Fully Printed VO_2 Switch Based Flexible and Reconfigurable Filter

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***Abstract*— Frequency reconfigurable filters are high in demand because they can cover multiple frequency bands, thus minimizing system level cost and size requirements. Another emerging trend is the flexibility or conformability of the electronic components, so that they are suitable for mounting on non-planar objects as well as for wearable applications. In this work, we demonstrate a frequency reconfigurable bandpass filter that has been fully printed on a flexible Kapton substrate. The frequency reconfigurability has been achieved through a switch made of Metal Insulator Transition (MIT) material Vanadium-di-oxide (VO_2). The VO_2 switch has been printed through a custom ink. The switch is in OFF condition (insulating condition) at room temperature and turns ON (becomes conductive) at MIT temperature of 68°C. The microstrip bandpass filter employs dual mode resonators and can switch from 4.0 GHz to 3.7 GHz. The required thermal bias is provided through a printed heater which is attached to the backside of the filter. Due to the flexible Kapton substrate and the printing process, the prototype of the filter is highly flexible and low cost. Measured results are promising and in good agreement with the simulation results.**

***Keywords*— VO_2, dual-mode, full printed, MIT, reconfigurable filter.**

I. Introduction

Nowadays, many wireless standards coexist with different operating frequencies. For example, Wi-Fi works at 2.4 GHz and 5 GHz, GSM works at 800-900 MHz and 1800-1900 MHz, etc. Modern wireless devices, such as smartphones, are employing various wireless standards to cater for multiple applications. Filters are integral part of any radio and are typically large in size. Conventional RF filters generally cover a single frequency band, which means a large number of filters are required in a wireless system, increasing the size and cost of the system. Thus, reducing the number or the size of the filters in a wireless system will help in lowering the cost as well as size. Frequency reconfigurable filters, that can change their band of operation on demand, can be a potential solution to this problem. Another emerging trend is wearable wireless devices, which require the electronics to be conformal to the human body so that they are convenient to wear. So flexible and lightweight filters are also very desirable in addition to low cost and compact size.

Most of the above features can be achieved through additive manufacturing. In additive manufacturing such as inkjet printing and screen printing, the material is only deposited where required in a digital fashion, unlike the conventional subtractive methods where the material is deposited everywhere and the pattern is realized through removal (etching) of material. So, there are considerable cost savings. Further cost savings are also possible because printing does not require a cleanroom environment or expensive vacuum-based processes. Moreover, the printing process is quite compatible with flexible substrates.

Reconfigurable filters based on switches [1]–[4] or varactors [5]–[7] can be found in literature, but none of them is printed. A couple of VO_2 MIT based reconfigurable filters have also been demonstrated but have been realized through expensive and time-consuming cleanroom-based processes such as sputtering [2], [8]. Several additively manufactured filters have also been reported in the literature [9]–[12]. In [9], W-band bandpass filters are presented using the aerosol jet printing process. Whereas in [10], a 12 GHz inkjet printed hairpin bandpass filter has been fabricated on a liquid crystal polymer substrate. Another inkjet printed dual-mode ring bandpass filter has been demonstrated in [11]. In [12], an inkjet printed parallel-coupled microstrip filter has been demonstrated on a flexible Kapton substrate at 85 GHz. It is noticeable that none of the printed filters in the literature show any kind of reconfigurability. This is probably because attaching small switches or diodes to the printed traces is not easy as they cannot sustain conventional soldering[13]. Furthermore, these are rigid surface mount components and thus not flexible. Finally, switches at mm-wave can be very expensive, where a single switch can cost up to 38 dollars[14]. All the above-mentioned issues can be alleviated if the switch can also be printed with the RF component [15].

This work demonstrates a fully printed frequency reconfigurable filter utilizing a Vanadium Dioxide (VO_2) based switch on a flexible substrate. Silver paste has been used for printing the metallic traces as well as the metal ground plane. VO_2 ink has been used to print the RF switch thus there is no requirement of soldering. The filter has been realized through an extremely low-cost printing process. The VO_2 based RF switches in this filter can be activated by applying external heat, which is realized by a printed heater on the backside of the filter. The fabricated filter demonstrates an acceptable insertion loss of around 2.6 dB at the two operating frequencies, i.e. 3.75 GHz and 4 GHz. This is a unique filter that is fully printed as well as frequency reconfigurable and can operate in flat and bent conditions.

