Computationally Generated Velocity Taper for Efficiency Enhancement in a Coupled-Cavity Traveling-Wave Tube

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Abstract—A computational routine has been created to generate velocity tapers for efficiency enhancement in coupled-cavity traveling-wave tubes (TWTs). Programmed into the NASA multidimensional large-signal coupled-cavity TWT computer code, the routine generates the gradually decreasing cavity periods required to maintain a prescribed relationship between the circuit-phase velocity and the electron-bunch velocity. Computational results for several computer-generated tapers are compared to those for an existing coupled-cavity TWT with a three-step taper. Guidelines are developed for prescribing the bunch-phase profile to produce a taper for high efficiency. The resulting taper provides a calculated RF efficiency 45 percent higher than the step taper at center frequency and at least 37 percent higher over the bandwidth.

I. INTRODUCTION

It is well known that in a properly designed traveling-wave tube (TWT), electron bunches form in the decelerating phase of the circuit electric field. As each bunch is decelerated, its energy is transferred to the circuit wave which continues to grow until either the electrons slip back into an accelerating field or the bunch dissipates due to space-charge effects. In order to prolong the energy extraction process and obtain a high RF power efficiency, the bunch and circuit wave must travel at synchronous or near-synchronous velocities. This is most easily achieved by decreasing the circuit period to slow its phase velocity in step with the decelerating electrons for as long a distance as possible. The problem which this paper addresses is how to determine a velocity taper profile to obtain a high efficiency for a given coupled-cavity TWT.

An early analytical approach to designing velocity tapers for improved efficiency was the "hard-kernel bunch" theory [1], [2]. In this theory, it is assumed that all the charge per beam wavelength is concentrated at a position in the center of the bunch. The circuit period is then decreased at the proper rate to keep the hard-kernel bunch located at the maximum decelerating phase of the circuit field. In order to obtain a closed-form solution for the circuit amplitude and phase, it is necessary to ignore space-charge, velocity spread, and radial circuit and beam variations. Thus it is not surprising that, although considerable improvements in efficiency over nontapered circuits were achieved, the experimental results did not agree well with theory.

Consequently, most helical TWT velocity tapers designed have been simply linear [3], [4], and most coupled-cavity TWT velocity tapers have been either linear or step tapers with up to three constant period sections [5]-[7]. Although not optimized, these tapers have been very successful in increasing efficiency.

Another analytical approach is the "dynamic velocity taper" approach for helical TWT's [8]. This taper improves the linearity of the power-transfer characteristics while also significantly improving efficiency. The theory prescribes an exponential decrease in helix pitch. A helical TWT computer model is used to find the parameters involved in the exponential pitch function that results in the highest efficiency.

An approach more in spirit with that of the hard-kernel bunch theory is taken in this paper. The keys to designing a taper for high efficiency are to form a strong, tight electron bunch, and to maintain the bunch in a strong decelerating electric field. However, in this paper, unlike in the hard-kernel bunch approach, space-charge, velocity spread, and radial circuit and beam variations are incorporated into the calculation by using a sophisticated multidimensional computer model. The model is used to determine the electron bunch phase and velocity and the gradually changing cavity lengths required to maintain a prescribed synchronism between the circuit signal and the electron bunch. By computing the TWT performance over a range of two input parameters, a computer-generated velocity taper that provides high efficiency can be obtained.

II. ANALYSIS

A one-dimensional large-signal computer model for coupled-cavity TWT's based on the formulation of Vaughan [5] was developed by the NASA Lewis Research Center in the 1970's [9], [10]. In 1984, O'Malley [11] expanded the model to what is generally referred to as two-and-a-half dimensions by simulating a two-dimensional circuit field and an electron beam with axially symmetric rings of electric charge which have axial, radial, and azimuthal velocity components. The model has since
been further refined and revised [12] and computational results were shown to agree very well with experiment.

