A reconfigurable inductor based on Vanadium Dioxide insulator to metal transition

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***Abstract*— This letter introduces a reconfigurable planar square-coil-shaped inductor exploiting as the tuning mechanism the insulator-to-metal transition (IMT) of a Vanadium Dioxide (VO_2) switch placed in the inter-winding space in an unprecedented manner. The VO_2 thin film bar-shaped switch is electrically connected to provide a temperature-selective current path that effectively short-circuits a part of the inductor coil changing the inductance of the device. The inductor is fabricated on a high-resistivity Silicon substrate (HR-Si) using a CMOS compatible 2D planar low-cost technology (4 photolithography steps). The design, optimized to work in the 4 to 10 GHz range, provides measured inductances at 5 GHz of 2.1 nH at 20 °C and 1.35 nH at 100 °C with good stability in the entire frequency band (4-10 GHz) resulting in a reconfiguration ratio of 55 %. The quality factor (Q-factor) at 7 GHz is about 8 at 20 °C (OFF-state) and 3 at 100 °C (ON-state), outperforming tunable inductors employing VO_2 with 2 orders of magnitude higher Q-factor and a smaller footprint. This represents an advancement for the state-of-the-art of 2D CMOS compatible inductors in the considered frequency range.**

***Index Terms*—Inductors, Reconfigurable inductors, C-band, K-band, thin films, Vanadium Dioxide**

I. Introduction

Reconfigurable inductors have been used along with variable capacitors to tune the frequency bands in many RF circuits such as: Voltage-controlled oscillators (VCOs), tunable LNAs, matching networks, phase shifters and filters as well as in wireless sensors and actuators [1]. The development of tunable inductors currently involves techniques relying on MOSFETs or MEMS relay switches, which require large device area and high manufacturing costs.

In order to overcome the issues, we propose in this letter to use Vanadium Dioxide (VO_2) as a tuning element in reconfigurable inductors exploiting its IMT transition: VO_2 undergoes an electronic and structural phase transition from an insulator with monoclinic crystalline structure to a metallic rutile phase when heated above 68 °C. This phenomenon has been used lately in various microwave components such as switches [2], [3], transmission lines [4], attenuators [5], phase shifters [6], bandstop filters [7] and for the first time as a reconfigurable inductor [8]. However the inductor in [6], made with two coils switched with a 170 µm × 20 µm VO_2 bar, exhibits extremely low quality factors, below 0.12 in all states up to 2 GHz, if computed with the given equivalent circuits.

In this letter, an original and more compact design with limited losses and improved performance is proven for higher and more stable inductance values (1.35-2.1 nH) in a larger frequency band (4-10 GHz). A 50 µm × 2 µm VO_2 switch is implemented directly, for the first time, in the inter-winding space of a single inductor and used as tuning mechanism. The fabrication consists of a CMOS compatible process on HR-Si. The tuning is achieved by thermal actuation of the VO_2 film above the IMT temperature (68 °C) causing the conductivity to increase of about three orders of magnitude. The measured results are in excellent agreement with simulations and results in a reconfiguration ratio (defined as in [1]) of 55 %. The Q-factor has a maximum of 10.8 at 20 °C (limited by the 2D planar HR-Si technology) and of 3 at 100 °C. The achieved RF performance are on the state-of-the-art comparing other inductors technologies [1] with a much easier fabrication process in a compact design, while exhibiting similar inductance values. Enhancement of the Q-factor is potentially reachable by applying our design methodology to other lower RF losses substrates or technologies [1, 7-8]. A similar phase-change tuning mechanism with comparable performances has also been employed using $Ge_xSb_yTe_z$ [11].

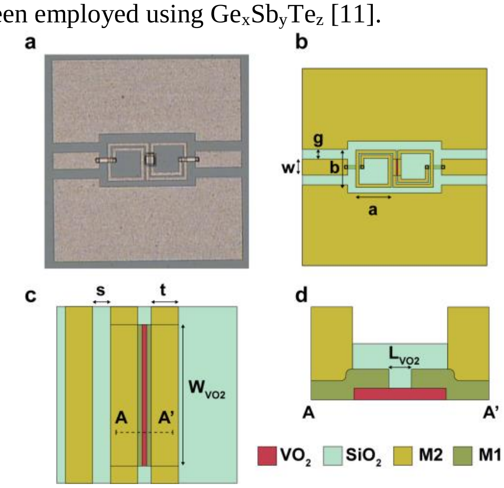

Fig. 1. (a) Optical image of the fabricated VO_2 tunable inductor. (b) Schematic with indicated inductor dimensions a=220 µm, b=230 µm and waveguide dimensions w=100 µm, g=60 µm. (c) Detail of the VO_2 switch in the inter-windings with indicated coil size t=20 µm and spacing s=10 µm. (d) Cross-section along the AA' segment.

