Design of Helix Slow-Wave Structures for High Efficiency TWTs

Vishnu Srivastava, Richard G. Carter, *Member, IEEE*, B. Ravinder, A. K. Sinha, and S. N. Joshi

***Abstract*—TWTs for space applications commonly have a helix pitch profile which incorporates a section with increased phase velocity followed by a negative phase velocity taper. A simple method is described for the initial design of a helix slow-wave structure of this kind to achieve high overall efficiency. It is shown that the use of a section with increased phase velocity increases the beam efficiency of a TWT while reducing the generation of second harmonic power. The technique is illustrated by its application to a 70 W Ku-band TWT and the performance is shown to be comparable with that of an existing TWT.**

***Index Terms*—Design, helix, traveling-wave tube.**

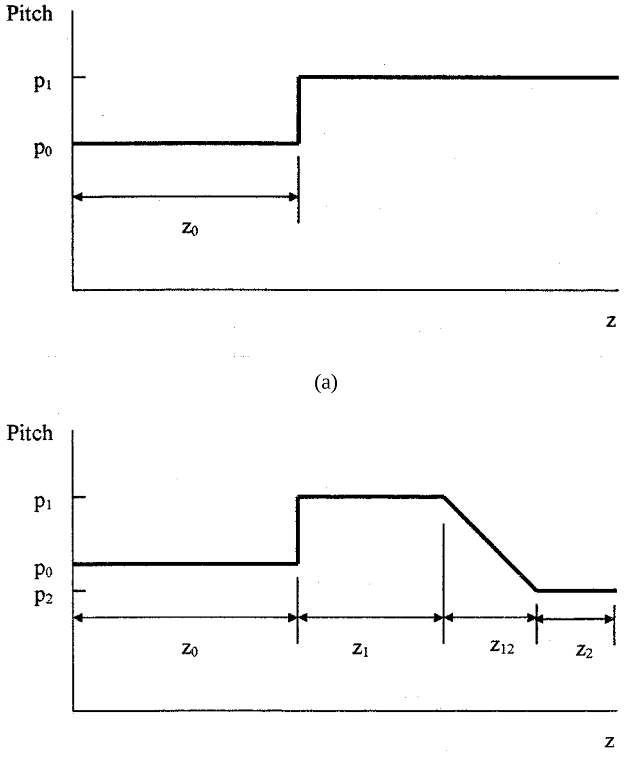
I. INTRODUCTION

THE HELIX traveling-wave tubes employed as the final power amplifiers in space systems such as satellite communications and direct broadcasting must deliver power output in the range 50 to 200 W with the best possible conversion efficiency, linearity and reliability. Good conversion efficiency is important because of the limited power available on the satellite and because of the difficulty of dissipating heat in space. High linearity is required so that the tube can be operated as close to its saturated output power as possible. The achievement of high linearity will be of particular importance to the development of broadband multicarrier systems in future. In order to achieve these requirements, tubes for space applications are commonly constructed with a helix pitch profile comprising [1], [2],

1) an input section to establish the growing wave;
2) a section with increased phase velocity to gather the electrons into bunches as effectively as possible;
3) a section with reduced phase velocity to extract the energy from the bunched beam as effectively as possible.

This pitch profile increases the efficiency of the TWT in two ways:

i) by increasing the proportion of electrons which are in the retarding phase of the field of the helix in the output section of the tube;
ii) by reducing the proportion of electrons which are accelerated in the output section of the tube so that the proportion of the spent beam energy which can be recovered by a multi-element depressed collector is increased.



(a)

(b)

Fig. 1. Helix pitch profile used to determine (a) z_0 and (b) z_1.

The saturated efficiencies of space TWTs which use this approach exceed 65% at Ku-band and below [3], [4]. This technique should be distinguished from the use of a section of helix with increased phase velocity to suppress backward wave oscillations [5] although it is likely that it would also have that effect. In general the introduction of a taper leads to a reduction in the linearity of a tube, but it has been found that the addition of a section of helix with increased phase velocity can counteract this effect. Although helix slow-wave circuits designed in this way have been in use for at least ten years no general procedure for their design has been published. The purpose of this paper is to present a general procedure for achieving the initial design of a high efficiency TWT which is close to optimum.

