Tunable parallel plate waveguide array based on VO$_2$ thin films

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Abstract. Vanadium dioxide (VO$_2$) is a material with a metal-insulator phase transition. We report a way of application of VO$_2$ thin films as functional elements of reconfigurable parallel plate waveguide array (PPWA). The PPWA presented here is designed to work in X, Ku and K bands. A transmission coefficient of the array with VO$_2$ elements can be altered using temperature by more than 10 dB across the entire experimentally studied frequency range. We demonstrate a method of design and manufacturing of the PPWA. The PPWA may be used as a basic component in more advanced reconfigurable devices.

1. Introduction
Parallel plate waveguide arrays are key components for electromagnetic beam steerers [1], lenses [2] and antennae [3]. The reconfigurability of those systems can only be achieved using mechanical methods. Mechanical switching methods can not be used in applications where the fast tuning of the device is required. Recent researches show that this issue can be resolved using functional metal oxides that have a metal-insulator transition property.

Among materials with the metal-insulator transition, vanadium dioxide (VO$_2$) thin films have proven to be the most promising, due to their large contrast in resistivity between two states. Switching between the states can be induced by heating the film to 60°C [4] or applying voltage bias [5]. Thanks to the metal-insulator transition, VO$_2$ thin films are reported as a switching element in reconfigurable RF slot antennae [6], RF coplanar switches [7] and tunable planar RF filters [8]. The typical size of the VO$_2$ switching elements utilized in those devices varies from 10×10 µm to 1×1 mm. In order to use VO$_2$ thin films as a switching element for the parallel plate waveguide array, a surface area of thin films should be in the region of square centimeters.

In our previous work [9] we presented the method of synthesis of the high quality 30 cm$^2$ VO$_2$ thin films with a 10$^3$ ratio of the sheet resistance in the insulator state to the resistance in the metal state. Metal-insulator transition attributes of the obtained thin films were uniform through the films’ surface area. In the present work, we demonstrate a way of application of VO$_2$ thin films as walls of the tunable parallel plate waveguide array (PPWA). The frequency response of the device can be tuned by thermal actuation of the metal-insulator transition in VO$_2$ thin films. When VO$_2$ thin films switch from insulator to metallic state, the transmission coefficient of the PPWA drops by more than 10 dB in a 6-24 GHz frequency range.
2. Model and numerical simulation
The shift of the PPWA transmission coefficient is related to the resistivity change of the waveguide walls material. While VO$_2$ is in the dielectric state, PPWA is transparent for RF electromagnetic waves. When VO$_2$ transits into the metallic state, it acts as a lossy conductor on the PPWA walls so that electromagnetic wave with vector $E$ parallel to the walls attenuates. To estimate the shift of the PPWA transmission coefficient, a transmission coefficient of the single parallel plate waveguide (PPW) was analyzed.

Attenuation due to conductor loss $\alpha_c$ in a single parallel plate waveguide (figure 1) equals to [10]:

$$\alpha_c = 8.686 \cdot \frac{R_s}{Zd} \text{ dB/m} \quad (1)$$

where $d$ is a distance between parallel plates, $Z$ is an impedance of the medium in the waveguide and $R_s$ is a surface resistance of the material which covers walls of the waveguide. According to (2), $R_s$ depends on wall material resistivity $\rho$ and skin depth $\delta_s$, however, a skin depth of VO$_2$ thin films, obtained in this work exceeded their thickness across the entire frequency range. For example, at 12 GHz skin depth of VO$_2$ thin films in the metallic state, in which resistivity equals to $1.44 \cdot 10^{-5}$ Ohm·m, is $1.74 \cdot 10^{-5}$ m (calculated according to (3), where $\mu$ of VO$_2$ equals to $\mu_0$ [11]). The thickness of VO$_2$ films used here was 120 nm. Therefore, instead of skin depth in (2), the thickness of the films should be taken. In that case, $\alpha_c$ will be 10 dB/cm. This means, that the transmission coefficient of PPW should decrease by 10 dB after switching from “opened” state (when VO$_2$ is insulator) to “closed” state (when VO$_2$ is a lossy conductor) for 1 cm length ($l$ dimension on figure 1) PPW.

$$R_s = \frac{\rho}{\delta_s} \quad (2)$$

$$\delta_s = \sqrt{\frac{2\rho}{\omega \mu}} \quad (3)$$

Figure 1. Schematic of the parallel plate waveguide, PPW.

Figure 2. The model applied for the PPWA simulation in HFSS software.

Figure 3. The primitive cell of the PPWA, a side-view.
From (1) it is evident that the bigger the distance between plates, the smaller $\alpha_c$. Consequently, the usage of PPWA instead of single PPW would allow covering apertures with an area of several square centimeters without significantly extending length $l$ to compensate for the decrease of $\alpha_c$.

