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Virtual Prototyping and Development of Rotary Field Ferrite Phase Shifter

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ABSTRACT

Review of the virtual prototyping and physical development of the rotary field ferrite phase shifter is presented. A description of the basic principle of operation of the rotary field ferrite phase shifter has been given along with the key aspects about the design and virtual prototyping of various parts of the phase shifter viz ferrite rod, yoke, polarisers and matching section using HFSS and 3-D Maxwell softwares. Calibrated simulation performance of the phase shifters is presented and it shows good agreement with physical measurement results. Three prototypes and one hundred production capable phase shifter modules were fabricated, functionally tested and RF characterised. This is an indigenous development of the physical prototypes of rotary field class of ferrite phase shifters of C-band. This class of ferrite phase shifters finds application in phased array radars, such as battery level radar and weapon locating radar, because of its high phase accuracy and high power handling capability.

Keywords: Rotary field phase shifter, 3-D maxwell, phased array radar

NOMENCLATURE

3-D	Three dimensional
ATP	Automated test procedure
CEL	Central electronics limited
DMPS	Dual mode phase shifter
HFSS	High frequency structure simulator
RF	Radio frequency
RFFPS	Rotary field ferrite phase shifter
RMS	Root mean square
SSPL	Solid state physics laboratory
VNA	Vector network analyzer

1. INTRODUCTION

The phase shifters are critical elements for electronically scanned phased array radars which allow the beam to be steered at very high rate resulting in multiple target acquisition and tracking with multimode capability. These are needed in large numbers in the antenna for proper beam formation. By varying the phase of the RF signal incident on the phase shifters it is possible to steer the beam in the desired direction. The phased array radars are employed where it is necessary to shift the beam rapidly from one position in space to another or where it is required to obtain information about many targets at a flexible, rapid rate. The ferrite based passive phased array provides a cost effective, well proven approach to achieve a high performance ground based radar system.

The C-band rotary field ferrite phase shifter (RFFPS) with integrated Microcontroller based digital driver, developed indigenously for the first time, are intended for phased array radar subsystem application viz. advanced version of battery level radar in *Akash* air defence system and weapon locating radar. This class of linear phase shifters will lead to more precise control of steerable beam of the array antenna with lower side lobe levels, lower operating power by 25 per cent and high peak power capability upto 315 W instead of 250 W when compared with C-band dual mode phase shifter (DMPS). The C-band RFFPS exhibits lower max. RMS phase error of 4° compared to 6°/8° in Rx/Tx, respectively, in case of C-band DMPS and also dispenses with the requirement of look-up tables. This is a major step towards technology upgradation and for achieving self reliance in the strategic area of advanced phased array radars.

2. VIRTUAL PROTOTYPING *VS* TRADITIONAL DEVELOPMENT PROCESS

Virtual prototyping refers to design, simulation and testing of new ideas, concepts, products, schemes or processes in an interactive computer environment. After finalizing the conceptual model of a product, the concepts and ideas are realised by designing various parts of the product using software such as HFSS, Maxwell, etc. The procedure includes essential steps such as modelling of parts, generation of input parameters, etc. Thereafter, as the project progresses, the simulations for design verification become more refined, leading to greater accuracy and reducing the need for expensive physical prototyping and testing by getting the design right, the first time. The extensive use of virtual prototyping for generation of parts and sub-assemblies of a phase shifter has been demonstrated here. This simulation-driven virtual prototyping process has been used to predict the dynamic behaviour and performance of phase shifter parts before building the physical prototypes leading to significant

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reduction in the time and cost of making and testing multiple physical prototypes. Virtual prototyping reduces the number of physical iterations of a product substantially as is evident from Fig.1 and Fig. 2 showing the traditional development process and the virtual prototyping process.

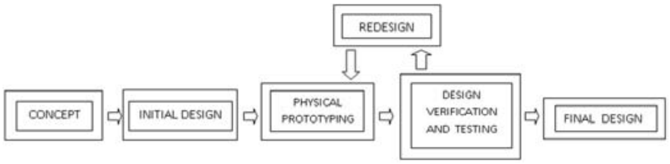


Figure 1. Block diagram for traditional physical prototyping of a phase shifter.