II. DESIGN PROCEDURE

The work described in this paper was carried out using the following two software packages developed at CEERI.

i) HELTAPE [6] computes the electrical properties of a helix slow-wave structure from its dimensions, and

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TABLE I
SPACE TWT SPECIFICATIONS

PARAMETER	UNITS	C-BAND	KU-BAND
Frequency range	GHz	3.6 to 4.2	10.7 to 12.75
Saturated output power	Watts	60	70
Saturated gain	dB	>50	>50

TABLE II
SPACE TWT DESIGN DATA

PARAMETER	UNITS	C-BAND	KU-BAND
Beam voltage	kV	3.0	4.88
Beam current	mA	75	54.7
Beam radius	mm	0.63	0.275
Helix radius	mm	1.26	0.695
Helix pitch (p_0)	mm	0.76	0.600
Tape thickness	mm	0.175	0.035
Tape width	mm	0.325	0.140
Support rods (3)		APBN	Beryllia
Wedge angle	degrees	17	20
Shield radius	mm	3.05	1.66
Helix pitch (p_1)	mm	0.84	0.655
Helix pitch (p_2)	mm	0.70	0.575
Helix loss	dB/m	20	24

ii) SUNRAY 1-D [7], [8] is a one-dimensional (1-D) large-signal interaction model of a TWT including multiple signals, harmonics and intermodulation products.

The use of a 1–D program was found to be satisfactory for the initial design process. Using these packages the design procedure was carried out in a number of steps, as follows.

1) The input electron beam power was determined from the output power required and an estimate of the electronic efficiency of the tube. This was converted into the beam voltage and current by choosing the perveance of the electron gun. The rf input power was determined from the specified saturated output power and gain. This input power was kept fixed throughout the remainder of the design process.
2) The mean helix radius (a) was chosen so that $\beta_{e}a \approx 1$ where $\beta_e = \omega/u_0$, ω is the signal frequency in radians/sec. at the band center and u_0 is the initial velocity of the electron beam. The tape width and thickness, the shield diameter and the material and dimensions of the helix support rods were also chosen in the conventional manner.
3) SUNRAY 1-D was used to determine three values of the axial propagation constant of the helix at the center frequency of a tube having a single section of helix with uniform phase velocity corresponding to [9]:
   i) Maximum small-signal gain ($G_{\max}$);
   ii) Maximum beam bunching ($I_{1,\max}$);
   iii) Maximum electronic efficiency ($\eta_{e\ \max}$).

