GRAPHENE RF NEMS SHUNT SWITCHES FOR ANALOG AND DIGITAL PHASE SHIFTERS

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ABSTRACT

We present the wafer-level fabrication and the first measurements of RF capacitive NEMS switches based on CVD multilayer graphene for wideband RF phase shifters for analog and digital applications. We assess the phase shifter performance by using the characterization data of the fabricated NEMS switches to perform calibrated simulations using an equivalent circuit. We demonstrate the possibility to achieve 355°/dB at 2.4 GHz for the analog design and 138°/dB at 2.4 GHz for the digital one.

KEYWORDS

Graphene, Multilayer, CVD, Radio-frequency (RF), Micro-Electro-Mechanical Systems (MEMS), Capacitive Switches, Micromachining, Phase Shifter, DNTL

INTRODUCTION

Motivation

Phase shifters are crucial components in smart antennas, beam steering or scanning applications for wideband communications and remote sensing systems. RF micro-electro-mechanical systems (MEMS) have shown various advantages for the realization of phase shifters over conventional semiconductor switching devices, as field-effect transistors (FETs) or p-i-n diodes, such as low losses at high frequency, low power consumption and excellent linearity [1], [2].

Conventional metal MEMS switches have been demonstrated reliably up to 40 GHz with low insertion loss and high linearity [3], [4]. However, MEMS based phase shifters are limited to relatively slow scanning applications due to their mechanical switching time (1-15 µs).

One potential solution to overcome this drawback is to use graphene instead of metal for the MEMS membrane, due to its outstanding mechanical properties like high mechanical stiffness, high strength and low mass [5], [6]. These qualities make graphene nano-electro-mechanical systems (NEMS) achieve faster switching than traditional metal MEMS, thus they are more promising for fast scanning applications.

However, the potential of graphene-based NEMS for phase shifters at RF frequencies has not yet been investigated.

In this paper, we perform a comprehensive study of the use of graphene based NEM capacitive switches in distributed NEMS transmission lines (DNTL) analog and digital phase shifters, by microwave circuit analysis based on electromagnetic simulations using an equivalent circuit model and the data obtained from the experimental characterization of a graphene NEMS switch. The detailed fabrication and characterization at RF frequencies of the single graphene NEM switch is presented elsewhere [7].

Concept

Distributed MEMS transmission lines (DMTLs) are the most common type of phase shifters based on the loaded-line topology [8], particularly suitable for RF MEMS integration. They mainly consist of a coplanar waveguide (CPW) transmission line periodically loaded by lumped tunable capacitors in shunt configuration. In this work we use as loading elements graphene-based RF NEMS voltage-controlled switches. These loads affect the characteristic impedance of the line and consequently, the propagation velocity and resulting phase shift can be controlled.

By applying a single analog control voltage to the signal line of the CPW, below the pull-in voltage V_{pi} of the graphene-based tunable capacitor, the resulting electrostatic force causes the graphene membrane height to vary, thus the distributed capacitive loading on the transmission line and, therefore, its propagation characteristics, can be varied.

Analog DMTL phase shifters achieve a continuous variable phase shift commonly limited by the low capacitance ratio ($C_r < 1.5$) of MEM switches in their up-state stable region.

Furthermore, we study digital DNTLs, based on digital capacitive switches with two controllable capacitive states, achieved by using fixed capacitors in series to the graphene NEMS switch. Digital DNTL phase shifters achieve higher differential phase shift than analog approaches and are only limited by acceptable impedance matching. They have the advantages of size reduction and Brownian noise effects alleviation [1] in spite of higher actuation voltage and power consumption.

DESIGN AND IMPLEMENTATION

Graphene RF NEMS Tunable Capacitor

The graphene tunable capacitor consists of a suspended multilayer graphene membrane, doubly clamped on a CPW. The schematic of the single graphene NEMS tunable capacitor is depicted in Fig.1. The different composing materials are indicated as well as the fabrication method for each layer.

