5-Bit RF MEMS Phase Shifter Development in Ku Band for Phased Array Applications

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By

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CERTIFICATE OF COURSE WORK

This is to certify that Mr. ANESH KUMAR SHARMA was admitted to the candidacy of the Ph.D. Degree in December 2010 and successfully completed all the courses required for the Ph.D. programme. The details of the course work done are given below.

Sl. No.	**Course No.**	**Course Name**	**Credits**
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3	EE 5120	VLSI Technology	3
4	EE 5110	Device Physics & Modeling	3

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IIT HYDERABAD

Dated:

Dedicated

to

My Parents

Mrs. RAJ RANI SHARMA

Shri MAHENDRA SHARMA

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ABSTRACT

MEMS based devices represent an extremely attractive alternative to MESFET devices for realization of the programmable phase shifters. The stable operation of RF MEMS devices is impacted by the actuation voltage, restoration force and the structural stresses. These can induce severe functional deformities into the device leading to operational problems. These parameters can be optimized by the concept of built-in reliability through design. In the present work, the study of Ku band 5-bit MEMS phase shifter was associated with the switch development. The hybrid design topology of switched and loaded line was adopted for the phase shifter. This topology has been the best trade off among large phase shift, low loss and reduced space requirement in the defined frequency band. This approach requires 18 switches per 5-bit phase shifter and all must work simultaneously in order to achieve the phase shifter fully functional. Hence the study was initiated with switch development keeping the focus on the above mentioned parameters.

The capacitive shunt and ohmic series switch were designed with a split beam concept which has been evolved uniquely in comparison to the holes commonly available in the literature. This has been implemented to overcome the various criticalities of restoration force and structural stress for stable operation and the advantage of the structure release due to large split area during the release process. In fact, it has been emphasised to achieve the higher spring constant with lower structural stress arising due to the structure design. A complete analysis of the spring constant and the stress was carried out to address the long term operation. In capacitive shunt type, two variations i.e. single and double dc bias was taken up for study. Both these configurations have been provided the symmetric actuation along the RF line for uniform pull-in. The configuration having single bias pad was conceived for simple implementation of the switch in the systems during practical application. Single DC bias pad has lot of ease in applying the DC potential in comparison to the two bias pad configurations however this needed to create a discontinuity in the RF line. The discontinuity has been provided in the single DC bias pad design. All other design parameters have been exactly same in both the configurations. Both the configurations have bias pad on the periphery so that smaller length of bond wire is sufficient during assembly and packaging to avoid the parasitic effects at high frequencies. The proposed split beam versus rectangular holes beam, most commonly exists in literature, analyzed with FEM (Coventorware simulator) for stress analysis. To observe the significance of split beam design

over rectangular holes type, beam surface area, thickness, material and mass were kept same. The analysis shows that the stress in case of rectangular holes is 630 MPa and 380 MPa for the split beam configuration about 35-40% lower. This analysis shows the superiority of split beam design with respect to the rectangular holes. The similar approach was followed for the ohmic series switch. In case of the cantilever the structural stress was found lower by 25-30% in comparison to the rectangular holes approach. The fabrication and characterization of these switches has shown the actuation voltage as 24.6V for capacitive shunt configurations. The RF parameters have been measured as insertion loss 0.20dB and 0.24dB, return loss 24.0dB and 22dB while isolation as 40dB and 37dB over 4-20 GHz frequency range for two dc bias pad and single bias pad configurations respectively. In case of the ohmic series switch the actuation voltage of 18.1V was achieved. The measurement has shown RF parameters as insertion loss 0.18dB, return loss 21dB and isolation better than 40dB over the DC-12GHz.

After developing a significant understanding, the study on the RF MEMS switches was extended to the design, simulation, fabrication and characterization of the 5-bit Ku band phase shifter. In the best of my knowledge this is first attempt to develop and implement a 5-bit MEMS based phase shifter in Ku band for the active phased array. This involves the singular bits, integrated 5-bit phase shifter on CPW configuration and microstrip version for implementation into the T/R module. The three bits namely 180^o, 90^o and 45^o have been designed using switched microstrip lines with series ohmic MEMS switches to achieve the large phase shift. The lower phase bits namely 22.5^o and 11.25^o have been designed using microstrip line sections loaded by ohmic MEMS switches in shunt mode. Microstrip topology additionally provides lower loss and enhanced compactness with respect to CPW. Electromechanical analysis of the MEMS parts of phase shifter has been carried out to optimize the critical parameters such as i) actuation voltage, ii) contact force due to series resistance and iii) deformation arising because of stress gradient. These have been studied in detail in order to ascertain the stable operation. The CPW version was characterized on-wafer using the TRL kit dedicatedly fabricated along with the devices. The measured RF results obtained for the monolithic 5-bit CPW MEMS phase shifter have been measured as the return loss better than 12dB and average insertion loss better than 3.21dB for the 32 states in the 16-18GHz frequency band. The minimum and maximum insertion loss was 2.15dB and 3.84dB respectively. The average return loss is 20.64dB. The average phase shift error has been 1.52 degrees. The worst case phase shift error was observed as 1.84 degrees over the 32 states.

Finally, our focus was on the microstrip version, and in order to evaluate the microstrip version, the control circuitry was developed to drive the phase shifter with the programmable microcontroller for logic combination having the high voltage driver. The hardware has been provided an USB port to connect for PC interface to control the 12 dc signals necessary to drive the 5-bit phase shifter for 32 states measurement. The RF performance for the microstrip version has been measured as return loss better than 12.73dB and average insertion loss 4.68dB (IL_{min} = 4.03dB, IL_{max}=5.17dB) and the phase shift error (rms) for the 32 states is 2.83degrees. This insertion loss includes the loss towards the RF connectors and the test jig which is of the order of 1.35dB. The effective loss of the micro-strip version phase shifter is 3.33dB for 5-bit phase shifter over 32 states in the 16-18GHz frequency band. These results have shown the potential of 5-bit Ku band MEMS phase shifter that can replace the MESFET based phase shifter in T/R module for AESA applications.

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ABBREVIATIONS and ACRONYMS

Symbol	Description	Unit
k	Spring constant	N/m^2
d	gap between electrodes	µm
A	Area of electrode	$µm^2$
ε	permittivity of air	F/m
t	Thickness of membrane	µm
E	Young's Modulus	GPa
W	width of the beam	µm
t_s	Switching Time	µsec
V_p	pull in voltage	Volts
V_s	source voltage	Volts
f_o	resonant frequency	KHz
V	applied voltage	Volt
x	displacement	µm
v	poisson's ratio	--
C_{up}	Upstate capacitance	fF
C_{down}	Downstate capacitance	pF
$\Delta\Phi$	Differential phase shift	degrees
Φ_2	Phase of delay path	degrees
Φ_1	Phase of reference path	degrees
S_{21}	insertion loss	dB
S_{11}	return loss	dB

Abbreviations:

AESA	Active Electronically Steerable Antennas
PESA	Passive Electronically Steerable Antennas
RF	Radio Frequency
IC	Integrated Circuit
MMIC	Monolithic Microwave Integrated Circuit

EW	Electronic Warfare
MEMS	Micro Electro Mechanical Systems
MESFET	Metal Semiconductor Field effect transistor
T/R	Transmit/ Receive
GaAs	Gallium Arsenide
CPW	Coplanar Waveguide
PECVD	Plasma Enhanced Chemical Vapor Deposition
SEM	Scanning Electron Microscope
SOLT	Short Open Load Thru
SPST	Single Pole Single Throw
TRL	Thru Reflect Line
LPCVD	Low Pressure Chemical Vapor Deposition
DC	Direct current