Additively Manufactured Dual Mode Reconfigurable Filter Employing VO₂ Based Switches

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Abstract— Modern wireless devices operate on multiple frequency bands, and thus can benefit from frequency reconfigurable Radio Frequency (RF) components, especially filters as they are typically larger in size and are required for every frequency band. In addition, many applications such as wearable electronics, desire stable performance from the devices when they are bent or flexed. However, most of the reconfigurable filters are built on rigid substrates and utilize expensive discrete RF switches, which need to be soldered to the filters. In this work, we present a fully printed filter that achieves reconfigurability through printed Vanadium Dioxide (VO₂) based switches, which are extremely low cost and do not require any soldering for their attachment. The filter design is based on a dual-mode resonator which enables a second-order filter despite a single resonator, thus helping in making the filter compact. It also helps in maintaining a decent insertion loss (2.6 dB), despite relatively low conductivity of the metallic ink. The switches, when activated thermally through a printed heater at the backside, reconfigure the frequency from 4 GHz to 3.75 GHz. The filter has been realized on a flexible Kapton substrate, making the filter conformable to any surface. Measurements under various bending conditions reveal stable performance, making this filter design suitable for a number of wearable and Internet of Things applications.

Index Terms— Screen Printing, Reconfigurable Filter, VO₂, Dual Mode, RF switch.

I. INTRODUCTION

IN the wireless industry, there is a big drive for reconfigurable radio-frequency (RF) components (such as antennas and filters) which can be tuned to different frequency bands on demand. For the highly integrated wireless devices, such as mobile phones, a reconfigurable filter can reduce the overall number of filters required for various frequency bands. In addition, the standards for frequency bands vary somewhat in various parts of the world.

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In order to have a global device that can be adjusted to varying wireless standards in different parts of the world, the RF components need to be tuned to these frequency bands.

For the emerging applications such as Internet of Things (IoT), where billions of wireless sensors are required to be placed on non-planar surfaces, the wireless components are also expected to be flexible, lightweight as well as extremely low cost. Printing these components on low cost and flexible substrates can achieve the required conformability for IoT applications, however it is difficult to print the switches which are responsible to provide the frequency reconfigurability.

Typically, frequency reconfigurability in filters has been achieved through discretely packaged surface mount components, such as PIN diodes [1], micro-electromechanical system (MEMS) [2], and varactors [3]–[7]. However, these kinds of switching components are neither flexible nor low cost. The cost of a single piece of the switch operating up to 3 GHz or 4 GHz can be up to 5.8 USD [8]. In addition, the cost increases for higher frequency bands. For example, a MESFET-based RF switch from Analog Devices Inc., operating from 23 to 30 GHz, costs up to 38 dollars [9]. Furthermore, an attachment method is required to connect these switching components to the reconfigurable component. This may be a cumbersome step which requires precise soldering. Furthermore, soldering is not compatible with many flexible substrates. Other reconfigurable filters, published in the literature, utilize expensive cleanroom processes which are typically expensive and not compatible with the traditional flexible substrates [10]–[17].

The above-mentioned issues can be alleviated if these reconfigurable components can be printed (additively manufactured) on flexible substrates. Additive manufacturing processes enable high low-to-medium, low cost, and versatile fabrication through the deposition of functional materials on the required location [18]. Motivated by these advantages, researchers have demonstrated some printed filters [19]–[22], however, none of them shows any reconfigurability. Some printed filters have been shown which are also reconfigurable but the switch or the switching mechanism has not been printed [23]. Also, these filters are

not flexible.

