Ku Band DMTL Medium Power Phase Shifters

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***Abstract* — The first part of this paper deals with curled shunt capacitive MEMS switched varactors with good power handling capabilities. These devices have been able to achieve 1 billion cycles under 5 W in hot switching conditions. These cantilevers have been used as switched capacitors periodically loaded along a Coplanar Wave Guide (CPW) line to form a Distributed MEMS Transmission Line (DMTL) phase shifter. In the second part, the integration of these beams in 90° and 180° DMTL sections operating at 15 GHz is shown. For these respective configurations, phase shifts of 89.3° and 178° have been observed and validate this conception. With reasonable loss of 60°/dB, these devices are among the first MEMS based phase shifter in literature able to operate at such power level in hot switching conditions.**

***Index Terms* — Cantilevers, DMTL, MEMS, microwave phase shifters, power handling, switched capacitors.**

I. INTRODUCTION

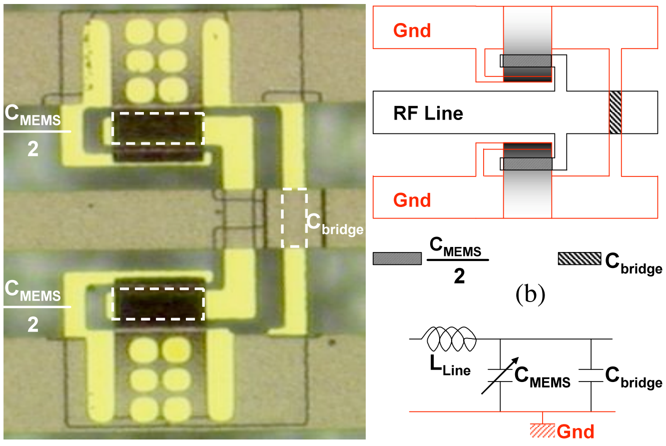
Micro electromechanical systems (MEMS) switching components are a way to reduce cost, size, power consumption and/or loss in semi passive devices compared to solid state equivalent [1]. However, most results published so far are showing good performances that can be reached at hundreds of mW or up to 1W at best [2]-[4] under hot switching conditions. Moreover, only cold switching conditions can guarantee no failure mechanism above 1W. In this case, RF signals have to be interrupted while reconfiguration. But many applications will require that signal is constantly maintained on MEMS device during its operation.

Good power handling and reliability are demonstrated here on curled switched shunt capacitive cantilevers. The design and measurements of DMTL phase shifters loaded with these beams are presented. Good agreement between theory and measured phase shifts is also demonstrated in the case of 90° and 180°.

II. DMTL MEMS STRUCTURE

A. Fabrication

One of the particularities of these cantilevers is their curled shape achieved by a 2 μm thick gold layer between 2 chromium layers, the lower one being 60 Å thick while the upper one is 90 Å. The thicknesses of these layers control the curve radius of the cantilever and this stressed shape have demonstrated good properties [5] and promising power handling behavior [6]. Two switched capacitors have been implemented in shunt configuration on a CPW line as shown on Fig. 1.



(a) (c)

Fig. 1. (a) Picture of a unit cell (b) schematic view of two cantilevers integrated in a CPW line and the additional air bridge (c) equivalent lumped element circuit of the loaded line

The structure is fabricated on fused silica substrate. Down electrodes are 150 nm thick evaporated gold layers and are entirely covered with 0.4 μm thick Al_2O_3 dielectric. The electrostatic actuation is done by applying 70 V between the RF line and beam anchors which are connected to ground. The vertical stress of the beam in up state position is large enough to create contrast. Pairs of cantilevers are followed by an additional shunt fixed capacitor of 20 fF, with the bottom metallization used to link ground planes, and suppress slot modes in the CPW line.

We can observe holes on each beam to reduce actuation voltage. A picture of a typical unit test cell for reflection type measurement and its dimensions are presented on Fig. 2.

The dielectric charging is mitigated by using an air gap that separates the upper capacitive electrode from the lower one in the down state position. Indeed, the air gap limits dielectric charging and electric charges are evacuated from the contact area to ground. However, this metal is only 150 nm thick, and this is explaining why the phase shifter loss are higher than state of the art RF-MEMS phase shifters. However, increasing this thickness will allow reducing loss.