Multilayer graphene is transferred by wet transfer using PMMA as transport polymer, then it is patterned for 1 minute in O_2 plasma in order to define the NEMS membranes. After it is clamped by the ground plane metal it is released by sacrificial etching of the underlying LTO (low temperature SiO_2) [7]. The SEM image of the final device is presented in Fig. 2 (a) and the corresponding equivalent lumped circuit including the distributed element of the CPW line in Fig. 2 (b).

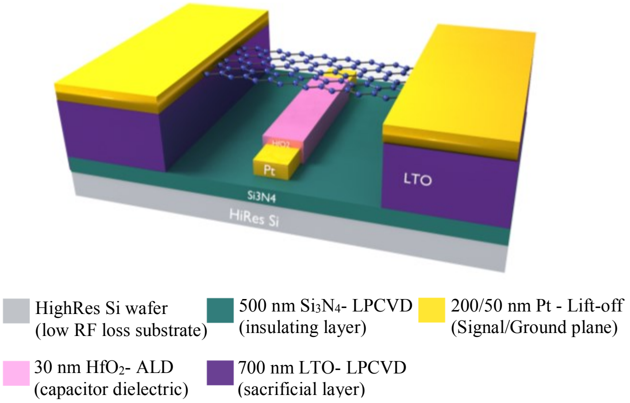
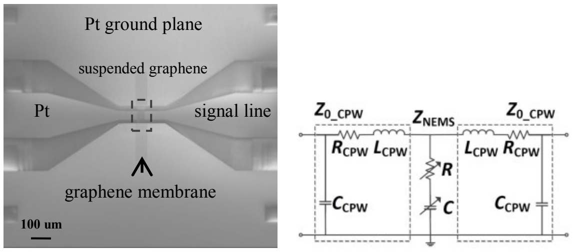


Figure 1: Schematic representation of the graphene NEM tunable capacitor illustrating the different materials, thicknesses and the fabrication method.



(a) (b)

Figure 2. (a) SEM picture of the graphene NEMS switch (b) equivalent lumped circuit of the NEMS switch including CPW and pads parasitics.

DNTL Phase Shifters

The goal of this paper is the design and simulation of DNTLs based on the graphene NEMS tunable capacitors presented in the previous section, operating at a frequency around 2.4 GHz, standard for RFID applications.

The design of the DNTLs requires an accurate knowledge of the distributed loading capacitance and resistance of the NEMS membranes. These parameters are highly dependent on the fabrication process, which must be carefully characterized in order to obtain an accurate design.

Fig. 3 shows the approximated distributed equivalent circuit of an analog and digital DMTL phase shifter loaded with graphene NEM capacitors. The proposed DNTLs comprise 30 stages with 500 µm period, in order to obtain a good tradeoff between phase shift and loss at 2.4 GHz.

For more controllable and miniaturized solutions, we propose a digital phase shifter using periodically-loaded digital capacitors in series with fixed capacitors, in order to achieve a well-controllable capacitive ratio of 3.

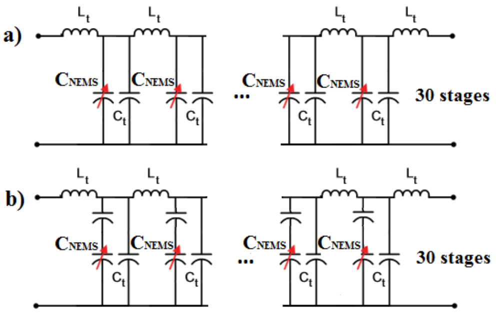


Figure 3: Simplified equivalent circuit of a loaded DNTL a) for analog and b) for digital applications

The DNTL design procedure is based on the metamaterial transmission line theory; we obtained the phase shift Φ (rad) and attenuation S_{21} (dB) of the whole DNTL by calculating the propagation constant $\gamma = \alpha + j\beta$ of the unit cell:

$$\gamma = -\ln(\xi)/(\Delta L) \quad (1)$$

$$\Phi = \beta \cdot n \cdot \Delta L \quad (2)$$

$$S_{21} = 20 \cdot \log 10[e^{(\alpha \cdot n \cdot \Delta L)}] \quad (3)$$

where n is the number of stages, ΔL is the period and ξ is the eigenvalue of the ABCD matrix of the unit cell [9].