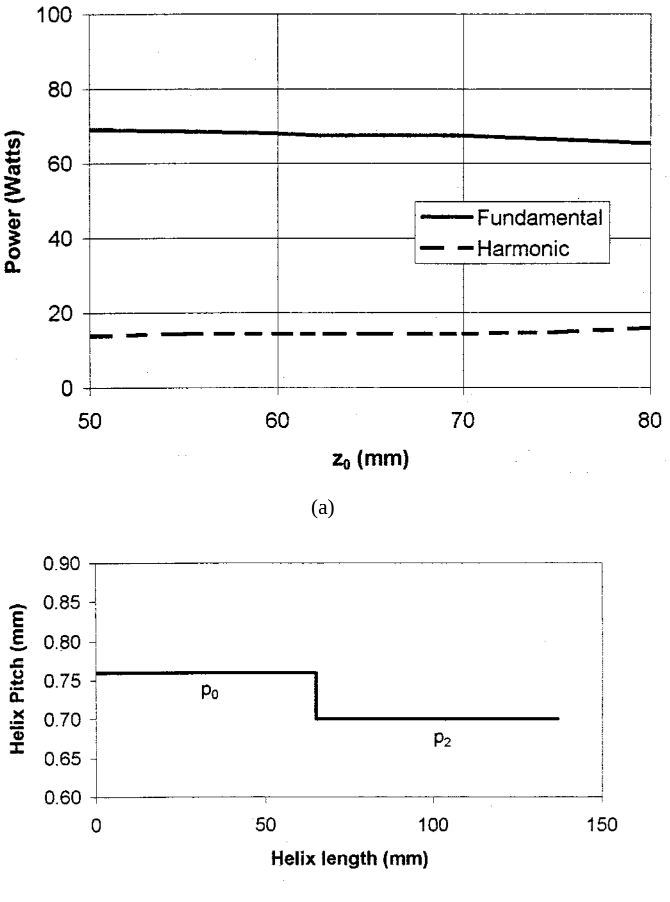
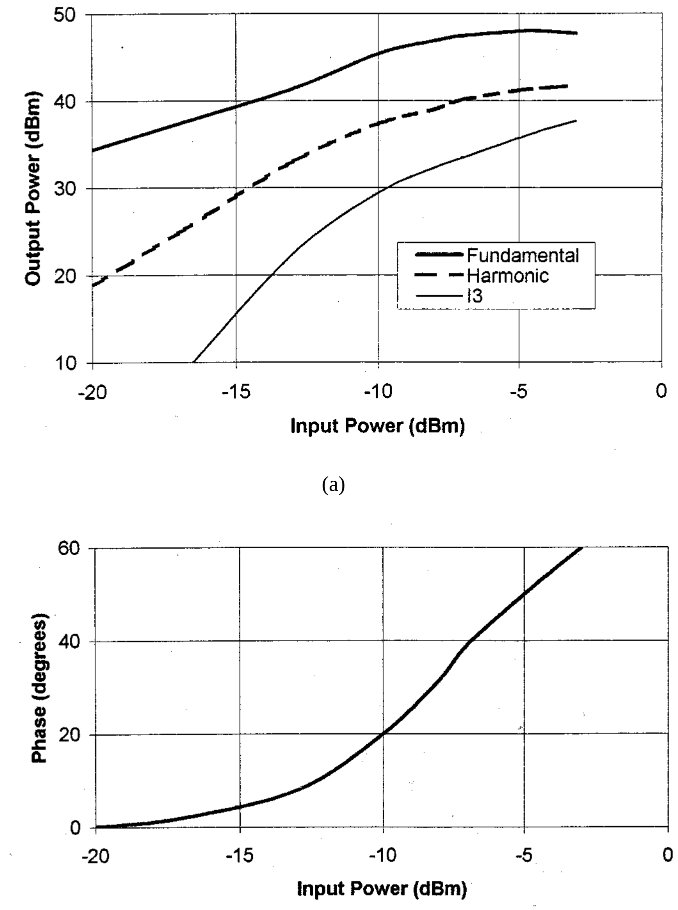


Fig. 2. (a) Variation of fundamental and harmonic output power with z_0, and (b) Pitch profile for *circuit 1*.

HELTAPE was then used to determine the helix pitch corresponding to each of these conditions: p_0 for $G_{\max}$, p_1 for $I_{1,\max}$ and p_2 for $\eta_{e,\max}$. It has not been proved that these are the optimal pitches in a multipitch design but the results which have been obtained using this design method are not far from those achieved in optimized TWTs.

4) Checks were carried out using SUNRAY 1-D to ensure that effective beam bunching was achieved at the bottom of the intended frequency band of the tube when the helix pitch is p_1. Similar checks were carried out to ensure that sufficient efficiency was achieved at the top of the frequency band when the helix pitch was p_2. Some adjustments to p_1 and p_2 could be carried out at this stage if necessary.
5) The cold loss of the helix was taken to be of the order of 20 dB/m. It was found that the circuit could conveniently be severed between the input section of pitch p_0 and the section with pitch p_1. The attenuators on each side of the sever were taken to be two or three wavelengths long with linearly increasing attenuation and a one-way loss of 60 dB.
6) Using the arrangement shown in Fig. 1(a) an initial value of z_0 was chosen to give a gain of at least 20 dB in the input section to ensure that the growing wave was fully established. The length z_0 was then adjusted to obtain the maximum beam bunching (I_1) in the section of the circuit having pitch p_1, and arbitrary length, for the given input power. If the



(a)

