Low-loss vanadium dioxide-enabled mmWave tunable reflective electromagnetic surface with complementary unit cells for wave manipulation

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ABSTRACT
This study presents a novel implementation of vanadium dioxide (VO2) phase change material in an electromagnetic (EM) surface with beam steering capabilities. For the first time, we present the design, fabrication, and measurement of a globally actuated, VO2-based beam-forming reflective EM surface. We propose a design featuring complementary unit cells that enable beam steering with a single excitation, marking a pioneering use of low-loss VO2 in creating a complementary EM surface for the mmWave band. The unit cells incorporating VO2 exhibit low-loss characteristics, with $-0.92$ and $-1.9$ dB in the hot state and $-0.49$ and $-0.25$ dB in the cold state, respectively. We incorporate both positive and negative phase variants alongside two temperature-independent phase unit cells. The complementary design enables us to utilize two beam operating states, effectively exploiting the otherwise unused cold state. We experimentally demonstrated beamforming at $\pm 5^\circ$ and $\pm 10^\circ$ from the broadside. In the case of $\pm 10^\circ$, the measured gains at 35 GHz in the cold and hot states were 19.4 and 20.3 dB, respectively, which aligned well with the simulated gains of 20.9 and 21.5 dB. Manipulation of the electromagnetic wave direction with a single excitation has the potential for imaging, sensing, and communication applications. The complementary unit cell design methodology can be further adapted for mmWave beamforming, absorbing, and cloaking reconfigurable EM surfaces. Furthermore, the use of VO2 can be extended up to sub-THz frequencies due to the wideband, low-loss characteristics compared with conventional reconfigurable devices, such as PIN diodes or MEMS switches.

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I. INTRODUCTION
Smart electromagnetic (EM) surfaces, including beam-switching and frequency-shifting metasurfaces, have gained widespread attention in industry and academia, after initially serving mainly military functions.1−4 Their application has broadened to encompass wireless systems and satellite networks.5−7 Consequently, there is a growing demand for beam-switching reconfigurable EM surface solutions, particularly for applications such as point-to-multipoint links, reconfigurable intelligent systems, and base stations.8

Phase change materials (PCMs) are useful in the development of reconfigurable systems, owing to their tunable properties such as electrical resistivity or optical transmittance.9,10 Vanadium dioxide (VO2) is particularly noteworthy among PCMs for its reversible solid-to-solid phase transition at a relatively low temperature of 68 °C, facilitated by simple external thermal inputs (heating or cooling), making it ideal for integration into robust EM surfaces.11 Specifically, VO2 exhibits insulating properties when the temperature remains below 68 °C, whereas it assumes a conductive nature above this threshold, as illustrated in Fig. 1. This significant contrast in conductivity is attributed to the inherent responsiveness of VO2’s crystalline structure to changes in temperature, strain, or electric field. Below the transition point, the crystalline structure of VO2 is monoclinic. As the temperature rises, it transforms into a tetragonal rutile structure, triggering the insulator–metal transition (IMT), which decreases the resistivity of VO2 by a factor of three to
four. Additionally, VO₂ is a solid-solid phase change material with a transition temperature near room temperature, making it a good choice for practical applications where power consumption is an important consideration.