In this model, the electron beam is divided into a series of disks, each of which is further divided into a maximum of four axially symmetric rings (the innermost ring is a disk). The rings rotate azimuthally and expand and contract radially, penetrating each other in both the radial and axial directions. The trajectories of the electron rings and the circuit fields are determined from the calculated axial and radial space-charge, circuit, and magnetic forces as the rings pass through a sequence of cavities. Each cavity has independently entered geometrical and electrical parameters. This enables the model to simulate severs, voltage jumps, and velocity taper designs. Backward wave, space-charge, and relativistic effects are included. The multidimensionality of the model allows it to simulate cathode flux and solenoid or periodic permanent magnet (PPM) focusing. Solutions are obtained iteratively by alternately making forward and backward integrations through the cavities until convergence of the circuit amplitude and phase is obtained. In order to define the bunching of the electron beam, the program does a Fourier analysis of the charge contained in the electron rings. The bunch magnitude and position are given by the fundamental Fourier component calculated at the gap center of each cavity.

When the model is used to generate a velocity taper, all the cavities are assumed to be of the standard pre-taper period in the first forward and backward passes through the TWT. In succeeding forward passes, the period of taper cavity \( n + 1 \) is calculated when the integration is at cavity \( n \) as described in the following: The degree of synchronism between the circuit-phase velocity and the bunch velocity is prescribed by choosing a value for Pierce’s velocity parameter \( b \), defined in the relationship

\[
v_{n+1} = \frac{u_{n+1}}{1 + bC}
\]

where \( v_{n+1} \) and \( u_{n+1} \) are, respectively, the circuit-phase velocity and electron-bunch velocity at cavity \( n + 1 \). \( C \) is Pierce’s gain parameter [13]

\[
C = \left(\frac{KI}{4V}\right)^{1/3}
\]

where \( K \) is the beam-interaction impedance, \( I \) the beam current, and \( V \) the beam voltage. By definition, the circuit-phase velocity at cavity \( n + 1 \) is given by

\[
v_{n+1} = \frac{\omega L_{n+1}}{(\beta L)_{n+1}}
\]

where \( \omega \) is the angular frequency, \((\beta L)_{n+1}\) is the circuit wave phase shift, and \( L_{n+1} \) is the period of cavity \( n + 1 \) to be determined.

Combining (1) and (3) gives

\[
L_{n+1} = \frac{(\beta L)_{n+1} u_{n+1}}{\omega(1 + bC)}.
\]

In (4), \( \omega \) and \( b \) are constants and \( C \) is a slowly varying quantity given by (2). The value for \((\beta L)_{n+1}\) is estimated from a third-order polynomial least squares curve fit made through the circuit wave phase shift per cavity values calculated at cavities \( n - 3 \) through \( n \) and the values calculated at cavities \( n + 1 \) through \( n + 5 \) in the previous pass. From this the circuit wave phase shift per cavity is interpolated at the center of cavity \( n + 1 \). A similar interpolation gives an estimation for the bunch velocity at cavity \( n + 1 \).

Once the length of cavity \( n + 1 \) has been estimated, its gap length, interaction impedance, and attenuation loss must be determined. It was assumed that the gap-to-cavity length ratio is equal to that in the standard pre-taper cavity, 0.304. Data from the CTS TWT [9] indicates that to a good approximation, the interaction impedance decreases proportionally to the cavity period to the \( 3/2 \) power and that the attenuation loss increases at the same rate. Thus

\[
K_{n+1} = K_0 \left(\frac{L_{n+1}}{L_0}\right)^{3/2}
\]

and

\[
\alpha_{n+1} = \alpha_0 \left(\frac{L_0}{L_{n+1}}\right)^{3/2}
\]

where \( L_0, K_0, \) and \( \alpha_0 \) are, respectively, the period, interaction impedance, and attenuation loss of a standard pre-taper cavity. (These relationships for impedance and attenuation loss are not generally applicable, but are dependent on the gap and cavity dimensions for a particular TWT. To generate a taper for a TWT with different gap ratios, the appropriate exponents in (5) and (6) must be determined.)