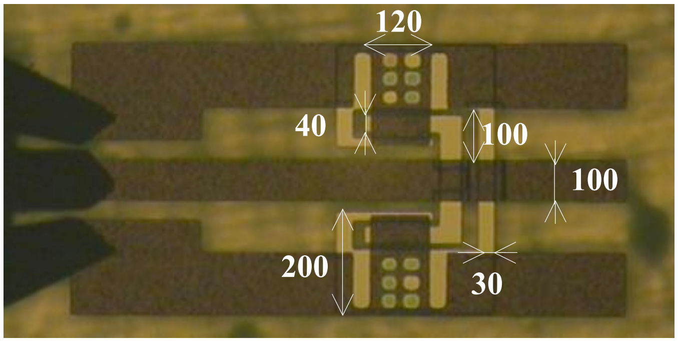


Fig. 2 Open circuited unit test cell and its dimensions in μm.

B. Reliability Measurements

The reliability of our cantilevers has been measured with a test bench similar to those presented in [7] and [8] and a schematic view is shown on Fig. 3.

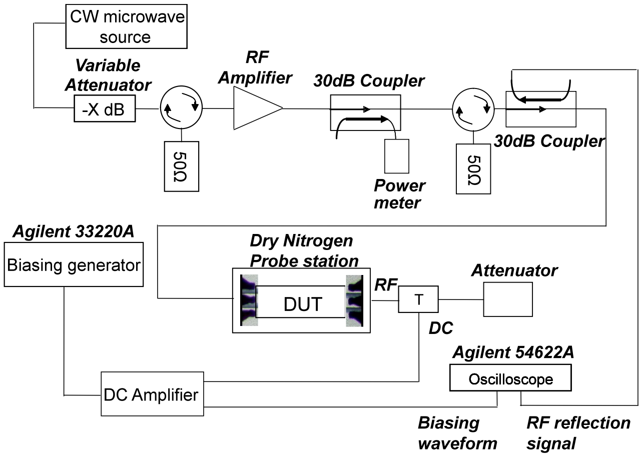


Fig. 3 Schematic of the RF MEMS power reliability test bench.

The purpose of this set up is to detect the response of a unit test cell in hot switching conditions with an applied 5 W RF signal at 10 GHz. A constant wave RF source delivers this signal via a RF Power Amplifier and an isolator is placed between them to prevent the source from any reflection. RF power level is tuned by a variable attenuator and displayed on a power meter via a 30 dB coupler. The device under test (DUT) is enclosed in a dry nitrogen probe station. MEMS is connected to another 30 dB coupler to detect its RF reflection response on an oscilloscope. Bias signal is applied on the second port of the device. Its waveform also appears on the Agilent 54622A for time synchronized display about bias/response signals.

The DMTL sections do not provide enough contrast between the up and down states to detect a sharp transition (since they are designed to be matched in both states) and only the up state/down state contrast is recorded. During our power reliability measurements, a square bipolar cycling bias signal is applied at the frequency of 20 KHz. This applied bias waveform is fully stored in the memory of an Agilent 33220A waveform generator and enables 3 seconds step data storing via Labview software [9]. Measurements on RF reflection response of MEMS structures are presented on Fig. 4 and demonstrate a significant up state/down state contrast up to 1 billion cycles when test was stopped.

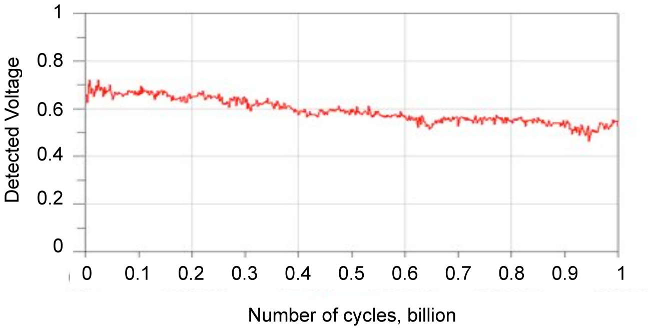


Fig. 4 Detected voltage on RF reflection unit test cell response in 5W hot switching conditions.

III. MEDIUM POWER DMTL PHASE SHIFTER

A. Design Principles

Designing a DMTL phase shifter [10]-[12] consists in placing periodically elementary phase shifting cells, like unit cells tested above, along a transmission line. Each one is equivalent to a switched capacitor modifying loaded impedance of the line and resulting a phase shift given by (1).

$$\Delta\phi = \frac{360 fsZ_0\sqrt{\varepsilon_{eff}}}{c}\left(\frac{1}{Z_{up}} - \frac{1}{Z_{dwn}}\right) \qquad (1)$$

$\Delta\phi$ is expressed as a function of:

- f the design frequency in Hz
- s the length of unit cell in m
- Z_0 characteristic impedance in Ω
- ε_{eff} the effective dielectric constant
- c light velocity in vacuum in m/s
- Z_{up} and Z_{dwn} loaded impedance in up and down state respectively in Ω

Maximum return losses (RLmax) can be tuned by choosing appropriate loaded impedances. The length between each unit cell is a critical parameter to determine Bragg frequency, above which there is no power transmitted from one port to the other. All the design parameters are presented in Table I. They have been chosen in order to reach well defined phase shifts: 0°, 90°, 180° and 270°. For example, 8 and 16 unit cells are 90° and 180° phase shifters respectively.