The major challenge with the fully printed reconfigurable components is that the switches are difficult to print. We have recently demonstrated a vanadium dioxide (VO_2) based ink and a printed switch [24]. VO_2 is a metal-insulator-transition (MIT) material, which has insulating properties at room temperature and becomes conductive at the transition temperature (68°C in this case). The advantage of this switch is that it can be printed where required and thus does not need any additional attachment method. It is extremely low cost (a few cents), customizable in dimensions and compatible with the flexible substrates. In this work, we have demonstrated a fully printed reconfigurable filter which is also flexible. A compact filter with dual-mode resonator has been designed which utilizes the VO_2 switches to reconfigure from 3.75 GHz to 4 GHz. Due to the dual-mode open-loop resonator configuration, the size of the filter has been reduced to approximately half of the typical single-mode resonator-based filter. The switch is activated by a printed meander heater on the backside of the filter. The fully printed filter has been characterized in flat as well as bent conditions and the performance is consistent for both positions. The results from this work are encouraging and useful for upcoming IoT and wearable applications.

II. VO_2 BASED FULLY PRINTED SWITCH

As mentioned above, VO_2 is an MIT material, capable of turning from an insulator at room temperature (also called OFF state) into a conductor when the ambient temperature is above the metal transition temperature (68°C , also called ON state). For a fully printed system, VO_2 also needs to be printable and thus a suitable ink must be developed.

A. Screen Printable VO_2 Ink

In order to prepare VO_2 ink, first high purity and crystalline VO_2 particles, with the average particle size of $4\text{--}6\ \mu\text{m}$, have been prepared using an autoclave reactor in an aqueous environment. To develop screen printable VO_2 ink, a mixed solution of terpineol, ethanol, and ethyl cellulose (EC) has been prepared. Then, VO_2 particles have been mixed with the above solution at a controlled weight ratio and then agitated to obtain stable VO_2 ink suitable for screen printing, as shown in Fig. 1(a). This ink has been deposited on various substrates with different printing passes through the AUREL 900PA screen-printer. After screen printing, the printed VO_2 films have been exposed to 120°C for 1 h to dry them out by evaporating the solvents. It should be noted that a high speed of $220\ \text{mm/s}$ has been used to print the VO_2 films and only a few minutes are required to complete the fabrication. Furthermore, electrical behavior has been assessed for the printed VO_2 films while exposing them to different temperatures. Fig. 1(b) shows the measured resistance of the printed VO_2 films with various printing passes. It may be noted that a higher temperature of 90°C has been used instead of the transition temperature of 68°C . It is well known that the VO_2 conductivity increases abruptly at its transition temperature around 68°C , however, the conductivity continues

to increase by further increasing the temperature [25]. Therefore, a higher temperature of 90°C is utilized in this work to obtain a better conductivity. The resistance at both OFF and ON state decreases rapidly for larger printing passes, as a thicker VO_2 layer is formed. It is demonstrated in Fig. 1(b) that the ON/OFF ratio is fixed at around 270, which is much higher than that of the inkjet printed VO_2 films. [26]. This is because the micro-sized VO_2 particles used in the screen printing process have higher crystallinity than that of nano-sized particles used in the inkjet printing process.

Fig. 1. (a) Optical image of the prepared VO_2 ink. (b) The measured resistance and calculated ON/OFF ratio of the printed VO_2 patterns as a function of printing passes at 25°C (OFF state) and 90°C (ON state).

B. VO_2 Switch Fabrication and Characterization

To examine the RF performance of the screen-printed VO_2 switches, we have realized two different configurations, i.e., series switch and shunt switch, as shown in the inset of Fig. 2(a) and 2(b). For a series switch configuration, the VO_2 film is placed in a gap between the signal terminal (like a bridge) and the RF signal is only transmitted when the VO_2 film is turned ON. In contrast, the VO_2 film is placed between the signal and the two grounds lines in the shunt switch configuration, where the signal is transmitted when the VO_2 film is in OFF condition. This can be clearly seen in the inset of Fig. 2, where the VO_2 switches are printed in series (Fig. 2(a)) and in shunt (Fig. 2(b)) configurations. The dimensions for the series switch in terms of length, width, and thickness are $20\ \mu\text{m}$, $85\ \mu\text{m}$, and $14\ \mu\text{m}$, whereas the dimensions for the shunt switch are $50\ \mu\text{m}$, $1000\ \mu\text{m}$, and $14\ \mu\text{m}$. The S-parameters of the printed series and shunt switches have been measured in both ON and OFF states and are shown in Fig. 2(a) and 2(b), respectively. In Fig. 2(a), it can be seen that the measured S_{21} is about 3 dB when the VO_2 film is in ON condition, allowing the signal to transmit. When the VO_2 film is in OFF condition, the S_{21} becomes -25 dB, indicating that the RF signals have been blocked thus no transmission happens. For the shunt switch shown in Fig. 2(b), the measured S_{21} is -0.8 dB when the VO_2 film is in OFF state and the signal gets transmitted to the other end, while the S_{21} is -20 dB when the VO_2 film is in ON state, demonstrating no signal transmission. Similar conclusions can be made for the measured S_{11} (dashed curves) which demonstrates the reflectance of the signal at port 1. These measurements

