also shown in Fig. 2, from which it is obvious that the errors resulting from the simplification are indeed negligible, even for $\mu > 0.1$.

V. SUMMARY AND DISCUSSION

The simplified design procedure can be summarized in terms of the following steps: first, from the specified μ, calculate r using (13); second, find d closest to, but greater than, $\pi/(r^{-1} - 1)$, satisfying (10); and third, find ϕ_0 closest to, but less than, $1.133\ (r/d)$, satisfying (14).

The limits on the array length and the corresponding beamwidth can be easily established as follows. In order to have the second null in the visible region Fig. 1(b) shows that $\pi/(l - d) < 1$, i.e., $l > \pi/(1 - r)$. Also, $d > \pi/(r^{-1} - 1)$. Thus the total array length will satisfy $2x_2 > \lambda/(1 - r)$ and the corresponding first null beamwidth will be given by $2\theta_n = 2 \sin^{-1}[\pi/(l + d)] < 2 \sin^{-1}[(1 - r)/(1 + r)]$. For example, $r = 1/3$ gives $2x_2 > 1.5\ \lambda$ and $2\theta_n < 60°$. If one wishes to reduce the sidelobe level further, r is to be reduced (see Fig. 2); this will result in a lower $2x_2$ and a higher $2\theta_n$. For example, $r = 1/4$ gives $2x_2 > 1.33\ \lambda$ and $2\theta_n < 73.8°$.

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Characteristics of 1 to 8 Wavelength Uniform Helical Antennas

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Abstract—**The measured voltage standing wave ratio (VSWR), gain, pattern, and axial ratio characteristics of a uniformly wound helical antenna are presented. Experimental parametric studies were made of 1) fixed length helices with variable diameter and pitch angle (8.6 to 10 turns), and 2) variable length helices with constant diameter and pitch angle (5 to 35 turns). Parametric curves are presented to show the gain and half-power beamwidth (HPBW) of a constant pitch helix as a function of axial length L/λ and circumference C/λ. Empirical expressions are derived for the antenna peak gain and bandwidth as a function of the helix parameters. In addition, the antenna gain-beamwidth products are examined.**

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I. INTRODUCTION

The basic concepts of an axial- or beam-mode helical antenna were established by Kraus [1], [2] in 1947 and summarized by Harris [3]. More recently, Maclean and Kouyoumjian [4], Maclean and Farvis [5], and Maclean [6] investigated the bandwidth characteristics and the low- and high-frequency limits for a class of helical antennas. The helical beam antenna is a very simple structure possessing a number of interesting properties including wideband impedance characteristics and circularly polarized radiation. Some measurements have been made to determine the characteristics of helical antennas [2], [4], [7]; however, wide bandwidth gain characteristics are generally not available in the open literature. The purpose of this note is to summarize the results of an extensive study [8] of the pattern and gain characteristics of helical antennas, 1 to 8 wavelengths long, in the UHF frequency range from about 650 to 1100 MHz. All the helices were wound with a uniform diameter. It is shown in a separate study [9] and [10] that by tapering the end of the helix, the voltage standing wave ratio (VSWR), pattern, and axial ratio characteristics can be improved over those of a completely uniform helix.

II. GENERAL DESCRIPTION

The antenna was made by winding 3/16-in diameter copper tubing around a styrofoam cylindrical form. The helix diameter is defined as the center-to-center distance of the copper wire. A 1.125-in diameter aluminum tubing was inserted coaxially into the foam to provide mechanical rigidity. A 10.3-in diameter by 5-in high circular cavity was used to back the helix, rather than a conventional ground plane. These cavity dimensions were found to be approximately optimum for a 10-turn helix. The overall length of the helix $= NS + L_F$, where N is the number of turns, S is the separation between turns, and L_F is the length of the feed strap ~ 0.8 in.

A 4.7-in long linear taper microstrip transformer, constructed from teflon–fiberglas printed circuit board and placed on the bottom of the cavity (inside), was used to match the helix impedance ($\sim 140\ \Omega$) to a $50\text{-}\Omega$ coaxial input [11]. The VSWR characteristics of the various helices tested are similar over the frequency range of interest. Generally, the VSWR measured at the input of the matching transformer is $<1.9:1$ over the 650 to 1100 MHz frequency range, and typically it is $\leqslant 1.5:1$.

