Scale Changing Technique for MEMS-controlled phase-shifters

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***Abstract* — The original Scale Changing Technique is applied to the electromagnetic modeling of MEMS-controlled phase-shifters used in reconfigurable reflectarrays. The phase shift is derived from the simple cascade of networks, each network describing the electromagnetic coupling between two scale levels. This technique allows computing quasi-instantaneously the *1024* phase-shifts achieved by *10* RF-MEMS switches distributed on the surface of the phase-shifter. Moreover it takes into account the ohmic loss introduced by each RF-MEMS switches. Experimental data are given for validation purposes.**

***Index Terms* — Scale changing technique, RF-MEMS, phase-shifters.**

I. Introduction

MEMS-controlled phase-shifters may be used in reconfigurable Reflectarrays [1]. In this paper the planar phase-shifters are composed of 3 metallic patches and 10 RF-MEMS switches (Fig. 1). The phase variation is controlled by the up/down state of the RF-MEMS switches that allow several interesting discrete tunes of the slot length [2]. A specific electromagnetic simulation tool is required for a rapid and accurate prediction of the 2^{10} phase-shifts available from the 10 RF-MEMS switches. We propose here to apply the Scale Changing Technique [3,4]. This original and efficient technique allows the computation of the phase-shift variation provided by the MEMS-controlled phase-shifter from the simple cascade of networks, each network describing the electromagnetic coupling between two scale levels. In the computation of the reflection coefficient, the ohmic losses and up/down capacitances introduced by the 10 switches are taken into account. Experimental data are given for validation purposes.

II. Scale changing technique

Experimental characterizations of planar phase-shifters used in reflectarrays are generally carried out by placing the phase-shifters in the cross section of a metallic square waveguide and by considering a TE_{10} incident mode. In this Section, the scale changing technique is then applied for predicting the phase-shift introduced by the phase-shifter on the two propagating (TE_{10}-mode and TE_{01}-mode) in a metallic square waveguide.

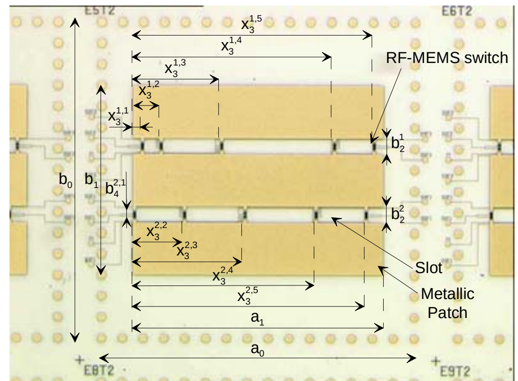

Fig. 1. Planar phase-shifter used in Ku-band MEMS-controlled reflectarrays manufactured on an alumina substrate (relative permittivity : 9.8; thickness : 254 µm).

As shown in figure 2, in the Scale Changing Technique, the equivalent network of the MEMS-controlled planar phase-shifter given in figure 1 is reduced to the cascade of 4 scale changing networks describing the electromagnetic coupling between two scale levels. The networks can be computed separately by assuming that:

- high order evanescent modes at a given scale level are shunted by their (pure imaginary) modal impedance;
- low order modes allow the accurate computation of the electromagnetic coupling between two scale levels.

The cascade of networks is shunted by 10 one-port networks, each modeling a RF-MEMS switch. These networks are classically modeled by a complex impedance Z_{switch} [5]:

$$Z_{switch} = R + \frac{1}{jC\omega} \quad (1)$$

where R and C denote the resistance and the capacitance of the RF-MEMS switch, respectively.

The impedance matrix [Z] of the two-port network modeling the electromagnetic coupling between the TE_{10}-mode (port 1) and the TE_{01}-mode (port 2) is then derived and the scattering matrix can be finally deduced :

$$[S] = ([z]-[I])([z]+[I])^{-1} \quad (2)$$

with [I] the identity matrix and

$$[z] = \begin{bmatrix} Z_{11}/Z_{TE_{10}} & Z_{12}/\sqrt{Z_{TE_{10}} Z_{TE_{01}}} \\ Z_{21}/\sqrt{Z_{TE_{10}} Z_{TE_{01}}} & Z_{22}/Z_{TE_{01}} \end{bmatrix} \quad (3)$$