RESULTS AND DISCUSSIONS

Graphene RF NEMS Tunable Capacitor

We characterized the fabricated RF NEMS tunable capacitors by measuring the S-parameters up to 6 GHz (Fig. 4). We superimposed a DC voltage, V_{DC}, to the RF signal to apply an electrostatic force between the signal line and the graphene membrane, and in consequence tune the capacitance. The S-parameters have been fitted to the simulations of the equivalent circuit shown in Fig. 2(b) in order to extract the resistance R and capacitance C of the switch for each V_{DC} value.

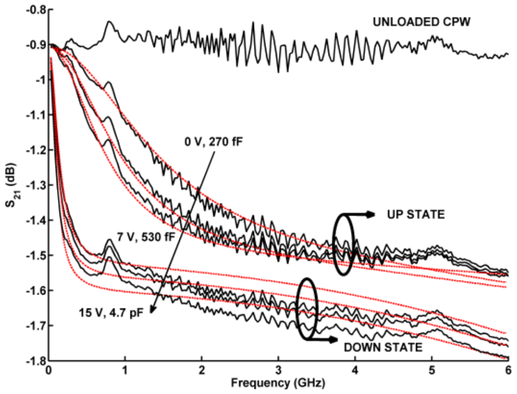


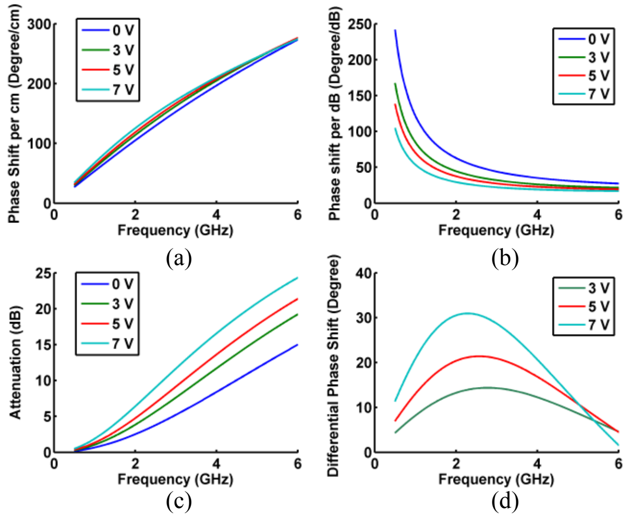
Figure 4. S-parameter measurements (black) and equivalent circuit model (red) of the graphene RF NEMS capacitive switch used as loading element for DNTLs phase shifters.

DNTL Analog Phase Shifters

To assess the feasibility of a DNTL phase shifter using the presented graphene RF tunable capacitors, we perform microwave circuit analysis based on electromagnetic simulation of the CPW and the extracted lumped circuit model of the capacitor, as explained in the design section.

The results for the DNTL analog phase shifter are summarized in Fig. 5, showing the phase shift (normalized per cm and dB), the attenuation and the differential phase shift, respectively for each characterized bias voltage and corresponding switch capacitance value.

The DNTL analog phase shifter, actuated below the pull-in voltage V_{pi}, achieves a continuous and quasi-linear phase shift in the whole range of frequencies employed for the characterization of the tunable capacitor (0-6 GHz), with a maximum value of 220° at the design frequency (2.4 GHz) when actuated at the highest voltage level measured before actuation (7 V). The differential phase shift presents a peak of 30° at 2.4 GHz, but the high resistance of graphene deteriorates the differential phase shift linearity and attenuation (8.5 dB at 2.4 GHz).