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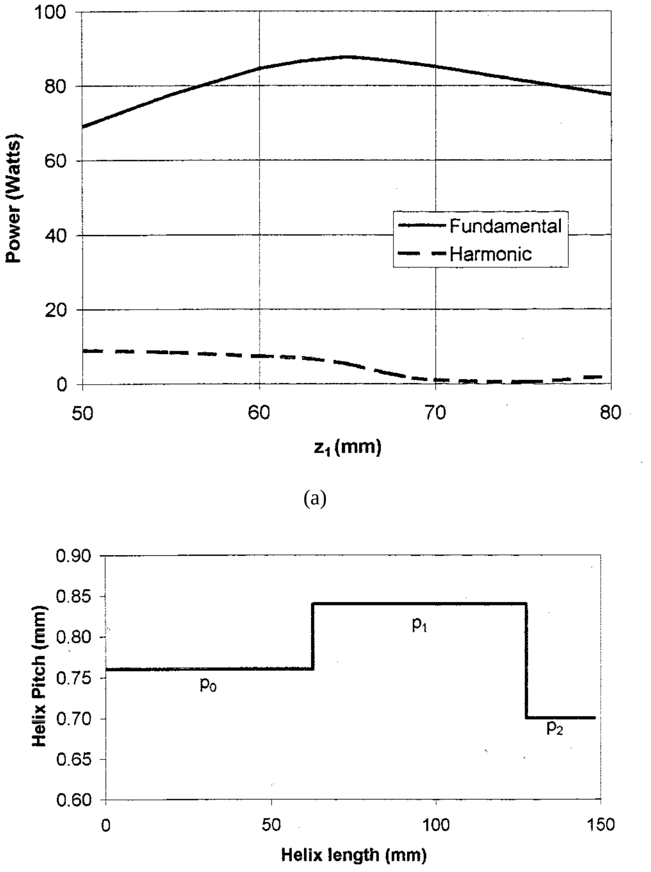
Fig. 3. Transfer characteristics for *circuit 1*.



(a)

(b)

Fig. 4. (a) Variation of fundamental and harmonic output power with z_1, and (b) Optimum pitch profile for *circuit 2*.

gain in either section is too high then feedback or backward wave oscillations may occur. The maximum permissible gain depends on the properties of the helix and the electron beam and on the reflection coefficients of the attenuators and the input and output connections.

7) Using the arrangement shown in Fig. 1(b) the length z_1 was adjusted to give maximum forward circuit power in the section of the circuit with pitch p_2 and arbitrary length. The length of the transition between the positive and negative tapered sections of the helix (z_{12}) was taken to be at least three wavelengths to minimize reflections caused by the change in impedance. The length z_2, was chosen so that the forward power saturated at the end of the section.

The procedure described has been found to give a good starting point from which the design can be improved, if required, by adjustments to the pitch profile of the helix.

III. EFFECT OF A REGION WITH INCREASED PHASE VELOCITY

The benefits of introducing a section of helix with increased phase velocity are shown by two simple examples based on a C-Band TWT whose specification and basic data are given in Tables I and II, respectively.

First a tube was simulated with an input section having pitch p_0 followed by an output section with pitch p_2 as shown in Fig. 2(b). The output section was taken to be of arbitrary length and no severs, tapers or terminal mismatches were included in the model. This circuit is referred to as *circuit 1*. The length of the input section (z_0) was varied with constant drive power and the maximum forward power in the output section determined. Fig. 2(a) shows that the saturated output power and the harmonic power at saturation varied only slowly with z_0. For the purposes of illustration z_0 was chosen to be 65 mm, as shown in Fig. 2(b). This value produces slightly less than the maximum output power but ensures that the gain of the output section is small enough to ensure that the tube will be stable. The length of the output section was chosen so that the forward wave reached saturation at its end. Fig. 3 shows the transfer characteristics of this tube including the harmonic power and the two-tone third-order intermodulation product power. The latter was computed from the single carrier transfer characteristics using IMAL2 [10].

The second tube (*circuit 2*) had a section of helix having pitch p_1 as shown in Fig. 4(b). Initially, this tube was simulated with a second section of arbitrary length and z_0 was adjusted to achieve the highest value of fundamental beam current I_1 in the second section. Then a negative step to pitch p_2 was added and the length (z_1) of the second section adjusted to obtain the maximum forward power in the output section. Fig. 4(a) shows how the output power and the harmonic power for *circuit 2* varied

