Planar helix-based slow-wave structures for millimeter wave traveling-wave tubes

Zhao, Chen

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**PLANAR HELIX-BASED SLOW-WAVE STRUCTURES FOR
MILLIMETER WAVE TRAVELING-WAVE TUBES**

ZHAO CHEN

School of Electrical and Electronic Engineering

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ABSTRACT

Circular helix is a very popular slow-wave structure (SWS) for application in traveling-wave tubes (TWTs). But it is not easy to be fabricated using printed-circuit or microfabrication techniques which are important for low-cost fabrication and high frequency applications. In this context, during the last few years, a planar helix SWS with straight-edge connections (PH-SEC) has been proposed and studied. Unlike the circular helix, the PH-SEC is suitable to be fabricated using printed circuit or microfabrication techniques. However, there are still some issues and problems that need to be addressed for the PH-SEC when used in millimeter wave TWTs. First of all, there can be backward wave oscillations when the TWT is working at high voltages. Secondly, the size of the SWS, the electron beam tunnel, and the beam get very small, causing difficulty in fabrication, alignment, and focusing of the electron beam. Thirdly, at millimeter wave frequencies, it is more likely that the electrons hit the supporting dielectric, causing dielectric charging which will affect the performance of the TWT adversely. Moreover, PH-SEC can be dispersive in the presence of dielectric loading, reducing the bandwidth of operation. This thesis presents novel SWSs which are based on the PH-SEC and solve some of these problems.

First of all, two types of coupled planar helices, an unconnected pair of PH-SECs and a coaxial pair of PH-SECs, are proposed. Their dispersion characteristics are derived from analysis based on field-theory. The characteristic equations and field expressions are obtained to explain the nature of different modes that propagate in the coupled structures. Coupling impedance is also calculated. Effects of variations in dimensions are studied. The analysis results match well with simulations. Simulation results are presented to show that the unconnected pair of planar helices has a reduced interaction with backward waves as compared to that for a corresponding single PH-SEC.

Based on the above knowledge of various modes, an unconnected pair of PH-SECs has been designed together with a stripline power divider in order to provide input signals with equal magnitude and phase. Also proposed is a connected pair of PH-

SECs which can be fed in a much simpler way by a coplanar waveguide (CPW) feed. The latter structure offers a larger electron-beam tunnel and lower risk of backward wave oscillation compared to the single PH-SEC. Moreover, the connected pair of PH-SECs has a higher gain growth rate than that for the single PH-SEC. The connected pair also shows a significantly higher coupling impedance compared to a recently reported meander-line based SWS. Both the unconnected and the connected pair of PH-SECs have been designed and fabricated using printed circuit techniques. The measurement results match well with the simulation results.

A Ka-band symmetric PH-SEC has been proposed with the aim of decreasing dielectric loading and mode competition as compared to an un-symmetric structure. The symmetric PH-SEC has also been examined for dielectric charging problem. First, it is shown that the phenomenon of dielectric charging can be simulated accurately using CST Particle Studio. Next, simple modifications in the design are suggested to reduce dielectric charging. Simulation results are presented for a Ka-band planar helix SWS to demonstrate very significant reduction in dielectric charging while maintaining a low insertion loss with these modifications.

Dispersion control of the PH-SEC using vane-loading and coplanar ground planes has been studied. It is shown that the addition of metallic vanes to the PH-SEC can produce a flatter dispersion curve. Further, even stronger dispersion control can be achieved by the use of metal vanes together with extended coplanar ground planes on the dielectric substrates. As proof-of-concept, one of the designs of the planar helix SWS including metal vanes and operating at S-band frequencies has been fabricated and tested; the measured phase velocity results match very well with the simulation results. These dispersion control techniques have been applied to a Ka-band PH-SEC which is planned to be microfabricated. Both the cold-test and hot-test parameters have been investigated. The fabrication process has also been presented.

The techniques mentioned above are not limited to SWSs based on PH-SEC. These techniques may also be applicable to some other microfabricated SWSs such as meander-line, rectangular ring-bar, and biplanar interdigital structure.

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LIST OF ACRONYMS AND SYMBOLS

ACRONYM	FULL EXPRESSION
3D	Three dimensional
APBN	Anisotropic pyrolytic boron nitride
BJT	Bipolar junction transistor
BWO	Backward wave oscillator
CNC	Computer numerical control
CPW	Coplanar waveguide
CST	Computer simulation technology
CW	Continuous wave
DC	Direct current
DRIE	Deep reactive ion etching
ECM	Electronic countermeasure
EDC	Effective dielectric constant
EDM	Electrical discharge machining
FET	Field effect transistor
GPU	Graphics processing unit
GSG	Ground-signal-ground
HFSS	High frequency structure simulator
HPM	High power microwave
LIGA	Lithography, electroplating, and micro-molding
MEDC	Modified effective dielectric constant
MPM	Microwave power module
MWS	Microwave studio
PH-SEC	Planar helix with straight-edge connections
PIC	Particle-in-cell
RF	Radiofrequency
RMS	Root-mean-square
RRB-SEC	Rectangular ring-bar with straight-edge connections
SEY	Secondary electron yield
SWS	Slow-wave structure
SSPA	Solid state power amplifier
TSV	Through-silicon via
TWT	Traveling-wave tube
UC	Unidirectionally conducting
VED	Vacuum electron device

SYMBOL	MEANING
β	Phase constant
β_0	Phase constant of the fundamental mode
β_n	Phase constant of the n^{th} space harmonic
γ	Propagation constant
ϵ	Permittivity of a medium
ϵ_0	Permittivity of free-space
ϵ_{eff}	Effective dielectric constant
ϵ_r	Relative permittivity of a medium
η	Efficiency
λ_g	Guide wavelength
μ	Permeability of a medium
μ_0	Permeability of free space
μ_r	Relative permeability of a medium
σ	Conductivity
ϕ	Pitch angle
ϕ_{eff}	Effective pitch angle for PH-SEC
ω	Angular frequency
c	Speed of light in free space
$E_z \{0\}$	On-axis longitudinal electric field intensity
f	Frequency
I_0	Zeroth-order modified Bessel function of the first kind
I_1	First-order modified Bessel function of the first kind
I_{beam}	Electron beam current
k	Wave number in a medium
k_0	Wave number in free space
k_n	Wave number in region n
k_{xn}, u, v, w	Transverse decay coefficients
K_0	Zeroth-order modified Bessel function of the second kind
K_1	First-order modified Bessel function of the second kind
K_c	Coupling impedance (or interaction impedance)
n	Integer index
P	Power propagating through the structure
P_{in}	RF input power
P_{out}	RF output power
r, θ, z	Circular cylindrical coordinates
S_{11}	Reflection coefficient
S_{21}	Transmission coefficient
v_p	Phase velocity

v_g	Group velocity
V_{beam}	Electron beam voltage
x, y, z	Cartesian coordinates
Z_0	Characteristic impedance
Au	Gold
BeO	Beryllium oxide
Cu	Copper
Si	Silicon
SiO_2	Silicon dioxide

CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Vacuum Electron Devices (VEDs)

In the last few decades, vacuum electron devices (VEDs) have played an important role in our society. They have been used as high power microwave amplifier or oscillator in numerous applications such as radio/TV broadcast, satellite broadcast and communications, radars, military systems, medical/biomedical, high energy particle acceleration and microwave heating, etc. [1]. Their working frequency can range from below 100 MHz up to hundreds of GHz or even Terahertz. The output power of VEDs can range from hundreds of watts to several megawatts [2]. For some special application, for example, high-power microwave (HPM) weapons, the peak power may exceed gigawatts [1]. There are many types of VEDs that are being used. Magnetrons, one of the earliest invented microwave tubes, are able to provide kilowatts of power easily and are widely used in microwave ovens now. Klystrons, with high output power, are used in radars as well as particle accelerators. Traveling-wave tubes (TWTs) are used in satellites due to their wide bandwidth, high gain and efficiency. Gyrotrons can easily work at 100s of GHz without tube size reduction.

A strong competitor of VEDs is solid state power amplifier (SSPA) and the two types of devices have their relative merits and demerits. The basic principle for both devices is to convert the kinetic energy of electrons into microwave power. In SSPA, such as bipolar junction transistor (BJT) or field effect transistor (FET), the electron stream flows in a semiconductor material. They have the advantage of easy mass production and lower noise than most of the VEDs. They are replacing VEDs in some applications such as civilian communication and low frequency transmitters. However, in some other applications, for example, satellite communication, VEDs

still own many advantages that SSPAs cannot provide. First, SSPAs can only work with relatively low driving voltage and low power level. In SSPAs a significant amount of kinetic energy of charge carriers is converted to waste heat, causing temperature rise in the device. Besides, SSPAs are not able to operate under high temperature (over 200°C) conditions for a long time due to semiconducting channel chemical degradation as well as carrier mobility reduction [3]. Due to this problem, SSPAs require bulky heat sinks. By contrast, in VEDs the electron stream flows in vacuum, the output power can be much higher than SSPA, and typical efficiency is also better. Moreover, VEDs can operate at higher temperatures. For these reasons, VEDs are still widely used today and are irreplaceable in high power applications. It is also possible to combine the advantages of SSPAs and VEDs in a single module, as has been done successfully in microwave power modules (MPM) [1].

1.1.2 Traveling-wave Tubes (TWTs)

TWTs are one of the most widely used types of VEDs. A TWT works as a power amplifier for frequencies ranging range from below 1 GHz to above 100 GHz. The continuous wave (CW) output power can range from a few watts to thousands of watts. The peak pulse power can reach over a megawatt. The efficiency of space traveling-wave tubes usually exceeds 60%. Although magnetrons or klystrons can achieve much higher output power, TWTs display better linearity, and more importantly, broadband capability. TWTs can achieve octave or even decade bandwidths in practice [2].

TWTs find application in many kinds of communication systems. In satellite communication systems (down-link from satellite, up-link from ground-based, airborne or shipboard transmitters to satellite), TWTs are becoming more and more dominant due to their higher bandwidth and linearity. Besides, TWTs turn out to have a much longer operating life (> 15 years), higher reliability and efficiency (> 60%) than solid state devices. TWTs are also the most widely used VED in radar and electronic countermeasure (ECM) systems thanks to their wide bandwidth, high gain and low noise [1].

Figure 1.1: Simplified schematic diagram of a TWT.

The principle of operation for the TWTs is simple. First, from the physical point of view, when high speed charged particles pass through a medium at a speed greater than the phase velocity of light in the medium, Cherenkov radiation occurs. This is basically how an electron beam transfers energy to an electromagnetic wave in a TWT. However, making the electrons' speed higher than the electromagnetic wave is not easy. The most commonly used method is to use a slow-wave structure (SWS) in which the electromagnetic wave propagates slower than in air.

A schematic diagram of a TWT is shown in Figure 1.1. As shown in this figure, a traveling-wave tube usually consists of six major parts: an electron gun, a SWS, focusing magnets, a collector, RF input/output and a vacuum envelope. The electron gun produces an electron beam and accelerates the beam to a certain speed. Low power RF signal gets into the tube from the input port. When the electron beam and electromagnetic wave have similar velocities (velocity synchronism), beam-wave interaction occurs. When the condition for Cherenkov radiation is satisfied, the electromagnetic wave absorbs energy from the electron beam while traveling along the tube. Finally the amplified electromagnetic wave is obtained at the output port. The focusing magnets are used in order to counter the effect of repulsive radial space charge forces between the electrons. After passing through the SWS, the electrons still possess some kinetic energy since the beam power cannot be fully converted to electromagnetic power. A collector is needed to recover energy from

the spent electron beam. The whole structure, including the electron gun, SWS and the collector, is enclosed in an evacuated envelop.

1.2 SWS for TWTs

In a TWT, it is important that the electron beam has a velocity close to the phase velocity of the electromagnetic wave. However, the electromagnetic wave usually travels much faster than the speed of electron beam. In order to have velocity synchronism, a SWS is needed. A SWS is thus a key part for a TWT. It is a kind of waveguide that is able to support an electromagnetic wave with a phase velocity much lower than the speed of light.

Periodic structures are usually able to support waves with low phase velocity. Commonly used SWSs in TWTs are periodic structures, including helix SWS [4]–[6], coupled cavity [7]–[9], periodic loaded waveguide [10], folded waveguide [11]–[14], ladder circuits [15]–[17], etc. The most commonly used type of SWS among these is circular helix because of its wide bandwidth, ease of dispersion control, and high coupling impedance. Coupling impedance represents the strength of beam-wave interaction. Figure 1.2 shows one period of the circular helix, which is placed at the center of a cylindrical metal shield. In order to fix the circular helix SWS firmly inside the metal shield, supporting dielectric rods are often needed.

Figure 1.2: One period of a circular SWS [18].

1.2.1 Microfabrication of SWSs

As the operating frequency increases, the dimensions of various parts of a TWT, including the SWS, reduce. Table 1.1 shows the dimensions of helix SWS for different frequency ranges [19]. It is seen that the radius of the helix is only tens of micrometers at 300 GHz. At such frequencies, the conventional fabrication techniques can no longer fulfill the need. This adversely affects the attempts to miniaturize helix TWTs, to lower their cost, and to push up their frequency of operation. Besides, with such small dimensions, the alignment of different parts of a TWT becomes very challenging. Even a small error in the alignment may cause a big deterioration in the performance. Further, the electron beam may hit the SWS and the dielectric supports when there is misalignment or the focusing magnetic field is not strong enough. That may cause dielectric charging in the TWT which in turn may greatly affect the beam flow or may even cause dielectric breakdown.

Table 1.1 Radius of circular helix at different frequencies [19]

Frequency band/Power level	Helix radius (mm)
C-band (3.4-4.2 GHz/200W)	2.30
Ku-band(10.7-13.0 GHz/250W)	0.8
K/Ka-band (18-32 GHz/100W)	0.4
Q-band (37-42 GHz/50W)	0.24
V-band (60-65 GHz/30W)	0.16
W-band (95 GHz/10W)	0.1
Sub-mm band (300 GHz/1W)	0.032

The relatively recent development of the microfabrication techniques has enabled fabrication of SWSs with extremely small dimensions. Microfabrication techniques allow one to fabricate metal and dielectric structures with good precision and surface finish. These techniques can also provide the advantage of mass production by fabricating repeatable devices in large numbers, greatly reducing the cost of fabrication. Moreover, with microfabrication, it is possible in principle to put electron gun, SWS and collector on the same substrate. In this way, the alignment of different components can be improved significantly.

Although the circular helix is very widely used, the circular helix and its variations cannot be easily fabricated using printed-circuit or microfabrication techniques which can reduce the cost of fabrication and enable precise fabrication of small structures that are required for TWTs operating at millimeter wave frequencies (30-300 GHz) and higher [20]. Several SWSs with planar configuration that address this issue have been proposed in the literature. These include, for instance, the meander-line [21], rectangular (or square) helix [22], and the planar helix with straight-edge connections (PH-SEC) [22]-[23].

1.2.2 Planar Helix with Straight-edge Connections (PH-SEC)

In particular, the PH-SEC, as shown in Figure 1.3, retains the wideband properties of the circular helix and also offers the advantage of easy fabrication due to the straight-edge connections between the top and bottom arrays of inclined conductors. This structure has successfully been fabricated and microfabricated recently to demonstrate the ease of fabrication. A PH-SEC with multiple layers of dielectric has been analyzed and fabricated using printed circuit techniques [23]. A W-band (75 GHz-110 GHz) PH-SEC on a thick silicon substrate has been fabricated using microfabrication techniques [24]. Apart from the advantage of easy fabrication, sheet beam can be applied to PH-SEC with high aspect ratio, which can offer

Figure 1.3: Perspective view of planar helix with straight-edge connections (PH-SEC).

advantages such as easier fabrication of the SWS, easier focusing of the electron beam, increased gain etc. [25]. Besides, PH-SEC can provide good heat dissipation since the metal strips have a larger contact area with the support substrate.

Yet, there are still some issues and problems that need to be addressed for PH-SEC to facilitate its application in millimeter wave TWTs. First, the electron beam tunnel of the PH-SEC can be very small at millimeter wave frequencies. That may limit the working frequency of the PH-SEC based TWT in terms of fabrication precision, alignment of different components, realization of electron gun with adequate current density and realization of compact focusing magnets. Secondly, similar to the circular helix, the PH-SEC is likely to have undesirable backward wave oscillation under high power operation [26]. Thirdly, the dielectric charging problem is likely to occur in PH-SEC as there can be considerable amount of dielectric involved in the form of support substrate; this problem becomes more important at millimeter waves due to the difficulty in alignment and magnetic focusing. Finally, the PH-SEC is slightly more dispersive than circular helix [27] and the dielectric loading will make it worse [23]. Thus, in order to increase the bandwidth of the PH-SEC, it is necessary to study the methods to control the dispersion of PH-SEC.

1.3 Motivation

Millimeter wave or Terahertz frequency devices are getting more and more in demand due to their potential use in medical, security, communication and inspection applications. Many of these applications require a millimeter wave broadband, high gain, and high efficiency amplifier with compact size.

PH-SEC has proved to be a very attractive and promising structure with a planar configuration which is compatible with both printed circuit and microfabrication techniques. But there remain many issues and problems with the PH-SEC that need to be addressed to facilitate the application of PH-SEC in high frequency TWTs. One needs to increase the size of the electron beam tunnel, reduce backward wave oscillation, reduce dielectric charging effect, control dispersion, and improve feasibility of microfabrication.

The abovementioned requirement for improvement in the PH-SEC for application in millimeter wave TWTs provides the motivation for the work reported in this thesis.

1.4 Objectives

The objective of the work of the thesis is to improve the PH-SEC to make it more suitable for millimeter wave TWTs. The specific goals of the work are as follows:

1. Propose a SWS based on the PH-SEC with larger electron beam tunnel and less tendency for backward wave oscillation. Use field-theory approach to obtain the cold-test parameters such as dispersion characteristics and coupling impedance of the proposed SWS. Compare the results with those obtained using a 3D electromagnetic simulator such as Computer Simulation Technology (CST).
2. Design a practical SWS based on the above proposed configuration with suitable input and output couplers. Carry out experimental verification by fabricating the designed structure using printed circuit or microfabrication techniques.
3. Study hot-test parameters such as output power, gain, efficiency and bandwidth of the proposed SWS.
4. Study the dielectric charging effect in a TWT based on PH-SEC with the aim to suggest techniques to reduce this effect.
5. Study dispersion control techniques for the PH-SEC to increase the bandwidth.
6. Design a millimeter wave PH-SEC which can be microfabricated. Apply the dispersion control techniques to achieve a wide bandwidth. Examine its cold-test and hot-test parameters.

1.5 Major Contributions of the Thesis

1. Two new types of coupled planar helix SWSs with straight-edge connections, namely, an unconnected pair of PH-SECs and a coaxial pair of PH-SECs, have been proposed and analyzed. The analysis based on field-theory shows the nature of the propagating modes, dispersion characteristics, field distribution, and coupling impedance for the proposed structures. The unconnected pair of PH-SECs has a larger electron beam tunnel and a reduced interaction with

backward waves as compared to that for a corresponding single PH-SEC. The coaxial pair of PH-SEC can be used to couple power from one helix to the other.

2. The unconnected pair of PH-SEC covering 3 GHz to 6 GHz has been designed using dielectric substrates and fabricated using printed circuit techniques. A stripline Wilkinson power dividers are used at the input/output ports in order to excite the desired mode. Measured results match well the simulation results.
3. The unconnected pair of PH-SECs needs complex input/output couplers. Therefore another SWS, a connected pair of PH-SECs, has been proposed which can be fed in a much simpler way. The latter structure offers a larger electron-beam tunnel and lower risk of backward wave oscillation compared to the single PH-SEC. Moreover, the connected pair of PH-SECs has a higher gain growth rate than that for single PH-SEC. It has been shown that the connected pair of PH-SEC can provide an output power of 468 W with high gain (42.5 dB) and efficiency (21.9%). The connected pair also shows a significantly higher coupling impedance compared to a recently reported meander-line based SWS. The connected pair of PH-SECs has been designed and fabricated using printed circuit techniques. The simulation and measurement results demonstrate the ease of feed-design and wideband working frequency from 1.81 GHz to 4.98 GHz for the connected pair of PH-SECs.
4. A new Ka-band symmetric PH-SEC SWS has been proposed with the aim of decreasing dielectric loading and mode competition as compared to an un-symmetric structure. The new structure has higher coupling impedance and symmetric field distribution as compared to a PH-SEC on a thick substrate.
5. Dielectric charging effect in a TWT microfabricated on Si substrate has been studied using both analysis and simulation. Two techniques have been proposed to reduce the dielectric charging effect in the symmetric PH-SEC. These techniques help in achieving much lower dielectric charging voltage.
6. By using dispersion control techniques such as metal vanes and coplanar ground planes, the PH-SEC has been shown to provide a wider bandwidth without reducing the coupling impedance. Negative dispersion can also be obtained which can reduce in-band harmonics.
7. A new Ka-band PH-SEC with quartz substrates, suitable for microfabrication, has been proposed to provide good mechanical strength and reduced dielectric

loading effect. Dispersion control techniques including closer metal shield and coplanar ground planes have been used to flatten the dispersion of the SWS. It has been shown that the structure can provide a fairly uniform gain from 24 GHz to 36 GHz, an output power of 6.2 W, and efficiency of 16.9%. A detailed fabrication process has also been presented.

1.6 Organization of the Thesis

This thesis has been organized into seven chapters. Chapter 1 introduces the background of the research and describes the motivation for this thesis. Existing challenges for PH-SEC for application in millimeter wave TWT are mentioned. Major contributions of the present work are listed.