Gain, pattern, and axial ratio measurements were made on a 30 to 60 ft antenna range. To minimize the parallax in the pattern measurements, the helix was rotated about the phase center which was estimated to be 1/4 the length of the helix from the feed point [12]. The phase center of the helix was also used as the spatial reference for the gain measurements. Measurements were made at several range distances to improve the accuracy; thus, the gain data presented herein represent a "smooth-fit" curve to many data points.

III. GAIN AND PATTERN CHARACTERISTICS

A. Fixed Length Helix

Parametric evaluations were made to establish the gain and pattern characteristics of a fixed length helix with 1) a variable pitch angle and a constant diameter, and 2) a variable diameter and a fixed number of turns ($N = 10$).

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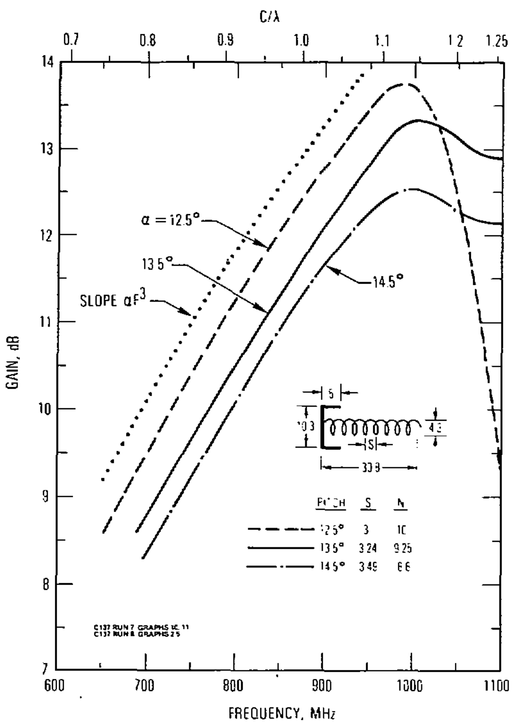

Fig. 1. Gain of 30.8-in length and 4.3-in diameter helix for pitch angles = 12.5°, 13.5°, and 14.5°.

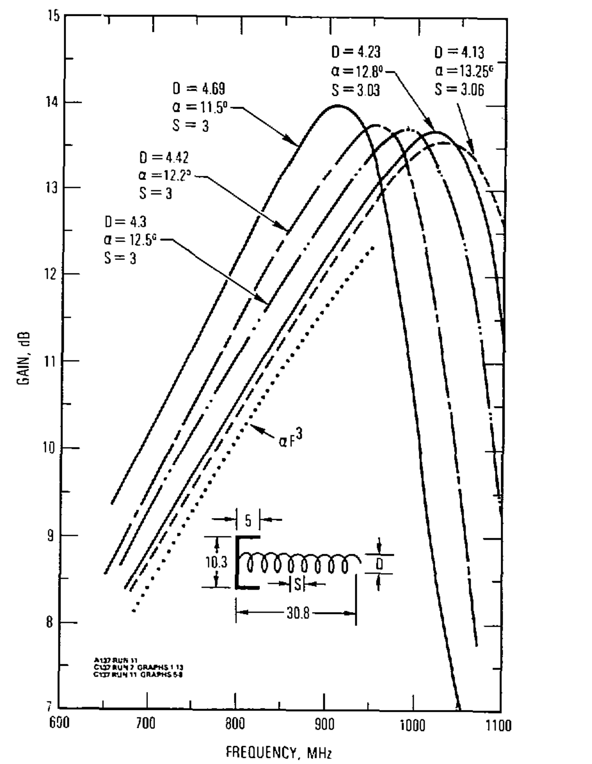

Fig. 2. Gain of fixed length (30.8 in) helical antenna for various diameters.