indicate decent RF performance for the printed VO₂ switches. It is worth mentioning here that for specific applications, the printed VO₂ switches can be optimized in terms of dimensions and thicknesses to get the required S-parameters. For example, the S-parameters of the two VO₂ shunt switches with different VO₂ thicknesses (38.4μm and 69.6 μm) are shown in Fig. 2(c). It can be seen that the switches with different thicknesses have somewhat different S-parameters. Specifically, the thicker VO₂ film-based switch shows better signal blocking performance (with the VO₂ film in the ON state).

Fig. 2. The measured S-parameters of fully printed VO₂ switches in series configuration (a) and shunt configuration (b). Insets are optical images of the printed switches. (c) The measured S-parameters of two printed shunt switches with different switch thickness at signal-block state (VO₂ film in ON condition).

III. FILTER DESIGN

A. Performance Estimation Through Ideal Filters

Before getting into the actual filter design, it is imperative to do an early theoretical performance estimation. It is well known that the insertion loss is strongly related to the order of the filter (i.e., the number of resonators in the filter) as well as the quality factor (Q) of the resonator. Conventionally, for filter designs, bulk metals such as Copper with a conductivity of 6e7 S/m and low-loss microwave substrates are used. The Q for planar resonators, realized in the arrangement mentioned above, is typically in the range of 200 to 300 [27]–[29]. This has also been verified from EM simulations, where a planar line resonator (shown in Fig. 3(a)) has been simulated and a Q of ~240 is achieved, as shown in Fig. 3(b). On the other hand, the printed resonators (similar to our case), have relatively low Q, in the range of ~75. This is due to the lower conductivity of the printed metal traces (around 1.8e7 S/m), higher porosity in the printed metal traces as well as a larger surface roughness (around 0.5μm). In order to visualize the impact of Q on the insertion loss, the most common equal-ripple bandpass filter (which is also referred to as Chebyshev filter) has been synthesized using the EM simulator. This filter's response is based on equation (1), where ϵ is the ripple constant, Ω is the frequency variable, and $T_n(\Omega)$ is the Chebyshev function of order n [30]. Fig. 3(c) and 3(d) illustrate the synthesized filtering performance for different orders with Q values of 75 and 300, respectively. In the high Q value (as shown in Fig. 3(d)), the insertion loss increases marginally with the increasing order of the filter. However, for the low Q value, a rapid increase in the insertion loss is observed with the higher-order filters. This suggests that the printed filter must not use a higher-order design due to the higher insertion loss.

$$|S_{21}(j\Omega)|^2 = \frac{1}{1 + \epsilon^2 T_n^2(\Omega)} \quad (1)$$

Fig. 3. (a) EM simulation model to evaluate the resonator's Q value. (b) Simulated Q value of the resonator with different metal conductivities. The Q value of the printed resonator is also marked. (c) and (d) S-parameters of the two synthesized Chebyshev filters with different Q values.