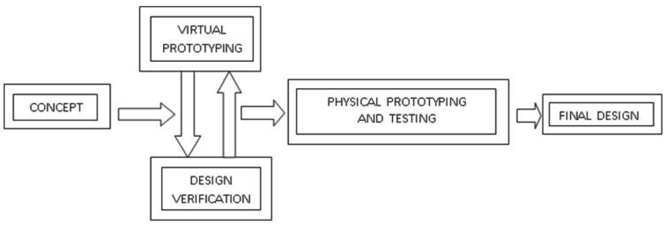


Figure 2. Block diagram for virtual prototyping of a phase shifter.

The phase shifters are constructed from the ferrite material that has a square hysteresis loop. These ferrite phase shifters change the phase of the incident RF signal by controlling the current sent to a pair of windings or coils present inside the stator. The magnitude and direction of the current flowing through these coils is so controlled that it finally provides the quadrupole magnetic field configuration in case of an 8-pole ferrite yoke phase shifter.

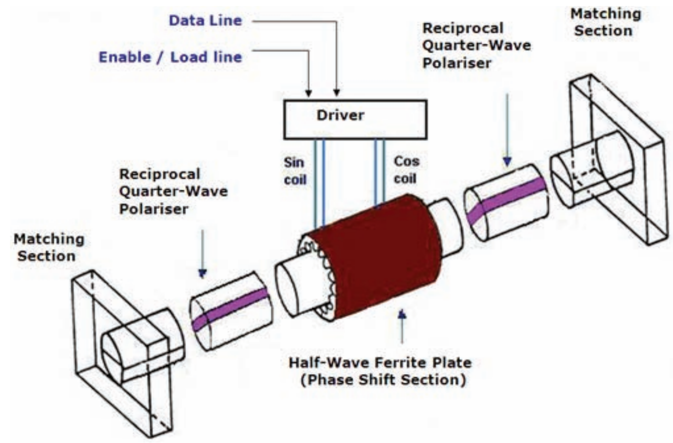
The basic configuration of the rotary field phase shifter is shown in Fig. 3. It consists of a ferrite rod coupled at both ends to dielectric quarter wave polarisers and ceramic matching sections or radiating elements to couple to standard rectangular waveguide. These dielectric quarter wave polarisers convert linear polarisation incident at either ends to circularly polarised TE_{11} mode waves.

The rod, polariser, and matching section assembly is metallised to form a circular waveguide. Outside this metallic waveguide wall, a ferrite frame known as yoke is placed, which physically resembles a motor stator consisting of a number of slots and wound with two interlaced coils or sine and cosine windings which produce a transverse four pole magnetic field with quadrupole characteristics.

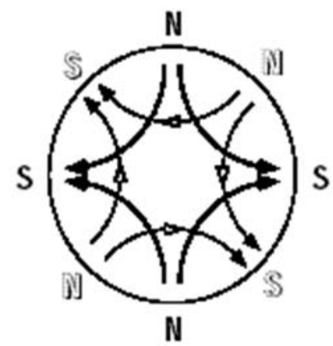
This quadrupole field is as shown in Fig. 3 is rotated to effect the phase shift. The ferrite rod is biased with this transverse four pole magnetic field to a level that creates a birefringence of 180° differential phase (i.e. a half wave plate). The electronic driver supplies current to these two windings such that the principal axis of the four pole bias field can be rotated to any arbitrary angle by proper setting of the currents in these windings. The differential phase shift is equal to twice the relative rotation of the magnetic half wave plate[1].

3. DESIGN OF PHASE SHIFTER PARTS USING HFSS

The phase shifter consists of the phase shift section with



(a)



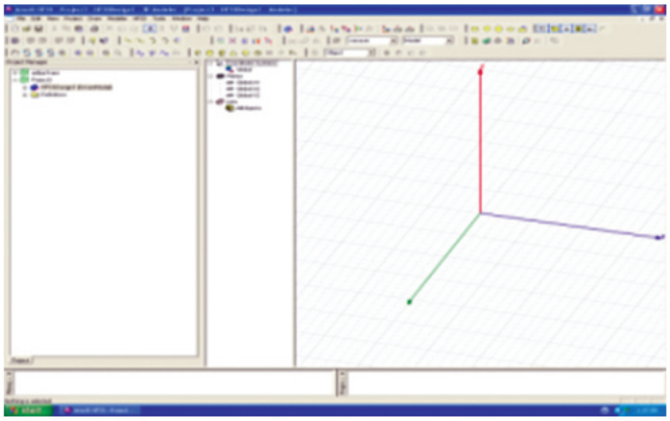
(b)

Figure 3. (a) Block diagram for rotary field ferrite phase shifter, and (b) Magnetic field pattern of the quadrupole field.

