A novel reconfigurable CMOS compatible Ka band bandstop structure using split-ring resonators and Vadandium Dioxide (VO$_2$) phase change switches

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Abstract**—The article presents the design, fabrication and characterization of a novel complementary metal-oxide-semiconductor (CMOS) compatible reconfigurable Ka band bandstop structure using split ring resonators (SRR) while employing the Vanadium Dioxide (VO$_2$) phase change (PC) thermally triggered transition. The work focuses on the VO$_2$ thin film conductivity levels challenges on silicon dioxide (SiO$_2$)/ silicon (Si) substrates caused by the limited conductivity in the metallic state of the VO$_2$ films versus their non-zero conductivity in the insulating state. We characterize first various samples of VO$_2$ thin films deposited on SiO$_2$/Si substrates and present different fabricated filters responses with several VO$_2$ switches dimensions. The filters show higher bandstop rejection levels than previously reported VO$_2$ based CMOS compatible bandstop filters for the Ka band and displays a higher reconfigurable range from: 29.7 GHz-38.7 GHz. The filters while introducing a new compact tuning mechanism present the first VO$_2$ reconfigurable SRR bandstop structures for the Ka band.**

Keywords**—bandstop filter, phase change materials, Vanadium dioxide, metal-insulator transition, thin film.**

I. INTRODUCTION

Reconfigurable microwave components are becoming increasingly significant due to the spreading of multi band and multi-functional wireless devices. Among reconfigurable microwave components tunable filters represent a key element in the receiver design for enabling efficient utilization of the frequency spectrum. The tuning of the microwave filters was usually achieved using a variety of switching elements such as semiconductors, ferroelectric materials, micro-electrical mechanical systems (MEMS) while lately phase change materials (PCM) [1-2] have garnered a lot of interest especially due to their very small size and high linearity.

Among PCM, Vanadium Dioxide (VO$_2$) [2], exhibits a Metal –to Insulator transition (MIT) and reversible insulator to metal transition (IMT) resulting in a sharp change of its electrical properties. The IMT transition can be triggered thermally around 68 °C with increasing temperature while MIT can be achieved with decreasing temperature. VO$_2$ has been employed in several reconfigurable components and deposited as a thin film on sapphire [3-7], Si [6], on Alumina [8], cooper [9], Quartz [10], FR4 [11], SiO2/Si [12-14], among others exhibiting a huge but inconstant change in the conductivity levels between its insulating (off) and conductive (on) states of several orders of magnitude. Table 1. presents various approximate conductivity levels reported within [3-14] for different VO$_2$ depositions of different thicknesses and employing different deposition techniques. It is worth mentioning that a large variety of these stated values are presumed based on similar configurations [3, 4, 7, 11, 13, 14], measured for the exact depositions [5, 6, 9, 12] while frequency dependent extracted [10] by de-embedding.

Table 1. Conductivity levels of various VO$_2$ thin films on different substrates reported in literature.

	Substrate composition	Approximate conductivity insulating phase (c_{off})(S/m)	Approximate conductivity metal state (c_{on}) (S/m)
[3-4]	Sapphire	10	$3.2*10^5$
[5]	SIO$_2$/Sapphire	5	$5*10^4$
[6]	Sapphire	20	$2*10^5$
[7]	Sapphire	344	$4.17*10^5$
[9]	Cooper	<131	$2.12*10^5$
[10]	Quartz	$50< c_{on} <200$	$c_{off} >4*10^4$ (100^0C)
[11]	FR-4	4600	$8*10^5$
[12]	SiO$_2$/Si	10	$2.3*10^4$
[13]	SiO$_2$/Si	20	unreported
[14]	SiO$_2$/Si	unreported	$3*10^4$

The aim of this paper is to present first the design/fabrication challenges of a complementary metal-oxide-semiconductor compatible (CMOS) Ka band rconfigurable bandstop structure in coplanar waveguide technology (CPW) while analysing initially the thin film conductivity levels of various VO$_2$ samples on SiO$_2$/Si substrates.

Further-more to overcome the previously reported reconfigurability range, bandstop rejection levels and sizes for Ka band Si based VO$_2$ bandstop reported filters [14] we propose a novel reconfigurable mechanism by employing split ring resonators SRR [15]. Using four 1µm*20µm VO$_2$ series contact switches on a 140nm thin film and uniplanar CPW SRR [15] we create an additional gap in the outer SRR rings metal and fill it at different angles with the VO$_2$ switches. Lastly the performances of our fabricated filters are compared with the results obtained in [14, 16] where VO$_2$ or MEMS switches were used for the same frequency band.