Chapter 2 presents the literature review of helix SWSs. Cold-test and hot-test parameters are introduced. Modifications and different variations of circular helix and PH-SEC are reviewed. Some analytical methods to obtain the cold-test parameters of circular helix and PH-SEC are presented. The existing microfabrication process and challenges are also included.

Two novel variations of PH-SEC, unconnected pair of PH-SECs and coaxial pair of PH-SECs, are proposed in Chapter 3. A method to analyze the cold-test parameters of the two structures immersed in free space is proposed. A genetic structure of four UC screens is analyzed first. Then the cold-test parameters of the two proposed structures are calculated based on the different modes of four UC screens. The cold-test parameters are also simulated using CST MWS eigenmode solver and compared with the calculated results. The unconnected pair of PH-SECs is compared with the single PH-SEC with respect to backward wave oscillation.

Chapter 4 presents the design and fabrication of the unconnected pair of PH-SECs and connected pair of PH-SECs. A Wilkinson power divider is designed to feed the two PH-SECs with equal phase and amplitude. The connected pair of PH-SEC is proposed as an improvement on the unconnected pair of PH-SECs. The cold-test parameters of this structure are compared with the unconnected pair of PH-SEC and a simple CPW feed is designed to feed the structure. The hot-test parameters of the

connected pair are simulated using CST particle-in-cell (PIC) solver and compared with those of the single PH-SEC. The connected pair of PH-SEC has also been compared with folded frame SWS. Both the unconnected pair and the connected pair of PH-SECs have been fabricated using printed circuit techniques and measured results have been obtained.

Chapter 5 describes studies on the dielectric charging problem in a microfabricated PH-SEC. A symmetric PH-SEC is proposed first in order to increase the coupling impedance and avoid mode competition. The phenomenon of dielectric charging is studied based on analysis and simulation of two simple models. The effects of different properties of the dielectric substrates are studied. Based on these studies, two methods are applied to the proposed symmetric PH-SEC to reduce the dielectric charging problem.

Chapter 6 first studies the dispersion control of the PH-SEC. The effect of metal vanes in the presence of dielectric substrates which support the PH-SEC as well as that of coplanar ground planes on the dielectric substrates is examined. A proof-of-concept structure operating over the frequency range of 1.6-4.2 GHz is fabricated and measured. This chapter next describes a Ka-band PH-SEC that can be microfabricated. Dispersion control techniques including closer metal shield and coplanar ground planes are used to flatten the dispersion of the SWS. Phase velocity and coupling impedance of the structure are simulated using CST eigenmode solver. The structure shows a wide band property, enabling a wide band beam-wave interaction. Both discrete port and CPW port are applied to the proposed SWS. Hot-test parameters of the Ka-band PH-SEC are also obtained. A detailed fabrication process is also presented.

Chapter 7 concludes the thesis by summarizing the findings and results of this research. Some suggestions for future study have also been listed in this chapter.

CHAPTER 2

LITERATURE REVIEW OF HELIX SLOW-WAVE STRUCTURES

As mentioned in Chapter 1, circular helix has been the mostly widely used slow-wave structure (SWS) in traveling-wave tubes (TWT) due to its wide bandwidth, ease of dispersion control, and strong beam-wave interaction. Planar helix with straight-edge connections (PH-SEC), a planar version of circular helix, retains these advantages. In addition, PH-SEC can be easily fabricated using printed circuit or microfabrication techniques which are important for millimeter wave TWTs.

In this chapter, a review of both circular and PH-SEC SWSs as well as their variations for application in TWTs are presented. In Section 2.1, the cold-test parameters of SWSs, phase velocity and coupling impedance, are introduced. General hot-test parameters such as saturated power, gain and efficiency have been introduced in Section 2.2.

Interactions of both forward wave and backward wave with the electron beam are mentioned. General analysis method to determine coupling impedance is reviewed. Section 2.3 reviews the circular helix. Some circuit modifications for dispersion control and input/output coupling are presented. A few variations of the circular helix to prevent backward wave oscillations (BWO) are also reviewed. In Section 2.4, the PH-SEC and its variations are reviewed. In Section 2.5, analytical methods to determine the dispersion characteristics of both circular helix and PH-SEC are reviewed. Section 2.6 covers some microfabrication techniques for SWSs and the challenges faced. Section 2.7 briefly mentions the computer aided design tools for SWS and TWT design and the simulation tools used here.

2.1 Cold-test Parameters of SWS

2.1.1 Dispersion Diagram

Figure 2.1: Dispersion diagram of a typical periodic structure.

The cold-test parameters are the electromagnetic properties of the SWS without the electron beam. These parameters include propagation constant, phase velocity, dispersion, coupling impedance, reflection, and transmission coefficient etc. The dispersion characteristics are the most important property of SWSs. In order to make the TWT operate with high gain and low unwanted oscillations, it is important to study how the propagation constant, phase velocity, and group velocity of different modes change with frequency.

Dispersion diagram or the k - β diagram is a useful tool to present the dispersion characteristics of a SWS. Figure 2.1 presents the dispersion characteristics of a typical periodic structure (normalized wave number, kL , versus normalized phase constant, βL); k is the wave number, $k = \omega\sqrt{\epsilon\mu}$, $\omega = 2\pi f$, $\epsilon = \epsilon_0\epsilon_r$, $\mu = \mu_0\mu_r$, L is the period, and β is the phase constant. Some useful parameters including phase velocity ($v_p = \omega/\beta$) and group velocity ($v_g = d\omega/d\beta$) can be obtained easily from this diagram.

We can see that like most waveguides, there is more than one mode supported by a periodic structure and there are passbands and stopbands formed by different modes. In most cases, the fundamental mode is of the most interest and higher order modes should be avoided. The $\beta = k_0$ curve is the free space phase constant line which indicates that any mode below this line will have the slow wave property. As seen in this figure, the phase velocity of the fundamental mode is slower than the speed of light in free space.

For a given k , multiple values of β exist; these arise from the space harmonic characteristic of periodic structures [2]:

$$\beta_n = \beta_0 + \frac{2\pi n}{L} \quad (2.1)$$

where β_0 is the propagation constant of the fundamental mode and n is an integer. Besides, both forward waves and backward waves are supported by a periodic structure. For the forward wave, the phase velocity has the same sign as that of the group velocity. On the contrary, for the backward wave, the phase velocity has a different sign from the group velocity. A dotted line is shown in the figure to represent the phase constant for the electron beam. TWTs operate at a point where the beam line intersects with one of the waves. Oscillations may occur when the beam line intersects with the backward wave; this should normally be avoided in a TWT. However, the interaction with the backward wave can also be used to realize a microwave source which is known as backward wave oscillator (BWO).

2.1.2 Coupling Impedance

Another important parameter of a SWS is the coupling impedance which represents the strength of beam-wave interaction. The symbol for coupling impedance is K_c and its unit is Ω . The coupling impedance is defined by Pierce as [28]:

$$K_c = \frac{E_z^2(0)}{2P\beta^2} \quad (2.2)$$

where $E_z(0)$ is the maximum value of the axial component of the electric field at the axis of the SWS and P is the average power flow of the electromagnetic wave which

is flowing in the z direction (shown in Figure 1.3). P can be calculated using the Poynting vector [2]:

$$P = \frac{1}{2} Re \int (\vec{E} \times \vec{H}^*)_z ds \quad (2.3)$$

2.2 Hot-test Parameters

The hot-test parameters describe the performance of the TWT with electron beam including output power, gain, efficiency etc. With a bunched beam, the output power of electromagnetic wave increases exponentially along the tube. As the length of the tube increases, the output power will reach a saturation point after which the output power will drop. The RF efficiency η of the TWT without a collector can be calculated as [29]:

$$\eta = \frac{P_{out}}{V_{beam} \times I_{beam}} \quad (2.4)$$

where P_{out} describes the output power; V_{beam} and I_{beam} describe the voltage and current of the electron beam.

In some applications such as electronic countermeasure (ECM) and radar, the TWT generally operate at the saturation point with a maximum efficiency [1]. On the other hand, the TWT often works in the linear region for communication applications.

The gain of a TWT can be easily estimated using Pierce TWT theory [28]. The maximum spatial amplification rate G_{max} can be calculated as:

$$G_{max} = \frac{0.866C\omega}{v_{beam}} \quad (2.5)$$

where C is the small signal gain parameter, $\omega = 2\pi f$ is the angular frequency, v_{beam} is the speed of the electron beam. The gain parameter C can be calculated as:

Figure 2.2: Configuration of a circular helix with dielectric support rods and metal shield.

$$C = \sqrt[3]{\frac{K_c I_{beam}}{4V_{beam}}} \quad (2.6)$$

Besides, if other parameters such as the space-charge parameters QC , detune parameter b , circuit attenuation parameter d and the number of wavelengths N in the circuit are known, the linear gain can be calculated using Pierce theory. For a simple case when ignoring space-charge effects and circuit loss, and using a synchronous beam ($QC = b = d = 0$), the linear gain of the tube can be simply calculated as:

$$G = -9.54 + 47.3CN \quad (2.7)$$

(Note: We use symbols b and d here for the sake of consistency with the literature; elsewhere in the thesis these symbols represent other quantities).

2.3 Circular helix

2.3.1 Introduction

Even though there is a large number of SWSs with different characteristics, circular helix is still the most widely used SWS in TWTs, especially for communication and ECM applications. The circular helix has the widest bandwidth among all SWSs. Its coupling impedance is also unmatched by many other SWSs. Figure 2.2 shows the configuration of a circular helix loaded with dielectric support rods. The helix is

formed by winding a tape conductor with a radius a and period L . Dielectric rods are used to support the helix inside the metal shield. The supporting rods are usually made of materials with high thermal conductivity such as beryllium oxide (BeO) and anisotropic pyrolytic boron nitride (APBN) in order to transfer heat away from the helix. The pitch angle of the circular helix φ is controlled by both the period and radius and is defined as [4]:

$$\varphi = \tan^{-1} \frac{L}{2\pi a} \quad (2.8)$$

2.3.2 Circuit Modifications

There are many parameters of the circular helix that need to be considered carefully in order to be used in TWTs. The phase velocity of the SWS needs to be synchronized with the speed of the electron beam over a wide bandwidth. Coupling impedance needs to be high enough for high gain and efficiency. A proper attenuation needs to be introduced to decrease oscillation and not reduce gain too much. Besides, a properly designed feed is very important to ensure low reflection and good transmission. In this section, dispersion control techniques and input/output couplers are introduced in details.

2.3.2.1 Dispersion Control

Since the helix SWS is a periodic structure, the phase velocity can be easily controlled by changing the period of the helix. Besides, as there are dielectric rods and a metal shield around the helix (as shown in Fig. 1.2), the phase velocity is affected depending on the dielectric constant of the supporting material, the amount of dielectric used, and the proximity of the metal shield. One would like that the phase velocity varies very little as frequency changes. Although the circular helix has the widest bandwidth, it does have dispersion to some extent. The dispersion is a very important property of a SWS since it determines the bandwidth of the TWT.

The dispersion in a circular helix TWT mainly arises because of two reasons [4]. Firstly, when the frequency decreases, the number of periods per wavelength increases so that the inductance of the circuit decreases and the phase velocity

Figure 2.3: Dispersion diagram of a circular helix with dielectric loading [18].

Figure 2.4: Circular helix (a) without vanes; (b) with solid vanes; (c) with T-shaped vanes; (d) with thin vanes [4].

increases. Secondly, the presence of metal enclosure decreases the phase velocity of the helix; the closer the shield, the greater the decrease. At higher frequencies, the field is closer to the helix while at lower frequencies the metal shield intercepts a greater portion of the field. As a result, the decrease of the phase velocity is more at lower frequencies. An example of the dispersion diagram of a circular helix is presented in Figure 2.3 [18]. The beam line intersects with the first two modes at points P and Q respectively. It is seen that the phase velocity is higher than the beam speed at frequencies lower than P and lower than the beam speed at frequencies higher than P. It should also be noted that the beam line intersects with the second

mode at point Q at the backward wave region. This may lead to backward wave oscillations for high power TWT. Besides, if the operating frequency is close to the π point, band edge oscillations may also occur [30].

The increase of phase velocity at lower frequencies resulting from the reduction of inductance can be offset by bringing the metal shield closer to the helix. However, if the metal shield is too close, the coupling impedance becomes very low, adversely affecting the gain and efficiency of the TWT. One method to make the dispersion curve of the helix flatter without changing the coupling impedance is to use metal vanes which extend from metal shield to the helix without touching the helix [4]. Figure 2.4 shows some of the vane designs that have been proposed [31]. With such vanes, the helix is able to provide sufficient interaction between the wave and the electron beam and produce a relatively flat gain over a wide bandwidth.

Apart from broadening the bandwidth, dispersion control is also applied for increasing output power in large signal regime. In the large signal regime, the electron beam loses energy, slows down, and loses velocity synchronism with the wave. By tapering the helix pitch, it is possible to synchronize the phase velocity with the beam velocity again, increasing the saturated power and efficiency [32].

2.3.2.2 Input and Output Sections

It is important to design the input and output sections of the helix for maximum power transfer and minimum reflection from input and output ends. Because of the periodicity, the impedance of the helix is usually higher than the impedance of standard coaxial line and varies significantly with frequency. In order to match the impedance of the helix with the load over a wide bandwidth, one way is to taper the helix or taper the coaxial line coupler [2]. Figure 2.5 (a) and (b) illustrate the two approaches respectively [4]. Optimization using simulation tools is the main method to achieve the best design [33]. Circuit impedance calculated from the transmission line theory [34] cannot reach sufficient accuracy for realistic designs. But it can assist the simulations by providing a good starting point for the simulations [35], [36].

Figure 2.5: Transition from circular helix to coaxial line: (a) tapered pitch helix, and (b) tapered coaxial line [4].

When the gain of the TWT is high, the output signal is large and a significant amount of signal may be reflected towards the input. There may be some reflection at the input end as well which contributes to a growing wave traveling towards the output. Repetition of this process can cause oscillations even for well-matched input and output sections. In high gain TWTs, attenuators or “severs” are usually used to suppress such oscillations [4]. As shown in Figure 2.6, the sever divides the SWS into two sections and prevents the reflected signal from reaching the input termination. The first section ends with a matched load and acts to modulate the beam. The second section begins with a matched load. The modulated beam carrying the information drifts into the second section and excites a new wave in the second section. The matched load of a sever typically can provide a reflection better than -30 dB. One disadvantage of a sever is that it reduces the gain and efficiency of a TWT as the bunching degrades passing through the sever region [1], [4]. Normally there is a limit of 20 dB gain for a TWT without any measures to prevent reflection related oscillations.

Figure 2.6: TWT with two-section sever.

2.3.3 Variations of Circular Helix

Several variations of the circular helix have been proposed for different applications and requirements. For beam voltages below 5000V, the normal circular helix works well. However, when the beam voltage increases, in order to meet the synchronism condition, one has to increase the period of the helix. This leads to stronger space-harmonics, causing the risk of backward wave oscillation [26]. Contra-wound helix [26], [37], [38] and ring-bar [39]–[42] have been proposed to solve this problem. As shown in Figure 2.7(a), the contra-wound helix consists of two identical circular helices wound in different directions. The ring-bar SWS is derived from the contra-wound helix and is made of rings joined with bars. A period of the ring-bar SWS consists of two rings and two bars which are arranged at 180° angular displacement (Figure 2.7(b)). The ring-bar structure is preferred in practice since it is more suitable for fabrication. The analysis of both two structures has been reported in the literature [26], [39]. It turns out that the contra-wound and ring-bar SWS are more dispersive than the normal circular helix. This limits the bandwidth of the contra-wound and ring-bar SWSs to just 10% - 20% [4]; but the backward wave interaction is greatly reduced. Very recently, a ring-based circular SWS (Figure 2.7(c)) consisting of two circular helices connected by circular rings has also been proposed to operate at high frequencies and beam voltages without backward wave oscillation [43].

Figure 2.7: Variations of the circular helix SWS: (a) cross-wound circular helix, (b) circular ring-bar SWS, (c) ring-based circular SWS, (d) coaxial circular helices [44].

Another variation of the circular helix is the coaxial helices. As shown in Figure 2.7(d), this structure consists of two coaxial contra-wound circular helices of different radii. This structure can be used for coupling input and output power from a helix [45], [46].

2.4 Planar Helix with Straight-edge Connections

As mentioned before, the circular helix and its variations cannot be easily fabricated using printed-circuit or microfabrication techniques which can reduce the cost of fabrication and enable precise fabrication of small structures that are required for TWTs operating at millimeter wave frequencies (30-300 GHz) and higher. Therefore there exists a strong motivation to develop a planar SWS that can have properties similar to those of the circular helix but can be fabricated using printed-circuit or microfabrication techniques. One such structure is a rectangular helix [22]. As shown in Figure 2.8(a), the rectangular helix is made by winding a conducting tape in a rectangular shape with a certain pitch angle. The rectangular helix can have

Figure 2.8: (a) Perspective view of a rectangular helix; (b) perspective view of PH-SEC.

different angles for the vertical and horizontal parts, φ_1 and φ_2 . The characteristic equation and coupling impedance of the rectangular helix with $\varphi_1 = \varphi_2$ have been obtained using the field analysis [22]. It has been found that the rectangular helix has relatively higher coupling impedance than a circular helix with comparable phase velocity.

Although the rectangular helix has a planar configuration, it is still not suitable for printed-circuit or microfabrication techniques since it has inclined strips on the edges. A planar helix with straight-edge connections (PH-SEC) (seen in Figure 2.8(b)) has been proposed, analyzed and fabricated [22]-[23], [44]-[45]. Unlike the rectangular helix, it has straight-edge connections to confine the structure in the transverse direction ($\varphi_2 = 0^\circ$). The PH-SEC retains the broadband property of a circular helix and can be easily fabricated using printed circuit or microfabrication techniques.

The PH-SEC structure immersed in free space has been analyzed using effective dielectric method (EDC) method [47]. The concept of an effective pitch angle is used in the analysis of PH-SEC. Similar to the circular helix, the phase velocity of the PH-SEC is proportional to the effective pitch angle. To take the effect of practical modifications such as metal shield, dielectric substrate and vacuum beam tunnel into consideration, PH-SEC with multilayer dielectric substrates has been analyzed using modified effective dielectric (MEDC) method [23], showing that the PH-SEC with multilayers of dielectric is able to provide a relatively flat phase velocity and significant values of coupling impedance.

The PH-SEC structure has been successfully fabricated using printed circuit techniques [23]. Besides, a W-band PH-SEC on thick silicon substrate has also been fabricated using microfabrication techniques [24], [44]. The issues of Si wafer resistivity, copper conductivity including the effect of surface roughness, temperature rise and maximum electric field have been studied. One important observation is that the W-band PH-SEC on thick silicon substrate has asymmetric coupling impedance due to dielectric loading. Mode competition and gain loss may happen because of the asymmetry. One suggestion is to reduce the thickness of Si and make a trench in the substrate to reduce dielectric loading [24].

2.4.1 Variations of PH-SEC

Analogous to the circular helix, the PH-SEC also has the issue of backward wave oscillation at high beam voltage which may affect the high power performance of a TWT based on PH-SEC. Two variation of the PH-SEC have been proposed to solve this problem, namely, the planar contra-wound helix and rectangular ring-bar with straight-edge connections (RRB-SEC) [44]. Figure 2.9 shows one period of both structures with supporting dielectric substrate.

Figure 2.9: Perspective view of the (a) planar contra-wound helix on dielectric substrates, and (b) rectangular ring-bar SWS on dielectric substrates.

2.5 Field Theory for Dispersion Characteristics of Helical SWSs

2.5.1 Dispersion Characteristics of Circular Helix

There are two analytical methods to derive the characteristic equation for the helix SWSs, namely, field analysis and equivalent circuit analysis. The equivalent circuit analysis treats the SWS as a transmission line and gets the equivalent capacitance C_e and inductance L_e [34]. The phase constant β is calculated as $\beta = \omega\sqrt{C_e L_e}$. The field analysis is more straightforward, involving solution of the eigenmode equation derived from the Maxwell's equations and boundary conditions. For the field analysis, two different models for the helix have been used: sheath helix model [28] and tape helix model [48]. In the following subsections, the derivation of the characteristic equation and coupling impedance for the sheath helix model is reviewed since this method will be used for the PH-SEC too.

2.5.1.1. Sheath Helix Model

The boundary conditions for the actual helix, which is a periodic structure, can be simplified by using the sheath helix model. As seen in Figure 2.10 (a), the actual helix consists of a tape wound into a helical shape with period L . When the tape width becomes small and p also becomes small, the spacing between the turns and the tape width can be assumed to approach zero. The structure then becomes continuous and the periodicity can be ignored, leading to a sheath-helix, as illustrated in Figure 2.10 (b). For the sheath-helix, at the surface $r = a$, the boundary conditions may be approximated such that the conductivity is infinite in the direction parallel to the tape and zero in the direction perpendicular to the tape. Such an approximation for the sheath helix model remains valid as long as:

$$L \ll \lambda \quad (2.9)$$

Figure 2.10: Helix model: (a) Tape helix; (b) sheath helix [2]; (c) Side view of the sheath helix model.

It should be noted that the sheath helix model can only yield the zeroth order spatial harmonic of the fundamental mode since the information of periodicity gets lost by applying the sheath helix model. As a result, at high frequencies when λ is small and spatial harmonics become important, a more realistic model should be used.