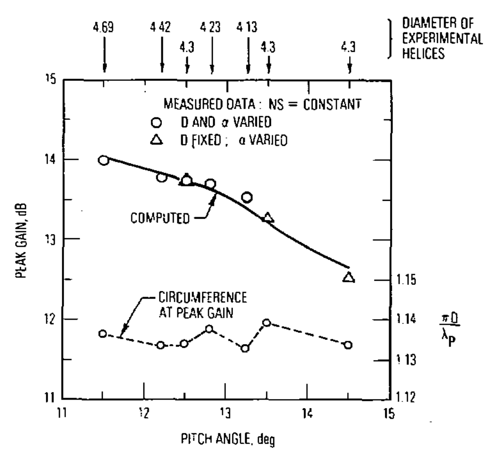

Fig. 3. Peak gain of fixed length helix (NS = 30 in) as function of pitch angle.

The gain versus frequency characteristics of a 30.8-in long and 4.3-in diameter helix are shown in Fig. 1 for three helix pitch angles ($\alpha = 12.5°$, $13.5°$, and $14.5°$). The 30.8-in length dimension includes 0.8 in for the feed strap. The helix with a smaller pitch angle (more turns per unit length) yields a higher peak gain and a lower cutoff frequency. To illustrate the frequency dependence, the dotted line shows a gain-frequency slope proportional to f^3, where f = frequency. Thus, it appears that the gain-frequency characteristics of Fig. 1 with $N = 8.6$ to 10 turns are in general agreement with Kraus [1], [2] for $C/\lambda < 1.1$. However, as will be shown later, experimental data indicate that the gain-slope depends on the antenna length and is approximately proportional to $f^{\sqrt{N}}$.

Fig. 2 shows the gain characteristics of a 30.8-in long helix ($N \approx 10$ turns) with variable diameter and pitch angle. The peak gains are within a few tenths of a decibel. In general, a slightly higher peak gain is observed for a larger diameter helix with a smaller pitch angle, but the bandwidth is narrower than a smaller diameter helix with a larger pitch angle.

Based on the gain data of Figs. 1 and 2, the peak gain may be empirically expressed as

$$G_p = 8.3\left(\frac{\pi D}{\lambda_p}\right)^{\sqrt{N+2}-1}\left(\frac{NS}{\lambda_p}\right)^{0.8}\left[\frac{\tan 12.5°}{\tan \alpha}\right]^{\sqrt{N}/2} \tag{1}$$

where λ_p is the wavelength at peak gain and α is the pitch angle. Note that $S = \pi D \tan \alpha$ and for a fixed length helix, NS is constant. The computed values are within ±0.1 dB of the measured data as depicted in Fig. 3. The data points indicated by the circle were obtained by varying the diameter and pitch angle while keeping the length constant with $N \approx 10$ turns, and those indicated by the triangle were obtained by varying the pitch angle while keeping the length and diameter constant ($N \approx 8.6$ to 10 turns). The diameters of the various experimental helices are shown on the top of the figure. It is interesting to note that, for these fixed length helices, the peak gains occur at nearly the same circumference $\pi D/\lambda \sim 1.135$.

Radiation patterns were measured at selected frequencies across the band [8]. Rather than presenting measured patterns, the half-power beamwidths (HPBW's) are plotted in Fig. 4 for the 4.3-in diameter helix with variable pitch angles (12.5°, 13.5°, and 14.5°). A slope proportional to $f^{-3/2}$ is shown for reference.

To provide parametric design equations for helices, Kraus [2] has suggested the following relations for the gain and HPBW as a function of C/λ and L/λ for constant pitch helices

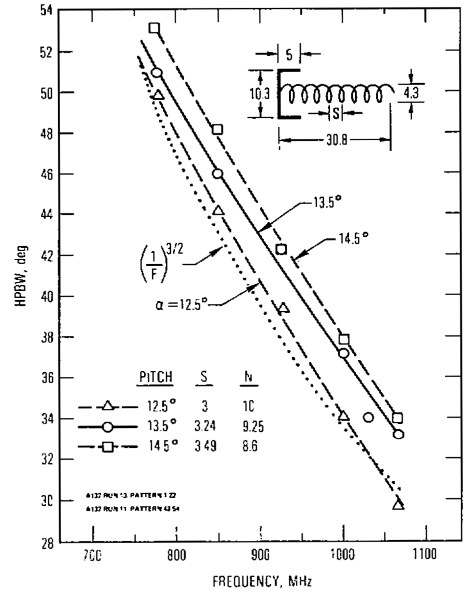

Fig. 4. Half-power beamwidths of 30.8-in length and 4.3-in diameter helix for pitch angles = 12.5°, 13.5°, and 14.5°.