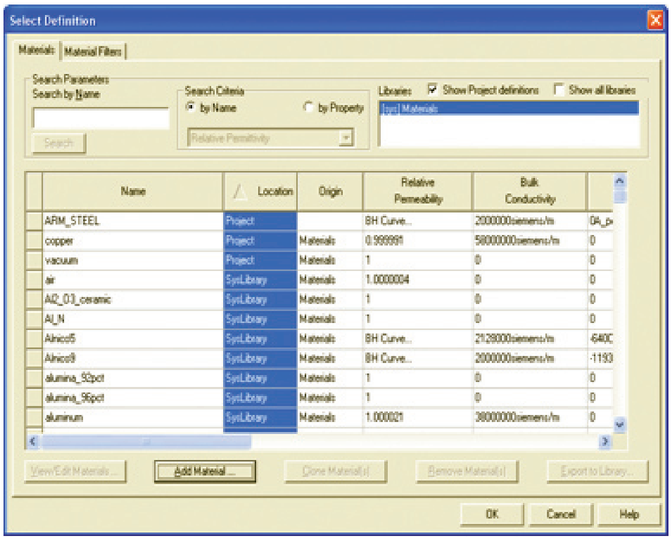
an electronic driver and the reciprocal dielectric polarisers with matching sections on either side of the phase shift section - all integrated into a single package. The phase shift section comprises of a metallised ferrite rod and a ferrite yoke placed over this rod. Each of these elements involves design considerations and in-depth trade-offs for achieving an optimum phase shifter design using mathematical formulae[2-4].

Advanced softwares are also being used to design and simulate the passive RF devices. The HFSS and 3-D Maxwell field solver software packages are high performance, interactive, full wave electromagnetic field simulators for arbitrary three dimensional volumetric passive device modelling and employ the finite element method, adaptive meshing and good quality graphics[5,6]. The objects are drawn in the HFSS 3-D modeller design window as shown in Fig. 4.

The design of rotary field phase shifter begins with the choice of the ferrite material and the geometry of the ferrite rod. The material properties for rod have an important effect on the performance of the phase shifter. The material must meet the requirements of operating frequency, bandwidth, loss, power rating and sensitivity to temperature variations. Cost is also an important factor in phased array antenna applications. The ferrite rod shown in Fig. 5 has been designed using the Ansoft HFSS software. At each end of the ferrite rod or half wave plate are placed dielectric polarisers or quarter wave plates. The circular waveguide forming the quarter wave



(a)



(b)

Figure 4. (a) HFSS 3-D modeller design window and (b) Material properties selection window.

plate is constructed using two materials of different dielectric constant. The high dielectric constant strip is embedded in the center. The smaller value of dielectric constant must be such as to ensure the normal mode of propagation.

The radiating element, also known as the matching section, consists of two sections. The first section has a diameter equal to that of the rod while the second section diameter is equal to that specified by the user. The second also acts as the radiator element. The length of both the sections is approximately one quarter of the guide wavelength.

The radiator end of the phase shifter is terminated in the waveguide simulator. A waveguide simulator is a square waveguide such that a single radiator terminated in it sees the same impedance that it sees when used in the array. This impedance is called 'active impedance' and is a function of scan angle and frequency of operation. The dimension of the simulator can be calculated from the relation : $A = \lambda / (2 \sin \theta)$ where A is the edge of square waveguide, θ is the scan angle and λ is the free space wavelength at the center frequency of the band[7]. The simulator dimensions are matched to those of WR-159 standard waveguide for C-band, so that the regular test bench can be used for S-parameter measurements[8,9].