II. VO_2 CONDUCTIVITY LEVELS INFLUENCES AND TUNNING MECHANISM

Firstly four thin films of various thicknesses are first deposited on a SIO_2 (300 nm)/amorphous Si (300 nm) /Si (525µm substrate) and characterized. The values presented in Table 2. show the conductivity of the VO_2 films in the on state (around one order of magnitude smaller than the ones reported on Sapphire, Cooper or Fr-4, see Table 1. but which are better than the ones reported in [12-14] for SiO_2/Si based depositions. On the other hand the values for the insulating (off state conductivity) are more than twice higher than the reported ones in [12-14] (for samples 2-4) and thus more care has to be taken in the design for the off state too.

Table 2. Conductivity levels of various VO_2 thin films deposited via sputtering and PLD measured in DC.

Sample	Deposition technique/thickness	Measured insulating phase (c_{off})(S/m) (in DC) at 20°C	Measured conductivity metal state (c_{on}) (S/m) at 100°C
Sample 1	Sputtering 200 nm	6.2	$3.2*10^4$
Sample 2	PLD 140 nm	28.2	$4.7*10^4$
Sample 3	PLD 140 nm	48.5	$6.5*10^4$
Sample 4	PLD 200 nm	47	$6.4 *10^4$

Starting from the uniplanar SRR [15] we have added four SRR in the slots at a same metal level with the central strip of a CPW line. Further the outer rings are additionally cut radially in order to change the electromagnetic field behaviour and depending on the position of the cut a different resonating frequency is achieved. Figs. 1-2 show the proposed tunning principle and dimensions of the fabricated devices:

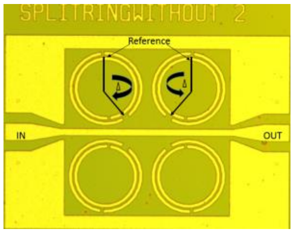
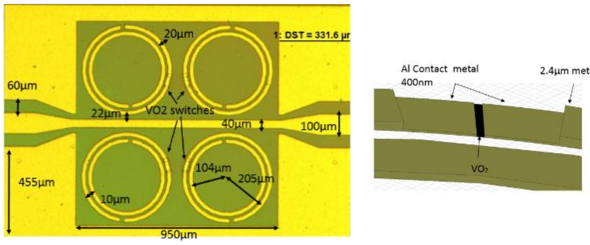


Fig. 1. Photo of a fabricated split ring bandstop filter with proposed tunning mechanism (without switches).The additional cut is placed at an angle Δ from the reference



(a)

(b)

Fig. 2. Photo of the fabricated filter with geometrical dimensions (a) and (b) VO_2 switches layout as simulated.

The angular position Δ of the switches in determines the tuning range (Δ increasing clockwise in respect to the upper input split ring reference and vice-versa in respect to the outer upper split reference ring-as shown in Fig. 1). The rejection levels on the other hand are mainly determined by the design values and fabrication technology.

Samples 3-4 from Table 2. are chosen due to the higher conductivity level in the metallic state, however the leaky values of 47 S/m-48.5 S/m in DC will have an impact in the insulating state of the filter since, resistive losses in VO_2 increase with frequency [10].

The VO_2 switches length (gap in the Al contact metal in Fig. 2b) and thickness have an important impact on the maximum attenuation level in both states. A shorter length would diminish the losses in the metallic state and increase them in the insulating state. An increased thickness level would diminish the losses in metallic state as reported also in [3] while increasing them in the insulating state. The results summarized in Table 3. show that a compromise between length& thickness has to be found in order to accommodate the conductivity levels found in Table 2. for a satisfactory on-off behavior.

Table 3. Thickness and length variation of the VO_2 switch influence on the Ka band losses for the filter in Fig 2 for a fixed width of the switches.

	Losses metallic state	Losses insulating state
Thickness ↑	↓	↑
Length ↑	↑	↓

Using the values from Table 2. -Sample 3 for the VO_2 conductivity in the off state and a thickness of 140 nm and length of 1µm we get the tunning capabilities presented in Fig.3 which show a superior maximum bandstop potential than the results reported in [14] where VO_2 was employed for the same Ka band.