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II. DESIGN AND FABRICATION

The inductor was fabricated in a squared double spiral shape as depicted in Fig. 1. In order to tune the inductance a VO_2 switch was inserted in the inter-winding space of the coil structure as depicted in Fig. 1.c. The layout of the inductor was chosen to minimize geometric asymmetry while achieving a maximum optimized tuning range between the two considered states. The final dimensions and switch position are obtained targeting a higher tuned inductance value of 2.1 nH and a reconfiguration ratio of 55 %, providing an inductance of 1.35 nH when the switch is activated and placed as in Fig.1.a, while obtaining Q-factor with peaking values over 8 at 7 GHz in the nonconductive state of the switch.

We call OFF-state the low conductivity regime where the switch can be electrically considered as an open circuit, and ON-state the high conductivity one where the switch can be considered as a short-circuit. When the VO_2 is in its insulating state, the switch does not contribute to the inductor performance, while when it is in the conductive state a part of the coil is shorted and the inductance value is lowered. To minimize the losses due to the limited conductance of the VO_2 switch, a short and wide switch was designed with length L_{VO2} = 2 µm and width W_{VO2} = 50 µm.

The inductors were fabricated using standard microelectronics processes starting with a high-resistivity (10 kΩ·cm) 525 µm thick Si substrate (Fig. 2) to ensure low RF losses. A 300 nm thick amorphous Si layer was deposited to improve radiofrequency performances [12]. The substrate was then passivated with 500 nm SiO_2 deposited by sputtering. The VO_2 film was prepared by pulsed laser deposition starting from a V_2O_5 target with a Solmates SMP 800 system. Deposition was done at 400 °C and was followed by a 10 minutes long post-deposition annealing at 475 °C. To evaluate film quality, Van der Pauw structures were fabricated together with the inductor to measure the variation of conductivity with temperature (Fig. 3): a conductivity ratio between insulating and conducting phase higher than 3 orders of magnitude was observed with a maximum of around 23000 S/m at 100 °C. After the deposition, the film was patterned using photolithography and wet etching. 20 nm of Titanium and 800 nm of Aluminum film were subsequently deposited with e-beam evaporation and patterned with lift-off to act as contact to the VO_2 film and to create the bottom part of the inductor coil. A 300 nm thick SiO_2 film was then sputtered. Vias were opened by photolithography and dry etching of SiO_2 to contact the bottom metal and a final 2 µm thick Aluminum top metal layer was deposited and patterned to create the CPW and the top part of the coil.

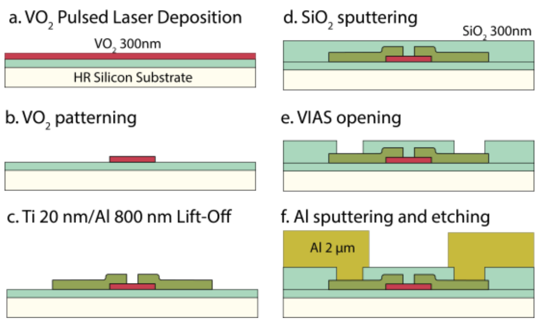

Fig. 2. Fabrication process of the vanadium oxide tunable inductor.

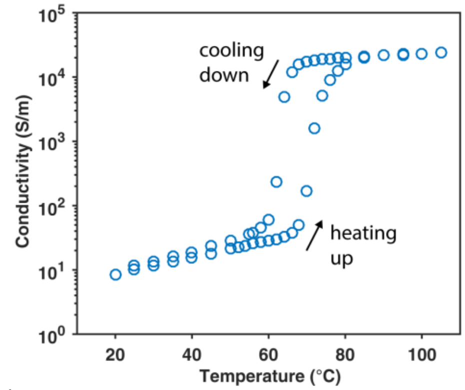

Fig. 3. (a) Dependence of conductivity on temperature for the deposited VO_2 film.

III. SIMULATION AND MEASUREMENT RESULTS

Inductance values were calculated with Eq. (1) to evaluate the design overall performance, considering, as in [8], the inductor as an ideal series element. Although the Q-factor can be evaluated in many ways [10-11], we used Eq. (2), as in [1, 6-8], in order to make a coherent comparison. Y_{21} and Y_{11} denote the two port admittance parameters while f stands for the frequency.

$$L = -\frac{Im(\frac{1}{Y_{21}})}{2\pi f} \quad (1)$$

$$Q = -\frac{Im(Y_{11})}{Re(Y_{11})} \quad (2)$$

Fig. 4 shows the simulated surface current density in the structure for the two states. In OFF-state (conductivity = 10 S/m) the presence of the VO_2 switch has almost no influence and the current flows along the coil, whilst for higher conductivity (30000 S/m) the current changes its path going mostly through the VO_2 switch effectively shortcutting part of the coil. It has to be pointed out that for the OFF-state simulations (with Ansys HFSS) the relative dielectric permittivity ε_r of the VO_2 switch was considered either frequency dependent as in [4] (with values ranging from 80-400) or fixed to 30 as in [5]. In both cases the results were unaffected due to the geometry of the designed inductor.

Conductivity value of the switch in the ON-state on the other hand greatly influences the inductance reconfigurability. Fig. 5 presents the equivalent inductance of the structure for different value of conductivities. When the VO_2 film conductivity increases from 10 S/m to 10^4 S/m, the inductance is reconfigured to lower value, although not in a stable manner for the lower frequency range, while with conductivities higher than 10^4 S/m the inductance tends to be stable in a larger frequency range.

