Shunt capacitive switches based on VO₂ metal insulator transition for RF phase shifter applications

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Abstract—This paper presents a wide-band RF shunt capacitive switch reconfigurable by means of electrically triggered Vanadium Oxide (VO₂) phase transition to build a true-time delay (TTD) phase shifter. The concept of VO₂-based reconfigurable shunt switch has been explained and experimentally demonstrated by designing, fabricating and characterizing an 819 µm long unit cell. The effect of bias voltage on losses and phase shift has been studied and explained. By triggering the VO₂ switch insulator to metal transition (IMT) the total capacitance can be reconfigured from the series of two metal-insulator-metal (MIM) capacitors to a single MIM capacitor. Higher bias voltages are more effective in this reconfiguration and give a higher phase shift. The optimal achievable performance has been shown heating the devices above VO₂ IMT temperature. A maximum of 16° per dB loss has been obtained near the design frequency (10 GHz).

Keywords—vanadium dioxide; phase transition; RF switch; true-time delay; phase shifter; tunable capacitor;

I. INTRODUCTION

Phase shifters are key components for beam-steering implementations, smart adaptive antennas and scanning applications for wideband communications and remote sensing systems. RF distributed MEMS transmission lines (DMTL) have been proven to be an interesting concept to achieve a high phase shift over a wider frequency band compared to traditional solid-state implementations (PIN diodes, GaAs FET, Ferrite materials). Nevertheless, critical issues of MEMS technology, such as reliability, process variability and packaging requirements are still a limiting factor for a widespread implementation.

Strongly correlated functional oxides exhibiting metal to insulator transition have recently emerged in research as promising materials for a large number of applications, including steep transistors [1], RF switches [2,3], reconfigurable filters [4,5] and antennas [6,7]. Vanadium Oxide (VO₂) has proven to be one of the most interesting among these materials thanks to its large change in conductivity between its two states and the possibility of achieving the phase transition by electrical excitation [8].

Compared to MEMS switches, VO₂ switches offer clear advantages such as an easier integration in microelectronic technological processes, smaller footprint and a three order of magnitude faster switching time [9]. A switched line phase shifter with thermally actuated VO₂ switches has been previously demonstrated in microstrip technology [10].

In this paper we present for the first time a shunt capacitive switch reconfigurable by means of electrically triggered VO₂ phase transition to build true-time delay phase shifters by periodically loading a coplanar waveguide (CPW) with the capacitive switches (Fig. 1). We present the concept of the device and we validate it by fabricating, designing and characterizing an 819 µm long unit, able to provide up to 16° phase shift per dB loss at 10 GHz.

Fig. 1. Optical image of the CPW phase shifter showing the cascaded VO₂-based capacitive shunt switches designed to achieve 3-bits phase states.

II. RECONFIGURABLE CAPACITIVE SHUNT SWITCH

The reconfigurable capacitive shunt switch consists of two fixed MIM capacitors in series, C₅ and C₆, where the first can be short-circuited by actuating a VO₂ two-terminal switch (Fig. 2). Below the phase-transition temperature and when no bias is applied, the VO₂ is in its insulating state so that the switch exhibits a high resistance level and can be considered open. The two capacitors are then electrically in series, offering an equivalent capacitance C_TO\,\text{TOT} = C₅ \ast C₆ / (C₅ + C₆). Whenever a bias larger than the switch actuation voltage is applied, the VO₂ film phase changes to its conductive state and the switch exhibits a low resistance value. In this case the C₅ capacitor is short-circuited by the switch and the equivalent capacitance between the signal and the ground line will be simply C₆. In this way the VO₂ switch allows to reconfigure the loading capacitance between C₆ and C_TO\,\text{TOT}.
The VO₂ switch can be electrically actuated by means of a bias line decoupled from the RF signal by means of a serpentine resistor realized with a 25 nm-thick Chromium (Cr) film. The switch resistance is in the high state until a critical power is achieved which causes a steep insulator to metal transition (Fig. 3). In order not to affect the RF performance, the length and width of the switch are chosen to be 1 μm and 30 μm respectively, so to obtain a high value of resistance in the off-state (> 1 kΩ) and low value of resistance in the on-state (~1 Ω), while keeping a reasonably low actuation voltage.

