RF MEMS SWITCHES FOR RECONFIGURABLE APPLICATIONS FROM RF TO MILLIMETER WAVE FREQUENCIES

NIHARIKA NARANG

CENTRE FOR APPLIED RESEARCH IN ELECTRONICS

INDIAN INSTITUTE OF TECHNOLOGY DELHI (I.I.T Delhi)

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by

NIHARIKA NARANG

CENTRE FOR APPLIED RESEARCH IN ELECTRONICS

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Dedicated to my Parents, Husband and Son

CERTIFICATE

This is to certify that the thesis entitled, "**RF MEMS SWITCHES FOR RECONFIGURABLE APPLICATIONS FROM RF TO MILLIMETER WAVE FREQUENCIES,"** submitted by **Ms. NIHARIKA NARANG** for the award of the degree of **Doctor of Philosophy** to the Centre for Applied Research in Electronics, **Indian Institute of Technology Delhi,** New Delhi, is a record of bona fide research work carried out during the time period from July 2018 to April 2024 by her under our guidance and supervision.

Ms. Niharika Narang has fulfilled the requirements for submitting this thesis, which has reached the requisite standards to our knowledge. The results in this thesis have not been submitted in part or in whole to any other university or institute for the award of any degree or diploma.

Prof. Pushpapraj Singh
Associate Professor
Centre for Applied Research in Electronics
Indian Institute of Technology Delhi
New Delhi-110016, INDIA

Prof. Ananjan Basu
Professor
Centre for Applied Research in Electronics
Indian Institute of Technology Delhi
New Delhi-110016, INDIA

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Abstract

Novel Reconfigurable RFICs with superior performance are the need of the hour for future technologies. The vast pool of applications includes military, medicine, industry, communication, and environment. MEMS switches have shown promising capabilities to cater to these applications' different requirements. Among them, Metal-based MEMS switches have become an active interest of the research community due to their excellent properties. The performance of RF MEMS devices has advanced progressively over the past years. However, low pull-in voltage, wide operating frequency range, and multi-functionality within a single switch are the demands of compact and high performance RFICs. This calls for future endeavors to expand their reach and knowledge governing their operation by exploring different techniques and approaches for device design and fabrication.

The following dissertation focuses on designing novel MEMS switches for power dividers and phase shifter applications. The dissertation first discusses the modeling, design, simulation, and fabrication of RF power dividers based on defect structures in the ground plane and external capacitive loading to improve performance and reduce size. The proposed power divider (with capacitive load and rectangular slot DGS) has a transmission line length reduced to λ/16. The overall size of this divider has decreased by 73.7% (0.14λg x 0.06λg) compared to the conventional divider structure. The designed power divider offers higher order harmonics suppression till 10th harmonics, along with providing good RF performance. The degradation in isolation due to the size reduction technique has also been improved. A parallel combination of resistor-capacitor is implemented in the isolation network to improve isolation instead of a single resistor element. The simulated result shows that the proposed power divider has a 3.02 dB insertion loss, reflection loss better than 25.66 dB, and isolation in output ports better than 22.43 dB (at the center frequency).

Further, a novel MEMS capacitive switch is designed and integrated into the RF power divider to achieve reconfigurability and compactness. The proposed RF MEMS power divider offers tuneability for operating in two different frequencies in the C band. Insertion loss and return loss are 3.57 dB and 24.6 dB (at 4.4 GHz) and 3.82 dB and 22.06 dB (at 5.4 GHz), respectively. The total area of the design is 3.1 mm^2. The design under consideration can suppress harmonics up to the 8^{th} order by 10dB.

The next part of the thesis focuses on designing a novel RF MEMS DC/Capacitive switch for the ultra-broadband range (DC-80GHz). The fabrication of this switch is simple and requires only four masks. A floating metal electrode has been used at the top of the dielectric layer to obtain a fixed downstate capacitance irrespective of the contact area variation between the top and bottom electrodes due to an even slight variation in applied voltage after pull-in voltage. Molybdenum is the beam material to obtain robustness against stress and temperature. This switch can be used as DC switch from 0-48GHz and a capacitive switch from 17-80GHz. However, the proposed structure can be switched between DC and capacitive load from 17-48GHz.

A novel 2-bit phase shifter with four different phase shifts (center frequency is 20 GHz) is designed and consists of only two above-designed RF MEMS DC/Capacitive switches. The RF MEMS DC/Capacitive switch (integrated into the designed phase shifter) can be switched between capacitive and DC load. It gives a 2-bit phase shift of 0^o, 5.625º, 11.25^o, and 22.5º. Surface micromachining is used to design the proposed RF MEMS phase shifter. Sapphire is used as a substrate to fabricate the phase shifter. RF characteristics are measured using a CASCADE probe station SUMMIT 1100 with Agilent E8361C PNA Network Analyzer (10 MHz-67 GHz). Isolation in either of the on states (DC and capacitive) is better than 10 dB from 16-45 GHz. The proposed phase shifter's measured return loss and insertion loss in all the states are better than 10 dB and less than 0.8 dB from 16-24 GHz. The novel phase shifter design with unique RF MEMS DC/Capacitive switches provides high RF performance in each state with a maximum RMS phase shift error of 0.98± and an RMS gain error of less than 0.28 dB. These outcomes validate the promising future of highly compact and less complex phase shifters using designed RF MEMS switches.

