

Thermally Actuated Vanadium Dioxide Millimeter Wave Reflectarray

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Abstract— This paper presents the development of a reconfigurable vanadium dioxide (VO₂) based reflectarray antenna using a novel 1-bit split patch element. The thermally actuated unit cell, composed of a quarter wavelength ($0.25\lambda_0$) copper patch and a VO₂ thin film switch is able to achieve 180° of phase at 35 GHz with a maximum loss of 0.35 dB. Such a design exploits the reversible metal to insulator transition properties of VO₂ at 68 °C. The simplicity of such an element provides a low cost practical reconfiguration strategy that can be extended to large apertures. A full-wave 40×40 ($10\lambda_0 \times 10\lambda_0$) simulation of the switchable device demonstrated a maximum gain of 21.1 dB at 0° and 1D beam scanning performance covering - 60° to +60° with a 4.5 dB reduction in peak gain over the full scanning range.

Index Terms—reflectarray, reconfigurable, Vanadium Dioxide.

I. INTRODUCTION

Due to the upward trend of new and innovative microstrip antenna technology, there has been continued interest in the area of microstrip reflectarray antennas. Microstrip reflectarrays while directive and high gain, satisfy the need for a low profile method of beam scanning for industrial communication applications. Compared to parabolic reflectors and phased arrays, microstrip reflectarrays reduce system complexity without sacrificing functionality [1].

Microstrip reflectarrays consist of a series of radiating elements arranged equidistant on a substrate and ground plane. These elements are designed such that when spatially fed, the incident energy is reradiated in a desired direction due to the phase distribution of the elements. While versatile due to the broad range of design possibilities, millimeter wave reflectarrays are susceptible to undesirable losses due to high path loss and propagation limitations.

Implementation of external components such as diodes [2] and MEMS switches [3] or tunable thin films like barium strontium titanate [4] (BST) and nematic liquid crystal [5] can enable beam steering and dynamic tuning of reflectarray elements. However, while effective at producing adequate phase control, these methods also increase system losses [6].

Building on our previous work in the area of fixed beam reflectarrays [7, 8], this work focuses on reconfigurable reflectarray design. Here we present the use of vanadium dioxide (VO₂) as a tuning mechanism on both the element and aperture level. VO₂, a temperature controlled phase-change material, undergoes a reversible dielectric to conductor phase transition at 68°C [9, 10]. Using the material, a thermally actuated linearly polarized element is realized. Capable of

180° of phase while maintain a loss < 1dB. This unit cell is used to develop a dual state 1-bit 35 GHz reflectarray antenna. This work explores the use of thermal reconfiguration by implementing a frozen design as demonstrated in [11] as a proof-of-concept. Here, a fixed beam reflectarray using various sized slotted elements is reconfigured using dielectric substrates of various heights. This unique strategy allows for design validation prior to the implementation of individual element tuning.

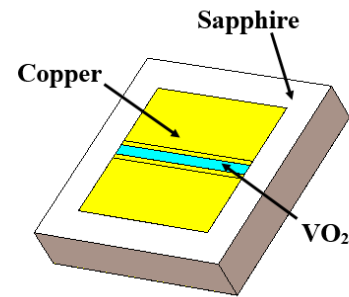


Fig. 1. Dual state VO₂ based unit cell element

II. SPLIT PATCH ELEMENT

The proposed unit cell shown in Fig.1 is designed at 35 GHz with a uniform element spacing of $\frac{\lambda_0}{4}$. The unit cell consists of a 1.5 mm copper patch (thickness = 750 nm) separated into two portions by a 55 μm rectangular gap. Underneath the gap is a VO₂ thin film (thickness = 100 nm). Using the thermal properties of the VO₂, a 180° phase change can be observed when the unit cell is heated above 68°C. In the cooled state, the VO₂ acts as a dielectric between the two metallic patches, prohibiting electrical connection. However, when the VO₂ is heated, the material becomes a conductor, connecting the two halves of the patch resulting in electrical behavior similar to that of a single patch. The unit cell is supported by a 450 μm sapphire substrate and copper ground plane (thickness = 1 μm).

While tuning an individual patch would require a single heater to actuate the VO₂ thin film switch, when applied to a larger scale, the number of heaters increases resulting in a single heater per element. This substantially impacts the system complexity due to the introduction of bias lines and several individually controlled heat sources. For this

reflectarray iteration, frozen designs are implemented as a device demonstration.