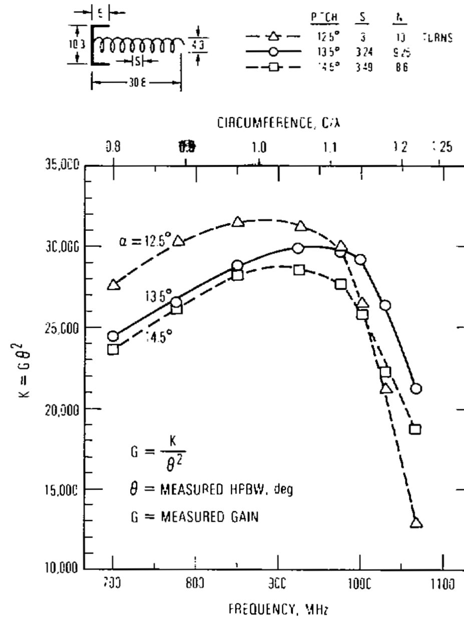

Fig. 5. Gain-beamwidth product for various pitch angles based on 30.8-in length, 4.3-in diameter experimental helix.

with $12^\circ < \alpha < 15^\circ$, $3/4 < C/\lambda < 4/3$, and $N > 3$:

$$G = K_G (C/\lambda)^2 (L/\lambda) \tag{2}$$

$$\mathrm{HPBW} = \frac{K_B}{\left(\dfrac{C}{\lambda}\right)\sqrt{L/\lambda}} \tag{3}$$

where K_G is the gain factor, K_B is the HPBW factor, $C = \pi D$ is the circumference, and $L = NS$ is the axial length. Based on a large number of pattern measurements, Kraus has quasi-empirically established $K_B = 52$. Also, he derived $K_G = 15$ for the directive gain (lossless antenna) based on the approximation $G = 41\,250/\theta^2$, where θ is the HPBW in degrees. A gain-beamwidth product $G\theta^2 < 41\,250$ is generally expected for most practical antennas [13] because of minor lobe radiation and beam shape variations.

For the fixed length helices consisting of 8.6 to 10 turns, the measured HPBW factors vary from about 61 to 70, compared with Kraus' empirical value of 52 for $0.8 < C/\lambda < 1.2$, and the gain factors, varying from about 4.2 to 7.7 over the same C/λ range, are considerably lower than Kraus' estimated value of 15 [8]. Also, it should be mentioned that further experimental results indicate that the gain and HPBW factors [(2) and (3)] depend on the design parameters and are relatively constant only for helices with approximately 10 turns.

The empirical values of the gain-beamwidth product as derived from the curves of Figs. 1 and 4 are shown in Fig. 5. For $0.8 < C/\lambda < 1.16$, the gain-beamwidth product varies from 24 000 to 31 500 as compared with 41 250 when the minor lobes are neglected. It appears that a higher value is attained for a helix with a smaller pitch angle.

The axial ratio characteristics were measured by using a rotating linearly polarized source. Generally, the measured axial ratio is less than 1.5 dB for $0.8 < C/\lambda < 1.2$. The axial ratio can be improved by tapering the last two turns of the helix, paticularly at the high end of the band [9].

B. Variable Length Helix

Measurements were made to establish the gain and pattern characteristics of a constant pitch helix consisting of 5 to 35 turns. A 4.23-in diameter helix was selected so that the antenna would operate over the UHF test frequencies with a helix circumference ranging from about 0.75 λ to 1.25 λ. A 12.8° pitch angle was chosen, which corresponds to a spacing $S = 3.03$ in. N was selected as 5, 10, 12, 15, 18, 22, 26, 30, and 35 turns.

Gain versus frequency for the various values of N are plotted in Fig. 6. The gain is referred to a circularly polarized illuminating source. The gain curves reveal that the peak gain occurs at $C/\lambda = 1.155$ for $N = 5$ and decreases to $C/\lambda = 1.07$ for $N = 35$. For reference, the dotted lines provide an estimate of the gain variations with frequency; e.g., for $N = 5$ the gain varies approximately as $f^{2.5}$, and for $N = 35$ the gain follows approximately a f^6 slope, where f is the frequency. Note that the measured gain slope is proportional to f^3 only when N is approximately 10 turns (see Fig. 1).