2.5.1.2 Field Expressions, Boundary Conditions and Characteristic Equations

For simplicity, here we review the analysis for a circular helix in air without dielectric support and metal shield. The wave is assumed to be propagating in the z direction and all the field expressions have a variation of $e^{j\omega t - j\beta z}$. Due to the anisotropic conductivity of the helix, the propagating modes are hybrid in nature. From the Maxwell's equations, the axial components of E and H fields, in cylindrical coordinates (see Fig. 2.10 (c)), can be expressed as [34]:

$$E_{z1,2} = \begin{cases} AI_0(\gamma r) & (r \leq a) \\ BK_0(\gamma r) & (r \geq a) \end{cases} \quad (2.10a)$$

$$(2.10b)$$

$$H_{z1,2} = \begin{cases} CI_0(\gamma r) & (r \leq a) \\ DK_0(\gamma r) & (r \geq a) \end{cases} \quad (2.11a)$$

$$(2.11b)$$

where $\gamma = \sqrt{\beta^2 - k_0^2}$, k_0 is the free space wave number, I_0 and K_0 are zeroth order modified Bessel functions. A to D are unknown amplitude constants.

All other components of E and H fields in the two regions indicated in Figure 2.10 (c), $r < a$ and $r > a$, can be expressed in terms of the axial components E_z and H_z as follows:

$$\frac{1}{r} \frac{\partial E_z}{\partial \varphi} - \frac{\partial E_\varphi}{\partial z} = -\mu \frac{\partial H_r}{\partial t} \quad (2.12a)$$

$$\frac{1}{r} \frac{\partial H_z}{\partial \varphi} - \frac{\partial H_\varphi}{\partial z} = \varepsilon \frac{\partial E_r}{\partial t} \quad (2.12b)$$

$$\frac{\partial H_r}{\partial z} - \frac{\partial H_z}{\partial r} = \varepsilon \frac{\partial E_\varphi}{\partial t} \quad (2.12c)$$

$$\frac{\partial E_r}{\partial z} - \frac{\partial E_z}{\partial r} = -\mu \frac{\partial H_\varphi}{\partial t} \quad (2.12d)$$

The derivative $\partial/\partial\varphi$ equals to zero as the field expressions do not contain φ . The boundary conditions for the sheath helix model of the circular helix are the following. E_φ and E_z are continuous across $r = a$. Electric field in the direction of conduction is zero. Also, the magnetic field in the direction of conduction is continuous across $r = a$. These can be expressed as:

$$E_{\varphi 1} \cos \varphi + E_{z 1} \sin \varphi = 0 \quad (2.13a)$$

$$E_{\varphi 2} \cos \varphi + E_{z 2} \sin \varphi = 0 \quad (2.13b)$$

$$E_{z 1} = E_{z 2} \quad (2.13c)$$

$$E_{\varphi 1} = E_{\varphi 2} \quad (2.13d)$$

$$H_{\varphi 1} \cos \varphi + H_{z 1} \sin \varphi = H_{\varphi 2} \cos \varphi + H_{z 2} \sin \varphi \quad (2.13e)$$

By applying these boundary conditions, the characteristic equation can be derived as:

$$\frac{k_0 \cot \varphi}{\gamma} = \left\{ \frac{I_0(\gamma a) K_0(\gamma a)}{I_1(\gamma a) K_1(\gamma a)} \right\}^{\frac{1}{2}} \quad (2.14)$$

For $\gamma a > 10$, the $I_0 K_0 / I_1 K_1$ will approach unity. In such a case, from (2.14), $\gamma = k_0 \cot \varphi$ from which we can see that the phase velocity is approximately proportional to $\sin \varphi$:

$$\beta = k_0 \csc \varphi, \quad v_p = \frac{\omega}{\beta} = c \sin \varphi \quad (2.15)$$

Figure 2.11: (a) Conducting tape array. (b) UC screen.

The coupling impedance can be calculated using equations (2.2) and (2.3).

2.5.2 Dispersion Characteristics of PH-SEC

2.5.2.1 Unidirectionally Conducting (UC) Screens

Just as the sheath helix model simplifies the analysis for the circular helix, the unidirectionally conducting (UC) screen model simplifies the analysis for a planar conducting tape array. Figure 2.11 (a) shows an array of conducting tapes conducting in the y' direction. When the tape width and the gap between each tape are much smaller than the wavelength, this model can be simplified to a UC screen as shown in Figure 2.11 (b). Similar to the sheath helix, the UC screen has infinite

conductivity in the direction of the tape (y') and zero conductivity in the direction perpendicular to the tape (z').

A pair of UC screens has been proposed and analyzed in the past [49]–[51]. As shown in Figure 2.12, it consists of two UC screens located at $x = \pm a$ with a separation of $2a$. Medium 1 constitutes the region outside the structure with permittivity of ϵ_1 while medium 2 which constitutes the region between the two screens has permittivity of ϵ_2 . The UC screens are infinite in the y and z direction.

Figure 2.12: A pair of UC screens.

The top and bottom screens conduct in y' and y'' directions which have an angle φ and $-\varphi$ with the y axis, respectively. Correspondingly, they are perfectly insulating in the direction z' and z'' .

Similar to the circular helix, the planar helix only supports hybrid modes; thus, both E_z and H_z exist. The symmetry of the structure suggests that the propagating modes should either be transverse symmetric (or longitudinal antisymmetric) or transverse antisymmetric (or longitudinal symmetric). For a transverse symmetric mode, the transverse components of E and H , i.e., E_x , E_y , H_x , H_y , have a symmetric variation with respect to x . Similarly, for a transverse antisymmetric mode, the transverse components of E and H fields have an antisymmetric variation and the longitudinal field components have a symmetric variation with respect to x . For TWT applications, the transverse antisymmetric mode is useful.

One assumes that the wave is propagating in the z direction, field components vary as $e^{j\omega t - j\beta z}$ and decay away from the screens. Since the structure is infinite and has no variation in the y direction, the field expressions should be independent of y , i.e. $\partial/\partial y = 0$. Thus, the longitudinal components for the transverse antisymmetric modes can be written as:

$$E_{z\ 1,2} = \begin{cases} Ae^{-k_{x1}(x-a)} & (x \geq a) \\ B \cosh(k_{x2}x) & (a \geq x \geq 0) \end{cases} \quad (2.16a)$$

$$(2.16b)$$

$$H_{z\ 1,2} = \begin{cases} Ce^{-k_{x1}(x-a)} & (x \geq a) \\ D \cosh(k_{x2}x) & (a \geq x \geq 0) \end{cases} \quad (2.17a)$$

$$(2.17b)$$

where fields only in the positive half space are mentioned; fields in the other half space can be easily got from symmetry. A - D are unknown amplitude coefficients. The transverse decay coefficients k_{x1} and k_{x2} and the propagation constant β have the following relationship:

$$k_{x1} = \sqrt{\beta^2 - k_1^2}, \quad k_{x2} = \sqrt{\beta^2 - k_2^2} \quad (2.18)$$

where

$$k_1 = \omega\sqrt{\varepsilon_1\mu}, \quad k_2 = \omega\sqrt{\varepsilon_2\mu} \quad (2.19)$$

The transverse field components of the structure can be obtained as:

$$E_x = -\frac{j\beta}{k_c^2} \frac{\partial E_z}{\partial x} - \frac{j\omega\mu}{k_c^2} \frac{\partial H_z}{\partial y} \quad (2.20a)$$

$$E_y = \frac{j\omega\mu}{k_c^2} \frac{\partial H_z}{\partial x} - \frac{j\beta}{k_c^2} \frac{\partial E_z}{\partial y} \quad (2.20b)$$

$$H_x = -\frac{j\beta}{k_c^2} \frac{\partial H_z}{\partial x} + \frac{j\omega\varepsilon}{k_c^2} \frac{\partial E_z}{\partial y} \quad (2.20c)$$

$$H_y = -\frac{j\omega\varepsilon}{k_c^2} \frac{\partial E_z}{\partial x} - \frac{j\beta}{k_c^2} \frac{\partial H_z}{\partial y} \quad (2.20d)$$

where $k_c^2 = k^2 - \beta^2 = -k_x^2$. The derivative $\partial/\partial y = 0$ as the field is constant in the y direction. Similar to the sheath helix model, the UC screens satisfy the following boundary conditions at $x = \pm a$:

$$E_{y1}\cos\varphi + E_{z1}\sin\varphi = 0 \quad (2.21a)$$

$$E_{y2}\cos\varphi + E_{z2}\sin\varphi = 0 \quad (2.21b)$$

$$E_{y1}\sin\varphi + E_{z1}\cos\varphi = E_{y2}\sin\varphi + E_{z2}\cos\varphi \quad (2.21c)$$

$$H_{y1}\cos\varphi + H_{z1}\sin\varphi = H_{y2}\cos\varphi + H_{z2}\sin\varphi \quad (2.21d)$$

The characteristic equation for the transverse antisymmetric modes is obtained as:

$$\frac{\frac{k_1^2}{k_{x1}^2} + \frac{k_2^2}{k_{x2}^2} \tanh(k_{x2}a)}{k_{x1} + k_{x2} \coth(k_{x2}a)} = \tan^2\varphi \quad (2.22)$$

For the transverse symmetric modes, the process of analysis is similar. The corresponding characteristic equation can be obtained by replacing ‘cosh’ function with ‘sinh’ function in equation (2.22).

2.5.2.2 Dispersion Properties of PH-SEC

The PH-SEC can be considered to be obtained by confining the pair of UC screens in the y direction. For an infinitely wide pair of UC screens, the current ‘flows forward’ at the same pitch angle in all parts of the structure. But when the UC screens are confined with straight-edge connections, the current is not ‘flowing forward’ in the straight connections. Therefore, in the analysis of PH-SEC, the concept of an ‘effective pitch angle’ is used. By comparison with a circular helix, the effective pitch angle of the planar helix with straight-edge connections (PH-SEC) is calculated as [47]:

$$\begin{aligned} \varphi_{eff} &= \tan^{-1} \left(\frac{\text{Period}}{\text{Perimeter of the cross section}} \right) \\ &= \tan^{-1} \left(\frac{L}{4(a+b)} \right) \end{aligned} \quad (2.23)$$

where L is the period of the PH-SEC and $2a$ and $2b$ are the transverse dimensions. The dispersion characteristics can be calculated by substituting the effective angle into equation (2.22). The results calculated using the effective angle are accurate except at relatively low frequencies where the effect of the transverse truncation is more severe. The EDC method can be applied to make the results more accurate at lower frequencies. But it is enough to just use the effective angle if the aspect ratio of the cross section of the PH-SEC is large [47]. The analytical dispersion characteristics show a very good match with simulations when the effective angle is smaller than 7 degrees. In [23], a dielectric loaded PH-SEC with an effective angle of 6.3 degree has been studied and the analytical results show a very good match with simulation as well as measurement results.

2.6 Microfabrication of SWSs and Challenges

2.6.1 Microfabrication Methods

To achieve small dimensions precisely for high frequency SWSs, it is necessary that microfabrication techniques be used. Here we introduce some of the candidate techniques for SWS microfabrication.

Lithographie, **G**alvanik, und **A**bformung (LIGA) is a lithographic process that is able to fabricate high aspect ratio metal structures [52]. This technique is able to build very straight metal walls with high aspect ratio features. Thus it has been successfully used in fabricating folded waveguide structures [53]–[55], PH-SEC, and RRB-SEC [44]. Deep Reactive Ion Etching (DRIE) is a fabrication process to etch high-aspect-ratio trenches in Silicon [56]. Together with silicon metallization or electroplating techniques, metal structures can also be fabricated. This technique has been used for fabricating folded waveguide [57], [58] and suspended meander-line SWSs [59]. Other fabrication techniques such as Electrical Discharge Machining (EDM), Computer Numerical Control (CNC) Machining and Laser Ablation have also been used for microfabricating millimeter wave structures [1].

2.6.2 Challenges for Microfabricated SWSs

In the microfabrication process, there are many challenges and issues that must be considered. Some of the issues are shared by all types of SWSs. Some other issues are critical for dielectric loaded SWSs such as circular helix, PH-SEC and meander-line SWS. Some of the important challenges are listed below.

2.6.2.1 Dimensional and Alignment Accuracy

For a SWS working at millimeter wave or terahertz frequencies, the dimensional accuracy of the structure becomes very important since a small error may lead to a big change such as frequency shift or additional reflection. In the fabrication process, each step in the fabrication may suffer from some variations and errors. If each fabrication step is not well-controlled, the performance may be affected seriously. In any case, the effect of such variations and errors needs to be considered at the design stage itself.

Accurate alignment of different parts of the SWS assembly is also a very important issue [60]. For helix SWSs, there are three parts: the metal helix, supporting dielectric rods, and the metal shield. The three parts are fabricated separately and assembled together. Misalignment of these parts may seriously degrade the performance of the circuit. In a similar manner, for microfabricated SWSs involving multilayer construction, accurate alignment of different layers is very important.

2.6.2.2 Attenuation

At high frequencies, the skin depth of conductors is very small. For example, at 100 GHz, the skin depth of copper is only around 200 nm. Limited by the metallization process, the roughness of the metal surface may be close to or larger than the skin depth of the conductors. In this case, the conducting structure fabricated for high frequency application will have a higher resistivity and higher loss than that for low frequency applications [24]. The root-mean-square (RMS) roughness of the conductor surface can vary significantly with different fabrication process. The folded waveguide SWS in [61] fabricated using LIGA is able to achieve a surface

roughness of 20-70 nm. In the W-band PH-SEC [24], the top and bottom metal strips have been fabricated using lift off process and electroplating, respectively; the two layers have a RMS roughness of 13.65 nm and 143.40 nm, respectively.

The loss in the SWS may come from dielectric materials as well. As the PH-SEC structure involves supporting dielectric substrates, it is important that the dielectric material have a low loss tangent at millimeter wave frequencies.

2.6.2.3 Heat Dissipation

With decreased area available for heat transfer and increased loss from reduced skin depth, the heat transfer is a significant issue for microfabricated SWS. Besides, the small dimensions at high frequency cause difficulty in electron beam alignment and focusing. If the electron beam is not focused well, more heat will be generated by collision of electrons and the structure. The heat generated will limit the maximum output power of the TWT. For structures with dielectric loadings, the contact area and the thermal conductivity of the dielectric play an important role in heat dissipation [62].

2.6.2.4 Dielectric Loading

Dielectric substrates are used in helix TWTs in order to support the SWS in the metal shield and conduct heat away from the SWS. Vacuum compatible materials with high thermal conductivity are often used in order to increase the thermal dissipation. But the dielectric support often has the loading effect, reducing the phase velocity as well as the coupling impedance. To reduce the dielectric loading effect, it is necessary to reduce the amount of dielectric or use materials with low dielectric constant.

In traditional circular helix TWTs, thin rectangular support rods made of Beryllium oxide (BeO , $\epsilon_r = 6.5$) or APBN ($\epsilon_r = 5.1$) are most widely used, as shown in Figure 1.2 [4]. For some recent microfabricated SWSs, silicon ($\epsilon_r = 11.9$) [24], [59] or diamond ($\epsilon_r = 5.7$) [63]–[65] have been used as supporting dielectric materials.

2.6.2.5 Dielectric Charging

Normally, the magnetic focusing in the TWT prevents the axially-flowing electrons from spreading in the radial direction, but some issues such as inadequate focusing magnetic field and/or misalignment of the electron gun (off-axis or inclined with respect to the axis) may cause the electrons to hit the surrounding SWS. The charge of the electrons that land on the metallic SWS is conducted away. But the charge of the electrons that land on the dielectric rods may accumulate there and cause a voltage difference between the SWS and the dielectric support material. This voltage may become so high as to cause dielectric breakdown. Even otherwise, a high voltage on the dielectric will affect the electron motion, leading to defocusing of the electron beam and in-turn causing more electrons to hit the structure. This problem becomes more severe at millimeter wave or Terahertz frequencies where precise alignment of various parts and good control of the magnetic field are more difficult to achieve.

2.7 Simulation Tools for TWTs

In the past, the properties of SWSs and TWTs have been studied using analytical methods. By solving Maxwell's equations subject to boundary conditions, the characteristic equation can be derived analytically. Frequently, some approximations are necessary in the analysis. For example, the effect of non-homogeneous dielectric support rods is calculated using a homogeneous effective dielectric constant. In the recent years, with the development of computers and simulation softwares, one is able to get the high frequency characteristics using numerical methods. Although simulations can be time consuming for complex shapes, the analytical method often fails to account for many details of the TWTs. Therefore it has become very common to carry out high frequency, particle and even thermal simulations using various simulation tools.

For TWT design, both the cold-test parameters and hot-test parameters need to be studied and simulated. The most commonly used commercial simulation tools to simulate the cold-test parameters include Computer Simulation Technology (CST)

Microwave Studio (MWS) [66], Ansoft High Frequency Structure Simulator (HFSS) [67] and FEKO [68]. The hot-test parameters can be simulated with particle-in-cell (PIC) simulation tools developed for plasma physics including ARGUS [69], MAGIC [70], Christine [71], VORPAL [72], CST MAFIA, and CST PIC [66]. We have chosen to use CST MWS and CST PIC for this research.

CST MWS is a software package for electromagnetic analysis and design for high frequency applications. It provides a modeling front end which is based on ACIS modeling kernel. After construction of the model, the mesh is automatically generated before simulation. CST MWS comprises several different solvers using different solving methods for various applications. Eigenmode solver and transient solver are mostly used for SWS design. The eigenmode solver is dedicated to simulate different operating modes in resonant structures without S -parameter simulation. Both hexahedral and tetrahedral mesh are available in the eigenmode solver. Periodic boundary conditions can be applied for SWSs to calculate the dispersion diagram of different modes. The transient solver can obtain the entire broadband frequency behavior of a device from only one calculation run. The transient solver is based on finite integration method together with some highly advanced techniques which increase the accuracy of simulations substantially [66].

The coupling between particles and electromagnetic field can be simulated using CST PIC solver. It can model all particle sources such as DC, Gaussian bunches, field emission and user defined emission. Interaction between particles and fields such as electrostatic, magnetostatic, eigenmode, transient electromagnetic and user defined fields, can also be simulated [66].

2.8 Summary

In this chapter, the literature on circular helix SWS and its variations has been briefly reviewed in the context of application in TWTs. Some details such as dispersion control and input/output couplers have been introduced. A planar version of the circular helix, namely the PH-SEC as well as its variations has been reviewed. The field-analysis of both circular helix and PH-SEC with certain approximations has been presented. After that, some existing microfabrication techniques and

challenges for SWS fabrication have been mentioned. The chapter ends with a brief introduction of the simulation tools for the design of SWS and TWT.

CHAPTER 3

COUPLED PLANAR HELICES WITH STRAIGHT-EDGE CONNECTIONS (PH-SECS)

3.1 Introduction

Variations of the circular helix slow-wave structures (SWSs) that offer particular advantages over the circular helix have been proposed both in the past as well as the current literature. For instance, the cross-wound helix [26] and its practical version, ring-bar structure [41], have been proposed to improve the traveling-wave tube (TWT) amplifier operation at high power levels. Coaxial contra-wound circular helices of different radii have been proposed to couple input and output power in a TWT [42]-[43]. Very recently, a structure consisting of two circular helices connected by circular rings has been proposed to increase the operating frequency and output power of TWTs [43].

As shown in Figure 3.1 (a), the planar helix with straight-edge connections (PH-SEC), which has been introduced in Chapters 1 and 2, retains the broadband property of the circular helix and is suitable for printed circuit or microfabrication techniques [22]-[23]. Analogous to the variations of the circular helix, variations of the PH-SEC that offer some advantages over the PH-SEC are also possible. For example, a rectangular ring-bar structure, which is a variation of the PH-SEC, can perform better than the PH-SEC at high power levels in a TWT [44]. Two further variations of the PH-SEC are shown in Figures 3.1 (b) and (c). We refer to the structure in Figure 3.1 (b) as an unconnected pair of PH-SECS. This structure is similar to the pair of square helices proposed in [73] which can provide a larger space for the electron beam and thus has the potential to increase the frequency of operation. The unconnected pair of PH-SECS is expected to offer the same advantages as the structure in [73], together with an easier fabrication due to the straight-edge connections. The structure in Figure 3.1 (c) is referred to as a coaxial

Figure 3.1: (a) Perspective view of the PH-SEC. (b) Cross-section view of the unconnected pair of PH-SECs. (c) Cross-section view of the coaxial pair of PH-SECs. Cross-section view of four parallel infinite UC screens: (d) case I, (e) case II.

pair of PH-SECs, and analogous to its circular counterpart, is expected to have applications in coupling input and output power in a TWT. This structure also offers easier fabrication using printed-circuit or microfabrication techniques.

Analysis of PH-SEC has been reviewed in Chapter 2. The PH-SEC can be considered to be derived from a pair of unidirectionally conducting (UC) screens by incorporating truncation in the transverse direction in the form of straight-edge connections. In a similar manner, the coupled PH-SEC structures shown in Figures 3.1 (b) and (c) can be considered to be derived from the generic structure shown in Figure 3.1 (d) and (e) which consists of 4 parallel infinite UC screens. The generic structure can lead to the structures in Figures 3.1 (b) and (c) by incorporating

straight-edge connections that connect the appropriate screens with suitable directions of conduction.