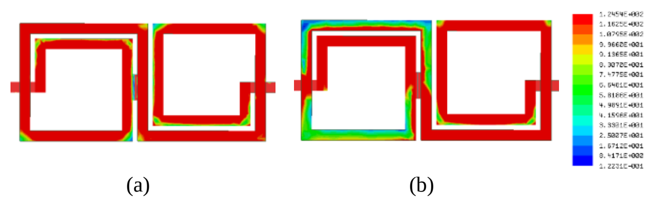

Fig. 4. Simulated current distribution at 5 GHz with Ansys HFSS assuming a conductivity of the VO_2 film of respectively 10 S/m (a) and 23000 S/m (b).

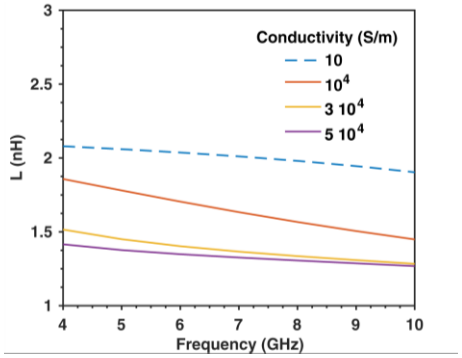

Fig. 5. Extracted inductance value for the structure simulated with Ansys HFSS for different values of the VO_2 film conductivity and dimensions L_{VO2} = 2 µm, W_{VO2} =50 µm and a VO_2 thickness of 300 nm.

The fabricated inductor was characterized by performing on-wafer *S*-parameter measurements with an Anritsu MS4647B Vector Network Analyzer calibrated with SOLT method in a Cascade Summit™ prober with controllable chuck temperature. The extracted inductance values of the fabricated inductor at 20 °C and 100 °C are reported in Fig. 6 together with ANSYS HFSS simulations that perfectly fits for the conductivity value from both states (10 S/m and 23000 S/m). The inductance value shows very stable results in both states with a relative change of less than 10 % in the 5 GHz to 10 GHz range.

The extracted value of *Q* at 7 GHz is about 8 at 20 °C and of 3 at 100 °C as depicted in Fig. 7. These values are limited by the Si substrate in the OFF/ON-state, by the lossy dielectric behavior of the VO_2 in the OFF-state and by the conductivity in ON-state.

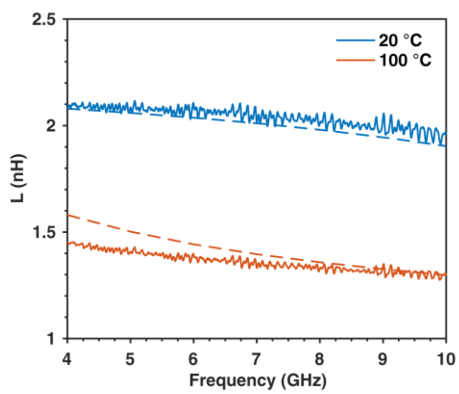

Fig. 6. Extracted inductance value for the measured results at 20 °C and 100 °C (continuous line) and for the simulations (dashed line). With a conductivity value of 10 S/m for 20°°C and 23000 S/m for 100°°C.

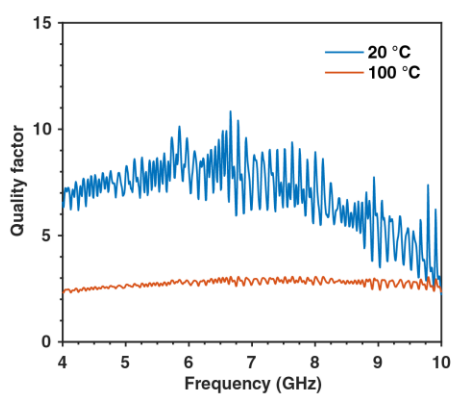

Fig. 7. Extracted quality factor value for the measured results at 20 °C and 100 °C (continuous line).

IV. Conclusion

We have presented a novel concept of reconfigurable inductor where a VO_2 bar positioned in the inter-winding space is used as a switch to reconfigure the current path in the coil thanks to the thermally triggered IMT of VO_2 while keeping a compact design. The impact of ON-state conductivity and switch geometry has been presented and discussed. The concept has been validated by fabricating with a CMOS compatible process an inductor whose inductance can be reconfigured from 2.1 nH to 1.35 nH at 5 GHz and shows a good stability in the 4 GHz to 10 GHz range. The inductor performances in terms of Q-factor, reconfiguration ratio, working bandwidth and layout compactness are beyond state-of-the-art of reconfigurable 2D-planar CMOS-compatible technologies [1] and outperforms the one resulted from a similar technology and comparable inductance values [8]. The presented reconfigurable VO_2-based inductor design offers a simple and cheap process with much faster reconfiguration time if compared to MEMS solutions. Enhancement of quality factor is possible and the technology is transferable to other substrates with better RF performance.

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