained if the r-f drive for the amplifier is of sufficient magnitude to cause saturation. The oscillogram in Fig. 4(a) of a rectified output pulse from the amplifier indicates that output rise times in the order of 4 millimicroseconds are obtainable under these conditions.

If lower r-f drive is used for the amplifier, the rise time will increase to about 20 millimicroseconds as shown in Fig. 4(b). The reason for slower rise time is that sharp wave fronts in the beam current, such as occur when the amplifier is pulsed on from a small current condition, cause shock-excitation of the helix. If the drive is sufficient to saturate the amplifier, the shock wave and its reflections along the beam helix have little effect. Under non-saturation conditions, however, the rise time is slowed, as indicated in Fig. 4(b), but is still in the order of 20 millimicroseconds. The effect causes no significant change in the fast decay time.

If moderate pulse amplitudes are used with the bias set equal to the pulse amplitude and with drives of
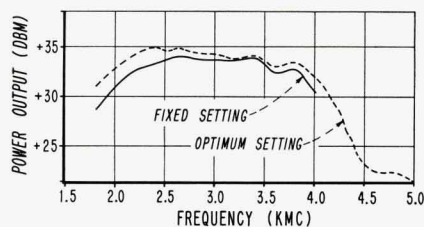
(a)
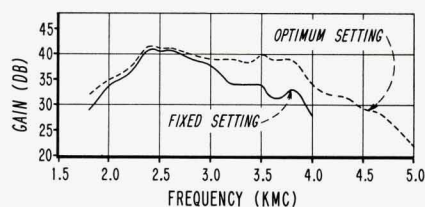
Small signal gain (−30 dbm input). Dashed lines show gain with optimum settings of anode and helix controls.

(b)
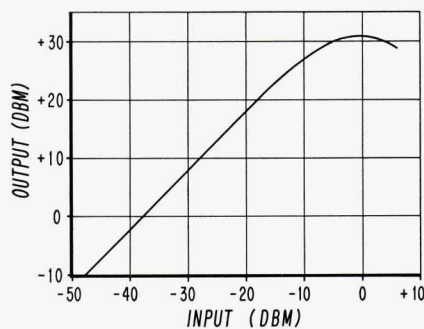
Transfer characteristic

(c)

Gain with 1 milliwatt input. Dashed lines show output obtained with optimum settings of anode and helix voltage controls.

Fig. 3.   *Characteristic curves for Model 491A 1-watt amplifier.*

less than saturation magnitude, rise times of approximately 4 millimicroseconds will be obtained, as indicated in Fig. 4(c), although the pulse on-off ratio will be lower. These ratios can be determined from the modulation characteristic shown in Fig. 2(d).

On a sine-wave basis the modulation characteristics of the 10-mw amplifier provide for very wide-band modulation. The modulation characteristic is essentially flat up to 200

megacycles with no zeros appearing up to at least 1,000 megacycles. On the low frequency end the characteristic is flat down to d-c, since the modulating electrode is direct-coupled.

Since the helix in the traveling-wave tube operates as a transmission line, it has a finite delay. In the 10-milliwatt amplifier this delay is approximately 20 millimicroseconds and in the 1-watt amplifier approximately 10 millimicroseconds, the shorter time occurring because of the coarser winding of the helix. In both amplifiers the lead-in cables introduce an additional delay of approximately 5 millimicroseconds.

For many applications it will be desirable to cascade the amplifiers in order to obtain as much sensitivity as possible. Cascading of the amplifiers is practical with the exception that two of the 10-milliwatt amplifiers should not be cascaded (unless the bandwidth is reduced by suitable filters). The reason for this is that saturation of the second amplifier will occur because of the noise output of the first. With existing noise figures, a 1 kmc bandwidth leads to an output noise power of approximately 4 microwatts from the 10-milliwatt amplifier, whereas the input level for saturation of the amplifier is some 3 microwatts.

With reference to Figs. 2(b) and 3(b), it will be seen that the transfer characteristics of the amplifiers provide for limiting when the amplifier is overdriven. This will permit the amplifiers to be used as limiting devices in f-m systems to improve the signal-noise ratio or to remove other unwanted amplitude variations.