Because the cavity period, circuit wave phase shift, and bunch velocity are interrelated, a number of iterations through the length of the taper are required for convergence of the solution. Typically, the number of iterations needed is about equal to the number of cavities in the taper.

III. RESULTS AND DISCUSSION

The velocity taper design formulation of the previous section was tested against the design of the Communications Technology Satellite (CTS) TWT [6], which is a 200-W X-band coupled-cavity TWT with 58 cavities in three sections separated by severs. Beginning with cavity 40 in the output section of the CTS TWT, there are three velocity taper steps separated by transition regions in which the cavity period length changes approximately linearly (see Fig. 3 given later). The cavity dimensions are given in [9] as well as the experimentally obtained attenuation loss, cold-phase shift, and interaction impedance per cavity over 0.05 GHz intervals from 12.00 to 12.20 GHz. In Fig. 1, it is seen that the efficiency is simulated very well over the bandwidth with the computer model.
The CTS TWT is an interesting test case with which to compare the velocity taper design formulation because its strongly tapered output section enhances RF efficiency (circuit power divided by initial beam power) to a high degree (Fig. 1). Even greater improvements in efficiency can be achieved with a taper calculated according to the formulation of the previous section. These computer-generated tapers will be referred to as "phase-adjusted tapers" (PAT's). Shown in Fig. 1 is the optimal PAT design which gives a significant improvement in efficiency above that achieved by the CTS taper over the entire bandwidth. This design will be discussed in Section III-B.

A. Synchronous Phase-Adjusted Tapers

The first PAT designs attempted maintained the circuit electric field in synchronism with the electron bunch \( (b = 0 \text{ in (1)}) \). Fig. 2 shows the efficiency as a function of the initial cavity of the taper, with the highest efficiency occurring when the taper begins at cavity 38. In order to understand the reason why beginning a synchronous PAT at cavity 38 maximizes the efficiency, tapers beginning at cavities 36, 38, and 40 will be examined in more detail. The notation that will be used throughout the rest of this paper for a phase-adjusted taper is PAT \( (I, b) \), where \( I \) is the initial cavity of the taper, and \( b \) is Pierce's velocity parameter defined by (1). In Fig. 3, the cavity periods for PAT \( (36,0) \), \( (38,0) \), and \( (40,0) \) are compared to those for the CTS TWT as a function of axial distance in the output section. The symbols on the curves indicate the locations of the individual cavities, beginning in each case at cavity 32. The curves for the tapers end at their saturation cavities except for PAT \( (40,0) \), which continues for an additional ten cavities beyond the scale of the figure.

The calculated efficiencies of the PAT's as a function of distance are shown in Fig. 4, along with those with no taper and the CTS taper. It is seen that the CTS taper gives a fourfold increase in efficiency over the calculated no taper case. PAT \( (36,0) \) gives a more rapid increase in efficiency than the CTS taper and saturates at a slightly larger efficiency and length. The highest efficiency synchronous PAT which begins at cavity 38 requires almost 3 cm more in length to saturate than the CTS taper, but gives a much higher efficiency. PAT \( (40,0) \) with the gentle taper correspondingly gives a gentle increase in ef-
ficiency. It does not saturate until achieving a length of about 6 cm beyond the CTS saturation cavity (off the scale of Fig. 4) at 29.1 percent, surpassing the 25.7 percent efficiency of the CTS taper but still below the PAT (38,0,) efficiency of 34.8 percent.

The bunch velocity (axial-phase velocity of the fundamental Fourier component of beam current) normalized with respect to the initial axial velocity is displayed in Fig. 5. The bunch velocity for each taper decreases as the bunch gives up energy to the circuit wave. The bunch velocity does not decrease monotonically towards the end of the output section but shows a minor superimposed oscillatory behavior. This is due to space-charge effects as the bunching amplitude increases. Comparing Fig. 5 to Fig. 4, it is seen that the rate of decrease in bunch velocity of a taper is directly related to the rate of increase in efficiency.