II. Filter Design and Fabrication

A. *Fully printed VO_2 switch*

VO_2 is an MIT material, which exhibits dielectric properties at room temperature or in the absence of bias current. It becomes conductive when the temperature is above the metal transition temperature (68°C in this case) or with the application of sufficient bias current. This means it can be used as a switch with OFF condition at room temperature and ON condition at or above 68°C. In this work, the switches have been realized through screen printing of a nanoparticles based VO_2 ink. A sample printed VO_2 switch (black color) in between a CPW line (silver color) and its performance at both ON and OFF conditions are shown in Fig. 1. As can be seen that under OFF condition (room temperature), there is a total reflection of the signal and thus no transmission happens. While at ON condition, there is decent matching and transmission at the frequency of interest.

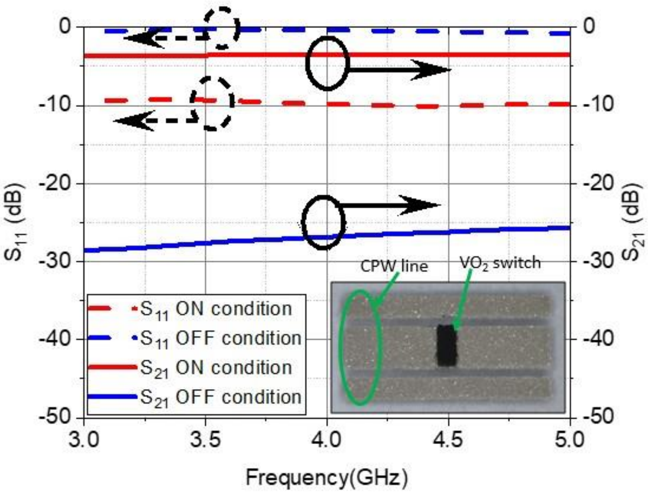

Fig. 1 The measured S parameter of fully printed VO_2 switch at ON (red curve) and OFF (blue curve) states. S_{11} and S_{21} are represented by the dash line and solid line, respectively. Inset is the picture of the printed VO_2 switch.

B. *Filter Design with Ideal Switches*

The approach for the filter design is to have frequency reconfigurability with a small size and relatively lower insertion loss for all the operating frequency bands. Since the intention is to print the filter as well as the VO_2 switch, the insertion loss issue becomes important as the typical conductivities of the metallic inks are lower than the bulk metal conductivities and thus the printed filters tend to have higher insertion loss, in general. In order to reduce the size, as well as minimize the insertion loss, a dual mode resonator filter has been designed, as shown in Fig. 2. The advantage of a dual mode resonator-based filter is that two resonances can be obtained from a single resonator and thus a better roll-off versus insertion loss tradeoff can be achieved as compared to a single mode resonator-based design. Furthermore, because the filter design is using one resonator for two modes instead of two resonators, the size can be smaller.

The proposed filter design layout is shown in Fig. 2 where the grayish lines indicate the metal traces. Three RF switches are integrated into the design and are shown in black color in the figure. If the RF switches are all in the OFF state, the three metal traces within the dashed orange rectangular in Fig. 1 will be disconnected from the main filter, which results in a shorter length of the filter. This shortened filter is designed to operate at 4 GHz. On the contrary, if all the three RF switches are in the ON state, the three isolated metal traces are bridged to the main filter body, which results in a longer length filter. In this state, the filter operates at 3.75 GHz. Note that the value of these two frequencies have been selected arbitrarily, and the values can be adjusted by varying the length of the three above-mentioned metal traces. To further reduce the size of the filter, some meandered lines are used in the middle section, which can be seen in Fig. 2. The dimensions of the filter have been optimized in EM simulator (CST Microwave) and are also shown in Fig. 2. Initial simulations have been done with ideal switches (zero conductivity in OFF state and infinity conductivity in ON state) and the results are shown in Fig. 3. It can be seen that the filter operates at 4 GHz with an insertion loss of around 1.6 dB in the OFF state. When the switches are turned on, the operating frequency changes to 3.75 GHz with a very similar insertion loss as in the ON state. The main source of the loss is the finite conductivity of the silver ink, which is 28% of bulk silver conductivity (the exact value used in the simulation is 1.8 x 10^7 S/m). Some loss is also due to the dielectric, which is Kapton in our case (ε_r =2.8, Tanδ = 0.002).