Fig. 7 is a plot of the peak gain versus the number of turns for the 4.23-in diameter helix. The corresponding values of C/λ_p are also shown in the figure, where λ_p is the wavelength at peak gain. The peak gain is not quite proportional to the number of turns; i.e., doubling the number of turns does not yield a 3 dB increase in the peak gain. The computed values for the peak gain, using (1) with $\alpha = 12.8^\circ$ and $N = 5$ to 35 turns, are compared with the measured data in Fig. 7. The deviation is within ±0.1 dB.

The gain-frequency response or bandwith is of practical interest. For the purpose of this study, the bandwidth was analyzed by defining an allowable gain drop with respect to the peak gain, which in turn determines the frequency range. Fig. 8 depicts the 3 dB and 2 dB bandwidths as a function of N. The choice between a 3 dB or 2 dB bandwidth would depend upon the particular application in question. If we denote the upper and lower frequencies by f_h and f_l, respectively, then the bandwidth in percent may be expressed

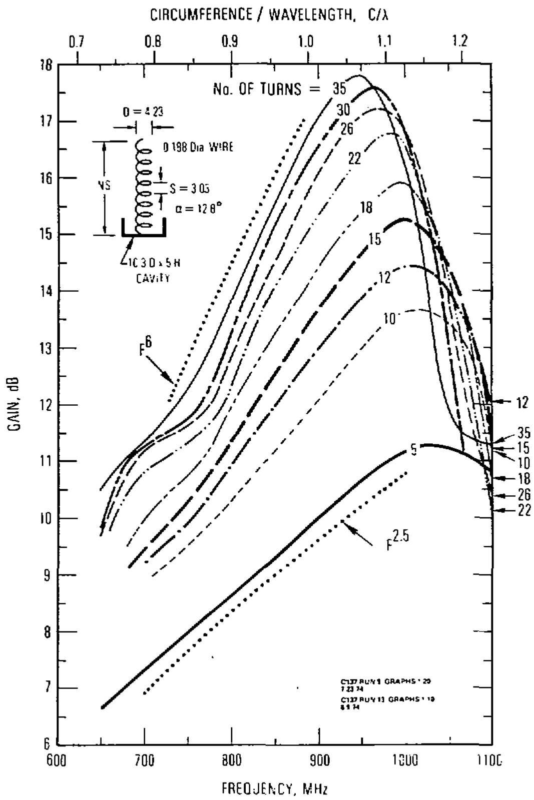

Fig. 6. Antenna gain versus frequency for 5- to 35-turn helical antennas, 4.23-in diameter.

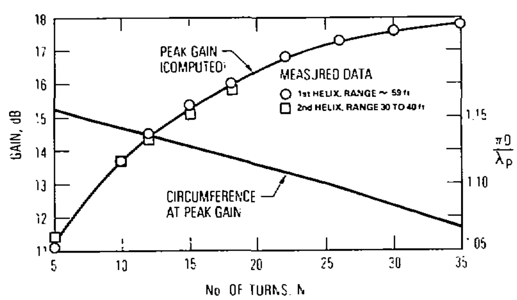

Fig. 7. Peak gain characteristics of 4.23-in diameter, 5- to 35-turn helix; $\alpha = 12.8°$.

as

$$B = \frac{f_h - f_l}{\left(\dfrac{f_h + f_l}{2}\right)} \times 100 \text{ percent}. \tag{4}$$

The frequency limits f_h and f_l may be determined by using the measured gain data of Fig. 6. Also, we note that the gain varies approximately as $f\sqrt{N}$, for $f < f_p/1.04$, and as $f^{-3\sqrt{N}}$, for $f > 1.03\ f_p$, where f_p is the frequency at peak gain. Based on these observations, the bandwidth frequency ratio may be empirically expressed as [8]

$$\frac{f_h}{f_l} \approx 1.07\left(\frac{0.91}{G/G_p}\right)^{4/(3\sqrt{N})} \tag{5}$$

where G_p is the peak gain from (1). The computed bandwidth characteristics for $G/G_p = -3$ dB and -2 dB agree reasonably well with the measured data as shown in Fig. 8. The bandwidth decreases as the axial length of the helix increases.