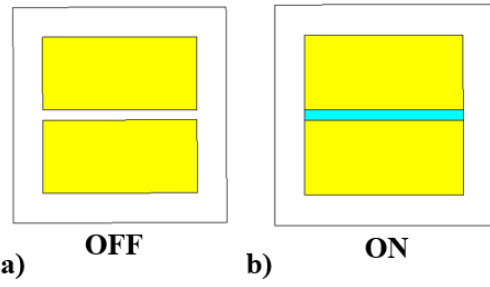


Fig. 2. The two separate unit cell representations: a) The OFF configuration where the VO₂ has been removed and b) the ON configuration where VO₂ acts as conductor between the two halves of the copper patch.

The original unit cell is separated into two unique representations one representing the OFF state and the second representing the ON state. The OFF state unit cell is created by removing the VO₂ while the ON configuration includes the VO₂. The separation of the unit cell allows for design simplification by eliminating the need for on chip heaters. Instead, the entire wafer is heated to produce the directive beam. The position of the beam on each device is controlled by the presence of the heated VO₂ thin film, mimicking the behavior of unique element heating. When the device is in the cooled state there is no beam present.

A simulation assuming periodic boundary conditions was performed in CST Microwave Studio to determine the behavior of each unit cell. In the ON configuration, the VO₂ was modeled with an assumed conductivity of 6.15×10^5 S/m, consistent with film measurements done during experimental depositions. The phase (Fig.3) and reflection amplitude (Fig.4) for both elements were evaluated. The maximum insertion loss was 0.08 dB in the OFF state and 0.35 dB in the heated state, respectively.

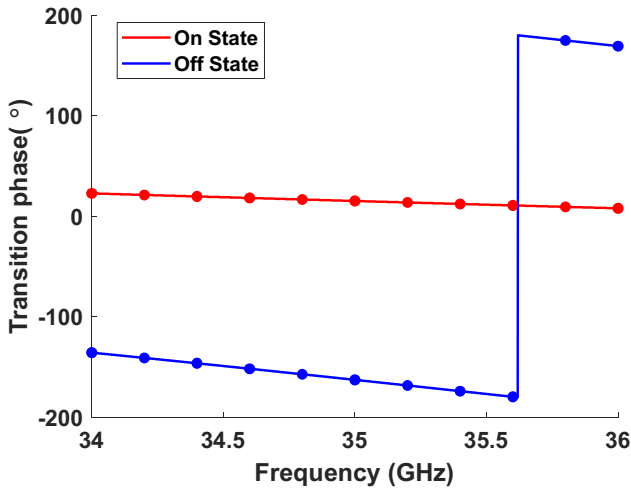


Fig. 3. Phase difference between the simulated OFF and ON reflectarray unit cells from 34 – 36 GHz

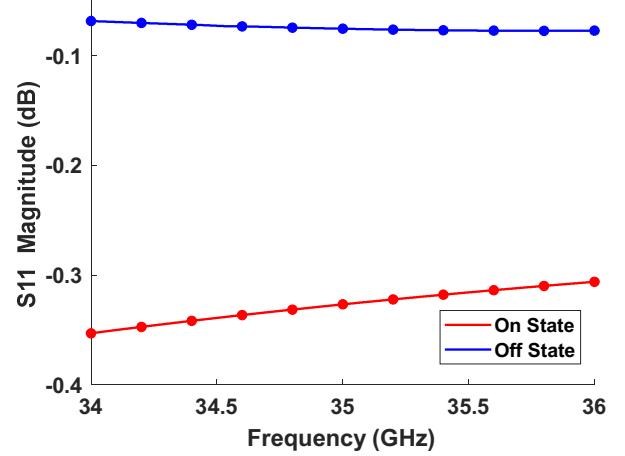


Fig. 4. The reflection coefficient of both the OFF and ON reflectarray unit cells shown from 34 - 36 GHz

III. REFLECTARRAY DESIGN

Using the element in Fig.2 several frozen 40×40 ($10\lambda_0 \times 10\lambda_0$) reflectarrays are simulated using CST Microwave Studio. Each reflectarray is developed individually resulting in one full design per simulated beam. To reduce simulation time due to high mesh volume, each reflectarray was constructed as an impedance surface. The impedance surface is created by importing the reflection characteristics of each unit cell into a 1D sheet using the calculated resistance and reactance generated during element simulations.

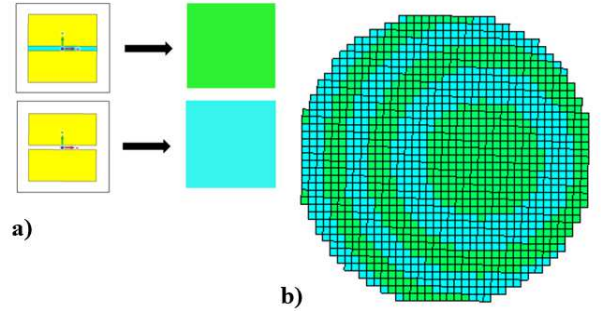


Fig. 5. Impedance surface reflectarray showing the conversion of each unit cell to the impedance sheet representation (a) and the full reflectarray impedance surface for a beam at 0° (b).