In this chapter, we describe a novel and simple technique to analyze the cold-test parameters of the unconnected pair of PH-SECs (Figure 3.1 (b)) and the coaxial pair of PH-SECs (Figure 3.1 (c)). In Section 3.2, two cases of the generic structure shown in Figure 3.1 (d) and (e) are analyzed and the dispersion characteristics including the modes of propagation, dispersion characteristics and field distribution are calculated. In Section 3.3, we obtain the dispersion characteristics and coupling impedance of the unconnected pair of PH-SECs and the coaxial pair of PH-SECs from the results of the generic structure. A comparison of the results based on simple analytical approximation with those obtained from simulations for the two structures are presented. The simulation results are obtained using the Computer Simulation Technology (CST) eigenmode solver and show a good match with the analytical results. Besides, a comparison of the unconnected pair of PH-SECs with a corresponding single PH-SEC is presented and it is shown that the former has a reduced interaction with backward waves.

3.2 Analysis of Four UC Screens

3.2.1 Configuration Description

The concept of UC screens has been described in Section 2.5.2.1. The generic structure consists of four UC screens. Each of the screens in the structure shown in Figure 3.1(d) and (e) is considered to be parallel to the yz -plane and infinite in the y -direction. The separation between the inner two screens along the x -direction is $2a_1$ while it is $2a_2$ for the outer two screens. The screens are symmetrically located with respect to the $x = 0$ plane.

Here we consider two cases of UC screens with different arrangements of pitch angles (i.e., the directions of conduction). The first case (Figure 3.1(d)) is that the inner two UC screens are assumed to be perfectly conducting in different but symmetric directions $\pm\varphi_a$ with respect to the y -axis; similarly, the outer two UC screens conduct in different but symmetric directions $\pm\varphi_b$ with respect to the y -axis.

The second case (Figure 3.1(e)) is that the inner two UC screens are assumed to be perfectly conducting in the same direction φ_a with respect to the y -axis and the outer two UC screens conduct in the same direction φ_b with respect to the y -axis. Both structures admit modes that are symmetric or antisymmetric with respect to the $x = 0$ plane. Just as a single pair of UC screens supports two types of modes (transverse symmetric and transverse antisymmetric) [49]–[51], the structure with two pairs of UC screens is expected to support four distinct types of modes of propagation.

3.2.2 Case I

3.2.2.1 Dispersion Diagram

Analysis for the structure for case I has been reported in the literature using the equivalent circuit approach [74]. However, only two of the propagating modes were mentioned and discussed. The field distributions were not discussed either. It was also not discussed how the results for the infinite structure could be applied to practical structures that are finite in the transverse direction. Here, using the field theory approach, we derive the characteristic equations and present the dispersion characteristics for all the four modes, together with details of the field distribution for all the modes. These results show clearly how each mode may be excited. This information is very helpful for obtaining approximate analytical results for the coupled PH-SEC structures shown in Figures 3.1 (b) and (c).

We assume that the wave is propagating with a phase constant β and the fields have a variation of $e^{j\omega t - j\beta z}$. The structure is assumed to be immersed in air. From the point of view of TWT applications, the modes of interest are those that have symmetric variation of E_z with respect to the $x = 0$ plane, i.e., transverse antisymmetric (or longitudinal symmetric) modes. The field expressions for these modes in different regions can be written as follows [50]:

$$E_z = \begin{cases} A \cosh(k_x x) & (0 \leq x \leq a_1) \\ B_1 \cosh k_x(x - a_1) + B_2 \sinh k_x(x - a_1) & (a_1 \leq x \leq a_2) \\ C e^{-k_x(x - a_2)} & (x \geq a_2) \end{cases} \quad (3.1)$$

$$H_z = \begin{cases} D \cosh(k_x x) & (0 \leq x \leq a_1) \\ E_1 \cosh k_x(x - a_1) + E_2 \sinh k_x(x - a_1) & (a_1 \leq x \leq a_2) \\ F e^{-k_x(x-a_2)} & (x \geq a_2) \end{cases} \quad (3.2)$$

where $k_0^2 = \omega^2 \epsilon_0 \mu_0$, $k_x^2 = \beta^2 - k_0^2$, A , B_1 , B_2 , C , D , E_1 , E_2 , and F are unknown amplitude constants. For slow-wave solutions, k_x is considered to be a positive real number. Expressions for E_y and H_y can be obtained from equation (2.20). Fields only in the half-space $x \geq 0$ are mentioned here; fields in the other half-space can be easily obtained from symmetry. Expressions for the transverse symmetric modes can be written in a similar manner.

Using the properties of the UC screens [50], which are similar to the sheath-helix approximation, the following boundary conditions must be satisfied for the structure:

- 1) E_y is continuous across $x = \pm a_1$ and $x = \pm a_2$;
- 2) E_z is continuous across $x = \pm a_1$ and $x = \pm a_2$;
- 3) Electric field in the direction of conduction is zero at $x = \pm a_1$ and $x = \pm a_2$;
- 4) Magnetic field in the direction of conduction is continuous across $x = \pm a_1$ and $x = \pm a_2$.

The characteristic equations for different modes of the structure can be obtained by looking for a nontrivial solution of the set of equations that arise by substituting the field expressions into the boundary conditions. Equations (3.3) and (3.4) are the characteristic equations for the transverse antisymmetric and the transverse symmetric modes, respectively.

$$\begin{aligned} & \left[\cosh(k_x a_1) + \left(1 - \frac{k_x^2}{k_0^2} \tan^2 \varphi_b\right) X \right] e^{k_x(a_2 - a_1)} \\ & + \frac{k_x^2}{k_0^2} \tan^2 \varphi_b [\sinh(k_x a_2 - k_x a_1) \sinh(k_x a_1) - \cosh(k_x a_2)] \\ & - \cosh(k_x a_1) U = 0 \end{aligned} \quad (3.3)$$

$$\begin{aligned}
& \left[\sinh(k_x a_1) + \left(1 - \frac{k_x^2}{k_0^2} \tan^2 \varphi_b\right) Y \right] e^{k_x(a_2 - a_1)} \\
& + \frac{k_x^2}{k_0^2} \tan^2 \varphi_b [\sinh(k_x a_2 - k_x a_1) \cosh(k_x a_1) - \sinh(k_x a_2)] \\
& - \sinh(k_x a_1) U = 0
\end{aligned} \tag{3.4}$$

$$X = \frac{\frac{-k_0^2}{k_x} \sinh(k_x a_1) + k_x \coth(k_x a_1) \cosh(k_x a_1) \tan^2 \varphi_a + \cosh(k_x a_1) V}{\frac{-k_0^2}{k_x} + k_x \tan \varphi_a \tan \varphi_b} \tag{3.5}$$

$$Y = \frac{\frac{-k_0^2}{k_x} \cosh(k_x a_1) + k_x \tanh(k_x a_1) \sinh(k_x a_1) \tan^2 \varphi_a + \sinh(k_x a_1) V}{\frac{-k_0^2}{k_x} + k_x \tan \varphi_a \tan \varphi_b} \tag{3.6}$$

$$U = \frac{-k_0^2}{k_x} \sinh(k_x a_2 - k_x a_1) \frac{\cosh^2(k_x a_2 - k_x a_1) \tan^2 \varphi_b - \tan \varphi_a \tan \varphi_b}{\sinh^2(k_x a_2 - k_x a_1)} \tag{3.7}$$

$$V = k_x \coth(k_x a_2 - k_x a_1) (\tan^2 \varphi_a - \tan \varphi_a \tan \varphi_b) \tag{3.8}$$

3.2.2.2 Field Distribution

The constants A to F can be expressed in terms of a single constant using field expressions and boundary conditions, for example, constant B to F can be expressed in terms of A . The expressions are shown as follows:

$$B_1 = A \cosh(k_x a_1) \tag{3.9}$$

$$B_2 = AX \tag{3.10}$$

$$C = A \cosh(k_x a_1) \cosh(k_x a_2 - k_x a_1) \tag{3.11}$$

$$D = A \frac{k_x}{j\omega\mu} \coth(\gamma a_1) \tan \varphi_a \tag{3.12}$$

$$E_1 = -A \frac{k_x}{j\omega\mu} \cosh(k_x a_1) \coth(k_x a_2 - k_x a_1) (\tan\varphi_a - \tan\varphi_b) \quad (3.13)$$

$$+ AX \frac{k_x}{j\omega\mu} \tan\varphi_b$$

$$E_2 = A \frac{k_x}{j\omega\mu} \cosh(k_x a_1) \tan\varphi_a \quad (3.14)$$

$$F = -A \cosh(k_x a_1) \cosh(k_x a_2 - k_x a_1) \frac{k_x}{j\omega\mu} \tan\varphi_b \quad (3.15)$$

Substituting (3.9)-(3.15) in the field expressions in (3.1) and (3.2), one can obtain the field distribution for various modes of the structure.

3.2.2.3 Results and Discussion

The dispersion characteristics for the various modes are calculated using (3.3) and (3.4) and plotted for a structure with $a_2/a_1 = 2.2$, $\varphi_a = -\varphi_b = 2.29^\circ$. As shown in Figure 3.2, there exist four modes in the structure with different phase velocities. Two of the modes are transverse antisymmetric (modes 1 and 2) and the other two are transverse symmetric (modes 3 and 4). Mode 1 has the highest phase velocity while mode 4 is the slowest. The phase velocities of the four modes are similar when $k_0 a_1 > 0.2$ since the coupling between each screen is weak at higher frequencies. The phase velocity approaches $\sin\varphi$ asymptotically. Dispersion curves for the structure with the same dimensions as those used in [74] have also been obtained for comparison and the curves for modes 1 and 2 turn out to be identical to those in [74].

The x -variation of the normalized E_z for $k_0 a_1 = 0.13$ and $a_2/a_1 = 2.2$ for all the modes is shown in Figure 3.3. From the field distribution as well as the symmetry of the structure, the different modes can be categorized by the sign of the voltage on each screen. Following the considerations made in [45], the symmetric variation in E_z between two adjacent screens corresponds to like signs of the voltages on the screens (++). On the other hand, the antisymmetric variation in E_z between two adjacent screens corresponds to unlike signs of the voltages on the screens (+-). Thus, as shown in Figure 3.3 (a), mode 1 can be described as the “++++” mode; this

Figure 3.2: Normalized phase velocity for the modes supported by the generic structure in Figure 3.1(d) (case I).

Figure 3.3: x -variation of the normalized E_z for $k_0 a_1 = 0.13$ for all the modes shown in Figure 3.2.

is represented in the inset in Figure 3.2. In the same manner, modes 2, 3 and 4 can

be described as “-+-”, “+--” and “+-+” modes, respectively. Mode 4 involves a strong coupling between all adjacent screens and correspondingly has the lowest phase velocity (see Figure 3.2). Also, mode 1 is of the most interest here since it has a relatively large longitudinal electric field in the center where an electron beam can interact with this field component.

3.2.3 Case II

Case II has different pitch angles compared to case I, which leads to a difference in the field expressions in region 1 ($-a_1 \leq x \leq a_1$) of the four UC screens. Assuming that E_z is symmetric with respect to $x = 0$, we have $E_{z1}(a_1) = E_{z1}(-a_1)$.

For case I, according to the boundary conditions,

at $x = a_1$,

$$E_{y1} \cos \varphi_a + E_{z1} \sin \varphi_a = 0 \quad (3.16)$$

at $x = -a_1$,

$$E_{y1} \cos \varphi_a - E_{z1} \sin \varphi_a = 0 \quad (3.17)$$

As a result, E_{y1} is antisymmetric with respect to $x = 0$, i.e., $E_{y1}(a_1) = -E_{y1}(-a_1)$.

According to the relationship between E_y and H_z :

$$E_y = -\frac{j\beta}{k_c^2} \frac{\partial E_z}{\partial y} + \frac{j\omega\mu}{k_c^2} \frac{\partial H_z}{\partial x} = \frac{j\omega\mu}{k_c^2} \frac{\partial H_z}{\partial x} \quad (3.18)$$

H_{z1} is symmetric with respect to $x = 0$, i.e., $H_{z1}(a_1) = H_{z1}(-a_1)$ which is consistent with the field expressions presented in (3.1) and (3.2).

But for case II

at $x = a_1$,

$$E_{y1} \cos \varphi_a + E_{z1} \sin \varphi_a = 0 \quad (3.19)$$

at $x = -a_1$,

$$E_{y1}\cos\varphi_a + E_{z1}\sin\varphi_a = 0 \quad (3.20)$$

Figure 3.4: Normalized phase velocity for the modes supported by the generic structure in Figure 3.1 (e) (case II).

Contrary to Case I, here E_{y1} is symmetric and H_{z1} is antisymmetric with respect to $x = 0$. Considering this, the field expressions for case II should be written as:

$$E_z = \begin{cases} A \cosh(k_x x) & (0 \leq x \leq a_1) \\ B_1 \cosh k_x(x - a_1) + B_2 \sinh k_x(x - a_1) & (a_1 \leq x \leq a_2) \\ C e^{-k_x(x - a_2)} & (x \geq a_2) \end{cases} \quad (3.21)$$

$$H_z = \begin{cases} D \sinh(k_x x) & (0 \leq x \leq a_1) \\ E_1 \cosh k_x(x - a_1) + E_2 \sinh k_x(x - a_1) & (a_1 \leq x \leq a_2) \\ F e^{-k_x(x - a_2)} & (x \geq a_2) \end{cases} \quad (3.22)$$

The remaining steps in the analysis for case II are exactly the same as those for case I. The dispersion diagram (Figure 3.4) is plotted with the same dimensions as for case I: $a_2/a_1 = 2.2$, $\varphi_a = -\varphi_b = 2.29^\circ$. Similar to Case I, there exist four modes, including two symmetric modes and two antisymmetric modes. These modes can also be described as “++++”, “-+-”, “+--” and “+-+” modes respectively. The

Figure 3.5: x -variation of the normalized E_z for $k_0 a_1 = 0.13$ for all the modes shown in Figure 3.4.

dispersion curves for the various modes are quite close to the curves in case I – at least for this set of dimensions. One difference should be noticed; in case I, mode 4 is the slowest among all modes, but for case II, mode 4 is a little bit faster than mode 2. The x -variation of the normalized E_z for $k_0 a_1 = 0.13$ and $a_2/a_1 = 2.2$ for all the modes is shown in Figure 3.5. We can see that although cases I and II involve different nature of H_z , the distribution for E_z is exactly the same; this will lead to comparable coupling impedance values for both cases. As a result, both cases of the generic structure have similar potential for application in TWTs.

3.3 Coupled PH-SECs

For practical application, the screens need to be confined in the transverse direction. This can be achieved by truncating the screens in the y -direction and connecting the edges of the truncated screens with straight-edge connections in different ways. In this section, we apply the results of the previous section to obtain approximate

analytical results for two practical structures that can be derived from the generic structure consisting of four parallel infinite UC screens. Two of these possibilities, shown in Figures 3.1 (b) and (c), are considered in the following.

3.3.1 Unconnected Pair of PH-SECs

The unconnected pair of PH-SEC is obtained from the generic structure when $\varphi_a = -\varphi_b$, and the top two screens are connected together and the bottom two screens are connected together. As presented in Figure 3.1 (b), this results in an unconnected pair of identical PH-SECs. In general, we expect only two modes in this structure since the sign of the voltages on the screens connected with straight-edge connections cannot be different. As a result, the two modes of this structure should correspond to mode 1 (++++) and mode 3 (++--). To apply the analysis of the previous section to this structure, we calculate an effective pitch angle which, by analogy with a circular helix, is defined as arctangent of the ratio of the period L and the perimeter $4a + 4b$ of the cross section of each PH-SEC (see Figure 3.1 (a)). Thus:

$$\varphi_{a_eff} = -\varphi_{b_eff} = \tan^{-1}\left(\frac{L}{4(a+b)}\right) \quad (3.23)$$

As this structure involves two identical PH-SECs, we just need one value of the effective pitch angle. The above value of the effective pitch angle is used to replace the pitch angles φ_a and φ_b in the expressions in (3.3) and (3.4) for case I. Further, the value of the coupling impedance K_c can also be calculated using equation (2.2). For a structure with infinite width along the y -direction, the power flow per unit width, $P_{u\ w}$, is often used [23]:

$$P_{u\ w} = \frac{1}{2} \frac{\beta}{\omega\mu} \int \left(\frac{\mu_0}{\epsilon_0} |H_y|^2 + |E_y|^2 \right) dx \quad (3.24)$$

The total power P can be obtained by multiplying $P_{u\ w}$ by the width in the y -direction:

$$P = P_{u\ w} \times width \quad (3.25)$$

Figure 3.6: Normalized phase velocity and coupling impedance for mode 1 (++++)
of the unconnected pair of PH-SECs for various values of the normalized period
 L/a_1 .

Figure 3.7: Normalized phase velocity for mode 3 (++--)
of the unconnected pair of PH-SECs for various values of the normalized period L/a_1 .

Figures 3.6 and 3.7 show the results calculated for case I from the approximate analysis mentioned above as well as the simulation results obtained from the eigenmode solver of CST Microwave Studio. The geometrical parameters of the

Figure 3.8: Distribution of E_z on the xy -plane for the unconnected pair of PH-SECs: (a) mode 1 (++++), and (b) mode 3 (++--).

structure are: $a_2/a_1 = 2.2$, $b/a_1 = 2.4$ and $L/a_1 = 0.24, 0.48$ and 0.75 . The results based on the approximate analysis match very well with the simulation results except for low frequencies where the effect of the transverse truncation is more severe and is not captured in the approximate analysis which is based on infinite screens. As expected, the phase velocity increases as the period increases. Further, as the period gets larger, the actual structure deviates more and more from the sheath helix model. As a result, the accuracy of the results based on the analysis reduces when the period is large. The coupling impedance of mode 3 (++--) is not shown in Figure 3.7 since E_z at $x = 0$ is zero for this mode.

For mode 1 (++++), and mode 3 (++--), which are supported by the unconnected pair of PH-SECs, the simulated field distribution of E_z over the xy -plane is also obtained. As shown in Figure 3.8 (a) and (b), for $L/a_1 = 0.48$ and a phase shift per period of 35° , the other dimensions remaining the same as those for the Figures 3.6 & 3.7, the simulated field distribution is consistent with the analytical results presented for these two modes in Figure 3.3 (a) and Figure 3.3 (c), respectively.

The results only for case I are presented here; the results for case II can be obtained in a similar manner.

3.3.2 Study of Backward Wave Oscillation

It is known that in a TWT based on the single circular helix or the single PH-SEC, there is a possibility of oscillations due to interaction with the backward waves,

especially at high power levels. We compare the cold-test parameters of an unconnected pair of PH-SECs with that of a single PH-SEC, both having the same electron beam tunnel cross-section of 4.8 mm x 4.8 mm, with respect to the interaction with backward waves. We use $2a = 0.6$ mm, and period $L = 1.5$ mm for the unconnected pair of PH-SECs, and $L = 3.8$ mm for the single PH-SEC so that both structures have the same phase velocity at 6 GHz for the forward wave. Figure 3.9 (a) presents the complete simulated dispersion characteristics for the first three transverse antisymmetric modes. To study the beam circuit interaction, two beam lines, beam 1 and beam 2, with different velocities are applied in the dispersion diagram. As is seen, the beam lines intersect the first modes of both structures at 6 GHz. They also have intersection with the backward wave of the second modes at around 8 GHz and 17 GHz, respectively. Thus, the working frequency of the single PH-SEC is much closer to the frequency of backward wave oscillation. Figure 3.9 (b) shows that the coupling impedance for the backward wave for the single PH-SEC is much larger than that for the unconnected pair of PH-SECs throughout the frequency range. Thus, as compared to the single PH-SEC, the unconnected pair of PH-SECs has a better potential for avoiding backward wave oscillations in a TWT at high power levels.

3.3.3 Coaxial Pair of PH-SECs

For this structure also $\varphi_a = -\varphi_b$; however, here the two inner UC screens are connected together and the two outer UC screens are connected together. As shown in Figure 3.1 (c), this results in a coaxial pair of PH-SECs. Similar to a coaxial pair of circular helices, this structure can be used to couple input and output power in a TWT. Using the same reasoning as for the previous structure, this structure also admits only two modes which can be labeled as mode 1 (++++) and mode 2 (----). In this case, we calculate two different values of the effective pitch angles – one for the inner PH-SEC, φ_{a_eff} , and the other for the outer PH-SEC, φ_{b_eff} . With reference to Figure 3.1 (c), these effective angles can be written as:

$$\varphi_{a_eff} = \tan^{-1} \left(\frac{L}{4(a_1 + b_1)} \right) \quad (3.26)$$

$$\varphi_{b_eff} = \tan^{-1} \left(\frac{L}{4(a_2 + b_2)} \right) \quad (3.27)$$

Figure 3.9: (a) Dispersion characteristics for the first three transverse antisymmetric modes, and (b) coupling impedance of a pair of unconnected PH-SECs and a single PH-SEC with the same cross section of the beam tunnel.

Figure 3.10: Normalized phase velocity and coupling impedance for mode 1 (++++)
of coaxial pair of PH-SECs for different values of the normalized period L/a_1 .

To determine the coupling impedance, the total power P in this structure is calculated by multiplying the power flow per unit width P_{uw} by an average width $2b = b_1 + b_2$. Figures 3.10 and Figure 3.11 show the results obtained from the above considerations as well as simulations. Coupling impedance of mode 2 (---) is not included in Figure 3.11 since the E_z field components of the inner and outer helices roughly cancel out, resulting in coupling impedance values close to zero. The dimensions of the structure are: $a_2/a_1 = 2.2$, $b_1/a_1 = 2.4$, $b_2/a_1 = 2.8$ and $L/a_1 = 0.3$, 0.48 and 0.75 . Once again, the results of the approximate analysis and simulations match very well except at low frequencies. As expected, a larger period results in a higher phase velocity. It is also noticed that, unlike the previous case, the phase velocities for the two modes in this case have different values at high frequencies; a similar observation was made in [49] and the difference is caused by different values of the effective pitch angles for the inner and the outer PH-SECs. This is explained more clearly with the help of the field distribution which is considered next.