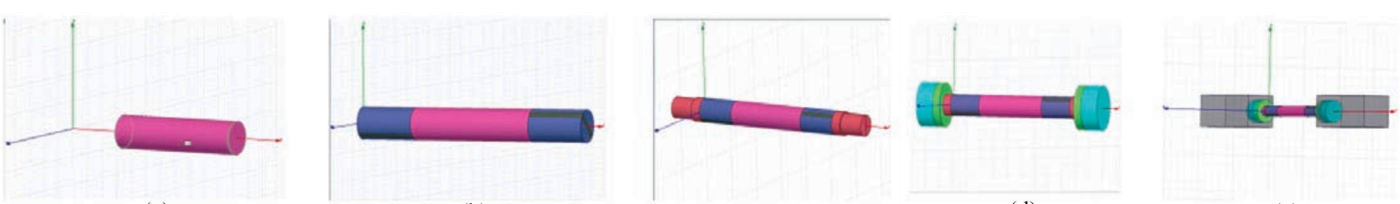
Design and simulation of the 8-pole ferrite yoke is carried out on Ansoft's 3-D Maxwell field solver software. 3-D Maxwell is a comprehensive electromagnetic field simulation software package for designing and analyzing 3-D/2D structures, such as motors, actuators, transformers and other electric and electromechanical devices common to automotive, military/aerospace and industrial systems as shown in Fig. 6. Based on the finite element method, Maxwell software can solve static, frequency-domain and time-varying electromagnetic and electric fields[6].

The ferrite yoke is designed first and then the coils are added to it. Thereafter current excitation is provided to the coils. The direction of current and the type of current (whether it is stranded or solid) is critical to obtain quadrupole magnetic bias. The magnetic field so generated is finally exported to the HFSS based design of rotary field phase shifter. Its ferrite rod is subjected to this rotary field (at different current levels in sine and cosine coils for constant magnitude of resultant current but varying phase conditions) to provide the required magneto static field excitation[5,6].

4. SIMULATION RESULTS

The ferrite rod is subjected to a rotary field (at different current levels in sine and cosine coils for constant magnitude of resultant current but varying phase conditions) to provide the required magneto static field excitation. The effect of this rotation of magetostatic field on the S-parameters of the phase shifter's input and output ports over the frequency band extending from 5.3 GHz to 6.0 GHz has been shown in Fig. 7.

The overlap error is sometimes received during the validation process when the volume of a 3-D object occupies the same space as two or more objects. This occurs because the solver is unable to determine which material properties to apply in the area of overlap. To correct this problem, boolean operations can be used to subtract one object from the other or the overlapping object can be split into smaller pieces that are completely enclosed within the volume of another object. When an object is completely enclosed there are no overlap errors.



(a) (b) (c) (d) (e)

Figure 5. Design of (a) ferrite rod, (b) dielectric polarisers, (c) matching sections, and (e) radiating end caps assembly with waveguide simulator in HFSS.