Although rated at 1 watt, the Model 491A amplifier will usually provide approximately 2 watts output over the center portion of the band. This order of power makes the amplifiers usable as power amplifiers for microwave transmitting
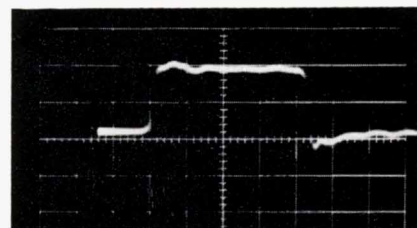
(a)

Output obtained with 50-volt modulating pulse and 50-volt bias. R-f driving power was set sufficiently high to saturate amplifier. On-off ratio is more than 40 db. Rise time is about 4 millimicroseconds (20 mμsec/division sweep).
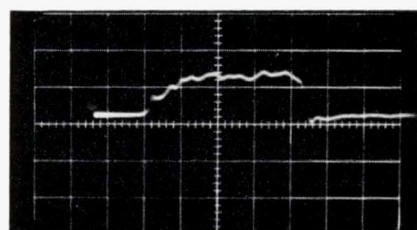
(b)

Output obtained under same conditions as in (a) except that r-f drive was reduced to well below saturation level. On-off ratio is about 40 db. Rise time is about 20 millimicroseconds (20 mμsec/division sweep).
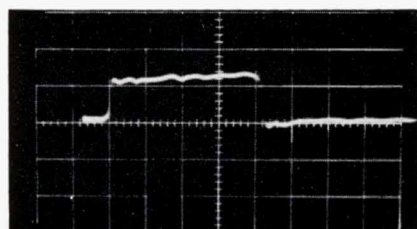
(c)

Output obtained with 15-volt modulating pulse and 15-volt bias. On-off ratio is about 18 db. Improvement of rise time over that in (b) results from smaller shock-excitation of tube helix.

Fig. 4.   *Oscillograms of rectified typical r-f output pulses from 10-mw amplifier obtained under various conditions of modulation.*

systems, especially in color tv relay work. Since the minimum life of the tubes, presently considered to be approximately 500 hours, compares favorably with other microwave tubes, the amplifiers are expected to find considerable usefulness in exploratory relay work.

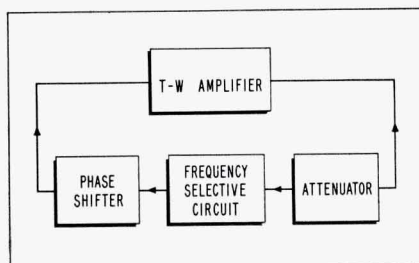Traveling-wave amplifiers can also be used as tunable wide-range power

Fig. 5. *Arrangement for converting twt amplifier to high-output tunable oscillator.*

oscillators when arranged in systems such as that shown in Fig. 5. If signal-noise ratio is of importance in a particular application, the 1-watt amplifier is to be preferred, not only because of its higher output, but also because of its 50 db dynamic range. The dynamic range of the 10-mw amplifier is approximately 30 db.

-hp- COUPLER

Traveling-wave tubes consist basically of an electron gun which projects a focused electron beam through a helically-wound coil to a collector electrode. Focusing of the beam throughout the helix is preserved by a static magnetic axial field. If a wave is coupled into the gun end of the helix, it will interact with the electron beam in such a way as to provide an amplified wave at the collector end of the helix. Since the helix is actually a broadband transmission line, twt's are also theoretically wide band. Until recently, however, no constructionally-satisfactory wide-band method for coupling into and out of the helix has existed. Consequently, the construction of twt's has been accompanied by serious problems and the tubes have received only restricted usage.

The -hp- helical coupler has proved to be a solution which is both economical and which achieves wider bandwidths than heretofore. The coupler consists of a second helix wound coaxially but in opposite sense with the beam helix. Since the coupler is physically short, one can be used for input coupling and a second for output coupling. The whole structure can thus be likened to an active transmission line.

Another important aspect of the helical coupler is that it separates the construction phase of twt's from the coupling phase. The helical couplers can be slipped over the glass stem of an already manufactured tube. Tube construction can thus be completed without introducing the coupling problem that has retarded tube manufacture.

The helical coupler is essentially a type of co-directional coupler. A useful though non-rigorous description of how the coupler transfers a wave to or from the beam helix is illustrated in Fig. 7. If two parallel transmission systems have mutual coupling between them along their lengths, a wave on one system will excite on the other a wave traveling in the opposite direction. Now if these systems are formed into two coaxial helices wound with opposite senses, the coupled wave will travel in the same direction as the primary wave even though the coupled wave is induced in the opposite direction. This principle is apparent in Fig. 7, where the Poynting vectors show the direction of propagation of the two waves. The opposite senses of the windings of the two helices cause both waves to proceed toward the right in Fig. 7.