In Fig. 6(a) through (f) the phases of the electron disks with respect to the circuit voltage are shown. For the sake of clarity in these figures the model was run with 24 electron disks per wavelength rather than the usual 72 rings per wavelength. The thick line in each figure represents the phase of the electron bunch. Electron disks between 0° and +180° are decelerated, with the maximum deceleration at +90°. Disks between -180° and 0° are accelerated, with the maximum acceleration at -90°. In each figure (except Fig. 6(e)), the disk phases are shown to the saturation cavity.

Fig. 6(a) shows the case with no taper, where it is seen that saturation occurs very quickly. The favorably phased (0° to +180°) disks at the beginning of the section steadily decrease in phase until at saturation about half the electron disks are in an accelerating phase.

The vertical dashed lines in Fig. 6(b) through (f) indicate the beginning of the taper. In Fig. 6(b) the CTS taper begins at cavity 40. In the pre-taper region, the bunch-velocity phase decreases smoothly from 90° to about 20°. The electron disks are converging in this region as the bunch-current amplitude increases. The phase of the bunch with respect to the circuit wave increases in the taper region and approaches 90° where maximum deceleration of the electron bunch occurs. By decreasing the circuit-phase velocity in the CTS taper, more of the electron disks are kept in a decelerating phase for a longer distance and give up much more energy to the circuit than in the no-taper case. However, the CTS taper decreases too rapidly for some of the electron disks. In Fig. 6(b), it is seen that 11 of the 24 electron disks reach a velocity with respect to the bunch that is too fast to remain in a decelerating phase. Thus the bunch weakens with length until it is quite weak at the saturation cavity.

Fig. 6(c) shows the disk phases of PAT (36,0,). Because the cavity periods are prescribed in such a way as to keep the circuit-phase velocity equal to the bunch velocity, the phase of the bunch velocity with respect to the circuit-phase velocity remains approximately equal to the value at the beginning of the taper, 60°. A disadvantage of this taper is that it begins before a strong bunch has formed. Comparing Fig. 6(c) to (b), it is seen that the electron disks have converged less in the pre-taper region of PAT (36,0,) than in the CTS design. The degree of convergence, which is a measure of the bunching strength, remains weaker throughout PAT (36,0,).

The advantage of PAT (36,0,) over the CTS taper is that, throughout most of the output section, the bunch phase is closer to the maximum decelerating phase of 90°. PAT (36,0,)’s advantage of superior phase throughout most of the output section overcomes its disadvantage of weaker bunching at the beginning, and thus its saturation efficiency is slightly higher than that of the CTS taper. The highest efficiency synchronous taper starts at cavity 38, with the disk and bunch velocity phases shown in Fig. 6(d). The bunch phase is about 35° throughout the taper. Since the taper begins two cavities before the CTS taper begins, the initial bunching is not quite as strong. However, the bunching remains intact for a greater length. The circuit does not saturate until 2.5 cm beyond the saturation cavity of the CTS design, and this longer interaction allows the circuit wave to grow considerably more, with the saturation efficiency significantly higher than in the CTS. An indication of the superior bunching is that only eight disks escape to an unfavorable phase (> +180°).

The reason that the bunch remains intact longer is that the bunch phase is closer to 0° throughout most of the taper. Thus more electron disks are between the maximum decelerating phase of +90° and the maximum accelerating phase of -90°. The disadvantage of this design is that because the bunch phase is farther from the maximum decelerating phase of +90° than in the CTS taper, the circuit wave does not grow as quickly, as can be seen in Fig. 4.

This effect can be seen even more clearly in PAT (40,0,). Fig. 6(e) shows the disk and bunch phases for the synchronous PAT beginning at cavity 40. The bunch remains at a phase of about 15° throughout the taper. This provides for outstanding bunching, as almost all electron disks remain between +90° and -90° and only three disks are lost to unfavorable phase up to a length of 20 cm. The circuit wave does not saturate until at a length of 22.552 cm (beyond the scale of Fig. 6(e)) with an efficiency about halfway between that of CTS and PAT (38,0,). Despite the outstanding bunching, the disadvan-
Fig. 6. Electron disk and bunch (thick line) phase with respect to circuit for (a) no taper, (b) CTS taper, (c) PAT (36.0.), (d) PAT (38.0.), (e) PAT (40.0.), and (f) PAT (40.0.15). The vertical dashed lines indicate position of initial taper cavity.