सार

शानदार प्रदर्शन के साथ नवीन पुन: कॉन्फ़िगर करने योग्य आरएफआईसी भविष्य की प्रौद्योगिकियों के लिए समय की आवश्यकता है। अनुप्रयोगों के विशाल पूल में सैन्य, चिकित्सा, उद्योग, संचार और पर्यावरण शामिल हैं। माइक्रो-इलेक्ट्रो-मैकेनिकल सिस्टम (एमईएमएस) स्विचों ने इन अनुप्रयोगों की आवश्यकताओं को पूरा करने की आशाजनक क्षमताएं दिखाई हैं। उनमें से, धातु-आधारित एमईएमएस स्विच अपने उत्कृष्ट गुणों के कारण अनुसंधान समुदाय की सक्रिय रुचि बन गए हैं। आरएफ एमईएमएस उपकरणों का प्रदर्शन पिछले वर्षों में उत्तरोत्तर उन्नत हुआ है। हालाँकि, वर्तमान अत्याधुनिक एमईएमएस स्विच मुख्य रूप से उच्च पुल-इन वोल्टेज आवश्यकताओं, कम ऑपरेटिंग आवृत्ति रेंज और बहु-कार्यक्षमता में सीमित हैं। इसके लिए डिवाइस डिज़ाइन और निर्माण के लिए विभिन्न तकनीकों और दृष्टिकोणों की खोज करके उनके संचालन को नियंत्रित करने वाली उनकी पहुंच और ज्ञान का विस्तार करने के लिए भविष्य के प्रयासों की आवश्यकता है।

निम्नलिखित शोध प्रबंध पावर डिवाइडर और चरण शिफ्टर्स अनुप्रयोगों के लिए उपन्यास एमईएमएस स्विच डिजाइन करने पर केंद्रित है। शोध प्रबंध पहले प्रदर्शन में सुधार और आकार को कम करने के लिए ग्राउंड प्लेन और बाहरी कैपेसिटिव लोडिंग में दोष संरचनाओं के आधार पर आरएफ पावर डिवाइडर के मॉडलिंग, डिजाइन, सिमुलेशन और निर्माण पर चर्चा करता है। प्रस्तावित पावर डिवाइडर (कैपेसिटिव लोड और आयताकार स्लॉट डीजीएस के साथ) की ट्रांसमिशन लाइन की लंबाई घटाकर $\lambda/16$ कर दी गई है। पारंपरिक विभक्त संरचना की तुलना में इस विभक्त का कुल आकार 73.7% ($0.14\lambda g$ x $0.06\lambda g$) कम हो गया है। डिज़ाइन किया गया पावर डिवाइडर अच्छा आरएफ प्रदर्शन प्रदान करने के साथ-साथ 10वें हार्मोनिक्स तक उच्च क्रम के हार्मोनिक्स दमन प्रदान करता है। आकार घटाने की तकनीक के कारण अलगाव में गिरावट में भी सुधार हुआ है। एकल अवरोधक तत्व के बजाय अलगाव को बेहतर बनाने के लिए अलगाव नेटवर्क में अवरोधक-संधारित्र का एक समानांतर संयोजन लागू किया जाता है। सिम्युलेटेड परिणाम से पता चलता है कि प्रस्तावित पावर डिवाइडर में 3.02 डीबी सम्मिलन हानि, प्रतिबिंब हानि 25.66 डीबी से बेहतर है, और आउटपुट पोर्ट में अलगाव 22.43 डीबी (केंद्र आवृत्ति पर) से बेहतर है।

इसके अलावा, एक नवीन एमईएमएस कैपेसिटिव स्विच को पुन: विन्यास और कॉम्पैक्टनेस प्राप्त करने के लिए आरएफ पावर डिवाइडर में डिजाइन और एकीकृत किया गया है। प्रस्तावित आरएफ एमईएमएस पावर डिवाइडर सी बैंड में दो अलग-अलग आवृत्तियों में संचालन के लिए ट्यूनेबिलिटी प्रदान करता है। सम्मिलन हानि और वापसी हानि क्रमशः 3.57 डीबी और 24.6 डीबी (4.4 गीगाहर्ट्ज पर) और 3.82 डीबी और 22.06 डीबी (5.4 गीगाहर्ट्ज पर) हैं। डिज़ाइन का कुल क्षेत्रफल 3.1 मिमी2 है। विचाराधीन डिज़ाइन 8वें क्रम तक के हार्मोनिक्स को 10 डीबी तक दबा सकता है।