As we have seen on Fig. 1, there is an additional shunt fixed capacitor on each elementary phase shifting cell, equal to 20fF. By considering this and the design loaded capacitances, each cantilever has to be 22 fF and 77 fF switched capacitors respectively for up and down state positions.

TABLE I
DMTL DESIGN PARAMETERS

f	15 GHz
f_b	35 GHz
s	780 µm
Z_0	95 Ω
ε_{eff}	2.4
RLmax	-15 dB
Z_{up} / Z_{dwn}	59.9 Ω / 41.8 Ω
C_{up} / C_{dwn}	64 fF / 176 fF
$\Delta\phi$	11.25°

B. S Parameters Measurements

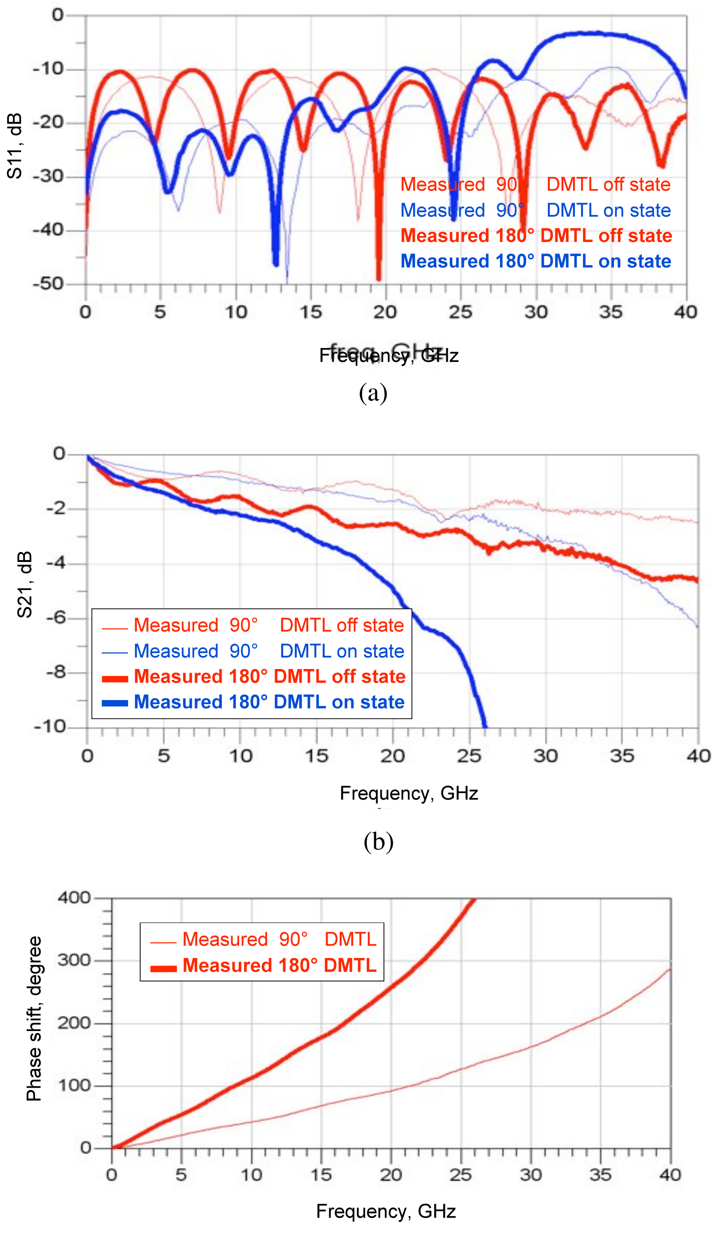
S parameters have been measured with a HP 8722 ES vector network analyzer. Results are presented on Fig. 6 for both 90° and 180° DMTL phase shifters with lengths that are 13 mm and 6.8 mm. Any return loss are greater than -10 dB up to 25 GHz. Insertion loss does not exceed 1.3 dB and 3.2 dB for 90° and 180° respectively which correspond to a figure of merit of about 60°/dB. Note that for 90° phase shifters, cantilevers are actuated with a unipolar 80 V bias voltage while 180° DMTL require 100 V.