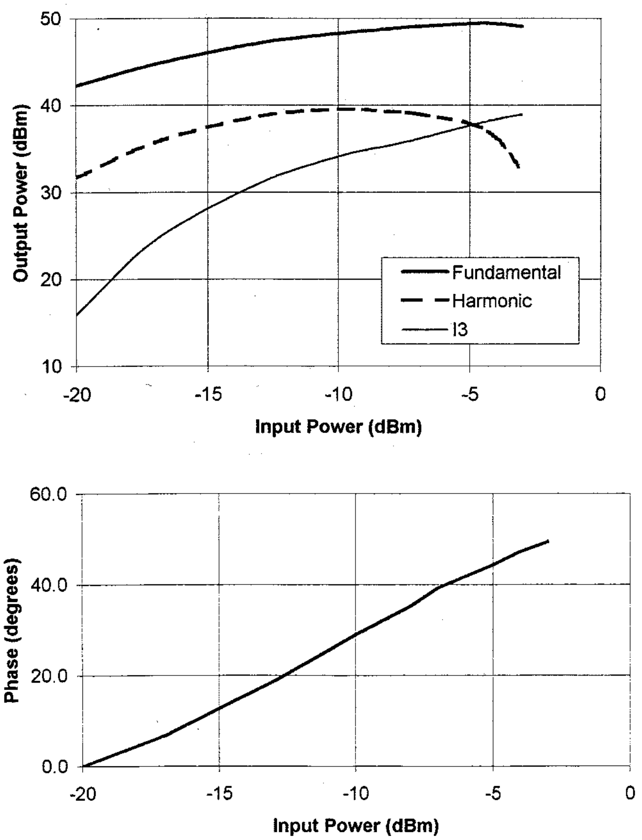
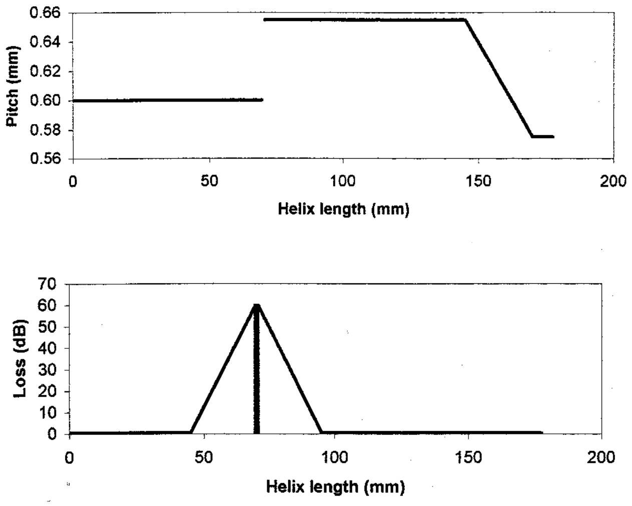


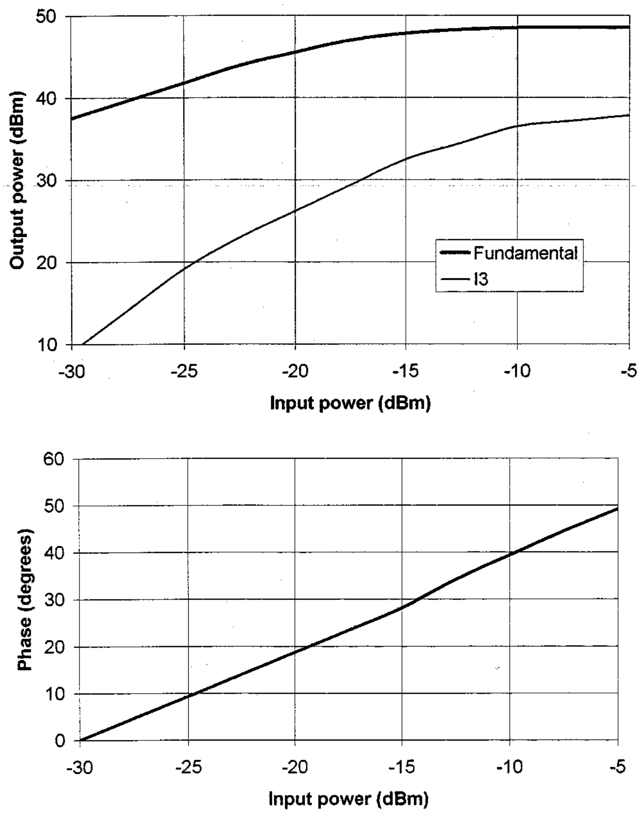
Fig. 5. Transfer characteristics for *circuit 2*.

with z_1. It is seen that the output power is increased and the harmonic output decreased by the addition of the section having increased pitch. The marked decrease in the harmonic power as z_1 is increased is presumably caused by the control which this section of the tube exercises over the bunching process and this effect deserves further study. Finally, z_2 was chosen so that the forward power reached saturation at the tube output. The dimensions of this circuit are shown in Fig. 4(b). Fig. 5 shows the transfer characteristics for *circuit 2*. Compared with *circuit 1* it is seen that, at saturation, the output power is increased and the harmonic power is decreased. There is a slight deterioration in the intermodulation distortion which is probably caused by the increase in the phase delay at low drive levels. The saturated output power could be increased still further by the use of a more complex output taper [11] but we have found, in a separate study, that a wide range of tapering strategies all produced an improvement of around 2 to 3 dB though with variations in the shapes of the transfer curves.