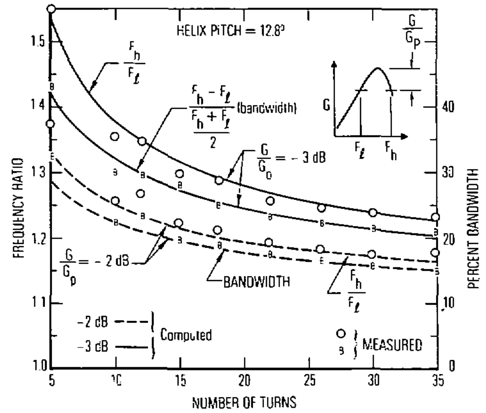

Fig. 8. Bandwidth characteristics of 4.23-in diameter 5- to 35-turn helix.

This bandwidth behavior follows the same trends described by Maclean and Kouyoumjian [4], although these authors employ a sidelobe criterion rather than a gain criterion. Beyond the -3 dB point (with respect to the peak), the gain drops off sharply at the high-frequency end as the upper limit for the axial mode is approached.

Typical measured radiation patterns for $N = 5$, 10, 18, and 35 are shown in Fig. 9. The axial ratio is ~1 dB over most of the measurement frequency range and is slightly higher at the band edges. The HPBW's derived from the complete set of patterns [8] are plotted in Fig. 10 with N as a parameter. The HPBW's are generally within ±1° in the two principal planes ($\phi = 0°$ and 90°). At frequencies a few percent above the peak gain frequency, the patterns begin to deteriorate. The beamwidth broadens rapidly, and the first sidelobes merge in with the main lobe as the operating frequency approaches the upper limit.

By using the measured data from the 4.23-in diameter, constant pitch helices with $\alpha = 12.8°$ and $N = 5$ to 35, parametric helix characteristic curves were derived for the antenna gain and half-power beamwidth. Figs. 11 and 12 show the antenna gain and HPBW, respectively, as a function of axial length NS/λ with circumference $\pi D/\lambda$ as a parameter. Thus, for a specified length and diameter the helix gain and HPBW can be estimated.

Fig. 13 depicts the gain-HPBW product $K = G\theta^2$ based on the measured gain data of Fig. 6 and the HPBW data of Fig. 10. This quantity is useful for estimating the gain when the HPBW is known, and vice versa. The gain-HPBW product is not constant but depends on N and frequency. All curves have been smoothed to within ±5 percent of the data points.

IV. CONCLUSION

Based on a large number of gain and pattern measurements, the performance characteristics have been established for a variety of helical antenna configurations. Parametric curves relating gain, HPBW, circumference C/λ, and axial length NS/λ were derived and presented. Empirical expressions were derived for the antenna peak gain and bandwidth as a function of frequency and the helix design parameters. Generally, the peak gain occurs at a circumference C/λ that depends on the axial length, ranging from $C/\lambda \sim 1.07$ for a 35-turn helix to $C/\lambda \sim 1.15$ for a 5-turn helix. For $C/\lambda < 1$, the gain-frequency slope varies approximately as $f\sqrt{N}$. At frequencies a few percent above the peak gain frequency, the gain drops off sharply ($\propto f^{-3\sqrt{N}}$), and the pattern characteristics deteriorate rapidly as the helix upper frequency limit is approached. For