Figure 3.11: Normalized phase velocity for mode 2 (---) of coaxial pair of PH-SECs for different values of the normalized period L/a_1 .

Figure 3.12: Distribution of E_z on the xy -plane for the coaxial pair of PH-SECs: (a) mode 1 (++++), and (b) mode 2 (---).

The simulated distribution of E_z over the xy -plane for mode 1 (++++), and mode 2 (---), supported by coaxial pair of PH-SECs, is also obtained. As shown in Figures 3.12 (a) and (b), for $L/a_1 = 0.48$ and a phase shift per period of 35° , the other dimensions remaining the same as for the Figures 3.10 & 3.11, the simulated field distribution is qualitatively consistent with the analytical results presented for these two modes in Figure 3.3 (a) and Figure 3.3 (b), respectively. Quantitatively, there

are differences in the field values since the results in Figure 3.3 are for the case of equal magnitude of the pitch angles for the four screens. Further, it can be noticed in Figure 3.12 (a) that for mode 1 (++++), the E_z values are stronger close to the inner PH-SEC, showing that at high frequencies the inner PH-SEC dominates for this mode. On the other hand, in Figure 3.12 (b), for mode 2 (−++−), the E_z values are stronger close to the outer PH-SEC; this shows that the outer PH-SEC dominates for this mode. Equations (3.26) and (3.27) show that the value of the effective pitch angle, φ_{a_eff} , for the inner PH-SEC is larger compared to the value of the effective pitch angle, φ_{b_eff} , for the outer PH-SEC. Accordingly, the phase velocity values at high frequencies for mode 1 (++++ in Figure 3.10 are higher than those for mode 2 (−++−) in Figure 3.11. The coaxial pair of PH-SECs does not own the advantage of less risk of backward wave oscillation compared to the single PH-SEC. But it is useful for coupling energy from one helix to the other, just like the coaxial circular helices [45], [46].

3.4 Summary

In this chapter, the dispersion characteristics for a generic structure consisting of four parallel infinite UC screens in air have been obtained and the nature of the modes supported by this structure has been examined. It has been shown for the first time that these results can be utilized to simply obtain approximate analytical results for two coupled planar helix structures with straight-edge connections (PH-SECs) which can be realized in practice using printed-circuit or microfabrication techniques. Results calculated from the approximate analysis match with the simulation results quite well, except at low frequencies. It has also been shown that one of the two proposed structures, the unconnected pair of PH-SECs, has a reduced risk of backward wave oscillation in a TWT, as compared to a corresponding single PH-SEC. The other proposed structure, the coaxial pair of PH-SECs, is expected to be useful as a coupler to transfer power from one helix to the other. The two coupled PH-SEC structures have applications in millimeter wave TWTs.

CHAPTER 4

UNCONNECTED AND CONNECTED PAIRS OF PLANAR HELICES WITH STRAIGHT- EDGE CONNECTIONS (PH-SECS)

4.1 Introduction

Unconnected pair of planar helix with straight-edge connections (PH-SECS) and coaxial pair of PH-SECS have been introduced and investigated theoretically in Chapter 3. It has been shown that two modes are supported in the unconnected pair of PH-SEC. It has a larger electron beam tunnel and less risk of backward wave oscillation compared to a single PH-SEC. Furthermore, it is suitable for printed circuit or microfabrication techniques and can incorporate sheet beam.

Similar to other coupled slow-wave structures (SWS) such as the multi-helix [73] and the double V-shaped microstrip meander line [75], the unconnected pair of PH-SECS supports both a longitudinal symmetric mode and a longitudinal antisymmetric mode. In order to excite the longitudinal symmetric mode in these structures, which is the mode useful for beam-wave interaction, one needs to ensure equi-amplitude and equi-phase inputs and outputs for the coupled SWSs. In this chapter, design and fabrication of an unconnected pair of PH-SECS using printed circuit techniques is described. We feed the structure with a stripline Wilkinson power divider. The simulation and measurement results covering 3-6 GHz verify the low loss and wide band properties of the unconnected pair of PH-SECS.

An improvement over the unconnected pair of PH-SECS, the connected pair of PH-SECS is also proposed here. The latter structure offers a much simpler feed design compared to the unconnected pair of PH-SECS and yet offers the same advantages as the unconnected pair of PH-SECS. Measured results for dispersion characteristics

covering 2-5 GHz are also presented for a proof-of-concept structure. The measured results compare well with the simulation results.

Simulation results for hot-test parameters for the connected pair of PH-SECs showing a higher gain growth rate compared to that of a single PH-SEC are also presented. We also compare the simulated cold-test parameters of the connected pair of PH-SECs at around 60 GHz with those of the recently reported folded frame SWS [76] which belongs to the microstrip meander-line category of SWSs. It is shown that the structure proposed here offers significantly higher coupling impedance values.

4.2 Unconnected Pair of PH-SECs

4.2.1 Unconnected Pair of PH-SECs with Dielectric Substrate

The unconnected pair of PH-SECs with dielectric substrates can easily be fabricated with printed circuit techniques. As shown in Figure 4.1, the unconnected pair of PH-SECs consists of two PH-SECs (upper and lower) with a separation of h . The top and bottom strips of each PH-SEC are printed on the top and bottom surfaces of two substrates and the strips of each PH-SEC are connected using through substrate vias. The period of the two PH-SECs is L (as indicated in Fig. 3.1 (a)). The dimensions of the structure are: $2a = 0.813$ mm, $2b = 6$ mm, $L = 1.5$ mm and $h = 1.626$ mm. The

Figure 4.1: Cross-section view of the unconnected pair of PH-SECs with dielectric substrates.

dielectric substrate used here is RO 4003 ($\epsilon_r = 3.55$, loss tangent = 0.0027, thickness = 0.813 mm).

4.2.2 Feed Design for the Unconnected Pair of PH-SECs

As mentioned in Chapter 3, the unconnected pair of PH-SECs can support both the longitudinal symmetric mode (++++) and the longitudinal antisymmetric mode (++--), with the former mode being of interest to us since this mode has a large coupling impedance at the center while the coupling impedance for the latter mode is nearly zero. To excite the longitudinal symmetric mode, we incorporate a stripline power divider in the feed so as to provide equal magnitude and in-phase signals to the pair of PH-SECs. The upper and lower helices are designed to match to a 50 Ω microstrip line and are fed with a pair of carefully designed stripline Wilkinson power dividers. One power divider is used at the input and the other one, as a combiner, at the output.

The perspective view of the Wilkinson stripline power divider is shown in Figure 4.2 (a). The conductor pattern in the power divider is sandwiched between two dielectric substrates RO 4003 ($\epsilon_r = 3.55$, loss tangent = 0.0027, thickness = 0.813 mm). As shown in Figure 4.2 (b), the power divider is fed with a 50 Ohm stripline with width of w_1 which splits into two 100 Ohm striplines with width of w_2 and then

Figure 4.2: (a) Expanded view of the stripline power divider/combiner. (b) Plan view of the conductor pattern of the stripline power divider/combiner.

matched to 50 Ohms. A 100 Ohm resistor is used to provide isolation between the two output ports.

Figure 4.3: (a) Plan view of the upper PH-SECs; (b) plan view of the lower PH-SECs; (c) perspective view of the stripline Wilkinson power divider.

The two PH-SECs are designed using the same dielectric substrate as the power divider/combiner. For maintaining complete symmetry, the configuration of case II (as explained in Section 3.2.3) has been utilized. As shown in Figures 4.3 (a) and (b), each PH-SEC is first matched to a 120Ω CPW which in turn is tapered to a 50Ω microstrip line. Figure 4.3(c) shows the perspective view of the stripline Wilkinson power divider. A part of the power divider assembly is sandwiched between the two PH-SECs. One output of the power divider (port 2) is connected to the input of the upper PH-SEC while the other output (port 3) is connected to the input of the lower PH-SEC. This arrangement helps to maintain the same amplitude and phase at the input to each PH-SEC. An identical power divider is used at the output of the two PH-SECs. Photos of the assembly of the designed structure with two different lengths (25 and 35 periods) are shown in Figure 4.4. Nuts and bolts are used to assemble the whole structure.

(a)

(b)

Figure 4.4: Photo of the assembly of the unconnected pair of PH-SECs with different number of periods: (a) 25 periods; (b) 35 periods.

4.2.3 Simulation and Measurement Results

The cold-test parameters of the designed unconnected pair of PH-SECs are simulated using CST Microwave Studio (MWS) eigenmode solver. As shown in Figure 4.5 (a), both the longitudinal symmetric and the longitudinal antisymmetric modes exist in the unconnected pair of PH-SEC. The phase velocity of the longitudinal symmetric mode is a little higher than that for the longitudinal antisymmetric mode. Figure 4.5 (b) shows that the symmetric mode has a large coupling impedance while for the antisymmetric mode it is nearly zero.

Figure 4.6 presents the simulated S -parameters of the entire assembly obtained using CST MWS transient solver, covering 3-6 GHz. Simulated S_{11} is below -15dB from 3.9 GHz to 5.3 GHz. The measured S -parameters are also included in the figure. The resistor and the pin of the SMA connector cause a small gap between the two substrates of the power divider, causing some mismatch between the measured and simulated S -parameters. In order to confirm this, air gaps of the size of $1.5\text{mm} * 1\text{mm} * 0.1\text{mm}$ are added at the position of the two resistors. The simulated results are shown in red curves in Figure 4.6, with a relatively better match with measurements.

(a)

(b)

Figure 4.5: (a) Normalized phase velocity, and

(b) coupling impedance for the unconnected pair of PH-SECs.

To determine the phase velocity of the structure, we measure two assemblies with different number of periods (25 and 35) and use the difference $\Delta\psi$ in the phase of S_{21} values. The difference in the number of periods is $\Delta n = 10$. Assuming identical feeds for both assemblies, the phase constant β can be expressed as:

$$\beta = \frac{\Delta\Psi}{\Delta nL} \quad (4.1)$$

Figure 4.6: Simulated and measured S -parameters of the unconnected pair of PH-SECs.

Figure 4.7: Comparison of measured and simulated normalized phase velocity for the symmetric mode.

The phase velocity can also be obtained easily from the ω vs. β plot as ω/β . As shown in Figure 4.7, the phase velocity is obtained using (4.1) from both transient simulation and measurement results. Both results match well with those obtained from the eigenmode solver for the symmetric mode. This verifies that the designed feed excites the desired symmetric mode in the assembly.

4.3 Connected Pair of PH-SECs

The feed with a power divider/combiner makes the entire structure of the unconnected pair of PH-SECs rather bulky. Moreover, any errors in the fabrication of the power dividers adversely affect the performance of the SWS. This problem may become more serious for higher frequencies of operation.

4.3.1 Dispersion Characteristics

As shown in Figure 4.8 (a), the connected pair of PH-SECs can be obtained by connecting the two PH-SECs in the unconnected pair, Figure 4.8 (b), by extending the straight-edge connections at the edges. The connected pair of PH-SECs can be seen as a planar version of the structure proposed in [43] which consists of two

Figure 4.8: Perspective view of one period of (a) connected pair of PH-SECs; (b) unconnected pair of PH-SECs.

Figure 4.9: Cross-sectional view of the printed circuit configuration of the connected pair of PH-SECs.

circular helices connected with circular rings; compared to a single circular helix, this structure is able to operate at higher frequencies and higher voltage levels with a larger electron beam tunnel and lower risk of backward wave oscillation. The connected pair of PH-SECs realizes the circular structure of [43] in a planar form so that it can be fabricated using printed circuit or microfabrication techniques.

In this section, we present proof-of-concept design and fabrication of the connected pair of PH-SECs using printed circuit techniques. Figure 4.9 shows the cross section of the connected pair of PH-SECs, incorporating two dielectric substrates, with one PH-SEC on each substrate. We use Rogers RO 4003 ($\epsilon_r = 3.55$, loss tangent = 0.0027, thickness = 0.813 mm) as the dielectric substrates. Simulations for both connected and unconnected pairs of PH-SECs with the same dimensions have been carried out using the CST MWS eigenmode solver. The dimensions of both structures are listed in Table 4.1. The current distributions for the symmetric mode on the two structures are presented in Figure 4.10 at a frequency of 4 GHz. We can see that in the connected pair, the current mainly flows along the upper and lower PH-SECs. Only a small amount of current flows from the upper PH-SEC to the

lower PH-SEC and this can be neglected compared with the current on each PH-SEC.

Table 4.1 Dimensions of the connected pair of PH-SEC

Symbol	Dimension in millimeter (mm)
h	2
$2a$	0.813
$2b$	6
L	1.5
SW	0.5
VD	0.1
RD	0.35

Figure 4.10: Current distribution at 4 GHz (a) on the connected pair of PH-SECs, and (b) on the unconnected pair of PH-SECs for the symmetric mode.

Thus, the current distribution for the connected pair of PH-SECs is very similar to that for the symmetric mode of the unconnected pair of PH-SECs. The phase velocity and coupling impedance of the two structures are presented in Figures 4.11 (a) and (b), respectively. It can be seen that the phase velocity and coupling impedance for the connected pair of PH-SECs are almost the same as those for the symmetric mode of the unconnected pair of PH-SECs. These results are sufficient to establish that extended conductors connecting the upper and lower PH-SECs do not have much influence on the characteristics of the connected pair for the lowest order mode of propagation. At the same time, since the two PH-SECs are connected in the

connected pair, this structure should be able to support the symmetric mode without a complex feed.

Figure 4.11: (a) Normalized phase velocity, and (b) coupling impedance for the single PH-SEC and connected and unconnected pairs of PH-SECs.

The dispersion and coupling impedance characteristics of the connected pair of PH-SECs are also compared in Figure 4.11 with the single PH-SEC that has the same

size of electron beam tunnel as the connected pair. The period of the single PH-SEC is set to 2.8 mm in order to have a comparable phase velocity with that of the connected pair. The substrate and other parameters are the same for both structures. The dispersion characteristics results in Figure 4.11 (a) show that the connected pair of PH-SECs and the single PH-SEC have the same phase velocity at around 4 GHz. Figure 4.11 (b) shows that the coupling impedance of the connected pair for the forward wave is mostly higher than that for the single PH-SEC; this would result in a higher gain growth rate in a TWT using the connected pair. Besides, the coupling impedance values for the connected pair for the backward wave are lower than those for the single PH-SEC; this would result in a lower risk of backward wave oscillation in TWTs.

The connected pair of PH-SECs has been fabricated on RO 4003 substrates using

Figure 4.12 Connected pair of PH-SECs fabricated using printed circuit techniques. (a) Perspective view showing two dielectric substrates with printed PH-SECs and microstrip feed; (b) side view showing the wire connections between the two PH-SECs and input/output SMA connectors.

printed circuit techniques. The perspective view of the printed structure is shown in Figure 4.12 (a). A photograph of the side view of the fabricated connected pair of PH-SECs is shown in Figure 4.12 (b). Instead of two bulky power dividers that would be required in the input/output feed for the unconnected pair, only simple microstrip line feeds are needed to excite the longitudinal symmetric mode in the connected pair.

Both the upper and the lower PH-SECs are first connected to $67\ \Omega$ microstrip lines which are then tapered to $50\ \Omega$ microstrip lines in order to connect to standard SMA connectors. The widths w_1 and w_2 of the microstrip lines are 1.1 mm and 1.81 mm for the two impedance levels, respectively. The taper-length L_g is 18.95 mm. The size and position of the ground plane for the microstrip lines has a great influence on the return loss and therefore needs to be designed carefully. After optimization using the CST MWS transient solver, we are able to achieve a design with low return loss. The inclined conductors of the two PH-SECs, together with plated-through holes, are printed on dielectric substrates which are then aligned and fixed together with nuts and bolts. Thin metal wires are inserted through the plated-through holes and soldered to connect the two PH-SECs and also to act as straight-edge connections.

In order to be able to measure the phase velocity of the connected pair, two structures with 16 and 21 periods are designed and fabricated. These two structures are same except for the number of periods.

Figure 4.13 (a) shows the simulated and measured S_{11} and S_{21} for the connected pair of PH-SECs with 16 periods over a frequency range from 1-7 GHz. The simulation results are obtained using the transient solver in CST MWS. The measurement results match well with the simulations. The measured S_{11} indicates a wide -15 dB bandwidth ranging from 1.81-4.98 GHz. Simulated as well as measured phase velocity results over the frequency range 2-5 GHz are shown in Figure 4.13 (b). The phase velocity is obtained using equation (4.1). The measured phase velocity values are a little bit lower than the simulation values. This difference may be attributed to fabrication tolerances, extra length of connecting wires at the solder joints, and the difference in the conductivity values used in simulation and those achieved in fabrication. Such effects have also been reported in [77], [78].

(a)

(b)

Figure 4.13: Simulated and measured results: (a) S -parameters for the connected pair of PH-SECs with 16 periods; (b) normalized phase velocity for the connected pair of PH-SECs.

4.3.2 Hot-test Parameters

Hot-test parameters for both the connected pair of PH-SECs and the single PH-SEC have been obtained by PIC simulations using the CST Particle Studio. The substrate parameters and the dimensions follow the values mentioned in the previous section.

In order to have a fair comparison of the hot performance of the two structures, we set the interaction length of the two structures to be the same. Thus, we use 50 periods with a total interaction length of 75 mm for the connected pair of PH-SECs and 27 periods with a total interaction length of 75.6 mm for the single PH-SEC. For simplicity, we feed both structures using a discrete port with different port impedance values over different frequency ranges to achieve good values of S_{11} [79]. After optimization using the CST MWS transient solver, the S_{11} values are lower than -20 dB for both structures from 3.6-4.2 GHz. An e-beam with beam voltage of 5.35 kV and current of 200 mA is applied at the center of the electron-beam tunnel. The elliptical cross section of the e-beam has a semi-major axis of 1 mm and a semi-

Figure 4.14: Linear gain vs. frequency for the connected pair of PH-SECs and the single PH-SEC for an input signal power of 100 mW.

minor axis of 0.5 mm. The focusing magnetic field is set at 0.5 T. Figure 4.14 shows the variation in linear gain with frequency for the connected pair of PH-SECs and the single PH-SEC with an input signal power of 100 mW. The linear gain is the small signal gain where the output power increases linearly with input power. At the peak gain frequency, the gain values for the connected pair and the single PH-SEC are 18.5 dB and 12.5 dB, respectively; the corresponding gain growth rate values for the two structures are 0.25 dB/mm and 0.17 dB/mm, respectively. Thus, as expected from the coupling impedance values, the connected pair has a higher gain growth rate than the single PH-SECs. But, since the design of the connected pair presented here is more dispersive than the single PH-SEC, it also has a smaller 3-dB bandwidth. However, the dispersion can be reduced, e.g., by incorporating a suitably designed metal shield [4].

Besides, we also estimate the linear gain of the connected pair of PH-SECs based TWT using Pierce theory. Some of the important parameters such as propagation constant and coupling impedance can be captured from Figure 4.11. Detune parameter b which represents the level of electron synchronism can be easily calculated using beam voltage. Attenuation parameter d can be calculated from the S parameters in Figure 4.13. A value of 0.1 is used for the space charge parameter QC . Details of the calculation process can be found in the Appendix. The calculated gain is also presented in Figure 4.14. The maximum gain is achieved at 4.1 GHz which is very close to PIC simulation results. It is noted that the gain calculated using Pierce is less than the simulated gain values. This may be caused by growing electron bunching and space charge effect along the circuit [80].

We also estimate the hot-test performance of the connected pair of PH-SECs for application in a high gain TWT. In order to reduce the reflected signal in the TWT, the structure is divided into two sections and an idealized sever is applied between the two sections which are 30 periods and 80 periods long. The sever consists of two ports with a separation of 7 periods. The two ports are used to absorb the forward and reflected signals. The e-beam parameters and the feed design are the same as those mentioned in the previous paragraph. Figure 4.15 shows the output power and gain of the connected pair as a function of input power at 4 GHz. The maximum

linear gain for this structure is around 42.5 dB and the maximum peak output power is 56.7 dBm (468 W) at the saturation point for an input power of 17.8 dBm (60 mW). The corresponding maximum efficiency is 21.9%. Figure 4.16 shows the simulated phase space parameter values as a function of the longitudinal position at saturation at 4 GHz after an elapse of 20 ns from the start. We can see that more electrons are decelerated than accelerated, indicating clearly that the e-beam loses energy to the electromagnetic wave.

Figure 4.15: Output power and gain vs. input power at 4 GHz for the connected pair of PH-SECs.

Figure 4.16: Phase space energy vs. the longitudinal position.

The design and simulation results presented here serve as proof-of-concept. In practical applications, the issues of outgassing, dielectric charging, and thermal dissipation need to be taken care of. The outgassing may cause cathode poisoning. The electron beam will cause the dielectric to charge up and may eventually cause breakdown. Thermal issues are also very important in determining the power handling capability of the TWT. These issues can be addressed with a suitable dielectric material selection and a suitable electrical and thermal design.

4.3.3 Comparison with a Meander-line SWS

With the need for pushing up the frequency of operation of TWTs, it is quite important to have a SWS that can be microfabricated. With a planar configuration, the connected pair of PH-SECs has a very good potential to be fabricated using microfabrication techniques, just like the single PH-SEC. Another category of SWSs that has been proposed for easy fabrication using printed circuit or microfabrication techniques and that can also accommodate a sheet electron beam, is related to microstrip meander-line SWS. Beginning with U-shaped meander-line [77]-[78], these structures include raised meander-line [59], V-shaped meander-line [21], double V-shaped meander-line [75] and its recent variation, folded frame SWS [76].