Numerical simulation was used to determine optimal dimensions of VO$_2$ elements used as PPWA plates and distance between them. PPWA with optimal dimensions should have had the highest transmission coefficient in “open” state (when VO$_2$ is insulator) and the lowest transmission coefficient in “closed” state (when VO$_2$ is a lossy conductor). Numerical simulation was conducted employing HFSS electromagnetic simulation software.

A primitive cell of the PPWA was used for PPWA simulation (figure 2). The primitive cell consisted of a plate of polycrystalline Al$_2$O$_3$ substrate with dielectric permittivity $\varepsilon_{sub}=9.7$ and dielectric loss tangent $\tan\delta=10^{-4}$ and a layer of air between two adjacent plates (figure 3). A thickness of Al$_2$O$_3$ substrate $d_{sub}$ was fixed at 0.5 mm during the optimization process since the same substrate was used for thin film synthesis. Both variable parameters: $d_{air}$ – a distance between adjacent plates, and length $l$ of the plates were varied in 4-20 mm range. That range was chosen for reasons of ease of manufacturing PPWA from synthesized films. VO$_2$ layer was simulated by applying impedance boundary condition on the front side (figure 2) of the Al$_2$O$_3$ plate. In “open” state value of impedance was $3\cdot10^5$ Ohm/□ and in “closed” state value of impedance was 120 Ohm/□, in accordance with measurements.

In order to simulate the interaction between the array of the primitive cells and plane electromagnetic wave, periodic boundary conditions were applied on the walls of the primitive cell. Periodic boundary conditions were applied on a pair of walls parallel to the YZ plane and on a pair of walls parallel to the XZ plane (figure 2). These conditions mean that the model represents a PPWA with an infinite $W$ dimension consisted of an infinite amount of the primitive cells, translated along the Y-axis (figure 2). That model was simulated in the 6-24 GHz frequency range for waves polarized along the X-axis.

Using the simulation, an optimal $d_{air}$ of 8.5 mm and $l$ of 11 mm were found. Calculated spectra (figure 4) of the transmission coefficient of the PPWA in both states demonstrate, that the transmission can be tuned by more than 10 dB across the entire frequency range, as it was expected from the theoretical estimation.

3. Experimental
Vanadium dioxide thin films were deposited by means of ion-assisted RF magnetron sputtering of pure V (99.3%) target on polished polycrystalline Al$_2$O$_3$ substrate. The substrate dimensions were 48×60×0.5 mm. The deposition was preceded by Ar ion etching of the substrate for substrate cleaning. The sputtering was conducted in an argon-oxygen atmosphere with 13.5 vol.% of oxygen. The total pressure
of the gas mixture was 1 mTorr. The substrate was kept at a temperature of 400°C and a negative voltage bias of -90V to enhance adatom mobility. Optimal sputtering parameters: oxygen concentration, substrate temperature, and voltage bias were determined in our previous work [9]. Deposition speed was 4 nm/minute and the thickness of the deposited VO$_2$ films was 120 nm. The thickness was obtained by an atomic force microscope (NT-MDT Solver P47H) in semi-contact mode (1 Hz), with a polycrystalline silicon ETALON© (NT-MDT) probe (tip radius curvature < 10 nm).

The magnetron sputtering was followed by post-deposition annealing in pure (99.999%) argon atmosphere in a tube-furnace. The duration of the annealing was 15 minutes and the temperature was 720°C. The argon flow rate during the annealing was 2000 sccm.

After the deposition, vanadium dioxide thin films were characterized by measuring sheet resistance vs temperature (R(T)) dependence, since it is a qualitative property of VO$_2$ thin films. R(T) dependence of the thin films was measured using the Solartron SI 1287 potentiostat in a two-probe configuration. To obtain sheet resistance of the VO$_2$ film, voltage bias of 1 V was applied to the sample and a current through the sample was recorded every 2 seconds while the sample was heated and cooled in a 20-90°C temperature range. The heating speed was 2°C per minute.

In order to form a parallel plate waveguide array, two thin films were cut to rectangle elements with length of 11 mm (l on figure 1) and width of 60 mm (W on figure 1). Those elements were installed in a holder made of PLA plastic (figure 3). Distance d (figure 1) between elements was 8 mm. 6 parallel plates were used to obtain an array with total dimensions of 60×40 mm, which can be measured in a present RF measuring bench.

The transmission and reflection coefficients of the sample at normal incidence of an electromagnetic wave in the frequency range from 6 to 24 GHz were measured using a methodology described in [12]. Ultra-wideband horn antennas with diaphragmatic lens and vector network analyzer R&S ZVA40 were used for the measurements.