B. Dual Mode Resonator Filter Design

The goal for the filter design is to achieve frequency reconfigurability with a compact size and with minimum possible insertion loss for all the operating frequency bands. To balance the insertion loss and the filtering performance, a second-order filter is selected for this work. The lower order filter helps in reducing the insertion loss as well as the size. Further reduction in the filter size as well as the insertion loss is possible by employing a dual-mode resonator. **It is noted that only a handful of filters employing dual-mode open-loop resonator have been demonstrated [31]–[33]. However, they are either non-reconfigurable or the design is not suitable for incorporation of VO₂ type thin film switches.** Different from the conventional single-mode resonator, the dual-mode resonator supports two resonance modes, i.e., the even-mode and the odd-mode. Therefore, instead of having two single-mode resonators, one dual-mode resonator is enough for a second-order filter. The proposed dual-mode resonator design is shown in Fig. 4(a). It is noticeable that the filter layout design is symmetrical along with the interface highlighted in the red dashed line, which is called the symmetry plane (S-S'). When it resonates in the odd mode, the two halves have opposite voltage potential and current distribution, so that the symmetry plane behaves as an electric wall, which can be replaced by a virtual short-circuit, as shown in Fig. 4(b). In this case, the current flows in the outer arm between the end marked as “x” and the end marked as “z”, as can be clearly seen from the current distribution in Fig. 4(d). The negligible current concentration on the inner meandered lines is due to the virtual ground. In contrast, when the dual-mode resonator operates in the even mode,

both halves have the same voltage potential and current distribution so that the symmetry plane can be replaced by a magnetic wall, and the middle of the resonator becomes virtually open-circuited (Fig. 4(c)). For the even mode, the current is distributed symmetrically along the magnetic wall, as it flows from the outer arms to their respective inner meandered arms (from “x” and “z” to “y”), as shown in Fig. 4(e).

Fig. 4. The designed dual-mode resonator (a) and its equivalent representation at odd mode (b) and even mode (c). The symmetry plane S-S' of the resonator is shown as the red dashed line in (a). The current distribution of the designed dual-mode filter is shown in (d) for odd mode and (e) for even mode.

The complete filter design with dimensions is shown in Fig. 5(a), where the feeding lines have been added to the above-mentioned dual-mode resonator. Kapton substrate with a relative permittivity of 2.8 and a loss tangent of 0.002 has been used in this work. The grayish lines represent the metal traces. The bandpass filter design has been optimized in the EM simulator (CST Microwave) to operate at 4 GHz with 500 MHz bandwidth. During the optimization, dimensions of the filter have been fine-tuned, which also includes the location of the feedlines. For example, Fig. 5(b) shows the filter's performance with different W3 values, where the optimum value for W3 is determined as 1 mm. **The reason for choosing W3 as the example for optimization demonstration is that the parameter W3 affects two of the longest trace segments, which have more impact on the overall insertion loss.** The filter design is scalable and can be optimized to another frequency band. The filter part outside the blue box is for reconfigurability and will be discussed in the next section.

Fig. 5. The layout of the optimized design of the dual-mode resonator reconfigurable filter. The black bar indicates the location of the VO_2 switch. Dimensions: $L_1=0.13$; $L_2=2.72$; $L_3=0.66$; $L_4=0.66$; $L_5=0.66$; $L_6=3.23$; $L_7=5.61$; $L_8=0.66$; $L_9=0.3$; $L_{10}=0.66$; $L_{11}=7.02$; $L_{12}=2.56$; $L_{13}=1.64$; $L_{14}=3$; $W_1=0.39$; $W_2=1$; $W_3=1$; $W_4=0.66$; $W_5=1.35$; $W_6=0.4$; $W_7=0.41$. All dimensions values are in millimeter.

C. Reconfigurability Through VO_2 Switches

It is well known that the operating frequency is inversely proportional to the electrical length of the microwave structure. For this particular design, the frequency decreases by increasing the lengths of the three open-ended traces located on the top (labeled as x, y, and z in Fig. 4(a)). Thus, the reconfigurability of the operating frequency can be achieved by integrating three RF switches in series configuration to control the lengths of the open-ended traces, as shown in the black color in Fig. 5(a). If the switches are all in the OFF state, the three metal traces (within the dashed orange rectangle in Fig. 5(a)) are disconnected from the main filter, resulting in a shorter length of the filter. Thus, the filter operates at 4 GHz. On the other hand, if all the three RF switches are in the ON state, the switches will act as bridges and thus the length of the filter will be extended. In this case, the operating frequency will shift to a lower frequency, i.e., 3.75 GHz. Notably, the two operating frequencies have been selected arbitrarily, and the values can be varied just by adjusting the lengths of the filter.