In this section, we scale the structure dimensions for operation at 60 GHz and compare the cold-test parameters of the connected pair of PH-SECs with those of the folded frame SWS. Figure 4.17 shows the perspective view of the folded frame SWS and the connected pair of PH-SECs. For simulations, all dimensions except the periods of the two structures are set to be the same as in [76] and are listed in Table 4.2. The bending angle of the V shape in the folded frame SWS is 6 degrees. In order for the two structures to operate with comparable phase velocity, the period of the connected pair of PH-SEC L is set to be 0.12 mm. Both structures are enclosed in a metal shield and the substrate material is boron nitride with a relative permittivity of 4.

Table 4.2 Dimensions of the folded frame SWS and the connected pair of PH-SECs

Symbol	Dimension in millimeter (mm)
h	0.19
$2a$	0.05
$2b$	0.44
w	0.02
t	0.01

Eigenmode simulations are carried out in CST MWS and the normalized phase velocity and coupling impedance results are presented in Figures 4.18 (a) and (b), respectively. Figure 4.18 (a) shows that the connected pair of PH-SECs is more dispersive than the folded frame SWS. But, as shown in Figure 4.18 (b), the coupling impedance for the connected pair is much larger than that for the folded frame SWS. The reason for this is likely to be the fact that the folded frame SWS has a microstrip form; thus the fields are concentrated within the dielectric substrates, leading to a reduction in the coupling impedance. The connected pair of PH-SECs is expected to have a much larger gain growth rate which will result in TWTs that are more compact or have a higher gain. It should also be possible to achieve relatively

Figure 4.17: Perspective view of (a) folded frame SWS, and (b) the connected pair of PH-SECs.

flatter dispersion characteristics of the connected pair by a suitable design of the shield etc. [4].

(a)

(b)

Figure 4.18: (a) Normalized phase velocity vs. frequency for the folded frame SWS and the connected pair of PH-SECs; (b) average coupling impedance values vs. frequency for the two structures.

In view of the required dielectric charging prevention, high temperature and vacuum compatibility of the SWSs in TWTs, the process steps as well as the material selection in the microfabrication play a very important role. From this point of view, more work needs to be done on the design of the connected pair of PH-SECs.

4.4 Summary

An unconnected pair and a connected pair of PH-SECs have been studied in this chapter. To excite the desired longitudinal symmetric mode, the unconnected pair is fed with a pair of stripline Wilkinson power divider. The SWS assembled with power divider has been fabricated using printed circuit techniques and measured. It has been shown that the longitudinal symmetric mode can be successfully excited. The measured results match with the simulations relatively well.

The connected pair of PH-SECs, which is an improvement on the unconnected pair of PH-SECs, has also been proposed and studied for application in TWTs. It has been demonstrated that the connected pair of PH-SECs offers a much simpler design for input/output feed and also maintains the advantages of the unconnected pair, namely, a larger electron beam tunnel and a better potential for avoiding backward wave oscillations compared to a single PH-SEC. As a proof-of-concept, the new structure has been designed and fabricated using the printed circuit techniques. Measured *S*-parameters and phase velocity results are presented over a frequency range of 1-7 GHz; these results match well with the simulation results and demonstrate the wide bandwidth capability of the proposed structure. Simulation results have been presented to show that the connected pair of PH-SECs has higher coupling impedance values and, correspondingly, a higher gain growth rate than that for the single PH-SECs. The performance of a TWT incorporating the connected pair of PH-SECs has also been investigated. It has been shown that such a TWT can yield at 4 GHz an output power of 468 W, with high gain (42.5 dB) and efficiency (21.9%).

The cold-test parameters of the connected pair of PH-SECs have also been compared with those of a recently proposed meander-line based SWS at frequencies around 60 GHz and it is shown that the connected pair has much larger values of

coupling impedance. Similar to a single PH-SEC, the connected pair of PH-SECs also has a good potential for fabrication using microfabrication techniques and thus it can be a good candidate for application in millimeter wave TWTs.

CHAPTER 5

DIELECTRIC CHARGING IN A MICROFABRICATED PLANAR HELIX SLOW-WAVE STRUCTURE

5.1 Introduction

As mentioned in Chapter 2, dielectric charging problem is very important for millimeter wave or Terahertz traveling-wave tubes (TWT) since it is difficult to control the alignment of different parts and to achieve adequate magnetic field at such high frequencies. If the electrons hit the SWS and the supporting dielectric, there will be a voltage difference between the SWS and the supporting rods. This voltage may defocus the electron beam and even cause dielectric breakdown when the voltage is high.

Some methods have been proposed in the past to address the problem of dielectric charging. One proposed method is to coat the dielectric with a thin layer of conductive material [83]. But the thickness of the coating is difficult to control and may induce excessive RF loss in the circuits. Another method is to coat the dielectric with BeO which has been proven to have relatively less dielectric charging effect [80]-[81]; but this also cannot fully avoid the problem in some cases. Yet another method proposed is to replace the material of the rods by a lossy dielectric material that exhibits a relatively high electrical conductivity at low frequencies [86]; but this may again cause high loss at millimeter wave frequencies.

In this chapter, we first propose a Ka-band symmetric PH-SEC SWS that can be fabricated using microfabrication techniques. As shown in Figure 5.1, instead of placing the PH-SEC on a thick silicon (Si) substrate, the symmetric PH-SEC has two thin symmetric Si substrates. The symmetry of the structure can help avoid mode competition and thin substrates reduce dielectric loading.

Figure 5.1: (a) one period of the symmetric PH-SEC, and (b) one period of the PH-SEC on thick substrate.

Next, two modifications to the symmetric PH-SEC are proposed to avoid dielectric charging problem. As a first step to solve this problem, we describe a simple single-dielectric model to study the dielectric charging phenomenon; the model is analyzed using an equivalent circuit and also simulated using CST Particle Studio. This exercise demonstrates that the phenomenon of dielectric charging can be simulated accurately. Then, a more realistic model consisting of two dielectric layers, Si and silicon dioxide (SiO_2), is studied; this model shows that even a thin layer of SiO_2 plays a dominant role in dielectric charging. This provides guidelines for modifications to the symmetric PH-SEC SWS to avoid the dielectric charging problem. First, the SiO_2 layer is removed between the metal strips to prevent the electrons from landing on the SiO_2 layer directly. Secondly, Si conductivity is enhanced appropriately to avoid build-up of charge and voltage. We present the effects of these modifications and it is shown that the modified SWS exhibits substantially reduced dielectric charging while maintaining a low insertion loss. The modifications proposed here are compatible with microfabrication.

5.2 Symmetric PH-SEC

As operating frequencies increase, the dimensions of the SWSs become quite small. Normal machining or printed circuit techniques can hardly achieve the required precision even for Ka-band frequencies. As a result, microfabrication techniques have become necessary for SWSs working at millimeter wave and higher

frequencies. Microfabrication of a PH-SEC at W band has been demonstrated on a thick Si substrate [24]; however, because of the asymmetry of the structure, the coupling impedance turns out to be asymmetric which may cause problems in a TWT [24]. One way to avoid this problem is to make a trench in the Si substrate beneath the PH-SEC [79]. In this section, we propose a symmetric configuration for PH-SEC, suitable for microfabrication, to solve the problem of asymmetry in an alternative manner. The simulated coupling impedance values for the new configuration are compared with those of the PH-SEC on a thick substrate when both structures are designed to operate at Ka-band frequencies.

5.2.1 Configuration of the Proposed Structure

The configuration of the proposed structure is shown in Figure 5.1 (a). Here we call it symmetric PH-SEC. Unlike the structure with a thick substrate at the bottom, shown in Figure 5.1 (b), the PH-SEC is symmetrically placed between two thin Si substrates. The entire structure is placed in a metal enclosure. The size of the metal enclosure can affect the dispersion and coupling impedance etc.

Figure 5.2 shows the cross-section of the symmetric PH-SEC. $2a$ and $2b$ are the height and width of the electron beam tunnel, respectively. The conductor strips have a width SW , thickness ST , and terminate in ring pads of diameter RD . The straight-edge connections of diameter VD connect two ring pads that face each other. The Si substrate has an ϵ_r of 11.9 and thickness h_2 . There is a thin layer of SiO_2 on each Si substrate, with an ϵ_r of 3.9 and thickness h_1 . The size of the metal enclosure is $2c \times 2d$. The period is L . The dimensions of the symmetric PH-SEC used in the simulations in CST eigenmode solver are listed in Table 5.1. The PH-SEC on thick Si substrate (750 μm) is also simulated in order to compare with the symmetric PH-SEC. The period of the latter structure is adjusted (450 μm) so that the two structures have similar values of phase velocity over the frequencies of interest. The metal enclosure for the PH-SEC with thick substrate starts at the bottom of the substrate and extends 750 μm above the PH-SEC.

Figure 5.2: Cross-section of the symmetric PH-SEC.

Table 5.1 Dimensions of the symmetric PH-SEC

Symbol	Dimension in micrometer (μm)
$2a$	300
$2b$	700
$2c$	1000
$2d$	2500
L	300
ST	20
SW	150
VD	100
RD	150
h_1	3
h_2	20

5.2.2 Results and Discussion

The phase velocity values of both structures are presented in Figure 5.3. It can be seen that these values for the two structures are quite close to each other over a wide range of frequencies. But the symmetric structure has a wider bandwidth.

Figure 5.3: Normalized phase velocity values for PH-SEC on thick substrate and symmetric PH-SEC.

Figure 5.4 shows the coupling impedance of the PH-SEC with thick substrate at two symmetric positions, $x = \pm 75 \mu\text{m}$. It can be seen that the coupling impedance values are not symmetric about the $x = 0$ plane; the values are higher for locations closer to the substrate since the E field is stronger at these locations. This may lead to problems such as mode competition and gain loss in a TWT.

The coupling impedance values of the symmetric PH-SEC are also shown in Figure 5.4. With less dielectric material present in this configuration, the E field is stronger in the region of the electron beam tunnel. Consequently, the coupling impedance values are much higher than those for the PH-SEC with thick substrate. In addition, the coupling impedance values at $x = \pm 75 \mu\text{m}$ are quite close to each other for the symmetric configuration.

Thus the proposed symmetric configuration for PH-SEC owns the advantages of higher and symmetric coupling impedance values compared to the PH-SEC on a thick Si substrate.

Figure 5.4: Coupling impedance for PH-SEC on thick substrate and symmetric PH-SEC.

5.3 Dielectric Charging in PH-SEC

It has been shown that the PH-SEC remains the advantages of broad bandwidth and high coupling impedance of the circular helix. It also provides potentially better heat dissipation by contacting the dielectric substrates over a large area. More importantly, it can be fabricated with microfabrication techniques, for example using Si, for high frequency applications [44] and can accommodate a sheet beam.

On the other hand, due to the presence of the dielectric substrates in the PH-SEC, there is increased risk of dielectric charging. For instance, consider the Ka-band symmetric PH-SEC described in the previous section. As shown in Figure 5.5 (a), the symmetric PH-SEC has two Si substrates, each with a thin isolation layer of SiO₂.

(a)

(b)

Figure 5.5 (a) Side view of the unmodified symmetric PH-SEC. (b) Side view of the modified symmetric PH-SEC.

Since the SiO₂ layer has very poor electrical conductivity, the voltage between the metal strips and the SiO₂ layer can build up and cause dielectric charging problem.

Fig. 5.5 (b) shows the same structure with some modifications to avoid dielectric charging and will be discussed later on.

5.3.1 Dielectric Charging Models

5.3.1.1 One-layer Model

The properties of the dielectric material, namely dielectric constant and conductivity, and the dimensions of the dielectric substrate affect the dielectric charging. In order to understand the impact of these parameters, we propose a simple single-dielectric model. The behavior of the model is analyzed using a simple equivalent circuit and is also simulated using CST Particle Studio.

Figure 5.6 (a) Single layer dielectric charging and discharging model. (b) Equivalent circuit of the model.

As shown in Figure 5.6 (a), we consider a dielectric substrate with dielectric constant ϵ_r , conductivity σ , area of cross-section S , and thickness h . The substrate is grounded at the bottom and has a particle source with current i placed above the substrate with the same emission area as the cross-section area of the substrate. The electron beam generated by the particle source impinges on the top of the substrate causing build-up of charge and voltage at the top surface. At the same time, current flows from the top surface to the bottom surface of the substrate. The twin

phenomena of charging and discharging can be represented by an equivalent circuit as shown in Figure 5.6 (b). In this circuit, the particle source is represented as a constant current source which is connected to a parallel combination of a capacitor C and resistor R . The values of C and R are calculated as follows:

$$C = \frac{\epsilon_0 \epsilon_r S}{h} (F), \quad R = \frac{h}{\sigma S} (\Omega) \quad (5.1)$$

The voltage V_c on the capacitor is the solution of the simple differential equation:

$$C \frac{dV_c}{dt} = -\frac{V_c}{R} + i \quad (5.2)$$

$$V_c = Ri \left(1 - e^{-\frac{t}{T}} \right) (V) \quad (5.3)$$

In equation (5.3), $T = RC = \epsilon_0 \epsilon_r / \sigma$ is the well-known relaxation time of the dielectric material. From equation (5.3), when $t \ll T$, using:

$$V_c \approx Ri \left\{ 1 - \left[1 - \frac{t}{T} + \frac{1}{2} \left(\frac{t}{T} \right)^2 - \dots \right] \right\} \approx Ri \frac{t}{T} (V) \quad (5.4)$$

it is seen that the voltage increases linearly with time for small values of t . Then, as the time t increases, the voltage increases less rapidly. Finally, when $t \gg T$, the voltage reaches the steady-state value of Ri . For a low conductivity material, the relaxation time T and resistance R are large and the steady-state voltage can build up to a high level. On the other hand, for a high conductivity material, the steady-state voltage is low and is reached sooner.

The behavior of the model in Figure 5.6 (a) is also examined through simulations by monitoring the time-varying voltage on the top surface of the substrate. We choose Si as the substrate material with the dielectric constant of 11.9. The conductivity σ of Si can vary according to dopant concentration. Four different cases with different combinations of S , h and σ , resulting in different values of the resistance R , have been calculated and simulated for a particle current equaling 0.02 A. The parameters for the four cases are shown in Table 5.2.

Table 5.2 Four cases of the one-layer model

Cases	1	2	3	4
h (mm)	4	2	4	4
S (mm ²)	400	100	100	100
σ (S/m)	0.01	0.01	0.015	0.01
ϵ_r	11.9	11.9	11.9	11.9

Figure 5.7: Dielectric charging voltage vs. time for four different cases.

The voltage vs. time results for both calculations (based on equation (5.3)) and simulations are presented in Figure 5.7. The curves represent simulation results and the markers, the calculation results. The simulated and calculated results match very well. It should be noted that the current here is negative. As a result, the corresponding voltage is also negative. Since the steady-state voltage is proportional to the resistance R , this voltage is different for each of the four cases. From the results for cases 3 and 4, which have the same dimensions but different conductivity values, it can be noted that the magnitude of the steady-state voltage is inversely proportional to conductivity. Thus it can be concluded that, with other parameters held constant, the conductivity of the dielectric material of the substrate can be used to restrict the build-up of voltage due to dielectric charging. In this context, it is very

useful that the conductivity of Si can be varied precisely by controlling the dopant concentration.

In an actual TWT the situation is more complex than that represented by the above model. For instance, the electrons do not hit the dielectric material at normal incidence. There may also be secondary emission from the dielectric material [84]. The secondary electron yield (SEY) depends on the material including surface coatings, the beam energy and the angle of incidence of the primary electrons. We first consider the SEY when the high-energy electrons of several keV impinge the Si layer. According to [87], the SEY of Si is below 0.2 for electron energies in the range of 3keV to 10 keV. We believe such a low value of SEY will not cause a significant change in our results. On the other hand, for Si or SiO₂-on-Si, SEY can be greater than one for low impact energies [88] and may lead to changes in the extent and polarity of dielectric charging at some locations in a TWT. If the dielectric charge is allowed to accumulate, it may lead to multipacting as well [89]. But if the dielectric charge is dissipated through higher conductivity of the dielectric material – as proposed by us – such problems are not likely to occur. Therefore, we do not consider the effect of secondary electrons in this work. This helps us to examine more realistic and complex TWT structures through relatively simple simulations.

5.3.1.2 Two-layer Model

Instead of one layer which is considered in the previous model, the proposed symmetric PH-SEC (Figure 5.5 (a)) has two layers of dielectric materials - Si and SiO₂. These layers are not grounded on the opposite side of the impingement area. Further, the maximum voltage difference due to dielectric charging is expected to develop between the metallic helix and locations midway between the helix turns. Therefore, next we study another model which takes into account these differences.

In the 2-layer model shown in Figure 5.8 (a), the upper layer is SiO₂ and the lower layer is Si. SiO₂ has a dielectric constant of 3.9 and an extremely low conductivity of 1e-14 S/m. The strip-shaped particle source generates electrons that hit a narrow strip on the right edge of the top surface of the SiO₂ layer. There is a thin metal strip

Figure 5.8: (a) Charging/discharging model with two layers of dielectrics. (b) Equivalent circuit of the model. (c) Current paths in the two layers.

on the left side of this surface which is connected to ground. When the electrons impinge on the SiO₂ layer, the charge and voltage build up, causing current flow to the grounded metal strip.

An equivalent circuit for the 2-layer model is presented in Figure 5.8 (b). As shown in Figure 5.8 (c), the current can flow either directly through the SiO₂ layer or through a path involving both SiO₂ and Si layers. The current through the first path encounters a resistance that is labelled as R_l -SiO₂. The second path goes down through the SiO₂ layer, covers the length of the Si layer, and finally goes back to ground, so that the corresponding resistances for this path are labelled as $2R_h$ -SiO₂ and R -Si. Equations (5.3) and (5.4) still apply for the voltage V_c , but the expressions for the capacitor and resistors are complicated by the fact that the charge and current distribution may not be uniform [90]. In general, assuming that the thickness of the SiO₂ layer is quite small compared to the distance between the impingement area and the grounded strip, the resistance for the second path is much smaller than that for the first path.

The 2-layer model is simulated using CST Particle Studio to study the effect of the thickness of the two layers and the conductivity of the Si layer. The surface area of the two layers is $20 \times 5.5 \text{ mm}^2$, the size of the particle source is $20 \times 0.5 \text{ mm}^2$ and the current is 1 mA.

For a Si layer thickness of 4 mm and conductivity of 0.1 S/m, the effect of the thickness h_1 of the SiO_2 layer is shown in Figure 5.9. It is seen that the voltage build-up between the impingement area and the grounded strip is quite sensitive to h_1 ; as this thickness decreases, the voltage also decreases. This happens because the resistor value R_h - SiO_2 decreases as the thickness of the SiO_2 layer decreases. It must be pointed out that in these results, the simulation time belongs to the $t \ll T$ regime; the steady-state voltage ($t \gg T$) for some of these cases can be of the order of 1000 V.

Figure 5.9: Dielectric charging voltage vs. time with different thicknesses of SiO_2 .

Figure 5.10: Dielectric charging voltage with different conductivities of Si.

The dielectric charging voltage for different conductivity and thickness values of the Si layer has also been studied, keeping the SiO₂ layer thickness at 1 mm. As seen in Figure 5.10, the voltage decreases as the conductivity increases; this is caused by a decrease in the value of the resistor R-Si. Figure 5.11 indicates that the value of the voltage is not really sensitive to the thickness of the Si layer. Figures 5.9, 5.10 and 5.11 indicate that the SiO₂ layer dominates the dielectric charging effect in the two layer model. This is caused by a large relaxation time T associated with the high resistivity of SiO₂. Thus one may conclude that the dielectric charging in such a two-layer structure can be reduced by removing the SiO₂ layer where possible and by increasing the conductivity of the Si layer while keeping an eye on the RF insertion loss.

While the above results have been obtained using a simple model with dimensions of the order of millimeters for easier simulations, the conclusions should hold good for structures with dimensions scaled down to microns.

Figure 5.11: Dielectric charging voltage with different thicknesses of Si.

5.3.2 Dielectric Charging in Symmetric PH-SEC

In this section, the dielectric charging effect is studied for the symmetric PH-SEC SWS (Figures 5.5 (a)) for application in a TWT. Most of the dimensional parameters are shown in Figure 5.2. The values of all the parameters used in the following simulations are same as those for the symmetric PH-SEC listed in Table 5.1.

In order to avoid the dielectric charging problem, two modifications are applied to the SWS. First, according to the conclusion in the previous section that the SiO_2 layer dominates the dielectric charging effect, the SiO_2 layer is removed except beneath the metal strips. This will largely prevent the electrons from hitting the SiO_2 layer directly. Besides, the RF performance of the circuit will not be affected since the SiO_2 layer is very thin. Secondly, doped Si with appropriate conductivity is used instead of intrinsic Si. These modifications are expected to reduce the relaxation time of the 2-layer structure and restrict the voltage build-up due to dielectric charging. The resulting modified symmetric PH-SEC is shown in Figure 5.5 (b).

Simulations have been carried out for the symmetric PH-SEC, both with and without the modifications mentioned above. We assume that the DC voltage of the SWS is

maintained at 0 V. Therefore, when the electrons hit the metallic SWS, the charge will be conducted away. On the other hand, when the electrons hit the dielectric substrate, the charge will accumulate if the substrate has poor conductivity.

