A Fully Printed Switch Based on VO₂ Ink for Reconfigurable RF Components

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Abstract — Recently, vanadium dioxide (VO₂) has emerged as an attractive phase change material which can be used for reconfigurable or switchable RF components. However, at present, VO₂ is deposited by expensive and complex thin film micro-fabrication techniques. With the surge in low cost, additively manufactured or printed components, it will be beneficial to print phase change materials or switches as well. The issue is there are no such functional inks available in the market. In this work, we present, for the first time VO₂ based ink that changes its conductive properties based on temperature. Precisely, it displays insulating properties at room temperature (resistance of $\sim 5\text{K}\Omega$ in the off-state), but becomes conductive when heated around 70°C (resistance of $\sim 10\Omega$ in the on-state). Based on this VO₂ ink and a custom silver-organo-complex (SOC) ink, we demonstrate a fully printed thermally controlled RF switch in this work. In a CPW based shunt configuration, the fully printed switch provides more than 15 dBs of isolation (in the off state) and a 0.5-2 dB of insertion loss (in the on state) from 100 MHz to 30 GHz frequency band. To demonstrate its application, a fully printed frequency reconfigurable planar inverted F antenna (PIFA) has also been demonstrated in this work.

Index Terms — Vanadium dioxide, printing, RF switches, CPW line, phase change, reconfigurability.

I. INTRODUCTION

Tunable or reconfigurable components are becoming increasingly important due to proliferation of multi-band and multi-functional wireless devices. Several kind of tuning and switching mechanisms are being explored such as P-I-N diodes, transistor based switches, micro-electro-mechanical systems (MEMS) switches, varactors, ferrite and ferro electric based devices [1-3]. Each one of these technologies has its own sets of advantages and disadvantages, however, one issue is common in all of them, i.e., all of them are based on complex subtractive photolithographic processes which are not only expensive and time consuming but also result in a lot of material wastage.

With the surge in additive manufacturing (inkjet, screen and 3D printing), which is extremely low cost, completely digital and highly suitable for rapid prototyping or large scale manufacturing [4-9], it will be beneficial if switches can also be realized through additive manufacturing. However, there are no functional inks available in the market which can become a base material for printing switches. Development of functional inks, which can tune their electrical, material or

optical properties with external stimuli such as temperature, light, applied field or voltage, could be a game changer for low cost printable switchable and reconfigurable devices. Recently, phase-change materials such as chalcogenides and vanadium dioxide provide an interesting alternative as they can tune their electrical properties with temperature or incident light [10-11]. Among them, vanadium dioxide (VO₂) has emerged as an attractive material which exhibits thermal tuning from insulator to conductor transition (ICT) in a reversible fashion [12-13]. This makes vanadium dioxide a promising material for high speed switching and reconfigurable devices. Recently, vanadium dioxide has been used to demonstrate various RF devices such as reconfigurable antennas, and MEMS actuators [12, 14-15]. In all these fabrication process, vanadium dioxide is deposited by the pulsed laser deposition (PLD) technique in an ultra-high vacuum pressure (8×10^{-6} Torr) and high temperature ($> 550^\circ\text{C}$) environment. Thus, it makes the fabrication quite complex and expensive and it will be neat if the same fabrication can be done through printing.

In this work, we present a novel VO₂ nanoparticles based ink which can be thermally tuned for its electrical properties. DC characterization of the ink reveals insulating properties at room temperature (resistance of $\sim 5\text{K}\Omega$ in the off-state), and conductive properties when heated around 70°C (resistance of $\sim 10\Omega$ in the on-state). Based on this VO₂ ink and a custom silver-organo-complex (SOC) ink, we demonstrate a fully printed thermally controlled RF switch in this work. In a coplanar waveguide (CPW) based shunt configuration, the fully printed switch provides more than 15 dBs of isolation (in the off state) and a 0.5-2 dB of insertion loss (in the on state) from 100 MHz to 30 GHz frequency band. In order to show the utility of the printed switch, it has been utilized in a frequency reconfigurable PIFA antenna which is capable of switching its frequency from 2.4 GHz to 3.5 GHz through thermal activation of the printed switch. The performance of this extremely low cost switch is encouraging and thus can be used for a number of tunable and reconfigurable applications.