The remarkable properties of VO₂ make it a focus of investigation for numerous multifunctional devices for the mmWave band (30–300 GHz). Previous research in our group showcases the potential of VO₂. The study presents VO₂ thin films with high resistivity contrast on silicon substrates using crystallized alumina (Al₂O₃) buffer layers. Another research focuses on investigating the performance and reliability of VO₂ thin film shunt switches integrated with coplanar waveguide (CPW) in the frequency range of 35–45 GHz. After subjecting the switches to 100 × 10⁶ thermal cycling, statistical analysis showed no degradation in the electrical properties of the VO₂ switches. The large, non-linear thermal coefficient of resistance in the IMT region of VO₂ is highlighted as a favorable characteristic for its application in antenna-coupled microbolometers at 35 GHz. These devices exhibit a change in electrical resistance when exposed to radiation, making them suitable for detecting black body radiation in the mmWave band. A dual-sense linear-to-circular polarizer utilizing vanadium dioxide is explored, targeting the Ka satellite communications uplink band (27.5–31 GHz) with a four-layer meanderline metasurface. Achieving two beams with global excitation requires unit cells capable of at least four distinct phase states, as shown in Figs. 3(b) and 3(c). Therefore, we propose complementary unit cells designed for wavefront manipulation, enabling beam steering with a single excitation. This novel method can be expanded to include applications in absorbers and cloaking. Moreover, to the authors’ knowledge, this study is the first demonstration of the design, fabrication, and measurement of a globally actuated reflective EM surface integrated with VO₂ with beam steering functionality. Earlier research primarily shows simulation outcomes of VO₂-based EM surface without measurement results or concentrates on the phase (or amplitude) modulation properties of the EM surface’s cells. Prior research has also been done using a transmitting surface rather than reflection for different applications. Preliminary findings in this research of the unit cell design and THz filter without using complementary methods have been previously published. The process employs

![FIG. 1. Resistivity vs temperature measurements comparing the resistivity of the VO₂ thin films on bulk crystalline C-plane sapphire wafers.](image1)

![FIG. 2. Visualization of the beam-switching complementary EM surface concept employing VO₂.](image2)
microfabrication, facilitating future integration with integrated circuits via monolithic integration.

The complementary unit cell methodology for the EM surface is described in Sec. II, while Sec. III explores unit cell designs that are practically realizable, each with a distinct response to temperature variations. The VO$_2$-integrated EM surface simulation is presented in Sec. VI, and the fabrication process is discussed in Sec. V. The measurement results are presented in Sec. VI. Finally, the paper culminates with a discussion and conclusion.

II. THEORETICAL COMPLEMENTARY DESIGN METHODOLOGY

The steering of the EM surface to achieve desired angles necessitates an analysis of the phase-shift distribution across the EM surface aperture. This analysis involves evaluating factors such as the distance between the phase center of feeds to each unit cell, the optimal phase value required to achieve the desired steering, and the corresponding phase adjustment necessary to attain the ideal phase value. For a beam directed toward the desired angles ($\theta$, $\varphi$), the phase requirement for the $i$th element of the EM surface can be mathematically expressed as

$$\phi_i = k_o (d_i - \sin \theta_i (x_i \cos \varphi + y_i \sin \varphi)) + \Delta \phi_i,$$  

where $k_o$ is the free space wave number and $d_i$ represents the distance between the $i$th element’s position and the phase center of the feeds. Equation (1) introduces extra design freedom by including a constant reference phase $\Delta \phi$. Then, $\phi_i$ is converted into a value between 0 and 360° by modulo operation. By employing uniform quantization, the range of achievable phase values $\phi_{qi}$ is constrained to only two distinct states as

$$\phi_{qi} = \begin{cases} 0^\circ, & 0^\circ \leq \phi_i < 180^\circ, \\ 80^\circ, & 180^\circ \leq \phi_i < 360^\circ. \end{cases}$$

The feed with a gain of 6.5 dBi is assumed to be 44 mm away from the EM surface phase center at $\Theta_{offset} = 15^\circ$ and $\varphi = 180^\circ$. Using (1) and the modulo operation, the phase distribution required to achieve the desired steering angles of $\theta = \theta_o$ and $\varphi = 90^\circ$ is plotted in Fig. 3(a). Subsequently, the phase distribution undergoes quantization, resulting in the phase shown in Fig. 3(b). Similarly, to achieve a steering angle of $\theta = \theta_o$ and $\varphi = 270^\circ$, (1) and (2) are used to generate the phase distribution shown in Fig. 3(c).