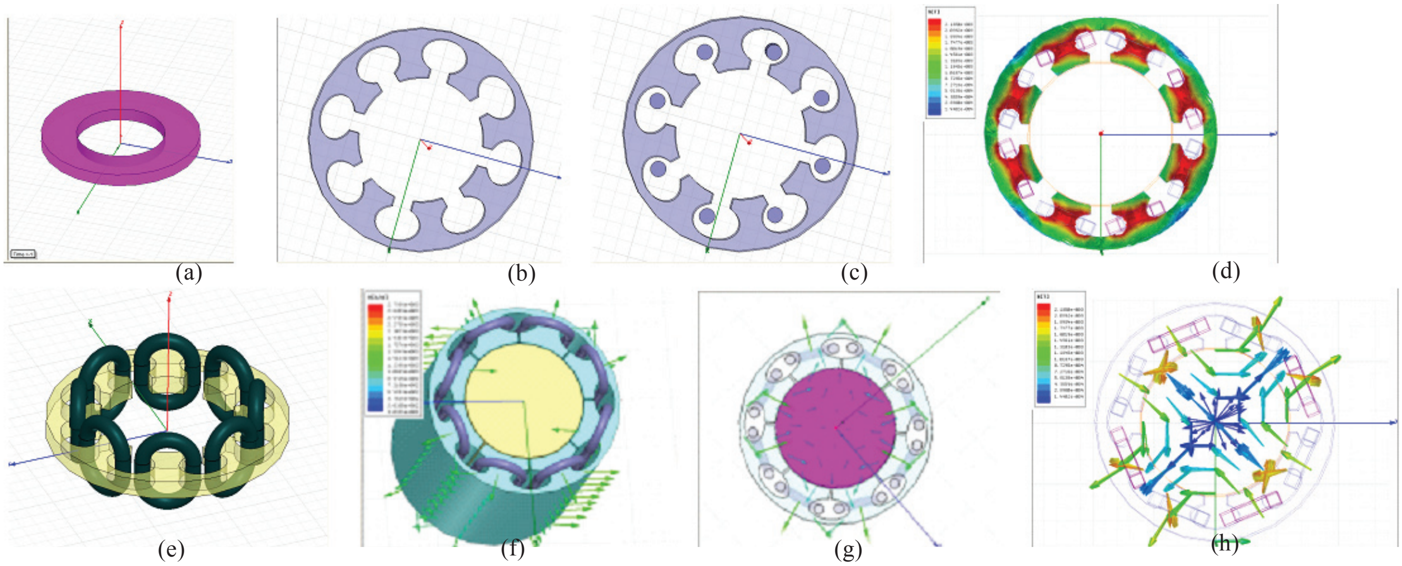


Figure 6. Different stages (a)-(h) of Eight Pole Ferrite Yoke design (cross sections with copper windings and electrical field distribution due to current excitation) using 3-D Maxwell software.

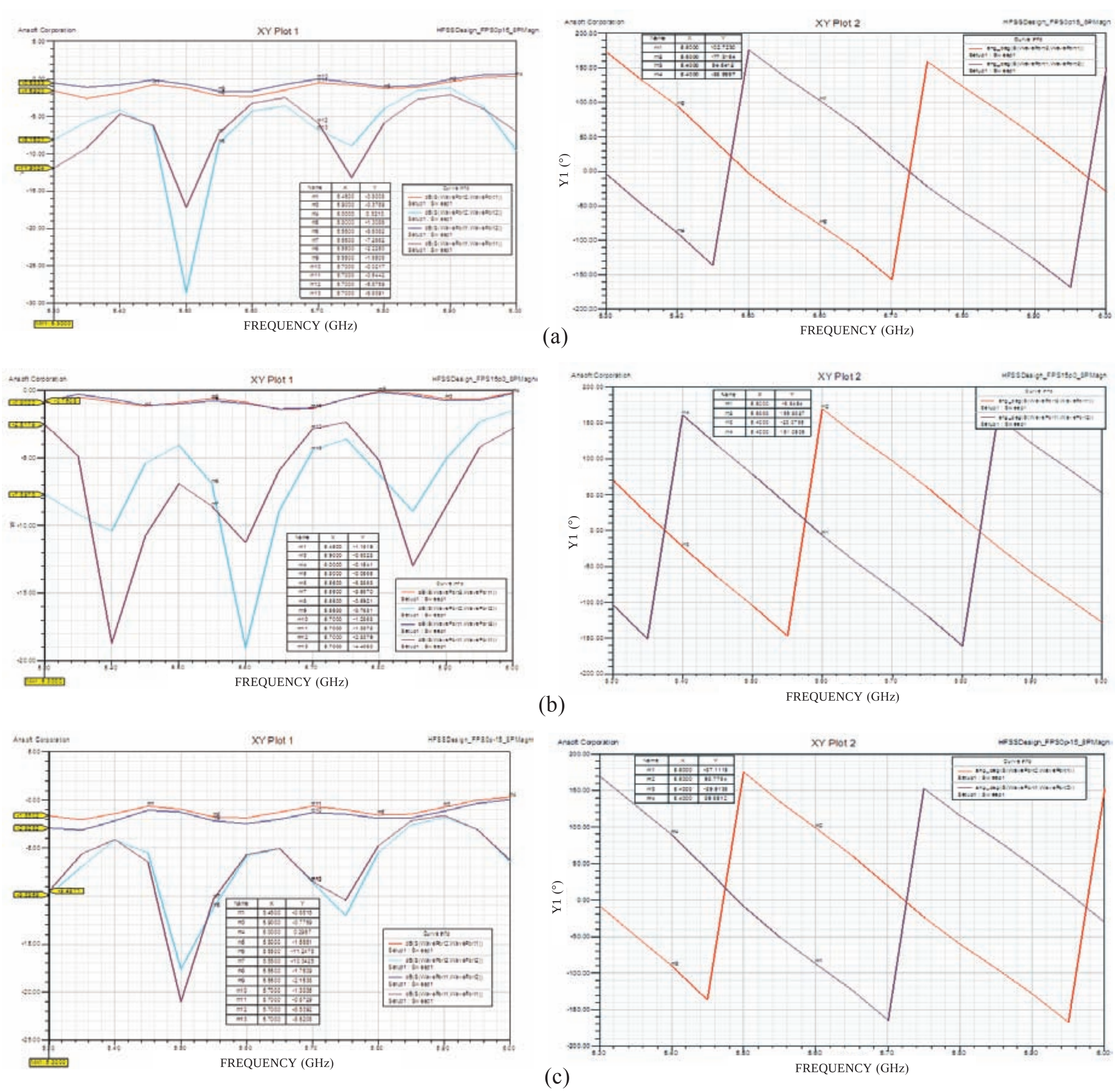


Figure 7. S-Parameter magnitude and phase plots at (a) 0°, (b) 90°, and (c) 180°, respectively