The reflectarray is created assuming uniform quantization denoted in equation 1, where φ_{mn} is the reflection phase of the element at coordinates (m,n) .

$$\varphi_{mn} = \begin{cases} 0^\circ, & 0^\circ \leq \varphi_{mn} < 180^\circ \\ 180^\circ, & 180^\circ \leq \varphi_{mn} < 360^\circ \end{cases} \quad (1)$$

The reflectarray is illuminated with a 26-40 GHz open ended waveguide probe with a half power beam-width (HPBW) of 32° and a maximum gain of 8.7 dB at 35 GHz. To avoid potential radiation shadowing the feed is angled 15° from the center of the reflectarray with a focus to diameter ratio of 0.53. Assuming these parameters, unique phase maps

of beams from -60° to 60° were created to demonstrate 1D scanning capabilities in the y - z plane.

IV. SIMULATION RESULTS

The simulation results (Fig.6a) show a broadside gain of 21.1 dB, HPBW of 6.8° with side lobes well below -15 dB at 35 GHz for the entire scanning range when the reflectarray is heated. At -60° the gain is reduced to 16.5 dB resulting in a 4.5 dB drop in peak gain. Similarly, at 60° the maximum gain is 16.6 dB. The simulated aperture efficiency is 13.8% in part due to the dielectric loss present due to the substrate. In the cooled state (Fig.6b) there is no beam present confirming the device dependence on the VO_2 thermal transition. This is true for all the configurations as the copper metal layer is identical in the frozen reflectarrays.

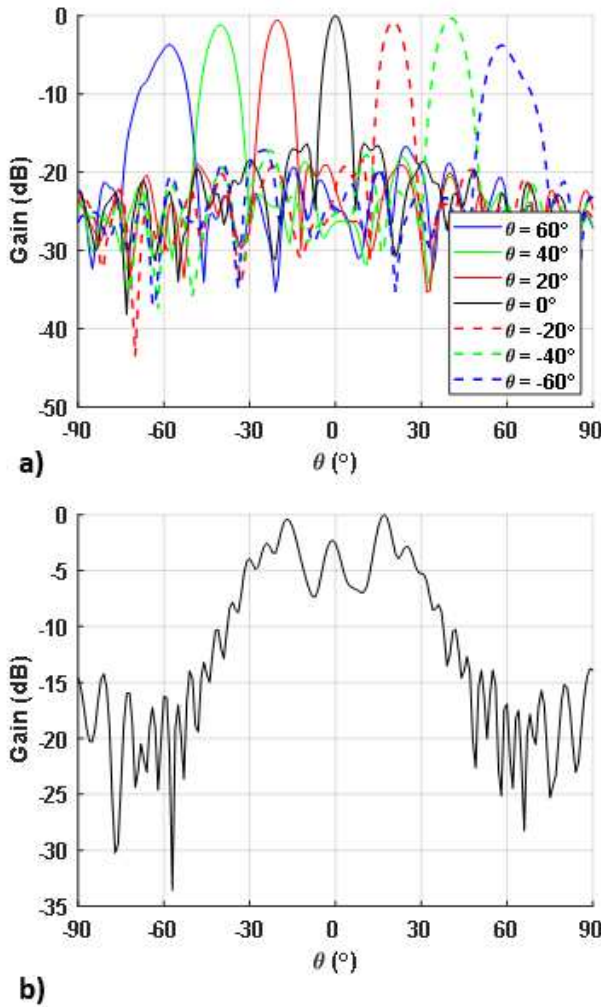


Fig. 6. The two states of the frozen reflectarray. The cooled state (a) where the reflectarray is in the heated state. Designs from -60° to 60° are shown at 35 GHz demonstrating a maximum gain of 21.1 dB at 0° (b) where the VO_2 is in the dielectric state and the radiating state.

V. CONCLUSION

As an alternative to traditional reconfiguration techniques, this paper presents the use of thermally actuated VO_2 as a method of reflectarray reconfiguration. Utilizing a tunable

thin film switch, a single bit reflectarray element is realized. The element is able to achieve 180° without the addition of active components allowing for simple design integration and fabrication. In addition to providing the necessary phase compensation, this element maintains a reflection loss of < 1 dB.

The application of the unit cell is demonstrated in the presentation of a 35 GHz tunable reflectarray capable of wide angle beam scanning from -60° to $+60^\circ$. We are currently fabricating several frozen reflectarray devices. Both fabrication and measurement results will be presented at the conference.

VI. REFERENCES

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