(b)

Fig. 6. Helix dimensions and loss profile of the Ku-band TWT.



(a)

Fig. 7. Transfer characteristics of the Ku-band TWT.

IV. EXAMPLE

The method described above was used to design a Ku-band TWT whose specification is typical of satellite communications tubes. The specification is shown in Table I and the basic design parameters in Table II. Fig. 6 shows the helix dimensions and loss profile for this tube and Fig. 7 its computed transfer characteristics. The collector efficiency with a four-stage depressed collector was computed from the spent beam curve to be 92%. To compute the overall efficiency a collector efficiency of 80% was assumed to allow for less than ideal collection of the electrons. Fig. 8 shows the variations of small-signal gain, saturated gain, phase delay at saturation and AM–PM conversion across the Ku-band downlink frequency band. The computed performance is summarized in Table III with data from the literature

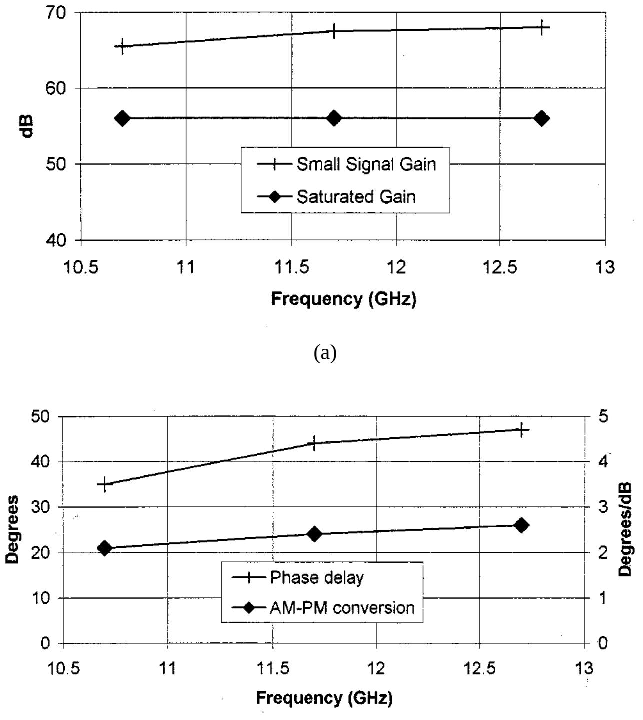


Fig. 8. Ku-band TWT: frequency dependence of (a) small-signal gain and saturated gain, and (b) phase delay at saturation and AM–PM conversion.

TABLE III
COMPARISON BETWEEN THE COMPUTED PERFORMANCE OF THE KU-BAND TWT AND PUBLISHED DATA [12]. THE FIGURES MARKED * WERE ESTIMATED FROM [12], FIG. 2

PARAMETER	UNITS	KU-BAND TWT	LD7833 [12]
Saturated output power	Watts	70	98
Saturated gain	dB	58	53
Phase delay at saturation	degrees	46	40
Phase slope	degrees/dB	2	4
Electronic efficiency	%	26	30*
Theoretical collector efficiency	%	0.92	0.91*
Overall efficiency	%	63	66

[12] for comparison. The method was also applied to a 60 W C-band tube with similar results.

V. CONCLUSIONS

The procedure proposed for designing a helix slow-wave structure with positively and negatively tapered sections is simple to carry out. The results computed compare well with figures reported elsewhere for state-of-the-art TWTs. It is concluded that this method provides an excellent way of achieving an initial design which is close to optimum and which can then be improved still further by design iterations.

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B. Ravinder, photograph and biography not available at the time of publication.

A. K. Sinha, photograph and biography not available at the time of publication.

S. N. Joshi, photograph and biography not available at the time of publication.