The advantage of this taper is that the bunch is only weakly decelerated because its phase is close to 0°.

B. Nonsynchronous Phase-Adjusted Taper

From the previous discussion, there are two features of the bunch phase which play important roles in a taper design for maximum efficiency. The first is that in order to form a strong bunch, the bunch phase needs to be positioned close to 0°. This was best exemplified by PAT (40.0.) of Fig. 6(e). The second feature is that the bunch needs to be positioned close to 90° to achieve a large degree of deceleration. This was best exemplified by PAT (36.0.) of Fig. 6(c). In a synchronous PAT where the bunch phase remains constant, the best results were obtained by a compromise between these two qualities, with the bunch phase about halfway between 0° and 90°. This was achieved with PAT (38.0.) of Fig. 6(d) which gave a significant improvement in efficiency over CTS.

However, in order to best utilize these two bunch-phase features, a nonsynchronous (b ≠ 0) PAT design is required. If the cavity periods are specified in such a way that the circuit-phase velocity is slightly less than the electron-bunch velocity, i.e., a small positive value of Pierce’s b parameter, the phase will slowly increase in
ment computationally demonstrated in this paper suggest a five-fold increase over the computed efficiency for a...eration and energy extraction at the end of the taper. This...NASA contract, "Study of Methods for the Reduction of TWT with no taper and 45 percent higher than that of the... incorporate into the last Ka-band ferruleless coupled-cavity...understanding was used to design a highly efficient nonsynchronous PAT which has a circuit-phase velocity parameter are chosen, the model calculates the gradually changing cavity periods required to maintain the desired synchronism between the circuit wave and the electron bunch.

Computational results for these "phase-adjusted tapers" were compared to those for the CTS TWT, which has a three-step taper design. Three synchronous PAT designs were examined in detail to provide a physical understanding of the bunching and energy extraction mechanisms. This understanding was used to design a highly efficient nonsynchronous PAT which has a circuit-phase velocity slightly less than that of the bunch velocity. This allows the electron bunch to gradually move from a phase that provides for good bunch formation at the beginning of the taper to a phase that results in strong bunch deceleration and energy extraction at the end of the taper. This PAT was computationally shown to have an RF efficiency of 34.8 percent at center frequency. This was more than a five-fold increase over the computed efficiency for a TWT with no taper and 45 percent higher than that of the CTS TWT at center frequency.

The PAT concept will be experimentally tested with the NASA contract, "Study of Methods for the Reduction of Distortion in High-Power TWT's," with the Hughes Aircraft Company. A NASA designed PAT will be incorporated into the last Ka-band ferruleless coupled-cavity TWT built in this program.

The very encouraging results of efficiency enhancement computationally demonstrated in this paper suggest several avenues of future study. One possibility would be to determine guidelines for choosing the combination of beam parameters, phase-adjusted taper, and a multistage depressed collector that would result in the highest overall efficiency. Another is to study the relationship of beam parameters and PAT's to phase-distortion characteristics. Finally, the PAT concept could be used to explore efficiency enhancement in helical TWT's.

IV. CONCLUSIONS

A computational routine has been created for the NASA multidimensional large-signal coupled-cavity TWT computer code to generate cavity-length tapers that maintain a specified relationship between the circuit-phase velocity and the electron-bunch velocity. Once the initial taper cavity and Pierce velocity parameter are chosen, the model calculates the gradually changing cavity periods required to maintain the desired synchronism between the circuit wave and the electron bunch.

The very encouraging results of efficiency enhancement computational study of large-scale atmospheric wave interactions between the middle latitudes and tropics.

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