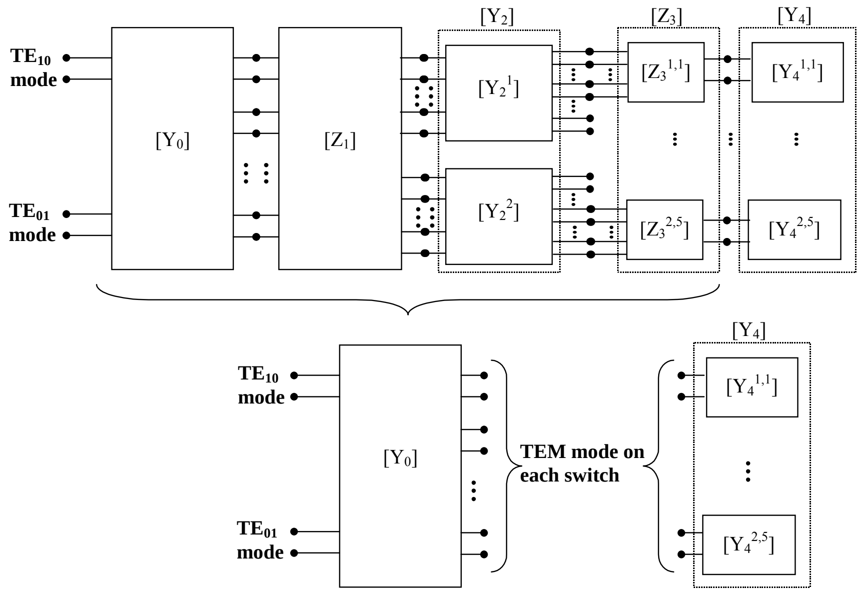

Fig. 2. Equivalent network of the phase-shifter as the cascade of scale changing networks

where the impedances Z_{TE10} and Z_{TE01} are equal and denote respectively the modal impedance of the TE_{10} and TE_{01} modes in the metallic square waveguide. Specifically, we derive from (2) the phase-shift $\Delta\phi = \text{Arg}(S_{11})$ introduced by the phase-shifter on the incident mode TE_{10}.

III. Results and discussion

In this Section, we adopted the following notations :

- the magnitude of the reflection coefficient S_{11} of the TE_{10}-mode is denoted by $|S_{co}|$, where the index "co" stands for "co-polarization";
- the magnitude of S_{21} describing the coupling between the TE_{10} and TE_{01} modes is denoted by $|S_{cross}|$, where the index "cross" stands for "cross-polarization";
- the ratio between the power dissipated by the phase-shifter and the power of the incident TE_{10}-mode is given by :

$$p = 1 - |S_{co}|^2 - |S_{cross}|^2 \quad (4)$$

For lossless RF-MEMS switches –i.e., R = 0 in (1)– numerical results obtained from the Scale Changing Technique are reported in figure 3 (the up state capacitance is 15fF and the down state capacitance is 1.5pF). Experimental data and simulation results obtained from the Finite Element Method are given for comparison. A good agreement is found with the measurements in this frequency range for four configurations of the 10 RF-MEMS switches. Moreover, the CPU time for the calculation of one phase-shift is 2,5 times less than that of the Finite Element Method with the proposed scale changing approach.

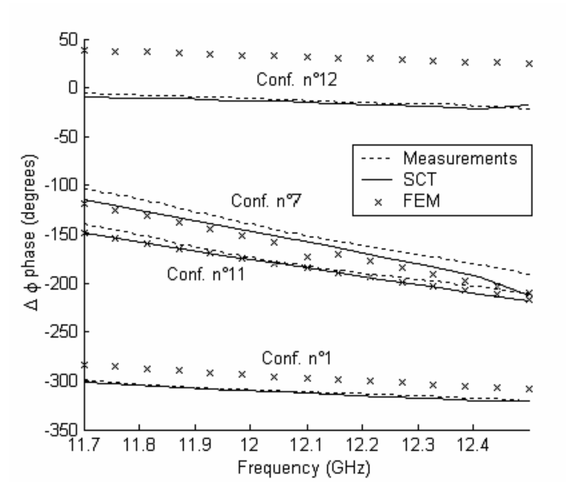

Fig. 3. Phase-shift versus frequency for four up/down RF-MEMS switches configurations.