As shown in Figure 5.12, 22 periods of the symmetric PH-SEC are simulated, placing 21 voltage monitors that measure the voltage between each metal strip and the nearest center point between two metal strips. The voltage monitor 1 is closest to the particle source and the voltage monitor 21 is farthest. The size of the particle source is $350\text{ }\mu\text{m} \times 150\text{ }\mu\text{m}$ and it generates a sheet beam. The voltage and current of the particle source are set to 3700 V and 0.15 A, respectively. In order to incorporate to a certain extent the effects of misalignment between the electron gun and the SWS, and angular spread of the electron beam, we assume that the particle source has an inclination of 2° with respect to the x -axis and emits a beam with an angular spread of 2° . The Brillouin magnetic field for a circular beam with the same charge density is 0.32 T. We use this value as a reference and set the focusing magnetic field at 0.3 T. In the simulations, the number of mesh cells is 2.3 million for 22 periods. The number of emission points in the particle source is 18. It takes about 28 hours for one simulation for 10 ns of TWT operation with Graphics Processing Unit (GPU) acceleration.

Figure 5.12: Simulation model for the symmetric PH-SEC; the enlarged view shows the location of the voltage monitors.

Figure 5.13: Dispersion diagram of the unmodified symmetric PH-SEC.

The PIC simulations are carried out without any RF input. Yet, the voltage obtained from the voltage monitors shows high frequency oscillations (results not shown here). To explain these oscillations, we refer to Figure 5.13 which shows the dispersion characteristics of the symmetric PH-SEC (without modifications) together with the beam line. The beam line intersects with mode 2 at about 54 GHz which is very close to the π point at 48 GHz. Fourier transform of the signal from the voltage monitor 4, presented in Figure 5.14, shows a peak at 48 GHz; this frequency can be considered to be backward wave oscillation but not band edge oscillation since this oscillation frequency value changes with beam velocity [30], [91]. Since the focus here is on dielectric charging, in the following discussion we only compare the DC voltage values by filtering out the high frequency components.

Figure 5.14: Spectrum of the dielectric charging voltage at voltage monitor 4.

The voltages corresponding to some of the voltage monitors for the unmodified structure are shown in Figure 5.15. It can be seen that at some of the locations, where more electrons hit the dielectric substrate, the magnitude of the voltage keeps increasing for the simulation time considered here. This is the case for the voltage from monitors 4, 6 and 20. As mentioned in the previous section, the steady-state voltage values can reach 1000 V and therefore approach the dielectric breakdown (dielectric strength of Si is 4-10 V/ μm). In any case, such high voltages can cause de-focusing of the electron beam. On the other hand, at some other locations where fewer electrons hit the dielectric substrate, the voltage is very low, for example, for monitors 12 and 16.

The voltages obtained from monitor 4 for the unmodified and the modified symmetric PH-SEC with different Si conductivity values are compared in Figure 5.16. We can see that the voltage magnitude for the unmodified structure increases rapidly with time. The modified structure has a lower voltage magnitude, which decreases further as the conductivity increases. When the conductivity of Si is 0.1 S/m, the voltage reaches a steady-state value of only -1.5 V. These results show that the modified symmetric PH-SEC with increased Si conductivity can avoid the dielectric charging problem.

Figure 5.15: Dielectric charging voltage obtained from different voltage monitors for the unmodified structure.

Figure 5.16: Voltage vs. time with different values of Si conductivity (from voltage monitor 4).

Figure 5.17: S -parameters of the modified symmetric PH-SEC with 22 periods.

Table 5.3 Loss per period at 27 GHz for different conductivities

Conductivity (S/m)	Loss (dB/period)
$2.5\text{e-}4$	0.035
0.01	0.038
0.1	0.064
0.25	0.106

The additional loss caused by the higher conductivity of Si has also been examined. To estimate the loss per period, two identical symmetric PH-SEC structures, with the only difference being the number of periods (22 and 37), are simulated using CST Microwave Studio (MWS). The structures are fed with matched discrete ports of impedance 80 Ohms. As an example, the resulting S -parameters of the 22-period structure are shown in Figure 5.17. The loss per period at 27 GHz for the proposed structure with four different conductivity values is calculated from the difference in S_{21} and number of periods. The results are presented in Table 5.3. It can be seen that even for 0.1 S/m, the loss is only 0.064 dB/period which may be acceptable in a TWT at Ka-band. PIC simulations for a TWT consisting of 136 periods of the

modified SWS show that increasing the conductivity of Si to 0.1 S/m reduces the TWT gain by ~2 dB compared to that for intrinsic Si. Besides, simulations using CST eigenmode solver show that the increased loss due to increase in conductivity of Si does not show significant effect on the phase velocity and coupling impedance values.

The modifications proposed here to avoid dielectric charging are compatible with microfabrication and may also be applicable to other microfabricated SWSs which have been proposed for application in TWTs, such as meander-line [22], [81], [85] and biplanar interdigital structure [92].

5.4 Summary

This chapter begins by proposing a symmetric PH-SEC incorporating thin symmetric Si substrates. The dispersion characteristics of the symmetric PH-SEC have been studied and compared with the PH-SEC on a thick Si substrate. It has been shown that the symmetric PH-SEC own a higher and more symmetric coupling impedance.

Then we examine dielectric charging effect in a PH-SEC which is fabricated using Si and SiO₂ layers. A simple dielectric slab model has been used to study the effect of conductivity and dimensional parameters of a dielectric substrate on dielectric charging. A corresponding equivalent circuit has been proposed and analyzed. The analysis results show an excellent match with simulation results obtained from CST Particle Studio. Another model with two dielectric layers, Si and SiO₂, has been studied next. Simulation results show that while the SiO₂ layer plays a dominant role in the dielectric charging process, Si conductivity also plays a role in this process. Based on these observations, modifications to a Ka-band symmetric PH-SEC SWS have been proposed to prevent dielectric charging in a TWT. It is demonstrated that these modifications greatly reduce the voltage build-up due to dielectric charging. The modifications involve partial removal of the SiO₂ layer and a careful increase in the conductivity of the Si layer. It is shown that the additional loss caused by the increased conductivity of Si can be acceptable in a TWT. The techniques to prevent

dielectric charging proposed here are compatible with microfabrication and may also be applicable to other microfabricated SWSs.

CHAPTER 6

DISPERSION CONTROL AND MICROFABRICATION OF A PLANAR HELIX SLOW-WAVE STRUCTURE

6.1 Introduction

The dispersion characteristics of a slow-wave structure (SWS) have a strong impact on the operation of the TWT. A relatively flat dispersion curve for the SWS is important for wideband operation [93] and negative dispersion can help to reduce the in-band harmonic content of a wideband TWT [94]. Therefore dispersion-shaping techniques have been studied by many researchers. One of the challenges in dispersion-shaping is not to allow the coupling impedance K_c to become too low since that would reduce the gain and efficiency of the TWT.

The circular helix has been a very popular SWS for TWTs since it offers very broadband beam-wave interaction and many studies have been carried out for its dispersion-shaping, including that of Paik [95], Galuppi et al [96], Kumar et al [97], Ghosh et al [98], as well as more recent ones [99]–[101]. The dispersion-shaping techniques that have been studied for the circular helix include bringing the metal shield close to the helix, reducing the dielectric constant of the rods that support the helix inside the shield, incorporating metal vanes of different shapes in the shield, and coating the dielectric support rods with a conducting layer.

Printed-circuit techniques are important for miniaturization as well as low-cost mass-production. Microfabrication techniques become important at high frequencies of operation where the dimensions become small; this is an important issue as future microwave systems move up in their frequency of operation [20], [102]. Due to its popularity, there have been several attempts at achieving microfabricated SWS

derived from the conventional circular helix. But no work has discussed dispersion control or dispersion shaping for the microfabricated structures.

Since the metal vanes have been found very effective in dispersion-shaping for the circular helix, the objective of this chapter is to report the use of metal vanes of different shapes for dispersion-shaping of the planar helix with straight-edge connections (PH-SEC) and compare the results with those for the circular helix. Further, the PH-SEC offers an additional feature for modifying dispersion, namely the possibility of coplanar ground planes on the surface of the dielectric substrates which support the PH-SEC [27]. Another objective of this work is to report the effect of metal vanes together with the coplanar ground planes on the dispersion characteristics of the PH-SEC.

The abovementioned techniques of dispersion control are applied to a Ka-band PH-SEC that is based on the symmetric PH-SEC described in Chapter 5. Both cold-test and hot-test parameters of the designed structure are investigated. The microfabrication process for the designed structure is also presented.

6.2 Dispersion Control Techniques for PH-SEC

6.2.1 Circular Helix and PH-SEC Immersed in Free Space

Effects of three types of metal vanes, namely, solid, T-shaped, and thin vanes have been studied on the dispersion characteristics and coupling impedance K_c of the PH-SEC. The corresponding structures for the circular helix and PH-SEC, both immersed in free space are shown in Figures 6.1 and 6.2, respectively. The dimensional parameters for the circular helix are: pitch length of 2.092 mm, helix tape width of 1.45 mm and helix tape thickness of 0.2mm. The metal-shield inner radius and the helix inner radius are 6.24 mm and 3.32 mm, respectively, resulting in shield-helix spacing of 2.72 mm. The vane-helix spacing is 1.26 mm. Simulation results have been obtained over the frequency range of 0.2-7 GHz and are presented in Figure 6.3. As observed in the past, e.g. [99], the addition of vanes to the circular

Figure 6.1: Model of one period of circular helix: (a) without metal vanes, (b) with solid vanes, (c) with T-shaped vanes and (d) with thin vanes.

Figure 6.2: Model of one period of PH-SEC: (a) without metal vanes, (b) with solid vanes, (c) with T-shaped vanes and (d) with thin vanes.

helix can produce a flatter phase velocity vs. frequency curve with only a moderate reduction of the coupling impedance and the T-shaped vanes provide flatter dispersion characteristics.

For PH-SEC, a square cross-section is designed keeping the pitch and the perimeter of the helix as well as the inner perimeter of the shield the same as those for the circular helix. The shield-helix spacing and the helix-vane spacing are also kept the same as those for the circular helix. The other dimensional parameters are: straight-edge connection (via) diameter = 0.5 mm, helix strip width = 1 mm, and helix strip thickness = 0.017 mm. The simulation results are presented in Figure 6.4. These results show clearly that the metal vanes have an influence on the phase velocity and coupling impedance values that is very similar to the case of circular helix. Here also, the T-shaped vanes produce the flattest phase velocity curve, with only

moderate reduction of the coupling impedance. The reduction in the phase velocity in the case of PH-SEC is somewhat less since the vanes are present only on the top and bottom of the SWS, not on the sides.

(a)

(b)

Figure 6.3: (a) Dispersion and (b) coupling impedance characteristics for circular helix with three types of vanes incorporated in the metal shield.

(a)

(b)

Figure 6.4: (a) Dispersion and (b) coupling impedance characteristics with three types of vanes incorporated in the metal shield for PH-SEC.

Comparing the PH-SEC of square cross-section with the circular helix, when both structures have the same length of turns as well as comparable dispersion

characteristics and coupling impedance, the cross section area of the former is smaller by a factor of $\pi/4$. As a result, the square PH-SEC may have a relatively low output power. Of course, the main advantage of the PH-SEC is its compatibility with printed-circuit or microfabrication techniques.

6.2.2 PH-SEC with Dielectric Substrates

When the PH-SEC is realized using printed-circuit techniques, the effect of dielectric substrates on the dispersion characteristics can be significant. This is similar to the case of circular helix in the presence of dielectric support rods. While the vacuum compatible substrate materials are alumina ($\epsilon_r = 9.1$), beryllia ($\epsilon_r = 6.5$), diamond ($\epsilon_r = 5.7$), silicon ($\epsilon_r = 11.9$) etc., we have chosen to use non-vacuum compatible Roger RO4003 substrate ($\epsilon_r = 3.55$) in this illustrative study due to ease of subsequent proof-of-concept fabrication.

The cross-section of the configuration chosen for this study together with the dimensional parameters is shown in Figure 6.5. The following features of the configuration are noteworthy. Since the sheet-beam offers many advantages for high

Figure 6.5: Cross-sectional view of the PH-SEC including metallic vanes and coplanar ground planes on the dielectric substrates. The dielectric substrates are outside the PH-SEC.

frequency TWTs [25], the aspect ratio b/a is kept greater than 3. The dielectric substrates are ‘outside’ the PH-SEC; this is similar to the configuration used in the circular helix TWTs which have dielectric support rods outside the helix. As compared to the configuration in which the dielectric substrates are ‘inside’ the PH-SEC, the present configuration can avoid the dielectric charging problem when an electron beam flows through the SWS. Also, previous studies on the dispersion characteristics of the PH-SEC have shown that the present configuration produces a flatter phase velocity curve compared to the configuration in which the dielectric substrates are ‘inside’ the PH-SEC [23]. The metal vanes considered are ‘solid’ type, due to their ease of fabrication. Figure 6.5 also shows coplanar ground planes on the ‘inner’ surfaces of the dielectric substrates. Such coplanar ground planes have been shown to provide a relatively flat phase velocity curve [27] and are easy to incorporate together with a coplanar waveguide (CPW) feed.

The structure dimensions are chosen as follows: height of the PH-SEC $2a = 2.44$ mm, width of the PH-SEC $2b = 8.0$ mm (so that the aspect ratio $b/a = 3.28$), substrate thickness $2c = 0.813$ mm, helix period = 2.092 mm, via diameter = 0.5 mm, helix strip width = 1 mm, thickness of helix strips and coplanar ground planes = 0.017 mm, shield-substrate spacing $t_1 = 1.95$ mm, vane-substrate spacing $t_2 = 1.0$ mm, and a lateral gap of 0.2 mm between the coplanar ground planes and the PH-SEC. The internal width of the shielding enclosure is 22 mm.

The simulation results for the phase velocity and coupling impedance for the PH-SEC printed on dielectric substrates are shown in Figures 6.6 (a) and (b), respectively, over the frequency range 0.2-5 GHz. Four different possibilities are considered: (i) neither the metal vanes nor the coplanar ground planes are present; (ii) only the coplanar ground planes are present; (iii) only the metal vanes are present, and (iv) both the metal vanes and the coplanar ground planes are present.

For case (i), for the chosen dimensions, the low-frequency values of the phase velocity and coupling impedance are close to those for the PH-SEC in free space; however, as may be expected due to the presence of the dielectric substrates, there is more dispersion and the values of both the phase velocity and coupling impedance decrease rather sharply at the high frequency end.

(a)

(b)

Figure 6.6: (a) Dispersion and (b) coupling impedance characteristics for the PH-SEC of Figure 6.5, showing the effect of coplanar ground planes, metal vanes, and coplanar ground planes together with metal vanes.

In general, compared to the PH-SEC in free space, addition of vanes and/or coplanar ground planes in the presence of dielectric substrates leads to greater reduction in the phase velocity and coupling impedance values. This effect can be attributed to

the fact that metal vanes and coplanar ground planes concentrate the field in a region that contains the dielectric material.

The dispersion effects mentioned above can be countered to some extent by using thinner dielectric substrates and keeping a low value of the dielectric constant. Moreover, dielectric substrates can be chosen to have a high value of thermal conductivity to facilitate dissipation of heat from the SWS in a TWT. In this context, a promising choice for dielectric substrates would be CVD diamond which has been proposed in the recent years [65]; it has a relatively low dielectric constant ($\epsilon_r = 5.7$), can be made in very thin self-supporting membranes that have very good mechanical strength, and possesses a high thermal conductivity.

As seen in Figure 6.6 (a), it is possible to achieve flatter dispersion characteristics in the presence of dielectric substrates compared to that for the PH-SEC in free space. Both, coplanar ground planes (case ii) and metal vanes (case iii) are effective in doing this individually, the latter producing a stronger flattening and even slightly negative dispersion at the low-frequency end. When both features are used together, it is possible to produce even more negative dispersion at the low-frequency end, with only a small further reduction in the coupling impedance as seen in Figure 6.6 (b). As mentioned earlier, negative dispersion can help to reduce the in-band harmonic content of a wideband TWT [94].

The extent of dispersion-shaping achieved here can be improved further by optimizing the various dimensions and material parameters. Also, these techniques are expected to be applicable to other planar SWSs, such as those derived from the meander-line, e.g., [75] or from the planar helix, e.g., [44].

6.2.3 Fabrication and Measurement

Figures 6.7 (a) and (b) show the configuration chosen for fabrication and testing to provide proof-of-concept. The configuration with RO4003 substrates inside the planar helix and solid vanes is chosen due to ease of fabrication. First the model shown in Figure 6.7 (a) is simulated in the CST MWS eigenmode solver to achieve reasonable dispersion and coupling impedance characteristics. Subsequently, the

model shown in Figure 6.7 (b) is simulated in the CST MWS transient solver; the latter model incorporates CPW feeds and also takes into account material loss.

The structure is fabricated using three layers of substrates, each of thickness 0.813 mm. The inclined strips of the PH-SEC and the CPW feed are fabricated on the outer surfaces of the top and bottom layers and the middle layer helps to achieve the overall height of the PH-SEC. The straight-edge connections (vias) of the PH-SEC are realized by using silver-plated copper wire pieces which are inserted through 0.5 mm diameter holes and soldered to complete the PH-SEC. Figure 6.8 shows the CPW feed design and the associated dimensions. The CPW feed tapers from the helix-end to a 50 Ω -end connected to a SMA connector. The dimensions are listed in Table 6.1.

Figure 6.9 depicts the simulated dispersion and coupling impedance characteristics. The results show that a flatter dispersion curve can be attained as the vane-helix spacing reduces. For smaller spacing of 0.763 and 0.263 mm, negative dispersion can also be obtained. But this comes at the cost of significantly reduced coupling impedance. Also, such close spacing values are difficult to achieve using the simple fabrication/assembly techniques adopted for this experiment. Therefore the vane-substrate spacing used for fabrication is 1.263 mm.

A photograph of one of the fabricated structure is shown in Figure 6.10. The three layers of the substrates are held together by nylon nuts and bolts. Air bridges are soldered so as to maintain the coplanar ground planes at the same potential. Two aluminum plates with solid vanes extend along the length of the substrates. The vanes on the plates are tapered as shown in Figure 6.10 (b), to avoid contact with the air bridges. Spacers of 3 mm height are used to support the metal plates and ensure the required vane-helix spacing. In order to short circuit the metal plates and the ground planes, steel screws, nuts and spacers are used to complete the assembly.

(a)

(b)

Figure 6.7: (a) Single period PH-SEC with solid metallic vanes; (b) PH-SEC on Rogers RO4003 substrates including the CPW feed (shield with metal vanes is not shown). See Table 6.1 for dimensions. The dielectric substrates are inside the PH-SEC.

Figure 6.8: Schematic of the CPW feed design (all dimensions in millimeters).

Table 6.1 Dimensions of the fabricated structure

Symbol	Dimension in millimeter (mm)	
$2a$	2.44	
$2b$	8	
Shield substrate spacing (t_1)	3	
Helix period (S)	2.09	
Via diameter (VD)	0.5	
Helix strip width (SW)	1	
Helix strip thickness	0.017	
Substrate thickness	2.44	
Vane width	8	
Vane-helix spacing (t_2)	1.26	
Substrate length	89	
Substrate width	36.5

(a)

(b)

Figure 6.9: (a) Dispersion and (b) coupling impedance characteristics for PH-SEC incorporating solid metal vanes with different values of vane-substrate spacing for the structure shown in Figure 6.7.

Figure 6.10: Photograph of (a) three layers of substrates, (b) one of the metal plates with solid vane and (c) the fabricated structure with 25 periods.

The simulation results for the S -parameters of the structure described above have been obtained over a frequency range of 0-7 GHz. Two otherwise identical structures, with 25 and 30 periods, respectively, are designed and fabricated in order to permit determination of the phase velocity from the measured phase of S_{21} . The measured and simulated S -parameter results are presented in Figure 6.11. A simulated S_{11} below -10 dB is observed over the frequency range 1.6-4.2 GHz; the measured S_{11} also covers a similar frequency range. The shape of the measured S_{21} curve matches that of the simulation results quite well but a higher attenuation is observed compared to the simulation values. This is attributed to the fact that the simulation values assume bulk conductivity of copper and also ignore the additional loss that may be caused by the soldered joints. The measured phase velocity characteristics, depicted in Figure 6.12, closely match the simulation results obtained with the transient mode solver. The phase velocity simulation results obtained using the eigenmode solver, also included in Figure 6.12, are slightly higher since these do not consider loss.

Figure 6.11: Measured and simulated S -parameters for the PH-SEC with 25 periods.

Figure 6.12: Measured and simulated normalized phase velocity for the PH-SEC with 25 periods.

6.3 Wideband PH-SEC Suitable for Microfabrication

The abovementioned techniques of dispersion control are applied to a Ka-band PH-SEC that is based on the symmetric PH-SEC described in Chapter 5. Feasibility of microfabrication has been emphasized in the design process. Both the cold-test parameters (propagation constant, phase velocity, coupling impedance, attenuation etc.) and hot-test parameters (gain, output power, efficiency etc.) have been studied. The microfabrication process has also been presented. The proposed structure is under fabrication.

6.3.1 Evolution of the Configuration

Figure 6.13: Evolution of the configuration of the Ka-band PH-SEC SWS.

For successful microfabrication of SWS and its application in a TWT, many issues such as the circuit loss, mechanical strength, vacuum compatibility and dispersion characteristics need to be considered in the configuration. As shown in Figure 6.13, several versions of the configuration have been considered during the design process.