The ideal switches, defined as zero conductivity in the OFF state and zero resistivity in the ON states, have been used for the initial simulations and the results are shown in Fig. 6 as dashed lines. It is seen that the designed filter operates at 4 GHz with an insertion loss of 1.6 dB under the OFF condition, while the operating frequency is shifted to 3.75 GHz, with the same insertion loss, when the switches are turned ON. But different from the ideal switch, the printed VO_2 switch has a finite resistance value for both ON and OFF states and the realistic ON/OFF resistance ratio is around 300. By varying the thickness of the VO_2 switch, different ON and OFF resistance value combinations can be obtained. Thus, it is necessary to optimize the filtering performance via choosing different resistances for both ON and OFF states. We simulate the performance of the filter by sweeping switch resistance values from 2 Ω to 3 k Ω . As shown in Fig. 6(a), lower insertion loss is achievable with lower resistance in the ON state and higher resistance in the OFF state. Considering the limitation of best-case scenario ON/OFF ratio of 300 for our printed VO_2 switch, we choose an ON resistance of 5 Ω and an OFF resistance of 1.5 k Ω . This choice helps to achieve a reasonable and balanced insertion loss for both conditions (Inset in Fig. 6(a)), i.e., 2.3 dB at 3.75 GHz and 4 GHz. As compared to the insertion loss of 1.6 dB for the filter with the ideal switches cases (lossless switches), the overall loss of the filter increases to 2.3 dB with non-ideal switches (with the right resistance capturing the loss of the switches in the model). Thus, it is clear that the additional 0.7 dB insertion loss in the filter is due to the three switches. We repeated the simulation with one real switch and two ideal switches and determined that the loss from a single VO_2 switch is around 0.2 dB. With a fixed switch length and width, the resistance value is determined by the thickness, which can be varied by simply increasing or decreasing the number of printed layers.

Fig. 6. The simulated (a) S_{21} and (b) S_{11} of the filter while sweeping the resistance of the VO_2 switch. The inset of (a) is the zoomed-in figure.

IV. FILTER FABRICATION

The designed filter has been fabricated on a flexible Kapton substrate with a thickness of $125\ \mu\text{m}$ using a screen printer (AUREL 900PA). The flowchart for the filter fabrication is shown in Fig. 7, whereas the two important fabrication steps and the corresponding printed prototypes are depicted in Fig. 8 (a-b) and Fig. 8 (c-d), respectively. In the first step, metal parts have been printed using a commercial silver paste (DuPont PE819) on a pre-cleaned Kapton substrate (Fig. 8(c)). After printing, the sample has been dried and annealed in a vacuum oven at $300\ ^\circ\text{C}$ for 1 h to achieve a conductivity of $1.8\ \text{e}7\ \text{S/m}$. Then, the VO_2 switches have been printed using the custom VO_2 ink, followed by drying them in an oven at $120\ ^\circ\text{C}$ for 1 h. Fig. 8 (d) shows the printed VO_2 switches at the desired locations. A total of 15 passes ($\sim 110\ \mu\text{m}$) have been printed to achieve the desired ON and OFF resistance, as discussed in the previous section. Finally, the ground plane has been printed using the silver paste and dried in an oven at $120\ ^\circ\text{C}$ for 5 min. A relatively lower annealing temperature has been used to prevent any potential damage or any material property change in the printed VO_2 film. A meandered line heater has been used to thermally activate the VO_2 switches, as shown in Fig. 8(e). It has been printed on a Kapton tape using Dimatix 2831 printer and nanoparticle silver ink purchased from ANP Co. Only one layer has been printed to increase the resistance. A curing step is done at $120\ ^\circ\text{C}$ for 5 min to solidify the silver film and achieve a resistance of around $50\ \Omega$. Since the Kapton tape is adhesive in nature, the printed heater is simply attached to the backside of the filter, as is illustrated in Fig. 8 (f). It is readily observed that the heater is located right beneath the three switches. During the activation, a current of 60 mA is passed to the heater to generate a surface temperature of about $90\ ^\circ\text{C}$, which is sufficient to activate the VO_2 switches and get the desired conductivity.