5. RF CHARACTERISATION OF PHASE SHIFTER

The phase shifter is tested by commanding it to different phase states from 0 to 63 for 6-bit control which correspond to differential phase shift from 0 to 360 degrees (max) and recording the data from the vector network analyzer (VNA). A computer is interfaced with the VNA through the GPIB port and the automatic test procedure (ATP) program performs all the tasks of instrument control, data acquisition and computation.

The typical data required for complete characterisation of the phase shifter intended for phased array radar application is:

(i) Phase shift with command states: S12 & S21 .
(ii) Average insertion loss: This is computed as the arithmetic mean of the transmission coefficients at all phase states at any given frequency, expressed in dB.
(iii) Average return loss : This is computed as the arithmetic mean of the reflection coefficients at all phase states at any given frequency, expressed in dB.
(iv) RMS phase error: This is the RMS of the deviation of RF phase shift values from the commanded values.
(v) Fluctuation in average insertion loss: This is computed as the square root of the mean of the squares of the difference between the average transmission coefficient and each individual transmission coefficients.
(vi) Insertion phase: It is the phase angle of the receive transmission coefficient for phase command state defined as providing zero degree differential phase shift.

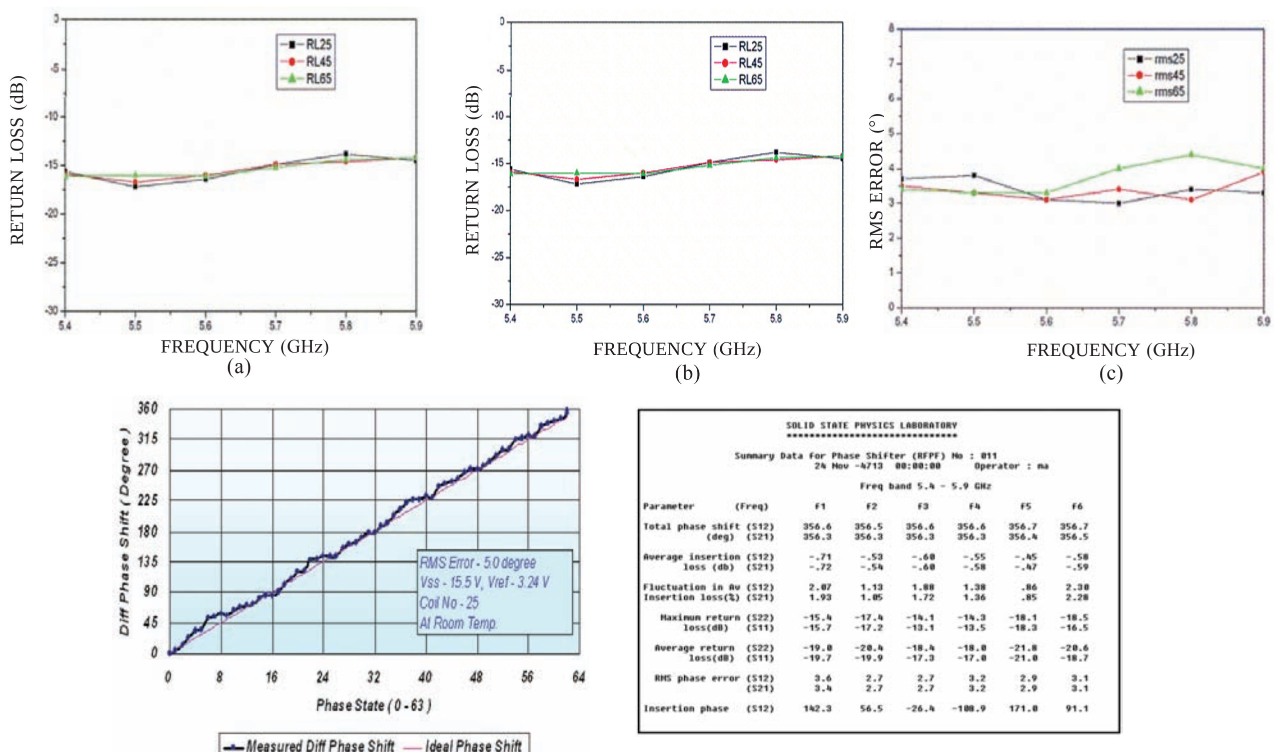
The above parameters are needed over the specified frequency band and over the operating temperature range for complete RF characterisation of the phase shifter. The phase shifters have been tested successfully for various parameters[10,11].