C. *Filter Design with Realistic Switches*

Different from the ideal switch where it models the switch as open-circuit when switched off and short-circuit when switched on, the VO_2 switch has finite resistances for both ON and OFF states. A limiting factor for the printed VO_2 switch is that the best ON/OFF ratio can be 300. However, different combinations of ON and OFF resistances can be chosen within this limit of 300. VO_2 switches with different ON and OFF resistance combinations will result in different filtering performances of the filter. Thus, the resistances for both ON and OFF state need to be optimized for desired filtering performance. The resistances are determined by the dimensions of the VO_2 switch, i.e. the width, the length, and

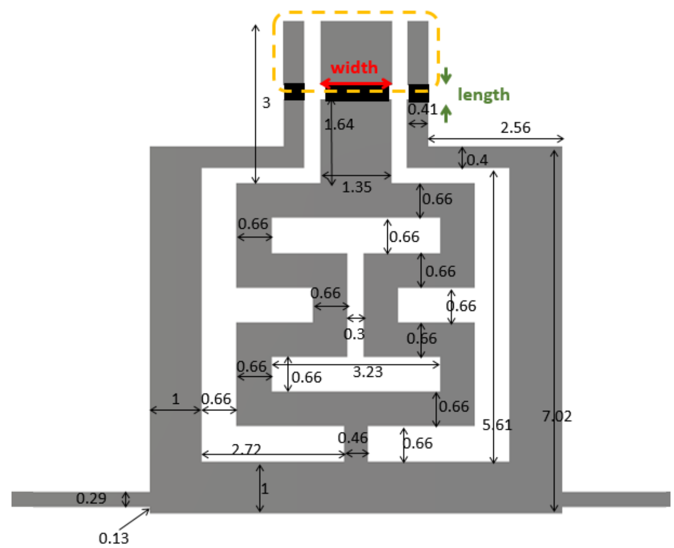

Fig. 2 The layout of the dual mode resonator filter. The black bar indicates the location of the VO_2 RF switch. The width of the switch is denoted in red and the length of the switch is denoted in green. The unit shown in the figure is in mm.

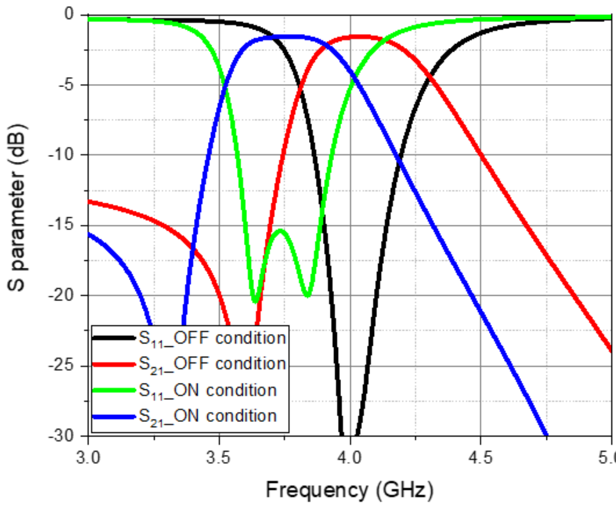

Fig. 3 The simulated S-parameters of the filter design with ideal switches.

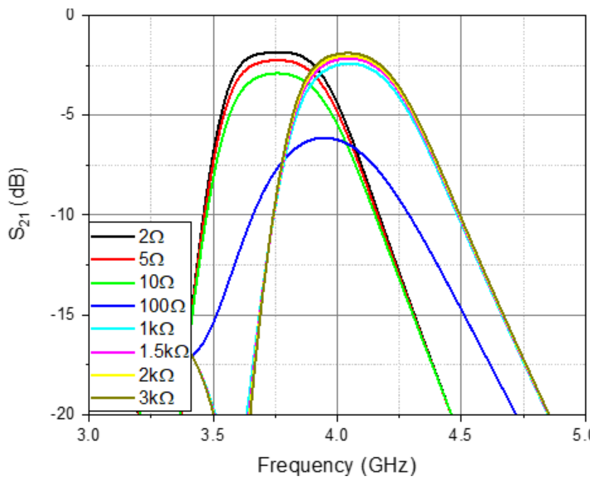

Fig. 4 The simulated S-parameters of the filter as sweeping the resistance of the RF switch (switch length set to 100 µm). Note that only S_{21} curves have been plotted for clarity purposes.

the thickness. The width of each switch will be the same as the width of the metal trace connecting to it, so it is a fixed value. We choose 100 µm for each switch's length to simplify the fabrication process. The resistance of the switches is varied by changing their thicknesses, which in fabrication is just increasing the number of printed layers. The simulated performance of the filter with different VO_2 switch resistance values is shown in Fig. 4. From the figure it can be observed that for the OFF state, a larger resistance value produces lower insertion loss, whereas for ON state, a smaller resistance value provides better performance. Considering an ON/OFF ratio of 300 can be realized for our fully printed VO_2 switch, we choose an ON resistance of 5 Ω and an OFF resistance of 1.5 kΩ as a combination to deliver reasonable and balanced insertion loss at both conditions, i.e. 2.3dB at 3.75GHz and 4GHz.