II. MATERIALS AND SWITCH CONFIGURATION

VO₂ is prepared in the form of nanoparticles by a simple solution process. Typically, VO₂ material has many crystalline structure phases, however, the preferable phase is monoclinic

Fig.1. A schematic depiction of the fabrication process

VO₂ (M) which has the ability to show low temperature (at 68 °C) phase transition [13-14]. To obtain the VO₂ (M) phase, as-prepared nanoparticles were optimized with annealing condition such as 200 °C for 1h in vacuum. The vanadium dioxide ink has been prepared by mixing the 10 wt% VO₂ nanoparticles in 3.5 ml 2-methoxy ethanol, 0.3 ml chlorobenzene and 0.2 ml ethanol. The resultant mixture is stirred for 12 h before printing.

The SOC metallic ink is prepared according to reported literature [16]. The particle-free SOC ink is preferred over nanoparticles based ink due to its long-term storage and excellent jetting stability without any clogging issue. As shown in Fig. 1, the stack-up consists of printing SOC ink on glass substrate (which is an arbitrary choice and it can be replaced with any other substrate). In this particular case, a CPW line is printed through SOC ink. VO₂ is printed on top of the silver ink (covering the signal and ground traces) to form a shunt switch configuration.

III. PRINTING PROCESS

As a first step, a glass substrate with thickness of 1 mm is taken which is pre-cleaned with water, ethanol and IPA before printing CPW lines. The metallic 50 Ω CPW transmission line is inkjet-printed on glass substrate using SOC based ink with precise line to line gap. A total of 12 layers of SOC ink with drop-spacing of 30 μm are printed and cured using infrared heating. The devices were designed to interface with 3-terminal, ground-signal-ground (GSG) microwave probes and are arranged in a 2-port series configuration (shown in Fig. 2). The VO₂ ink is printed with the area of 0.5×1 mm in a digital fashion in between the CPW line and ground plane, as shown in Fig. 2(b). To control the spreading of the VO₂ ink on the surface of CPW line, the printing is performed with platen temperature of 60 °C. A total of 20 layers of VO₂ ink using

DS=20 μm are printed. The final fabricated module is heated at 200°C for 1h in vacuum to attain the desired film quality.

We have fabricated two prototypes as shown in Fig. 2. First prototype is only a CPW line which acts as a reference structure (Fig. 2 (a)) and CPW line with printed VO₂ that acts as a switch (Fig. 2 (b)). The signal line in the CPW has a length of 2 mm, width of 340 μm and the gap between signal and ground is 73 μm. Through careful control in printing parameters, fine and uniform gaps have been achieved, as shown in Fig. 2 (c).

Fig. 2. Printed (a) reference CPW line (b) with VO₂ film and (c) zoomed view of CPW line

IV. DC CHARACTERIZATION OF VO₂ PRINTED FILM

For the Dc characterization, current-voltage (I-V) measurements have been performed to extract the resistance of the inkjet-printed VO₂ film (L=74±1 μm and W=500 μm) during ICT by varying the temperature on a thermal chuck, as shown in Fig 2(b). I-V measurements have been performed using a Keysight B2912A precision source meter on a hot chuck probe station capable of temperature control from 5-200 °C. The resistance is extracted by taking the inverse slope of I-V measurements in the linear low voltage regime where the voltage is swept between ± 1 V. In order to test the electrical tuning capability, the temperature of hot-chuck is varied from room-temperature to 100 °C. At room temperature, the resistance is around 5KΩ, which almost shows an insulating behavior. As the temperature is increased to 50 °C, a slight change in the resistance is observed. At 65 °C, the resistance of the printed VO₂ film starts to decrease swiftly, as shown in Fig. 3. Increasing the temperature beyond this point further reduces the resistance. At temperatures from 70 to 100 °C, the resistance becomes constant at a value around 10Ω. When the temperature is reversed from high temperature to low temperature (cooling stage), the resistance recovers its initial value. The resistance changes by three orders of magnitude from room temperature to the conducting phase, with the phase transition occurring at ~70 °C during heating cycle and 65 °C during the cooling cycle. From this characterization, it

can be deduced that the printed VO₂ film has similar conductor-insulator transition characteristics as reported before [13-15]. Two mechanisms are believed to be

Fig. 3. Measured DC resistance of printed VO₂ film

responsible for the phase transition: i) Peierls mechanisms that is based on electron-phonon interactions and ii) Mott-Hubard transition which is based on the strong electron-electron interactions [17]. Details of the exact mechanism for the phase transition are beyond the scope of this paper.