Fig.7 Flowchart of filter fabrication

Fig. 8. Schematic of screen printing of (a) silver traces on Kapton and (b) VO_2 switches. (c) printed prototype with silver traces only (d) prototype with printed VO_2 switches (e) printed heater. (f) illustrative figure showing the printed filter and the heater structure

V. MEASUREMENT RESULTS AND DISCUSSION

The fabricated filters have been characterized through a calibrated vector network analyzer (VNA) from 3 GHz to 5 GHz. The measured S-parameters have been extracted and shown in Fig. 9(a), together with the simulation results. As expected, in the OFF state of the VO_2 switches, the filter is operating around 4 GHz with a 3-dB bandwidth of 500 MHz. An insertion loss of -2.6 dB has been measured, as can be observed in Fig. 9(a) (the red solid curve). From the same figure, the measured S_{11} (black solid curve) is measured to be around -15 dB throughout the passband frequency, which indicates a decent input impedance match. In the ON state of the VO_2 switches, when the meandered heater is activated,

the effective length of the filter becomes longer, and the operating frequency moves to 3.75 GHz. The measured results under this condition have also been plotted in Fig. 9(a), where the blue solid curve represents S_{21} and the green solid curve represents S_{11} . Though the operating frequency is changed, the 3-dB bandwidth of 500 MHz and insertion loss of -2.6 dB are maintained as in the OFF state. The S_{11} also stays below -15 dB, like the OFF state. As compared to the simulation results, there is a slight increase (0.3 dB) in the insertion loss. This can be due to a slight underestimation of the conductor losses. Other than this, a slight downshift of the operating frequency (50 MHz) can also be observed. This is probably due to a slight overprint of the conductive traces, resulting in a slightly longer filter and thus a slightly lowered operating frequency. Nevertheless, these are minor variations and overall the measured and simulation results are in good agreement.

To investigate the performance of the filter under bent or flexed conditions, it has been characterized under various concave and convex bending conditions **both with a minimum bending radius of up to 5 mm** (Fig. 9(b)). As shown in Fig. 9(c), the measured S-parameters remain highly stable and are almost indistinguishable under all the bending conditions. This validates excellent stability and reliability of the fully screen-printed filter. The results indicate that the proposed filter is highly suitable for wearable and IoT applications.

Fig. 9. (a) The simulated and measured S-parameters (S_{11} and S_{21}) of the filter at both ON and OFF states. (b) fabricated filter under flat, concave bending and convex bending conditions. (c) The measured S-parameter of the filter under flat and bending conditions.

VI. CONCLUSION

A fully printed frequency reconfigurable filter based on printed VO_2 switches has been demonstrated in this work. A small size of the filter is achieved due to a dual-mode resonator as well as the meandering of lines in the design. By controlling the ON and OFF states of the three VO_2 RF switches, through thermal activation by a printed heater on the backside, the frequency of the filter can be reconfigured from 4 GHz to 3.75 GHz. The measurement results match well with the simulated result. Furthermore, a decent insertion loss of 2.6 dB has been recorded for both bands, despite the low conductivity of the silver ink used in the process. The flexibility has also been studied and the measurement results reveal stable S-parameters with negligible frequency shift when the filter is bent. The performance of this filter is comparable to other reconfigurable filter works realized through the conventional fabrication process, with the added advantages of flexibility, lower fabrication cost and fabrication time.

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