D. Fabrication Process

The fabrication of the designed filter is done through printing the conductive parts, i.e. the grayish area in Fig. 1, on a flexible Kapton film (125 µm in thickness) utilizing a commercial silver paste (PE819, DuPont) on a screen printer (AUREL 900PA). After printing, the sample is baked in a vacuum oven at 300 °C for 1 h. Next, the RF switch is printed at the desired area using the VO_2 nanoparticles-based ink, followed by sintering at 120 °C for 20 min. A total of 15 passes (110 µm) have been printed in order to achieve the desired ON and OFF resistance mentioned in the previous section. Finally, the ground plane is printed using silver paste. In the last step of the fabrication process, the sample is heated in an oven at 120 °C for 10 min. The fabricated sample is shown in Fig. 5, which is quite flexible, as is evident from the figure.

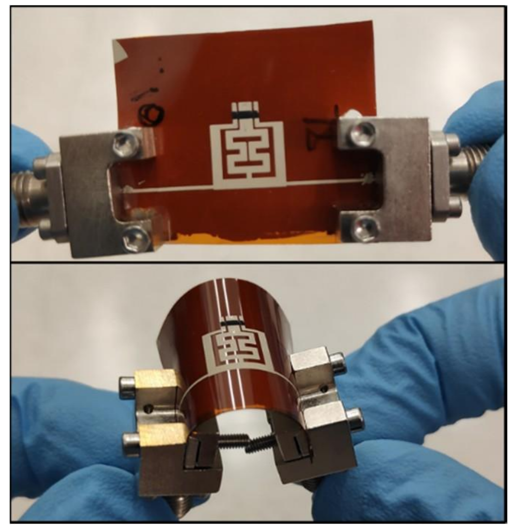
Fig.5 Picture of the fabricated sample at flat and bending conditions

III. MEASUREMENT RESULTS AND DISCUSSION

The fabricated sample has been characterized via a calibrated Vector Network Analyzer (VNA) from 2.5 GHz to 5.5 GHz. The measured and simulated results are plotted in Fig. 6, where the dashed curves represent the simulation

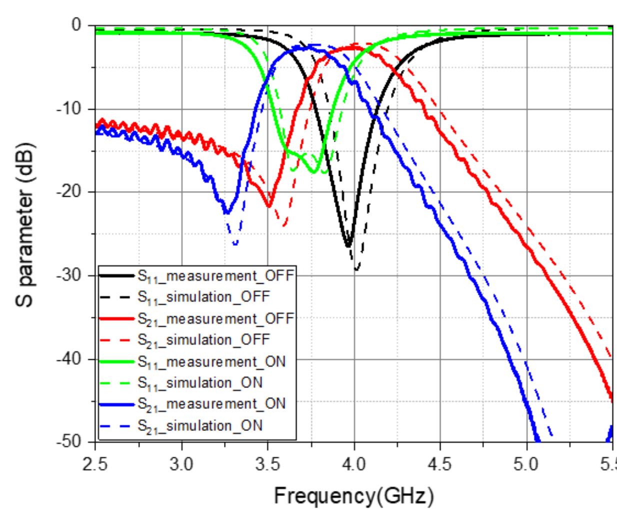

Fig. 6 The simulation and measurement results of the filter at both ON and OFF conditions.

results, and solid curves indicate the measurement results. As can be seen from the figure, for both the ON and OFF conditions, the measured results match well with the simulated results, except for a minor 50 MHz frequency downward shift for the measured values. This is probably due to the fact that the printed lines are slightly wider than the designed ones due to the ink spreading in the screen-printing process. The measured insertion losses at both ON and OFF conditions are 2.6 dB, which is slightly higher than the simulated value of 2.3 dB.

IV. Conclusion

In this work, a fully printed, frequency reconfigurable filter based on VO_2 RF switch has been demonstrated which is small in size due to the dual mode resonator as well as meandering of lines. The frequency reconfigurable filter operates at 4 GHz and 3.75 GHz in the OFF and ON state of the VO_2 switch respectively, through thermal excitation by a printed coil at the backside of the filter. The simulated and measured results are in good agreement. An insertion loss of 2.6 dB has been measured for both bands, which is decent provided the relatively low conductivity of the silver ink used in the process. This performance of the fully printed filter, which is quite flexible as well, is comparable to other reconfigurable filter works realized through the conventional fabrication processes, which can be expensive as well as time-consuming.

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