It is a further property of two coupled systems having the same velocities of propagation that all of the power in the primary wave will be transferred to the secondary wave if the systems are long enough. For still longer lines, the power flow will reverse and the power in the secondary system will be transferred back to the primary system. In designing the couplers, use is made of the first part of this phenomenon, i.e., that
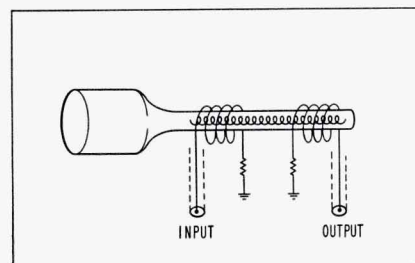

Fig. 6. *Schematic arrangement of input and output couplers. A third coupler wound from resistance wire is used for attenuation of backward wave.*

all of the power in the primary can be transferred to the secondary. If the coupling between the systems is not too loose, all of the primary power will be transferred to the secondary in a coupler containing only a few wavelengths of wire.

Attenuation of energy reflected from the output end of the tube is achieved by use of a similar coupler but one which is made lossy through use of resistance wire. This coupler is also located on the outside of the tube and serves the dual purpose of coupling out of the tube any reflected energy and then absorbing it in lossy wire. Attenuation of reflected energy in this manner further simplifies the basic tube construction by replacing the former method of in-
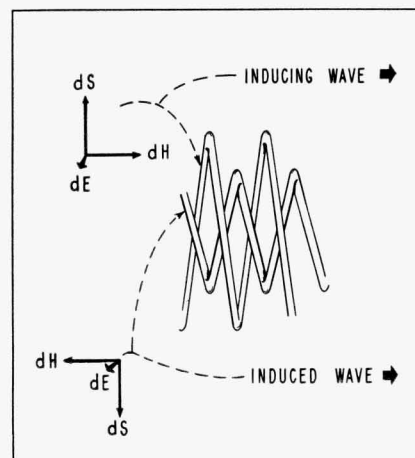

Fig. 7. *Sketch showing how opposite senses of winding of coupling and tube helices cause induced wave to travel in same direction as inducing wave.*
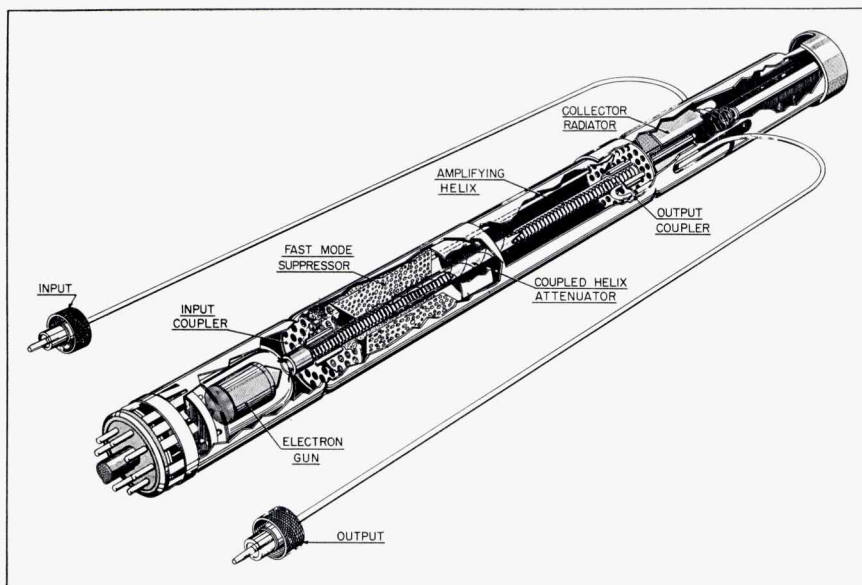
Fig. 8. *Encapsuled tube assembly.*

prevents excessive collector heating. The 10-milliwatt amplifier does not have sufficient beam power to require protection for the tube. Forced air cooling is used for the 1-watt amplifier cabinet.

The twt's are encapsuled in assemblies (Fig. 8) which insure that the alignment of the coupling helices will not be disturbed if the tube is removed or a replacement tube installed. Centering screws on the magnet assembly enable the capsule to be properly aligned with the focusing field.