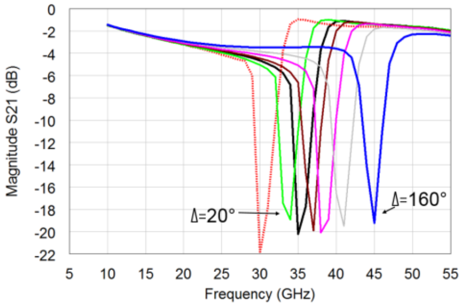
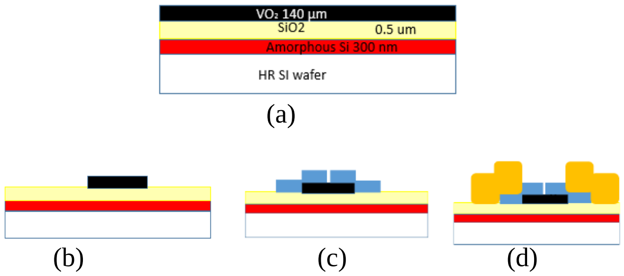


Fig. 3. HFSS simulated magnitude of the transmission parameter (dB): dotted (ideal on state with Al metallization, no VO_2 switch interruption), continues lines (with 4 VO_2 switches of 1µm lengths in off state (Table 2. , sample 3)) for the filter in Fig.2 a for 20°≤ Δ≤ 160°.

The final filter dimensions are presented on the photo microscope image of the filter in Fig. 2 a. No further optimization was done once the simulated results showed a better bandstop potential than in [14] and similar bandpass behaviour as in [16] (where MEMS and SRR are employed in a different configuration for the Ka band). The 22 dB maximum insertion loss (IL) (for ideal on state) in Fig. 3 was obtained considering Al switches (with a conductivity of $2.2*10^7$ S/m), while our desire was to overcome the 12.8 dB reported in [14] using VO_2 contact switches in the on state and keeping 18 dB in the off state.

III. FABRICATION FLOW AND MEASURED RESULTS

The filters were fabricated using standard microelectronic processes starting with a high-resistivity (10000 Ω·cm) 525 µm thick silicon substrate (Fig. 4a-d). A 300 nm thick amorphous silicon layer was first deposited to improve radiofrequency performances. The substrate was then passivated with 500 nm SiO_2 deposited by sputtering. 140 nm-thick VO_2 and 200 nm thick films (samples 3 and 4) were deposited at 400 C in oxygen atmosphere by a Pulsed Laser Deposition (PLD) system using a V_2O_5 target and then annealed at 475 C in the same system for 10 min. The film was then patterned using photolithography followed by dry etching. A Cr (20 nm)/Al (400 nm) bi-layer was deposited to contact the patterned VO_2 film (Fig. 2(b)). This thin contact layer allowed for the realization of 1 µm gaps between the contact pads. Additionally, a 2.4µm-thick Al layer was deposited on top of these contact pads by conventional lift-off methods to provide low RF losses (to create the final CPW elements). Thus, the process flow avoids the undesired presence of SiO_2 within the Al top metal slots existent in [12, 14] while assuring the ease of the 1µm gap realization by the use of the 400 nm Al contact metal.



(a)

(b) (c) (d)

Fig. 4. Process flow: (a) VO_2 deposition, (b) VO_2 dry etching, (c) Cr 25 nm/Al 400 nm contact metal lift off, (d) Cr 25 nm/Al 2.4µm lift-off.

Considering the four VO_2 switches of 1µm length, 140 µm thick and (20 µm wide and with the filter dimensions reported in section II), while $\Delta=125°$ (to have both central frequencies in the Ka band) we get the measured results presented in Fig. 5. The results show a reconfigurability range from 29.70 GHz to 38.70 GHz for the central frequency of the filter with a tunability (defined as in [14] as |fmax-fmin|/fmax where fmax stands for the highest central frequency and fmin for the minimum central frequency) of 23.3%. The maximum IL at 100 °C is 14.1 dB while being around 18 dB at 38.7 GHz at room temperature. The measured performances (tested with the ANRITSU Vector Star VNA) (0.1GHz-55GHz) are in good agreement with the simulations (the later performed between 5GHz-55GHz) (Fig. 6 - Fig. 7) further discussions on the designs being presented in part IV. Table 4. provides a comparison of the results obtained in this work to the other Ka band CMOS compatible reconfigurable bandstop filters [14, 16] performances (λ_0 stands for the free space wavelength at the highest reconfigurable central frequency). The size of the filter is considered the overall size of the device (unlike in [14] where just the defected ground plane area was considered in the comparison).

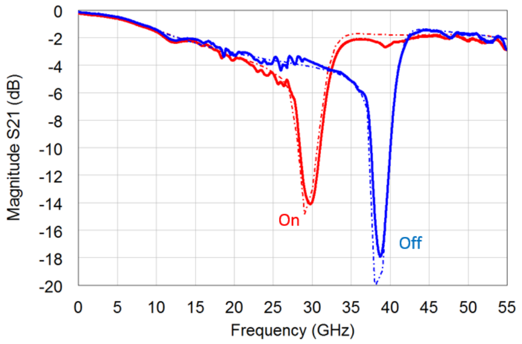


Fig. 5. Magnitude (dB) of the transmission parameter of the reconfigurable filter using four 1µm long and 140µm thick VO_2 switches (sample 3): simulated (dotted) vs measured (solid line) at: 100 °C on, (red) and at room temperature, off (blue).