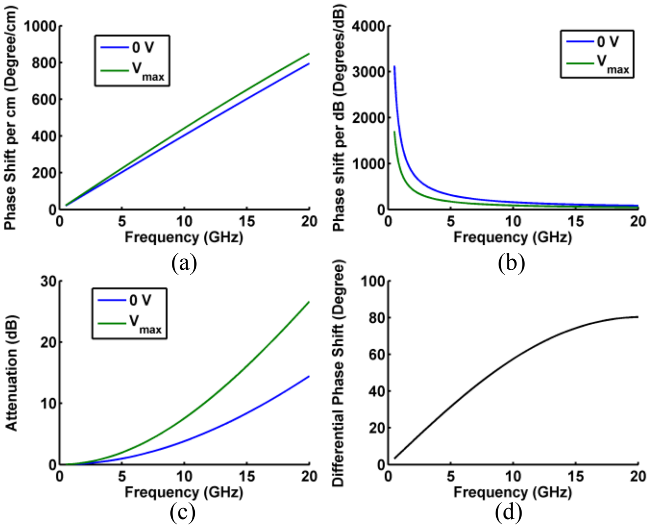


(a) (b) (c) (d)

Figure 5: Performance of the DNTL analog phase shifter assessed by calibrated simulations. (a) Phase shift per cm; (b) phase shift per dB; (c) attenuation; (d) differential phase shift.

To more accurately assess the potential of the graphene tunable capacitor for DNTL phase shifters in the presence of a feasible superior release process, we perform simulations using the graphene resistance measured before release, $R_\square=80\ \Omega/\square$, and a capacitance C_{UP}=100 fF in the UP state, calculated considering the theoretical gap and a parallel-plate capacitance model. For the actuation we consider the maximum value of capacitance obtainable in the analog tuning region, $C_{max} = 1.5 \cdot C_{UP}$.

The results of this analysis are summarized in Fig. 6, showing an improvement for all the figures of merit of the phase shifter, which exhibits an increase in phase shift per dB at 2.4 GHz from 25.5°/dB to 355°/dB and a linear differential phase shift over the entire frequency range.

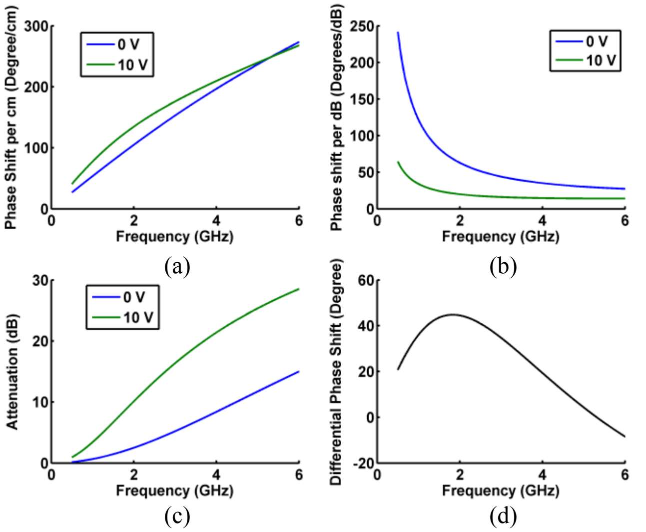


(a) (b) (c) (d)

Figure 6: Performance of the optimized DNTL analog phase shifter. (a) Phase shift per cm; (b) phase shift per dB; (c) attenuation; (d) differential phase shift.