The phase shifter was fabricated using standard microelectronics processes starting with a high-resistivity 525 μm thick silicon substrate passivated with 500 nm LPCVD-deposited SiO₂ (Fig. 4). The VO₂ film was prepared by reactive magnetron sputtering deposition starting from a Vanadium target [11]. After the deposition, a resistivity ratio higher than 3 decades was measured with a Van der Pauw measure performed at different temperatures (Fig. 5). The film was then patterned using photolithography and wet etching. The bias resistors were realized by lift-off of a 25 nm thick Cr film. A 200 nm thick Al film was subsequently deposited and patterned with lift-off to act as bottom metal. A 300 nm thick SiO₂ film was sputtered as insulating layer and as a dielectric for MIM capacitors. Vias were opened by photolithography and dry etching. A final 800 nm thick Al top metal layer was deposited to create the CPW and the contacts on the bottom metal bias lines.
III. UNIT CELL PERFORMANCE

The CPW was designed with a signal width of 100 μm and a ground plane spacing of 150 μm to obtain an unloaded waveguide impedance of 65 Ω. The design of the unit cell for the phase shifter was done following the method described in [12] in order to maximize the phase shift for the minimum insertion loss (IL). Starting from the chosen values of impedances in the ON and OFF state, respectively $Z_{ON} = 42$ Ω and $Z_{OFF} = 58$ Ω, and having chosen the Bragg frequency to be three times the frequency of design for the phase shifter, for a design frequency of 10 GHz the unit cell length was calculated to be 819 μm. The computed capacitances were $C_{ON} = 143$ fF and $C_{OFF} = 26$ fF resulting in a capacitance ratio of 5.5. Thus the MIM capacitances for the reconfigurable capacitive shunt switch are calculated as $C_S = 31.7$ fF and $C_G = 143$ fF.

The device was characterized by using an Anritsu VectorStar MS4647B Vector Network Analyser to measure S-parameters, a HP 4155B Semiconductor Parameter Analyser to provide the bias to operate the VO2 switches and a Cascade Summit prober with a thermo-chuck to control the substrate temperature.

![Fig. 6](image link)

Fig. 6. (a) Insertion Loss and (b) Return Loss of the measured unit cell at 20 °C and 100 °C. Circles correspond to ANSYS HFSS simulations. The simulations have been performed using the VO2 resistivity measured at 20 °C for the OFF state and 100 °C for the ON state.

![Fig. 7](image link)

Fig. 7. Insertion loss (continuous lines) and no-reflection losses (dotted lines) versus frequency, measured at 20 °C substrate temperature for 0 V, 20 V, 30 V and 40 V bias voltage and at 100 °C with no applied bias.

![Fig. 8](image link)

Fig. 8. (a) Phase shift and (b) phase shift per dB loss extracted from S-parameter measurements at 20 °C for 0 V, 20 V, 30 V and 40 V bias voltage at and at 100 °C with no applied bias.

The devices were measured for different bias values above the actuation voltage of the VO2 switches (Fig. 7). While the insertion loss seems to increase by increasing the bias, the loss at the design frequency is improved when the switch is at its lowest possible resistance value, obtained measuring at 100 °C. This behavior can be explained looking at the losses not due to reflection. While in the OFF state the insertion losses and no-reflection losses are almost coincident, indicating a good match, in the ON state the behavior varies depending on the bias. At 20 V the IL and total losses are similar, while at 30 V and 40 V a considerable part of the IL is due to the mismatch. At 100 °C the IL are lower than at the considered bias points and the no-reflection losses are minimized, showing better accordance with the FEM simulations.

The measured phase shift with respect to the OFF state increases with the applied bias but tends to saturate around 5 GHz for 40 V bias, while at 100 °C it is linear over the considered frequency band (Fig. 8). The phase shift per dB loss shows as well that the best trade-off is obtained for higher bias and indicates that best performances are obtained at 100 °C, where a maximum of 16° per dB loss is obtained slightly below the design frequency.

The limited performance of the device when electrically actuated suggests that for the used bias voltages, the conduction channel in the VO2 switch does not extend to the entire film width [13] and its resistance is still not low enough to grant a full capacitance reconfiguration and to prevent significant RF losses. We can assume that by applying a larger bias voltage and thus by injecting a larger current the performances will converge to the one measured at 100 °C.
The equivalent impedance of the loaded line was calculated using the method proposed in [14] and is shown in Fig. 9. In the OFF state the equivalent impedance is about 55 Ω at 10 GHz, not far from the simulated value of 56 Ω. In the ON state at 100 °C the measured impedance is lower than the simulated one, in accordance with the larger measured phase shift and larger insertion loss due to reflection.

IV. PHASE SHIFTER

In order to predict the performance of a phase shifter, the measured S-parameters in OFF and ON states (20 and 100 °C temperature) of the unit cell were mathematically cascaded to consider the presence of more stages in series. The predicted performance of a 6-stages phase shifter targeting 120° shift at 10 GHz is shown in Fig. 10. In order to actuate the different stages it is possible to use multiple bit lines that actuate group of switches to achieve the desired phase shift.

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