V. RF CHARACTERIZATION OF PRINTED SWITCHES

As mentioned in the fabrication section, two CPW lines have been printed, one without the VO₂ switch and the other with the VO₂ switch. First, the printed CPW line (without the VO₂ switch) is tested for its S-parameters to act as a reference for the VO₂ RF switch measurements. The RF measurement is done on a Cascade probe station with 500 μm pitch Ground-Signal-Ground (GSG) probes. The measured transmission, S₂₁ and reflection, S₁₁ for both reference CPW line and the shunt-switch based CPW line are shown in Fig. 4 and Fig. 5 respectively. It can be seen in Fig. 5 that CPW line shows decent transmission in the frequency range from 100 MHz to 30 GHz, when the RF switch is in the ON condition (VO₂ film is in insulator mode at room temperature). There is 0.5 dB of insertion loss from 100 MHz to 5 GHz and as the frequency increases from 5 to 20 GHz, the loss increases to 1 dB. Finally, a loss of ~2 dB is observed in the frequency range of 20-30 GHz. It is important to note here that the printed VO₂ film on the CPW line does not induce any additional loss as compared to the reference CPW line. When the temperature is increased beyond the phase transition point (70°C), the VO₂ film goes into the conductive mode and short circuits the signal trace to the ground. Thus, we see transmission levels dropping to around -15dBs, which represents the OFF state of the RF switch (VO₂ film is in conductive mode beyond phase transition temperature). It is worth mentioning here that the OFF state can be further improved, i.e., decreasing the transmission below -20 dBs, by simply increasing the thickness of the VO₂ film or by decreasing its planar

dimensions. The matching of the CPW line stays below -10 dBs for the entire bandwidth, in the ON state of the RF switch, which is important as the transmission is happening in that state (as can be seen in Fig. 5). When the RF switch is OFF, then the matching condition is changes, however this is not a concern as no transmission happens in this state.

Fig.4. Measured S₂₁ of the printed shunt switches at room temperature and at 100 °C

Fig.5. Measured S₁₁ of the printed shunt switches at room temperature and at 100 °C

VI. FULLY PRINTED RECONFIGURABLE ANTENNA

After validation of the RF switch functionality, it has been used in the design of a frequency re-configurable PIFA antenna, as shown in Fig. 6 (a). The VO₂ switch has been printed in a gap that has been created in the major arm of the PIFA so that the antenna can operate at a higher frequency when the switch is OFF (for shorter length of antenna). For the ON condition of the switch, the antenna has a longer length of the arm and thus operates at a lower frequency. The prototype of the antenna has been printed utilizing a silver-organo-complex (SOC) ink with dimensions of (mm): L1=60, L2=21, L3=11.8, L4=15.2, and with the gap between L3 and L4 to be 0.2 mm. In this particular case, a total of 8 layers of SOC ink

Fig.6. (a) As-fabricated PIFA antenna prototype and (b) Measured reflection coefficient of antenna with VO₂ switch ON/OFF

have been printed and cured using infrared (IR) heating for 5 min. As can be seen, the VO₂ is printed in between the gap of the antenna arm. The SMA is mounted on the coplanar waveguide line. The S_{11} of the antenna, as shown in Fig 6 (b) is less than -10 dB in the frequency band of 2.57-3.47 GHz when the switch is at “OFF” state, and in the frequency band of 1.65-2.60 GHz when at “ON” state.

VII. CONCLUSION

In this report, we presented a novel VO₂ nanoparticles based phase change ink which can be thermally tuned for its electrical properties. To demonstrate the phase change behavior of printed VO₂ film, a dc-characterization has been conducted. At room temperature, printed VO₂ film showed the resistance of around 5K Ω , which almost act as an insulator. When the temperature reached beyond transition temperature, the printed film showed the resistance in tens of ohm and act as a conductor. Based on this VO₂ ink and a custom silver-organo-complex (SOC) ink, we have demonstrated a fully printed process for shunt-configuration based switching and reconfigurable antenna. We have obtained temperature activated switching with relatively low losses and more than 15 dB isolation between ON/OFF states, on a broad bandwidth (100 MHz– 30 GHz). It is believed that isolation can be improved further by increasing the thickness of the VO₂ film or by decreasing its planar dimensions. The antenna is matched for WiFi (2.45 GHz) and 5G (3.5 GHz) bands when the switch is at “ON” or “OFF” state. The switching performance confirmed that printed VO₂ can be very useful for implementation of several tunable and reconfigurable microwave designs.

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