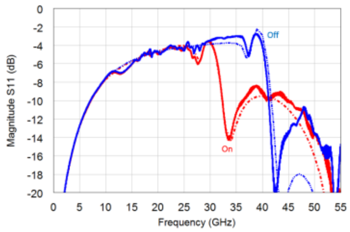


Fig. 6. Magnitude (dB) of the reflection parameter of the reconfigurable of filter using four 1µm long and 140µm thick VO_2 switches simulated (dotted) vs measured (solid line) at: 100 °C on, (red) and at room temperature, off (blue).

Table 4. Comparative performances with other Ka band reported reconfigurable filters.

	This work	[14] with VO_2	[16] (MEMS)
Tuning range	23.3%	19.2%	9%
Approximate total Area/ λ_0^2	0.21*0.15	0.24*0.145	0.64*0.19
Maximum IL	14.1 dB (on) 18 dB (off)	12.8 dB (on) 18 dB (off)	18 dB 20.2 dB

IV. DISCUSSIONS AND FURTHER WORK

A. *VO_2 switches conductivity challenges& thickness& length trade-offs*

It is worth mentioning that in the on state the maximum attenuation of the fabricated Ka reconfigurable is higher than in

[14] (Fig. 4) even by using a thinner thickness for the VO_2 film (sample 3). On the other hand the off state performances (in terms of max IL) are almost identical with the ones in [14] even though the conductivity of the VO_2 in the off state was 4.5 times bigger than the one reported in [14]. The similar off state performances was achieved by using a lower value of the VO_2 thickness 140 nm and thus reducing the impact of its undesired off state conductivity of sample 3 (which at 38.7GHz may be a couple of times higher than in Table 2. as reported in the frequency extraction done in [10]).

Samples 3 and 4 have practically identical conductivities, however their thickness disparity plays unneglectable role in their employment. In Fig. 7 the magnitude of the transmission parameter of the same filter fabricated with the 200 nm VO_2 thin film (sample 4) and with various switches dimensions is shown in the on state (100°C). It is seen that depending on the switches length various maximum IL levels can be acquired. The results also confirm the conclusions from the simulations listed in Table 3. in respect to the thickness: using four 200 nm thick and 1μm long VO_2 switches higher maximum IL can be obtained in the on state (15.1dB-Fig. 7 instead of 14.1 dB-Fig. 5). However the un-plotted results show deteriorating the off state performances of the filter using sample 4 since its higher thickness worsens the impact of the VO_2 off state conductivity.

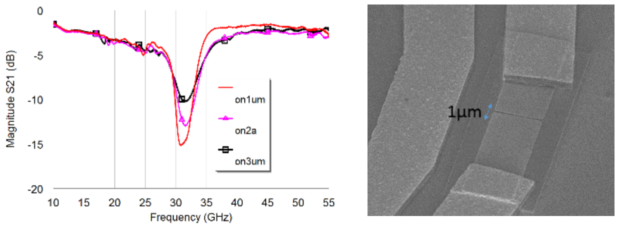


Fig. 7 . (a) Magnitude (dB) of the transmission parameter of the filter measured at 100 °C (on) using 4 switches of: 3μm (black), 2μm (pink) and 1μm (red) with a 200 nm VO_2 film thickness (sample 4) (b) SEM image of one of the switches

B. *Design and future work*

In respect to our initial design performances, the lower and upper bandpass characteristics of our design (Fig. 3 dotted curve (using ideal Al connection)) are similar to the ones reported in [16] but can be improved by adding matching networks at the input and output to accommodate the uniplanar split-ring placement while using the same tunning mechanism. Further the rings can be placed on a different layers to improve the bandstop characteristics [15] while more rings can be cascaded. Nevertheless, improving the deposition techniques and switching to a sapphire substrate would ease the achieving of higher attenuation levels due to the 1 order of magnitude higher conductivity of the VO_2 films in the on state on it.

V. CONCLUSIONS

The article presents the first CMOS compatible SRR based Ka reconfigurable bandstop structure employing VO_2 swtiches thermally triggered. Exploiting the ease of integration of VO_2 components, we propose a new tunning mechanism, based on an additional simple split- ring cut and replacement with 140 nm*1μm*20 VO_2 film traces. The fabricated device, characterized up to 55GHz (Fig. 2) shows the highest tunning range (Fig. 5) for reported CMOS compatible bandstop structures in this frequency band (23.3%). Overall the article intends to extend the understanding of VO_2 based reconfigurable devices challenges, once employed in mm-waves frequency ranges [17], while facing limited conductivity levels.

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