थीसिस का अगला भाग अल्ट्रा-ब्रॉडबैंड रेंज (0-80GHz) के लिए एक उपन्यास आरएफ एमईएमएस डीसी/कैपेसिटिव स्विच डिजाइन करने पर केंद्रित है। इस स्विच का निर्माण सरल है और इसके लिए केवल चार मास्क की आवश्यकता होती है। पुल-इन वोल्टेज के बाद लागू वोल्टेज में मामूली बदलाव के कारण ऊपर और नीचे इलेक्ट्रोड के बीच संपर्क क्षेत्र भिन्नता के बावजूद एक निश्चित डाउनस्टेट कैपेसिटेंस प्राप्त करने के लिए ढांकता हुआ परत के शीर्ष पर एक फ्लोटिंग धातु इलेक्ट्रोड का उपयोग किया गया है। मोलिब्डेनम तनाव और तापमान के खिलाफ मजबूती प्राप्त करने के लिए बीम सामग्री है। इस स्विच का उपयोग 0-48 गीगाहर्ट्ज से डीसी स्विच और 17-80 गीगाहर्ट्ज से कैपेसिटिव स्विच के रूप में किया जा सकता है। हालाँकि, प्रस्तावित संरचना को 17-48 गीगाहर्ट्ज से डीसी और कैपेसिटिव लोड के बीच स्विच किया जा सकता है।

चार अलग-अलग चरण शिफ्टों (केंद्रीय आवृत्ति 20 गीगाहर्ट्ज़) के साथ एक नया 2-बिट चरण शिफ्टर डिज़ाइन किया गया है और इसमें केवल दो उपरोक्त डिज़ाइन किए गए आरएफ एमईएमएस डीसी/कैपेसिटिव स्विच शामिल हैं। आरएफ एमईएमएस डीसी/कैपेसिटिव स्विच (डिज़ाइन किए गए चरण शिफ्टर में एकीकृत) को कैपेसिटिव और डीसी लोड के बीच स्विच किया जा सकता है। यह 0º, 5.625º, 11.25º और 22.5º की 2-बिट चरण शिफ्ट देता है। प्रस्तावित आरएफ एमईएमएस चरण शिफ्टर को डिजाइन करने के लिए सतह माइक्रोमशीनिंग का उपयोग किया जाता है। नीलमणि का उपयोग चरण शिफ्टर के निर्माण के लिए एक सब्सट्रेट के रूप में किया जाता है। आरएफ विशेषताओं को एगिलेंट E8361C PNA नेटवर्क एनालाइजर (10 मेगाहर्ट्ज-67 गीगाहर्ट्ज) के साथ कैस्केड जांच स्टेशन SUMMIT 1100 का उपयोग करके मापा जाता है। दोनों में से किसी भी स्थिति (डीसी और कैपेसिटिव) में अलगाव 16-45 गीगाहर्ट्ज से 10 डीबी से बेहतर है। सभी राज्यों में प्रस्तावित चरण शिफ्टर का मापा रिटर्न लॉस और इंसर्शन लॉस 16-24 गीगाहर्ट्ज से 10 डीबी से बेहतर और 0.8 डीबी से कम है। अद्वितीय आरएफ एमईएमएस डीसी/कैपेसिटिव स्विच के साथ नवीन चरण शिफ्टर डिजाइन प्रत्येक राज्य में 0.98± की अधिकतम आरएमएस चरण शिफ्ट त्रुटि और 0.28 डीबी से कम की आरएमएस लाभ त्रुटि के साथ उच्च आरएफ प्रदर्शन प्रदान करता है। ये परिणाम डिज़ाइन किए गए आरएफ एमईएमएस स्विच का उपयोग करके अत्यधिक कॉम्पैक्ट और कम जटिल चरण शिफ्टर्स के आशाजनक भविष्य को मान्य करते हैं।

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List of Abbreviations

RF: Radio Frequency

RFIC: Radio Frequency Integrated Circuits

MMIC: Monolithic Microwave Integrated Circuits

MEMS: Micro-Electro-Mechanical Systems

PLL: Phase Locked Loop

VCO: Voltage Controlled Oscillators

LNA: Low Noise Amplifier

PIN: Positive Intrinsic Negative

FET: Field Effect Transistors

BST: Barium Strontium Titanate

SPDT: Single Pole Double Through

CPW: Co-Planar Waveguide

RMS: Root Mean Square

DGS: Defect Grounded Structures

ACPW: Asymmetric Co-Planar Waveguide

GaAs: Gallium Arsenide

FEA: Finite Element Analysis

CLTL: Capacitively Loaded Transmission Line

List of Symbols

Z_0: Characteristics Impedance of Transmission Line

θ: Electrical Length

ω_0: Resonant Frequency

E: Young's Modulus

α: Thermal coefficients of expansion.

k: Stiffness

ε_0: Vacuum permittivity

ε_r: Relative permittivity

υ: Poisson's Ratio

λ: Wavelength

θ: Electrical length

ϱ: Density

Z_{oo}: Odd-mode impedance

Z_{ee}: Even-mode impedance

H: Hardness of the material

K: Thermal conductivity

R_C: Contact Resistance

T_S: Softening Temperature