The graphs of various RF characterisation parameters viz. Insertion loss, Return loss, RMS phase error vs frequency and table of these parameters are shown in Fig. 8. The linear dependence of the differential phase shift with applied command states is evident from these measurements. The phase shifter modules have also been successfully tested for high peak power performance upto 315 W at SSPL, Delhi.

6. CONCLUSION

An overview of the design and development of rotary field ferrite phase shifter parts using the Ansys HFSS and 3-D Maxwell softwares has been dealt with in this paper. The C-band RFFPS parts have been designed, developed and integrated as assemblies and tested successfully for various parameters. The design and simulation of the RFFPS parts has resulted in reducing the number of physical iterations substantially. This is particularly beneficial for the production process where considerable reduction in time and cost can be achieved for phase shifters of different frequency ranges. Three prototypes and one hundred production capable phase shifter modules were fabricated, functionally tested and RF characterised at SSPL and CEL.

The rotary field ferrite phase shifter provides high peak power capability upto 315 W, better phase accuracy, linear phase control behavior, low frequency dependence and dispenses



(a) (b) (c) (d) (e)

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Summary Data for Phase Shifter (RFPF) No : 011
24 Nov -4713 00:00:00 Operator : ma

Freq band 5.4 - 5.9 GHz

Parameter	(Freq)	F1	F2	F3	F4	F5	F6
Total phase shift	(S12)	356.6	356.5	356.6	356.6	356.7	356.7
(deg)	(S21)	356.3	356.3	356.3	356.3	356.4	356.5
Average insertion	(S12)	-.71	-.53	-.60	-.55	-.45	-.58
loss (db)	(S21)	-.72	-.54	-.60	-.58	-.47	-.59
Fluctuation in Av	(S12)	2.07	1.13	1.88	1.38	.86	2.30
Insertion loss(%)	(S21)	1.93	1.05	1.72	1.36	.85	2.28
Maximum return	(S22)	-15.4	-17.4	-14.1	-14.3	-18.1	-18.5
loss(dB)	(S11)	-15.7	-17.2	-13.1	-13.5	-18.3	-16.5
Average return	(S22)	-19.0	-20.4	-18.4	-18.0	-21.8	-20.6
loss(dB)	(S11)	-19.7	-19.9	-17.3	-17.0	-21.0	-18.7
RMS phase error	(S12)	3.6	2.7	2.7	3.2	2.9	3.1
	(S21)	3.4	2.7	2.7	3.2	2.9	3.1
Insertion phase	(S12)	142.3	56.5	-26.4	-108.9	171.0	91.1

Figure 8. Graphs of RF characterisation parameters viz. (a) Insertion loss, (b) Return loss, (c) RMS phase error vs. frequency at 25 °C, 45 °C, and 65°C, (d) Linear graph of differential phase shift vs phase (command) states, and (e) Table of various RF characterisation parameters.

with look up tables requirement – a significant advantage over other class of ferrite phase shifters.

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Ms Meenakshi Aggarwal has done BE (EC) from Delhi University and MTech (IT) from IIT, Delhi. Currently working as a Scientist in Solid State Physics Laboratory, DRDO, Delhi. She has experience in the design, simulation and fabrication of electronic circuits as well as modelling and development of virtual prototypes/ instruments for instrumentation and microwave electronics applications such as electronic intruder alarm system, digital drivers for ferrite phase shifters and characterisation of ferrite/ceramic materials.

She has carried out the design and simulation of ferrite yoke windings and waveguide simulator.

Mr B.S. Matheru did MSc (Physics) followed by MTech (ME) from Delhi University. Currently working as a Scientist in Solid State Physics Laboratory, DRDO, Delhi. He has experience in the design of microwave ferrite based devices viz. C-band dual mode phase shifter, S-band rotary field phase shifter, C-band rotary field phase shifter and characterisation of ferrite/ceramic materials.

He has carried out the design and simulation of ceramic matching sections with radiating end caps.