The design of the basic structures of these twt's was expedited by the cooperation of Stanford University in extending their experience in twt research. The tubes are constructed by Huggins Laboratories.

—*P. D. Lacy and
D. E. Wheeler*

serting in the tube a resistive film or mixture. The coupling helices are designed as 50-ohm lines and are connected to 50-ohm coaxial lines for lead-in purposes.

The beam helix itself is specially constructed by a method that gives an order of magnitude higher accuracy than the precision methods in use (see accompanying article). This factor, combined with the moderate output VSWR of 3:1 and the effectiveness of the backward wave attenuator, is such that self-oscillation does not occur at rated beam currents, even when the amplifiers are operated into seriously mismatched loads such as waveguide below cut-off (when 3″ x 1½″ waveguide is operated at 2,000 mc, for example).

GENERAL

The complete amplifiers consist of the encapsuled twt together with filament, anode, helix, collector, and magnet power supplies. A panel meter is provided for monitoring electrode currents, since it is possible to operate the tubes at sufficiently high gains so that self-oscillation can occur. In the 1-watt amplifier, physical protection of the

tube is provided in the form of a relay which prevents excessive helix currents and a thermal cut-out which

SPECIFICATIONS
-hp-
MODELS 490A, 491A TRAVELING-WAVE TUBE AMPLIFIERS

	Model 490A	Model 491A
FREQUENCY RANGE:	2 kmc to 4 kmc.	2 kmc to 4 kmc.
GAIN:	35 db minimum.	30 db minimum.
OUTPUT POWER:	10 milliwatts minimum into 50-ohm load.	1 watt minimum into 50-ohm load.
NOISE FIGURE	Less than 25 db.	Less than 30 db.
PULSE RISE & DECAY TIME:	Order of a few millimicroseconds.	Modulation not provided.
PULSE DELAY:	Approx. 50 millimicroseconds.	Modulation not provided.
MODULATING VOLTAGE:	Requires approx. 50 volts peak negative to reduce output to 1% of initial value. Input impedance: 50 ohms.	Modulation not provided.
HUM & SPURIOUS MODULATION:	At least 30 db below signal level.	At least 30 db below signal level.
ADJUSTMENTS PROVIDED:	Anode Voltage. Modulation Bias.	Anode Voltage. Helix Voltage.
METER MONITORS:	Cathode Current. Anode Current. Helix Current. Collector Current.	Cathode Current. Anode Current. Helix Current. Collector Current.
INPUT IMPEDANCE:	50-ohms. VSWR less than 2.	50-ohms. VSWR less than 2.
OUTPUT INTERNAL IMPEDANCE:	50 ohms. VSWR less than 3.	50-ohms. VSWR less than 3.
CONNECTORS, RF INPUT & OUTPUT:	Type N jacks.	Type N jacks.
MODULATION INPUT:	Type BNC jack.	Not provided.
SIZE:	7″ wide, 10¾″ high, 18″ deep.	7″ wide, 10¾″ high, 18″ deep.
WEIGHT:	70 lbs. net, 90 lbs. packed.	75 lbs. net, 95 lbs. packed.
POWER SUPPLY:	115 volts ±10%, 50-60 cps, approx. 125 watts.	115 volts ±10%, 50-60 cps, approx. 250 watts.
TRAVELING-WAVE TUBE:	Huggins Laboratories.	Huggins Laboratories.
ACCESSORIES FURNISHED:	-hp- M-72 Power Cord.	-hp- M-72 Power Cord.
REPLACEMENT TUBE PRICE, INCLUDING CAPSULATION:	$650.00, less $125.00 credit for return of defective tube and capsule. Specify -hp- 490A-73A.	$650.00 less $125.00 credit for return of defective tube and capsule. Specify -hp- 491A-73A.
PRICE, TRAVELING-WAVE TUBE AMPLIFIER, COMPLETE INCLUDING CAPSULATED TUBE:	$1,100.00 f.o.b. factory.	$1,100.00 f.o.b. factory.

Data subject to change without notice.

A NEW HELIX-FORMING MACHINE
WITH MICRO-INCH ERROR

TO construct practical traveling-wave tube structures, it is necessary that the beam helix be wound with as high an accuracy as the most advanced of modern mechanical methods will permit. In fact, one of the obstacles in producing twt's has been that the helices could not be wound regularly to sufficient accuracies. Further, existing methods introduced a periodicity in the winding that often restricted the usable bandwidth or even prevented satisfactory operation.