The sample was placed (figure 4) in the aperture of a metal diaphragm positioned in the near field of the horn antennas to minimize the impact of the diffraction at the edges of both: the test sample the antennae. During the measurement of the reflection coefficient, a matched load was mounted in the area behind the diaphragm. Radio-absorbing material shaped like a three-dimensional pyramid-type block was used as the matched load. The matched load had a low reflection coefficient across the analyzed bandwidth (-50 dB). A time selection of clutter reflections with suppression of the Gibbs phenomenon was used in a digital signal processing for eliminating multiple reflections between the sample and the horn antenna [12].
The reflection and transmission coefficients of the sample were measured with a polarization of the
electric field vector along the W dimension (figure 1) of the plates with VO$_2$. During the
measurements, the sample was heated from 20°C to 90°C using a heat gun, and the temperature of the
sample was measured using a pyrometer.

4. Experimental results and discussion

During metal-insulator transition in VO$_2$ thin films, used in PPWA, their resistance changed by 2600
times (figure 7).

![Figure 7. R(T) dependence of VO$_2$ thin films used in PPWA.](image)

Numerical simulation of the frequency dependence of the transmission and reflection coefficients
was in a good agreement with experimental results for “opened” state (figure 8 and figure 9). In the
“closed” state the agreement was worse. There were two main sources of the discrepancy. The first
source included discontinuities in the measurement bench and unprecise assembly of the PPWA.
Dimensions of the manufactured PPWA were within 0.2 mm of the dimensions used for the numerical
calculation. The second source included the use of the periodic boundary in the model, so certain
dimensions of the modeled PPWA were infinite. Because of it, an influence of the manufactured PPWA
finite size could not have been observed in the numerical simulation. The influence was the most
significant in the “closed” state, where PPWA had metallic walls. That is why the simulated reflection
coefficient spectrum had only one peak instead of four in the experimental spectrum (curves with solid
symbols in figure 9). Measurement and simulation of the transition coefficient were also different in the
“closed” state (curves with solid symbols in figure 8). The amplitude of the measured transition
coefficient was higher because the manufactured PPWA did not entirely cover the aperture of the
measurement bench. This discrepancy can be eliminated by using a model with finite dimensions.
However, a simulation of such a model will require more computational power.

In the “opened” state of PPWA at 20°C the transmission coefficient of the PPWA was -0.3 dB on
average in the analyzed frequency range. The loss of 0.3 dB was a result of the reflection from the upper
faces of the PPWA walls and the attenuation due to dielectric loss in the Al$_2$O$_3$ substrate. The reflection
coefficient spectrum of the PPWA in the “opened” state had an interference pattern (curves with open
symbols in figure 9). The interference was evident on both: measured and simulated curves. The
interference can be attributed to the distance between VO$_2$ plates.

Heating of the PPWA to 90°C induced metal-insulator transition in VO$_2$ thin films that resulted in
the decrease of the PPWA transmission coefficient by more than 10 dB (figure 8). At the same time, the
maximal value of the reflection coefficient increased from -11 dB in the “opened” state to -9 dB in the
“closed” state, which means that the drop of the transmission coefficient was caused mainly by the
growth of the attenuation due to conductive loss.
At 22.2 GHz the transmission coefficient in “closed” state had a minimum of -29 dB. The minimum is related to the length of the device (l dimension in figure 1). In the free space 22.2 GHz corresponds to 13.51 mm wavelength that is different from the length of the device, which was 11 mm. However, the primitive cell of the PPWA (figure 3) has effective dielectric constant $\varepsilon_{\text{eff}}$ that increases the length of the PPWA for an electromagnetic wave by a factor of $\sqrt{\varepsilon_{\text{eff}}}$. The $\varepsilon_{\text{eff}}$ of the layered medium consisted of air and Al$_2$O$_3$, can be calculated as follows [13]:

$$
\varepsilon_{\text{eff}} = 1 + \left( \varepsilon_{\text{sub}} - 1 \right) \frac{d_{\text{sub}}}{d_{\text{sub}} + d_{\text{air}}}
$$

(4)
The dielectric constant of VO$_2$ was not taken into consideration in (4) since the thickness of VO$_2$ was 5000 times less than the thickness of the Al$_2$O$_3$ substrate. In the PPWA $d_{sub}$ was equal to 0.5 mm and $d_{air}$ was equal to 8 mm, so the $\varepsilon_{eff}$ should be 1.48. Consequently, the effective length of the PPWA should be equal to $11\sqrt{1.48}=13.39$ mm, which is close to the resonant length of 13.51 mm obtained from the experimental data. It should be noted, that the reflection coefficient has the minimum at 22.2 GHz as well.

5. Conclusion
We report experimental fabrication and measurements of the VO$_2$-based parallel plate waveguide array with the tunable RF transmission coefficient. We present the method of synthesis of VO$_2$ thin films of sufficient size, method of numerical modeling, fabrication, and measurement of the PPWA. Fabricated PPWA changes transmission coefficient thought it from -0.3 dB to -16 dB on average in 6-24 GHz frequency range without significant growth of the reflection coefficient. To change the transmission coefficient of the PPWA, heating by hot air was used, which induced metal-insulator transition in VO$_2$. Proposed PPWA can be used as a reconfigurable element in various beam manipulating systems such as lenses and antennae.

Acknowledgments

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