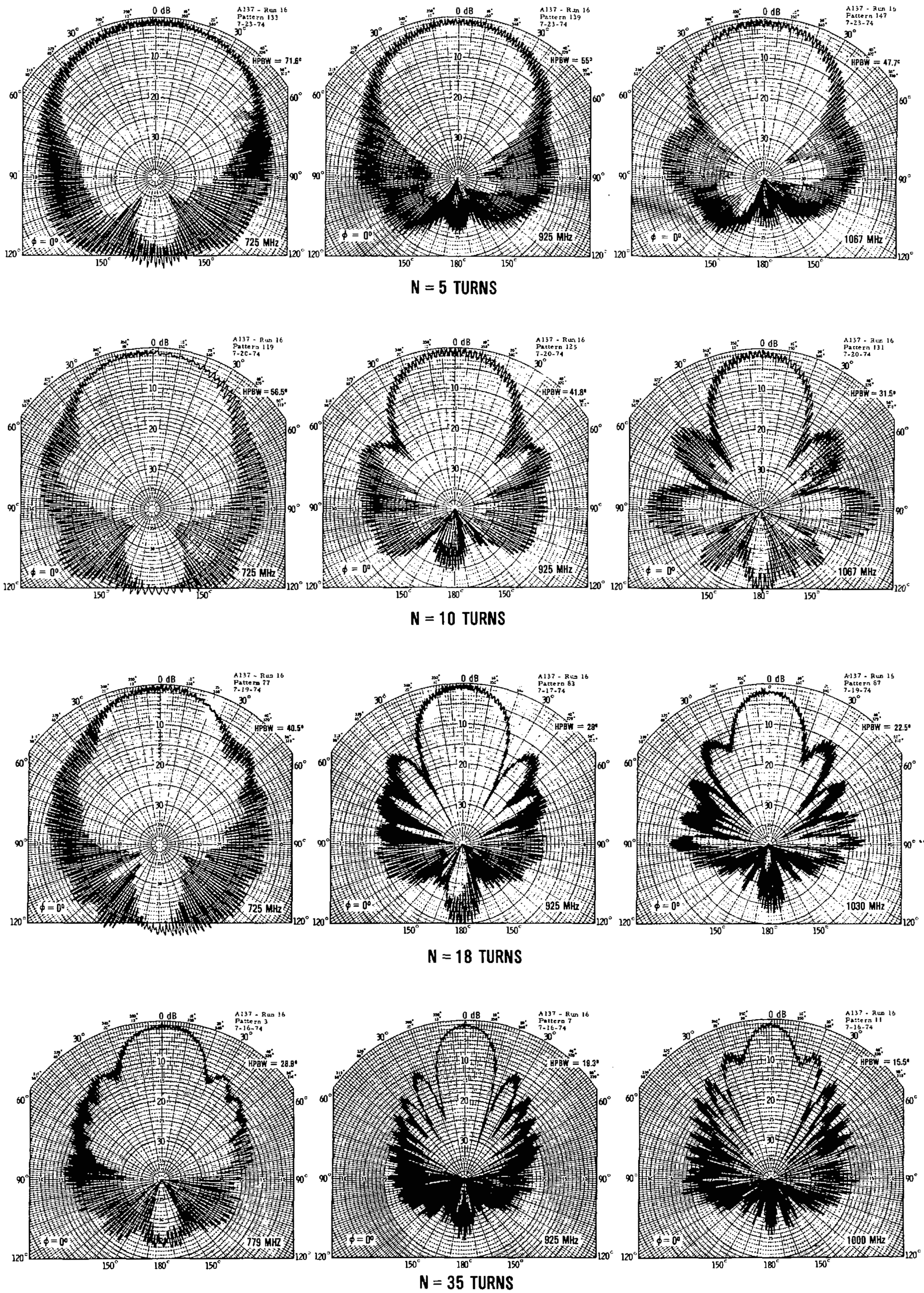

Fig. 9. Typical radiation patterns of 5-to 35-turn helix, 4.23-in diameter and 12.8° pitch angle (S = 3.03 in).

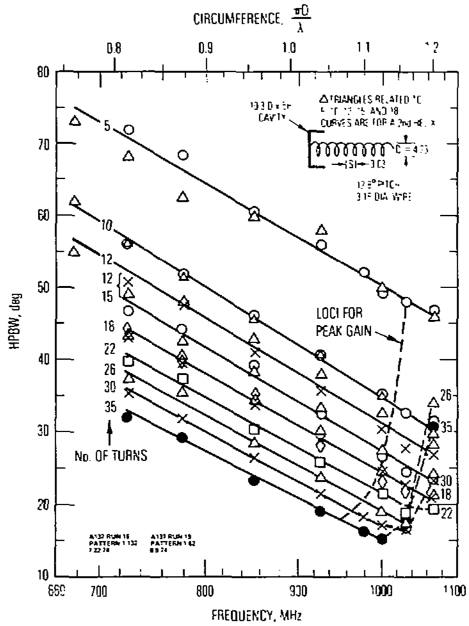

Fig. 10. Half-power beamwidths of 4.23-in diameter 5- to 35-turn helix.