Phase shifts observed on both configurations agree well with analytical computation since 89.3° and 178° have been reached, showing good design accuracy. Back simulations with Agilent ADS circuit software have been done to achieve capacitances given by our cantilevers and Table II summarizes up and down state equivalent capacitances for both DMTL phase shifters.

TABLE II
DMTL EQUIVALENT CAPACITANCES

Number of unit cells	C_{up} (fF)	C_{dwn} (fF)	Measured Phase Shift (degree)	Phase Shift Required(degree)
16	20	68	180	178
8	20	70	90	89.3

Equivalent capacitances in up and down state are quite similar to those discussed in design principles. These results validate the analytical design conception.



(a)

(b)

(c)

Fig. 6 Measured return loss (a), insertion loss (b) and phase shift (c) of 90° and 180° DMTL phase shifters.

C. Linearity Measurements

One interesting characteristic of the fabricated DMTL is their low sensitivity to Watt-range signals, and AM/PM measurements could be done up to 39 dBm on a 90° phase shifter at 10 GHz. A schematic view of the test bench is shown on Fig. 7.

The measurement setup is based on the use of a VNA in a receiver mode (4 sampling channels). An on-wafer conventional SOLT (Short-Open-Load-Thru) calibration procedure is performed before measurements. An absolute power calibration is also made by using a power meter. A power sensor is connected to the input of a reflectometer (coaxial reference plane) to get an error corrected value of the power at the DUT reference plane for an on-wafer probe contact. Reciprocity relationships [13] are used to determine power levels at the DUT reference planes. This is a lot more accurate than applying a de-embedding correction between reflectometer coaxial planes and the probe tip planes. The active component is a TWA (Traveling Wave Amplifier) and a step attenuator is used for power sweeping. The calibrated measurements provide the 4 absolutes power waves (a1, b1, a2 and b2) in the DUT reference plane.

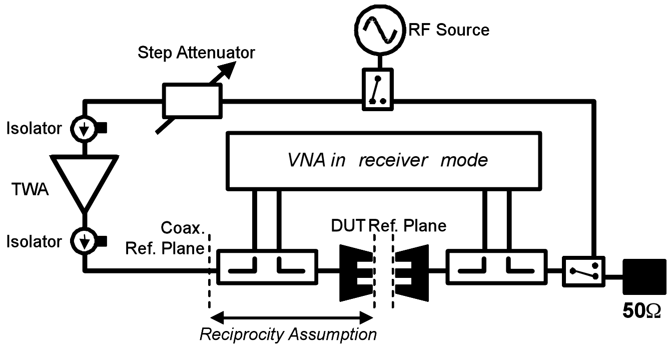


Fig. 7 AM/PM test bench of a 90° DMTL phase shifter at 10GHz.

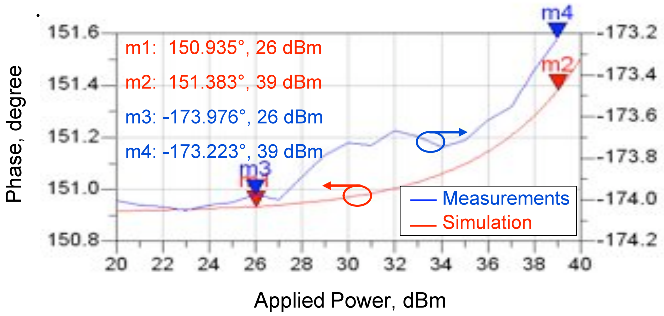


Fig. 8 Simulation and measurement results about phase variation of a 90° DMTL phase shifter at 10 GHz.

Good agreement between measurements and simulation is shown on Fig. 8. 1 dB step measurements have been done and no significant phase change has been observed until 26 dBm. Even up to 39 dBm, only 0.75° deviation is recorded which confirms ADS circuit simulations where 0.55° have been predicted.

IV. CONCLUSIONS

Most MEMS based phase shifters presented so far are limited to low power applications. Design of curl shaped cantilevers has been presented in this paper. Experimental results have demonstrated their high power reliability up to 5W. Their integration into a DMTL structure has been discussed and the analytical conception of these phase shifters has been validated by S parameters measurements. Finally, the extreme low phase sensitivity of our DMTL has been proved up to 8 W by AM/PM measurements.

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