The usual approach to the problem has been to wind the helices on the most accurate of available lathes. To obtain the quality of performance which the -hp- Traveling-Wave Amplifiers have, it was considered necessary to develop a new method for forming the helices. Such a method has been achieved in the realization of a new helix former devel-
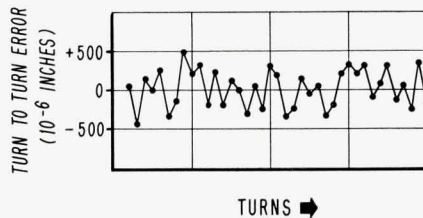

Fig. 3. *Plot of typical error in a precision lathe-wound helix.*

oped by Mr. R. A. Arms, Head of the -hp- Machining Department. The new machine departs from earlier methods in that it forms rather than winds helices.

A photograph of a highly-enlarged section of one of the helices formed on the new machine is shown in the accompanying illustration. While this photograph does not demonstrate the full accuracy of the helices, it is possible to see that no winding error can be discerned compared to the 7-mil wire from which the helix is formed. Further, the

helices exhibit no detectable periodicity. Because of this, the tubes have a smoother gain-frequency characteristic, while the tendency to self-oscillate is reduced.

The new machine forms helices with measured turn-to-turn accuracies of approximately ±50-millionths of an inch. The tolerance on these measurements is thought to be $\pm50 \times 10^{-6}$ inches, since it is possible to repeat measurements within this tolerance. The measurements are usually made over samples of an inch of helix at a time.

The helices are "set" by firing them in an oven. Firing reduces the accuracy of the helix somewhat, but because of the special characteristics of the forming machine the added error in firing is only equal to the forming error. Thus, the fired helices have turn-to-turn accuracies of ±100 $\times 10^{-6} \pm 50 \times 10^{-6}$ inches (approx.).
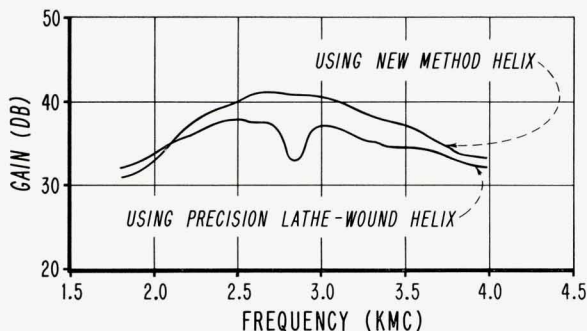

Fig. 1. *Helices formed by new methods typically give higher gains and smoother characteristics than precision lathe-wound helices as shown in above curves.*
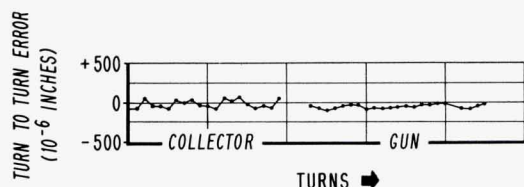

Fig. 2. *Error measured on typical helix formed by new method. Samples near gun and collector ends of helix are shown.*
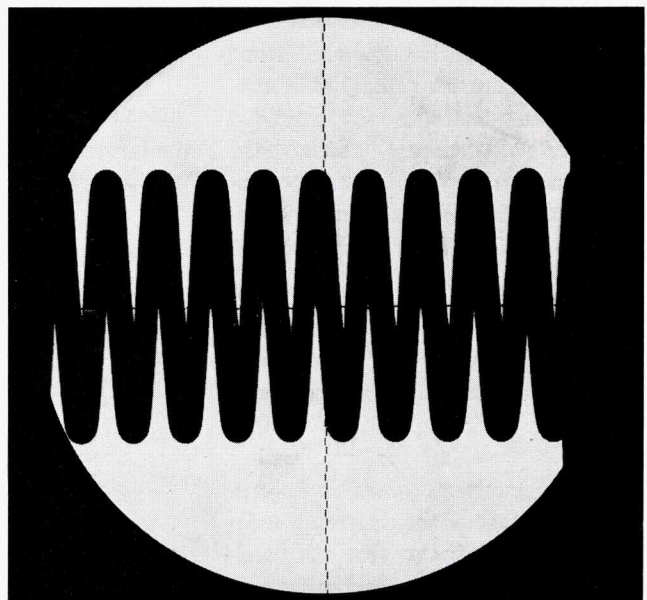

Fig. 4. *Enlarged view of helix formed by new method.*