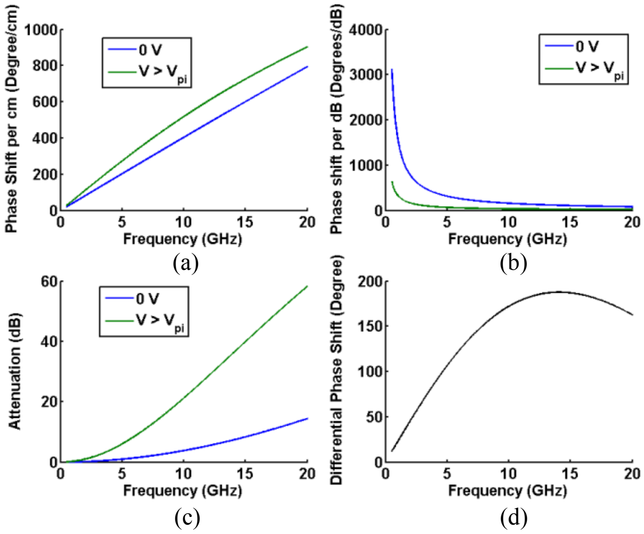
DNTL Digital Phase Shifters

The analysis of the performance of DNTL digital phase shifters using calibrated simulations and optimized parameters are shown, respectively, in Fig. 7 and 8. DNTL digital phase shifters allow increasing the differential phase shift, as a consequence of the higher capacitance ratio, at the expense of higher attenuation and no ability to continuously tune the phase shift. The DNTL digital phase shifter obtained using the parameters extracted from RF measurements presents a phase shift of 150° and a differential phase shift of 42° at 2.4 GHz and 12.7 dB attenuation. The performance is greatly improved for the phase shifter employing optimized capacitor parameters, which achieves a differential phase shift of 54° at 2.4 GHz with attenuation limited to 1.45 dB.



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

Figure 7: Performance of the DNTL digital phase shifter assessed by calibrated simulations.(a) Phase shift per cm; (b) phase shift per dB; (c) attenuation; (d) diff. phase shift.



(a) (b)

(c) (d)

Figure 8: Performance of the optimized DNTL digital phase shifter. (a) Phase shift per cm; (b) phase shift per dB; (c) attenuation; (d) differential phase shift.

Discussion

We summarize our results in Table 1. Digital DNTL phase shifters allow obtaining higher differential phase shift than analog DNTLs, at the expense of higher actuation voltage, power consumption and losses.

The performance-limiting factor for both the analog and digital DNTL phase shifters is the high resistance shown by the characterized suspended graphene membranes, which we attribute to imperfections caused by the release process, such as cracks and high residual stress.

In order to better assess the potential of graphene tunable capacitors for phase shifters applications, we repeated the analysis of the proposed devices by using graphene parameters achievable with an optimized release process. The obtained results ("opt" rows in Table I) show a dramatic improvement in performance due to the much lower attenuation caused by the graphene membrane resistance.

Table 1: Simulated phase shifters performance.

Phase Shifter Type		°/cm 2.4 GHz	°/dB 2.4 GHz	Attenuation (dB)	
				2.4 GHz	1-6 GHz
No bias	real	124	53.3	3.5	14
	opt	98	652	0.22	3.8
Analog tuning	real	145	25.5	8.5	24.9
	opt	108	355	0.45	2.8
Digital tuning	real	153	20	12.75	28
	opt	133	138	1.45	8.5

CONCLUSIONS

We have demonstrated analog and digital wideband compact phase shifters (10 mm^2) by employing graphene based RF NEMS tunable capacitors periodically loaded on a coplanar waveguide. The analog device has shown a differential phase shift of 30° at 2.4 GHz and the digital one a differential phase shift of 42° at 2.4 GHz. Repeating the analysis using improved graphene parameters achievable with an optimized membrane release process in which the sheet resistance preserves its value (80 Ω/□ before release), we have obtained a 14-fold improvement in phase shift per dB at 2.4 GHz for the analog DNTL and 6.9-fold for the digital DNTL. These results show that graphene-based RF NEMS are interesting candidates for RF phase shifters, providing additional features with respect to metal RF NEMS, if graphene release could be further controlled and optimized.

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