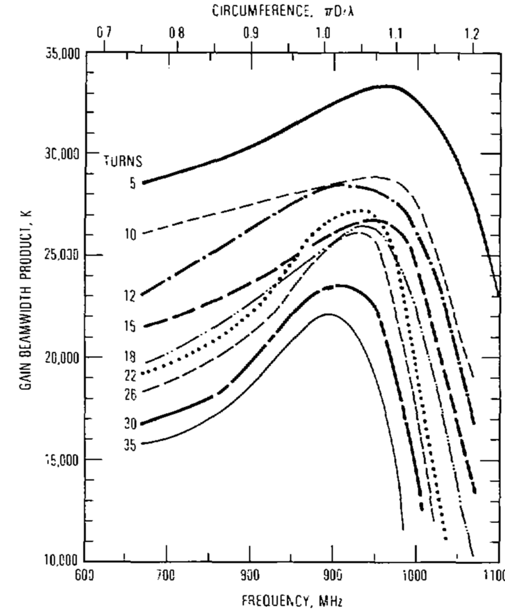

Fig. 13. Gain-beamwidth products of 4.23-in diameter, 5- to 35-turn helical antennas; $\alpha = 12.8°$.

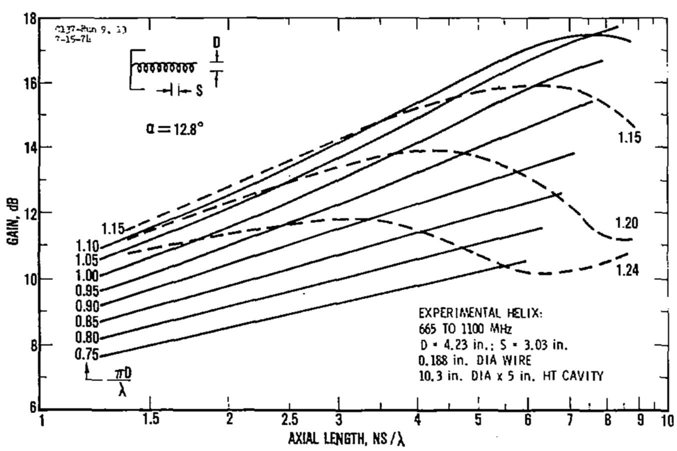

Fig. 11. Parametric helix antenna gain curves as function of axial length with circumference as parameter.

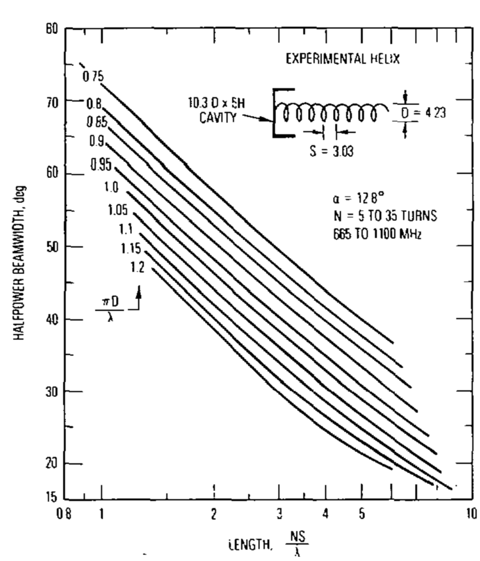

Fig. 12. Helix antenna parametric half-power beamwidth curves as function of axial length with circumference as parameter.

a fixed diameter and length, a higher gain can be achieved with a smaller pitch angle, but a higher upper frequency limit is attained with a larger pitch angle. The bandwidth, when defined by the frequencies where the gain is 3 dB below the peak gain, narrows as the axial length increases, ranging from ~42 percent for $N = 5$ to 21 percent for $N = 35$.

The gain-beamwidth product, which is often of interest, is not constant and depends on the axial length and frequency. A larger value is attained with shorter length helices. On the average, the gain-beamwidth product varies from 18 000 for $N = 35$ and $0.75 < C/\lambda < 1.1$ to 31 000 for $N = 5$ and $0.75 < C/\lambda < 1.2$.

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