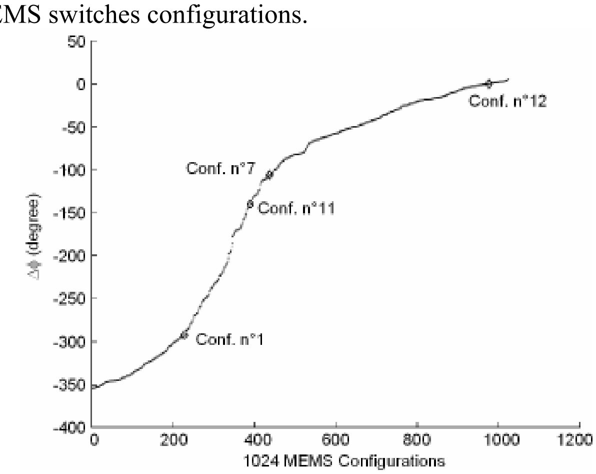

Fig. 4. The 1024 computed phase-shifts provided by the 10 RF-MEMS switches at 11.7GHz.

For some configurations of the up/down states of the RF-MEMS switches, the Scale Changing Technique allows the prediction of a non-zero electromagnetic coupling $|S_{cross}|$ between the two propagating modes (TE_{10} and TE_{01}) in the square metallic waveguide. As displayed in figure 5, we have $|S_{co}| < 1$ for these specific configurations of the RF-MEMS switches.

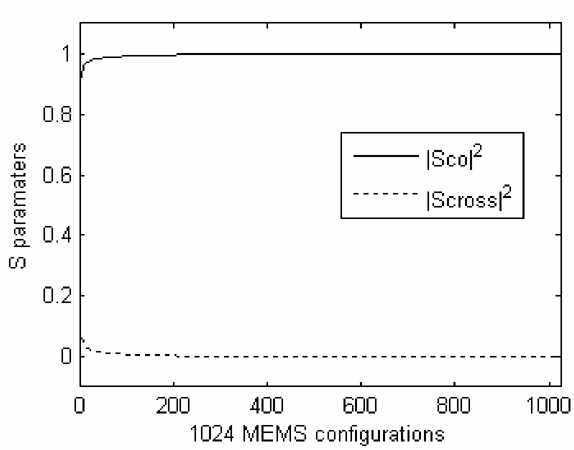

Fig. 5. $|S_{co}|^2$ and $|S_{cross}|^2$ for the 1024 available phase-shifts (numerical results) with C_{up}=15fF and C_{down}=1.5pF at 11.7GHz. (see text for the definitions of S_{co} and S_{cross})

The 1024 phase-shifts provided by the 10 RF-MEMS switches depend on the ratio C_{down}/C_{up}, where C_{down} and C_{up} are respectively the down- and up-state capacitances. For lossless RF-MEMS switches and C_{up}=15fF, the (computed) phase-shifts are displayed in figure 6 for the 1024 configurations. For ratio $C_{down}/C_{up} > 100$ we observe that the phase-shift for any configuration depends slightly on the ratio C_{down}/C_{up}.

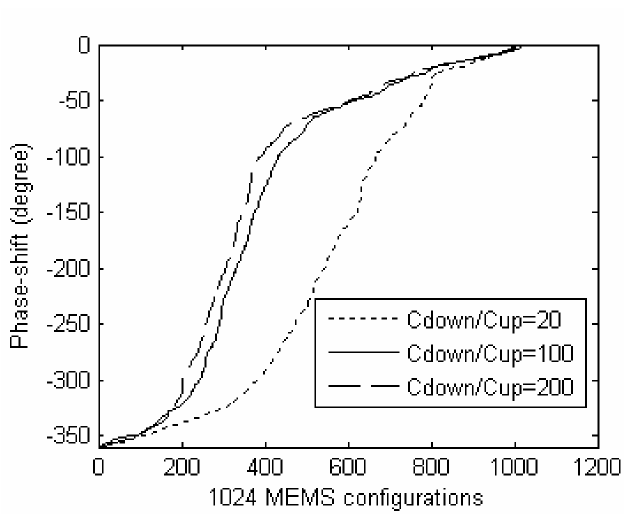

Fig. 6. Phase-shift for various C_{down}/C_{up} ratios at 11.7GHz.

Moreover, as expected the phase-shifts do not depend on the resistance R of lossy RF-MEMS switches. For some positions and up/down state of the lossy RF-MEMS switches, the electromagnetic power dissipation may be significant. Consequently, the magnitude of the reflection coefficient $|S_{co}|$ can be small. The dissipation can be evaluated at each MEMS port accurately. The Scale Changing Technique allows to predict efficiently this problematic loss of electromagnetic power.

IV. Conclusion

The original Scale Changing Technique has been applied for predicting efficiently the phase-shift provided by MEMS-controlled planar phase-shifters. A very good agreement has been observed between computational results and measurements. The approach has been applied to phase-shifters with lossy RF-MEMS switches.

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