The initial design is shown in Figure 6.13 (a). The PH-SEC is sandwiched between two U-shaped Si substrates whose inner surfaces are coated with copper and constitute the metal shield. Four coplanar ground planes are arranged beside the PH-SEC to make the dispersion curve flat and increase the bandwidth. Although this design shows a good performance with respect to high coupling impedance and low loss, the Si substrate is too thin to support the structure and is very fragile. With this in view, the configuration of the SWS is changed to that shown in Figure 6.13 (b), replacing the U-shaped Si substrates with relatively thick Pyrex substrates. Pyrex has a low dielectric constant of 4.82 and loss tangent of 0.0054. The metal shield is put directly on the quartz substrates so that it is closer to the SWS. While these changes make the SWS mechanically sturdier, less dispersive and wideband, the coupling impedance is too low because there is significant dielectric loading. Besides, pyrex causes rather high insertion loss which will reduce the gain. Also, it is not easy to bond the Si and pyrex layer. Next we move to the version shown in Figure 6.13 (c) in which the Si layer is completely removed and quartz replaces pyrex. Quartz has a low dielectric constant of 4.43 and a much lower loss tangent of 0.00003 at 30 GHz. A trench is made in the quartz substrates to reduce the dielectric loading. Si walls are used on the sides to support the quartz substrates and through-silicon vias (TSV) are applied to connect the top and bottom coplanar ground planes to maintain the same potential. But this version still has one issue in the fabrication process: the Si layer is etched after the bonding of quartz substrate and PH-SEC layer and it is difficult to just etch the center part and only leave the side walls. As a result, we use copper walls instead of Si walls to support the whole structure and reach the final version shown in Figure 6.13 (d).

6.3.2 Final Configuration of the PH-SEC SWS

Figures 6.14 and 6.16 respectively show the perspective and cross-sectional view of one period of the final version of the PH-SEC SWS. The two quartz substrates are placed at the top and bottom which support the SWS and transfer heat generated in the SWS. We can see that the coplanar ground planes and the metal shield are maintained at the same potential with the help of copper side walls and through substrate vias. The copper side walls make the structure mechanically stronger. The

parameters of the SWS are shown in Figures 6.15 and 6.16. The dimensions of the structure are presented in Table 6.2.

Figure 6.14: Perspective view of one period of the proposed PH-SEC.

Figure 6.15: Details of the PH-SEC.

Copper
 Quartz
 Cyclotene (BCB)

Figure 6.16: Cross-section of the proposed wideband PH-SEC.

Table 6.2 Dimensions of the proposed PH-SEC

Symbol	Dimension in micrometer (μm)
$2a$	300
$2b$	700
w_1	300
w_2	600
w_3	100
w_4	390
L	300
ST	20
SW	120
VD	100
RD	120
h_1	200
h_2	100

6.3.3 Dispersion Characteristics

The dispersion characteristics of the proposed SWS have been simulated using CST eigenmode solver. Figure 6.17 shows the phase velocity of the proposed structure. Since the variation in the phase velocity of the proposed PH-SEC is very small over a broad frequency range, the velocity synchronism with an e-beam can be

Figure 6.17: Phase velocity of the proposed SWS.

maintained over a wide bandwidth. As the metal shield and the coplanar ground planes are close to the PH-SEC, the electromagnetic field distribution does not change significantly with frequency. The coupling impedance is shown in Figure 6.18 and has a value of about 25 Ohm at 30 GHz.

Figure 6.18: Coupling impedance of the proposed SWS.

6.3.4 Transmission and Reflection

For the proposed structure, since the electromagnetic field distribution does not change significantly with frequency, it should be easy to get a good value of S -parameters without a complex impedance matching network. Here, we feed the proposed PH-SEC with two different kinds of feed.

First, a simple way to study the transmission characteristics is to use discrete ports with the port impedance defined directly. The perspective view of the proposed SWS with discrete ports is shown in Figure 6.19. Both the impedance and the length of the discrete port influence the transmission and reflection properties of the SWS. Here we optimize the discrete port impedance to 80 Ohm and port length to 100 μm to have good transmission properties of the SWS.

Figure 6.19: Perspective view of the SWS with discrete ports (150 periods).

Figure 6.20: S -parameters of the SWS with 150 turns with discrete ports of 80 Ohms.

The simulated S -parameters of the structure with discrete ports are shown in Figure 6.20. We can see that S_{11} is below -20 dB over a wide frequency range from 23.5 GHz to 35.9 GHz.

Figure 6.21: Perspective view of the SWS with CPW feeds (150 periods).

Figure 6.22: (a) Perspective view of the CPW port. (b) Cross-sectional view of the SWS with CPW port. (c) Dimensions of the tapered CPW port in μm .

Figure 6.23: S -parameters of the SWS with 150 turns with CPW ports.

Design incorporating coplanar waveguide (CPW) ports which can be tested on a probe station has also been carried out. The design with 150 periods is presented in Figure 6.21. Both the input and output ports are on the top face of the SWS. Figure 6.22 shows the details of the feed of the SWS. As seen in Figure 6.22 (b), a thin copper via goes from the last turn of the SWS through the substrate and is connected to the center strip of the CPW line. The impedance of the CPW is higher than 50 Ohm at the connection point. To match with the CPW probe, it is tapered to 50 Ohm CPW. The details and dimensions of the tapered CPW are shown in Figure 6.22 (c).

The designed SWS is simulated using CST transient solver. The S -parameters of the SWS with 150 periods are shown in Figure 6.23. It is seen that the S_{11} is below -20 dB from 26 GHz to 32.8 GHz. The attenuation is -3 dB which is quite low.

6.3.5 Hot-test parameters

The hot-test parameters of the proposed Ka-band PH-SEC SWS for TWT application are estimated using CST PIC solver for the structure with discrete port. An e-beam with beam voltage of 3.72 kV and current of 10 mA is applied at the

Figure 6.24: Gain vs. frequency with 150 periods and 10 mW input power.

Figure 6.25: Output power with different number of periods.

center of the electron-beam tunnel. The elliptical cross section of the e-beam has a semi-major axis of $350\ \mu\text{m}$ and a semi-minor axis of $150\ \mu\text{m}$. The focusing magnetic field is set at 0.2 T. Figure 6.24 shows the gain of the proposed SWS at five different frequencies with 150 turns and 10 dBm input power. The gain does not vary much with frequency since the flat phase velocity allows a wideband interaction with the

electron beam. Figure 6.25 shows the output power versus the number of turns of the proposed SWS at 30 GHz with 10 dBm input power. The output power increases with the number of turns and reaches saturation for 160 turns. The saturation power is 6.3 W with 17% efficiency. A comparison of efficiency of some of the Ka- band TWTs that have been proposed in the last few years is given in Table 6.3. The RF efficiency of the proposed PH-SEC TWT compares favourably with that of the other Ka-band TWTs.

Table 6.3 Comparison of RF efficiency of Ka band TWTs

Work	SWS type	RF Efficiency
This work	PH-SEC	17%
[103]	Folded waveguide	10%
[104]	Log periodic SWS	19.2%
[105]	Double-grating rectangular waveguide	14.7%
[106]	U-shaped meander line	14.4%

6.3.6 Microfabrication Process

Some microfabrication processes have been briefly mentioned in Section 2.6.1. As an example, a W-band PH-SEC without a metal shield has been fabricated on a thick Si substrate using LIGA [24]. Since the proposed structure consists of two symmetric substrates and a metal shield, a more complex fabrication process is required.

The fabrication steps for the proposed structure are shown in Figure 6.26. The PH-SEC layer and the quartz substrate layers are fabricated separately. As shown in Figure 6.26 (a), two Si substrates have been used. First, beginning with a device Si wafer attached on a sacrificial Si wafer, the vertical straight-edge connections of the PH-SEC and the side-pillars are fabricated using TSV process. Then we use copper deposition and photolithography to fabricate the horizontal parts of the PH-SEC and the coplanar ground planes on one side (Figure 6.26 (b) and (c)). Then the device and the sacrificial Si wafers are separated. The device wafer is turned around, after

which the horizontal parts of the PH-SEC on the other side are fabricated using the same copper deposition and photolithography process (Figure 6.26 (e) and (f)).

The trench in the quartz substrates is fabricated using micromachining or glass etching techniques and the metal shield is sputter-deposited on the outer surfaces of the quartz substrates. The PH-SEC and the two quartz substrates are bonded together using low loss Cyclotene BCB [107]. Finally, the Si wafer is etched away.

6.4 Summary

In this Chapter, the use of metal vanes for dispersion-shaping of a planar helix SWS with straight-edge connections (PH-SEC) has been studied. The PH-SEC can be fabricated using printed-circuit or microfabrication techniques. Both, coplanar ground planes and metal vanes have been shown to be effective in dispersion-shaping, individually, as well as in combination. A proof-of-concept structure operating over the frequency range of 1.6-4.2 GHz has been designed and fabricated and it has been shown that the measured phase velocity values closely match the

Figure 6.26: Fabrication process of the Ka-band PH-SEC SWS.

simulation values. With appropriate design, these techniques can lead to flat dispersion characteristics without significantly reducing the coupling impedance values; such a characteristic is important for broadband TWTs. These techniques can also provide negative dispersion at the low-frequency end; such a characteristic can help to reduce the in-band harmonic content of a wideband TWT. The dispersion-shaping techniques studied here are expected to be applicable to many other planar SWSs also, such as those derived from the meander-line or from the planar helix.

The abovementioned techniques of dispersion control have been applied to a Ka-band PH-SEC that is based on the symmetric PH-SEC described in Chapter 5. Feasibility of microfabrication has been emphasized in the design process. The structure shows a wide band property, enabling a wide band beam-wave interaction. Both discrete ports and CPW ports have been applied to the proposed SWS. The discrete ports provide an S_{11} below -20 dB from 23.5 GHz to 35.9 GHz while the CPW ports provide S_{11} below -20 dB from 26 GHz to 32.8 GHz. It has been shown that a TWT based on this SWS has a fairly uniform gain over a wide range of frequencies from 24 GHz to 36 GHz. Besides, the TWT is able to provide an output power of 6.3 W and an efficiency of 17%. The microfabrication process has also been described briefly. The proposed structure is under fabrication.

CHAPTER 7

CONCLUSION AND FUTURE WORK

7.1 Conclusion

This thesis focuses on slow wave structures (SWSs) derived from the planar helix SWS with straight-edge connections (PH-SEC) for millimeter wave traveling-wave tube (TWT) applications. For this high frequency range, microfabrication is a must for achieving high precision. Although the PH-SEC has proved to be quite promising as it is a wideband structure and is amenable to microfabrication techniques, it does suffer from various issues such as a small electron beam tunnel, risk of backward wave oscillation, risk of dielectric charging and increased dispersion in the presence of dielectric substrates. In this thesis, novel SWSs and designs based on the PH-SEC have been proposed to address these issues for application in millimeter wave TWTs.

Two types of coupled PH-SECs, the unconnected pair and the coaxial pair, have been proposed. To determine the propagation characteristics of the two structures, a generic structure consisting of four unidirectionally conducting (UC) screens has been analyzed. Two possible cases for the angle of conduction of the UC screens have been considered. It has been shown for each case that four modes exist including two transverse symmetric modes and two transverse antisymmetric modes. The dispersion characteristics of the two structures immersed in air have been obtained based on the generic structure. It has been shown that the analytical results for phase velocity and coupling impedance match well with the simulation results. Further, it has been shown that the unconnected pair of PH-SECs is able to provide a larger electron beam tunnel and lower risk of backward wave oscillation as compared to the single PH-SEC.

As the next step, the unconnected pair of PH-SECs has been designed and fabricated using printed circuit techniques for a proof of concept. A stripline Wilkinson power

divider has been implemented in order to excite the desired mode. The measured S -parameters and phase velocity values over a frequency range of 1-7 GHz show a good agreement with the simulated results.

An improvement over the unconnected pair, the connected pair of PH-SECs has also been proposed. It has been demonstrated that the connected pair of PH-SECs offers a much simpler arrangement for feed and also maintains the advantages of the unconnected pair, namely, a larger electron beam tunnel and a better potential for avoiding backward wave oscillations compared to the single PH-SEC. As a proof-of-concept, the new structure has been designed and fabricated using the printed circuit techniques. Measured S -parameters and phase velocity match well with the simulation results and demonstrate the wide bandwidth capability of the proposed structure. Simulation results have been presented to show that the connected pair of PH-SECs has higher coupling impedance values and, correspondingly, a higher gain growth rate than that for the single PH-SECs. A TWT incorporating the connected pair of PH-SECs has also been investigated and it has been shown that such a TWT can yield at 4 GHz an output power of 468 W, with high gain (42.5 dB) and efficiency (21.9%). The connected pair of PH-SECs also shows much larger values of coupling impedance at 60 GHz compared with a recently proposed meander-line based SWS.

A symmetric PH-SEC has been proposed in order to have higher and symmetric coupling impedance values compared to the PH-SEC on a thick Si substrate. Further, the dielectric charging problem for the symmetric PH-SEC has been investigated. Based on analysis and simulation results, the following modifications to a Ka-band symmetric PH-SEC SWS have been proposed to prevent dielectric charging in a TWT: 1. part-removal of the SiO_2 layer; 2. Increase in the conductivity of the Si layer. It is demonstrated that these modifications greatly reduce the voltage build-up due to dielectric charging. At the same time, the additional loss from Si is acceptable.

Dispersion control of the PH-SEC has been studied. It has been shown that metal vanes show a similar impact on dispersion of the PH-SEC as for the conventional circular helix. Coplanar ground planes have also been shown to be effective in dispersion-shaping. Both vanes and coplanar ground planes have been applied to a

PH-SEC with dielectric substrates. A proof-of-concept structure operating over the frequency range of 1.6-4.2 GHz has also been designed and fabricated. The measured phase velocity values show a good match with the simulation values. Flat dispersion characteristics can be achieved without reducing the coupling impedance much. Negative dispersion can also be achieved at the low-frequency end with proper design; this can help to reduce the in-band harmonic content of a wideband TWT.

The abovementioned dispersion control techniques are applied to a Ka-band PH-SEC that can be microfabricated. Besides relatively flat dispersion characteristics, the design achieves a -20 dB S_{11} over 26 to 32.8 GHz using CPW ports. The hot-test parameters for a TWT with the proposed SWS have been studied. It has been shown that such a TWT amplifier exhibits a fairly flat gain level from 24 to 36 GHz. With a beam voltage of 3720 V and current of 10 mA, a saturated power of 6.2 W at 30 GHz can be obtained.

The techniques reported in this thesis to reduce backward wave oscillation, dielectric charging and dispersion of the PH-SEC may also be applicable to some other types of microfabricated SWSs such as meander-line, rectangular ring-bar, and biplanar interdigital structure.

7.2 Recommendations for Future Research

The thesis presents new structures and techniques to solve some possible problems in millimeter wave TWTs using the planar helix SWS with straight-edge connections (PH-SEC). There are some related topics that can be studied further. These are mentioned below.

1. The analytical method used for unconnected pair of PH-SECs and coaxial pair of PH-SECs is based on the approximation of two pairs of infinite unidirectionally conducting (UC) screens. The truncations have been considered using an effective angle. But at lower frequencies, the effect of the truncations is rather severe. In this context, application of actual boundary conditions on the truncations and use of the tape helix model in the analysis to include the effects

of periodicity may help to improve the accuracy of the analytical results. Besides, the effects of dielectric support and metal enclosure for these structures can also be studied analytically.

2. As presented in Chapters 3 and 4, the single PH-SEC shows significant backward wave oscillation. It should therefore be possible to use this structure for backward wave oscillator (BWO) applications. The dispersion characteristics as well as the starting condition can be studied. Work can be done to estimate the operating voltage, output power, efficiency, and bandwidth of the BWO.
3. For millimeter wave TWTs, the heat dissipation is an important issue. Although the PH-SEC is expected to have a good heat dissipation property because of larger contact area between metal strips and dielectric substrates, issues related to material properties, design of metal enclosure, circuit loss etc. may increase the operating temperature. Work can be done to study the temperature profile for PH-SEC TWTs with different power levels.
4. In millimeter-wave SWS, the dimensions of SWSs are only hundreds of micrometers. This can result in high values of RF electric field strength at some locations and may result in breakdown, adversely affecting the power handling capability. This problem may get more severe as the target frequency increases. Therefore the values of the RF electric field at such locations need to be examined. In general, for a given power level, if the electric field is too high, it can be reduced by increasing the distance or gap between the different parts of the SWS. More work can be done to investigate the power handling of the PH-SEC TWTs.
5. The output power of microfabricated TWTs can be enhanced by incorporating power combining or by cascading of TWTs. Since multiple PH-SECs can be fabricated in a single run of the microfabrication process, it is quite promising to combine many PH-SECs to increase the power output significantly. More work can be carried out on the power combining and cascading of PH-SEC based TWTs.

APPENDIX

CALCULATION OF THE PIERCE'S GAIN [34]

The gain of a TWT using Pierce theory can be calculated knowing the following parameters of the SWS and the beam:

$$C = \left(\frac{K_c I_{beam}}{4V_{beam}} \right)^{\frac{1}{3}} \quad (A1)$$

where C is the small-signal gain parameter, K_c is the coupling impedance, V_{beam} and I_{beam} are the voltage and current of the electron beam.

$$N = \frac{\beta_e l}{2\pi} \quad (A2)$$

N is the number of electronic wavelengths and β_e is the beam propagation constant.

$$b = \frac{\beta_0 - \beta_e}{\beta_e C} \quad (A3)$$

b is a measure of the degree of synchronism between the beam and the electromagnetic wave.

$$d = \frac{\alpha}{\beta_e C} \quad (A4)$$

d stands for the circuit attenuation and is propotional to the attenuation constant α .

$$QC = \frac{\omega_q^2}{4C^2 \omega^2} \quad (A5)$$

QC is the space charge parameter and ω_q is the effective plasma frequency.

δ_1 , δ_2 and δ_3 are the roots of the cubic equation given next. These roots are functions of b (degree of synchronism), d (circuit antenuation), and QC (space charge):

$$\delta^2 = \frac{1}{(-b + jd + j\delta)} - 4QC \quad (A6)$$

These three roots correspond to three different modes that exist in a TWT. δ_1 corresponds to a growing wave, δ_2 correspond to a decaying wave and δ_3 correspond to a normal propagating mode. The gain can be calculated with:

$$Gain = A + BCN \quad (A7)$$

where

$$A = 20 \log_{10} \left| \left(1 + \frac{4QC}{\delta_1^2} \right) \left(\frac{1}{\left(1 - \frac{\delta_2}{\delta_1} \right) \left(1 - \frac{\delta_3}{\delta_1} \right)} \right) \right| \quad (A8)$$

and

$$B = 54.6x_1 \quad (A9)$$

in which x_1 is the real part of δ_1 .

AUTHOR'S PUBLICATIONS

Journal Papers

1. **C. Zhao**, S. Aditya, and C. Chua, "A microfabricated planar helix slow wave structure to avoid dielectric charging in TWTs," *IEEE Trans. on Electron Devices*, vol. 62, no. 4, pp. 1342 - 1348, Apr. 2015..
2. Krithi Swaminathan, **C. Zhao**, C. Chua, and S. Aditya, "Vane-loaded planar helix slow-wave structure for application in broadband traveling-wave tubes," *IEEE Trans. on Electron Devices*, vol. 62, no. 3, pp. 1017 - 1023, March 2015.
3. **C. Zhao**, S. Aditya, and C. Chua, "Connected pair of planar helices with straight-edge connections for application in TWTs," *IEEE Trans. on Electron Devices*, vol. 61, no. 6, pp. 1692 - 1698, Jun. 2014.
4. **C. Zhao**, S. Aditya, and C. Chua, "Analysis of coupled planar helices with straight-edge connections for application in millimeter-Wave TWTs," *IEEE Trans. on Electron Devices*, vol. 60, no. 3, pp. 1244–1250, Mar. 2013.

Conference Papers

1. **C. Zhao**, S. Aditya, S. Wang, "Study of a broad band planar slow wave structure for millimeter wave TWT applications", *IEEE International Vacuum Electronics Conference (IVEC)*, 22-24 April, 2015, Beijing, China.
2. A. Kommalapati, **C. Zhao**, S. Aditya, "A Printed planar helix antenna," *8th European Conference on Antennas and Propagation*, 12-17 Lisbon, Portugal, 6-11 April, 2015.
3. **C. Zhao**, J. Nilopal, S. Aditya, and C. Chua, "Planar contra-wound helix for application in TWTs with reduced backward wave oscillation," *44th European Microwave Conference (EuMC)*, Fiera di Roma, Rome, Italy, 05-10 October, 2014.
4. **C. Zhao**, S. Aditya, and C. Chua, "Symmetric planar helix slow-wave structure with straight-edge connections for application in TWTs," *IEEE International Vacuum Electronics Conference (IVEC)*, Monterey, California, USA, 22-24 April, 2014.

5. **C. Zhao**, S. Aditya, C. Chua, and C. Jin, “Design of an unconnected pair of planar helices with straight-edge connections for application in TWTs,” *IEEE International Vacuum Conference (IVEC)*, Paris, France, 21-23 May, 2013.
6. **C. Zhao**, S. Aditya, and C. Chua, “Unconnected pair of planar helices with straight-edge connections for application in TWTs,” *9th International Conference on Information, Communications and Signal Processing (ICICS)*, Tainan, Taiwan, 10-13 Dec, 2013.

Patent

S. Aditya, **C. Zhao**, ‘Solution Of dielectric charging problem for waveguide structures for vacuum electron devices’, patent application filed by NTU in Singapore on 7 Oct’14.

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