Given the association of the cold and hot states with the steering angles $\theta = \theta_o$ and $\varphi = 90^\circ$, and $\theta = \theta_o$ and $\varphi = 270^\circ$, respectively, the gray and yellow circles in Fig. 3 depict unit cells that exhibit a transition in phase from 0° to 180° and from 180° to 0° upon experiencing thermal actuation. To successfully realize two states that are supported by a single external control mechanism, such as temperature, the introduction of the reversible phase shift is essential. We introduce practical complementary unit cells to achieve the transition from 180° to 0° and from 0° to 180°, respectively. The cyan and purple circles in Fig. 3 require unit cells with a fixed phase value, regardless of temperature changes. This implies that two additional unit cells are needed to maintain a phase of either 0° or 180° throughout temperature variations. We also introduced complementary thermal invariant unit cells. The proposed beam is achieved by employing complementary unit cells that vary or are constant with temperature and exhibit inverse phase transitions.

III. IMPLEMENTATION OF COMPLEMENTARY UNIT CELLS

Two pairs of unit cells were designed for the complementary methodology employed in our EM surface. The first pair of unit cells incorporates VO$_2$, resulting in thermally switchable phase states. The other pair of unit cells does not include VO$_2$ and retain the same phase for both the hot and cold states of the EM surface.

A. Split patch unit cell

The VO$_2$-incorporated split patch unit cell aims to achieve two phases from 180° to 0° as the VO$_2$ transitions from the cold to the hot state. The unit cell demonstrates a decreasing phase curve when subjected to thermal actuation. The configuration consists of two copper patches separated by a layer of VO$_2$ as illustrated in Figs. 4(a) and 4(b). Designed to operate at a frequency of 35 GHz, the $\lambda/4 \times \lambda/4$ (L$_o \times L_o$) unit cell is constructed with a 0.7 μm thick (T$_1$) copper patch that incorporates a 100 μm gap (G). Within this gap, a rectangular VO$_2$ patch with a thickness of 100 nm (T$_2$) serves as the switching mechanism for the unit cell. The patch has a size of 1.49 $\times$ 1.49 mm$^2$ ($W_{op} \times L_{op}$). To account for potential misalignment during fabrication, the VO$_2$ layer extends 5 μm beneath both sides of the patch. The entire structure is positioned on a sapphire substrate with a thickness of 430 μm (H), a relative permittivity of 9.4, and a loss tangent of 0.004, with a 0.5-ounce copper ground plane (T$_g$) located beneath the substrate. The selection of sapphire as the...
substrate is motivated by previous research conducted by our group on VO$_2$ deposition attributed to the high contrast ratio of VO$_2$; however, other substrates such as glass or silicon can also be used. EM simulations of the unit cell were carried out with periodic boundary conditions in CST Studio Suite. In the simulation process, the hot state of VO$_2$ was modeled with a conductivity of $2.6 \times 10^5$ S/m and a permittivity of $10^4$. On the other hand, the cold state was modeled considering the dielectric permittivity with a value of $\varepsilon_r = 40^{28,29}$ and a conductivity of 65 S/m, which was determined through experimental measurement in Sec. V.

At the operating frequency of 35 GHz, the EM surface unit cell demonstrates a reflection coefficient of $-0.92$ dB in the hot state and $-0.49$ dB in the cold state as shown in Fig. 4(c). Moreover, as illustrated in Fig. 4(d), the unit cell can achieve a 181° reflection phase difference. Specifically, the phase in the hot state was $-161^\circ$, while 20° in the cold state at 35 GHz. The operating bandwidth of the unit cell is defined within the range of 33.7–36.7 GHz, with a phase range of $180^\circ \pm 30^\circ$. In the narrower frequency range of 34.8–35.8 GHz, the phase range narrows further to $180^\circ \pm 10^\circ$.

The application of heat to the unit cell induces an enhancement in the conductivity of VO$_2$, facilitating a transition from a dielectric to a conductive state. Consequently, the resonant frequency of the unit cell shifts, leading to a change in its phase response. In the hot state, the VO$_2$ thin film acts as an electrical bridge between the two halves of the patch, therefore altering the two separate patches to that of a conventional patch element. As shown in Fig. 5(a), the electric fields within the unit cell are maximized along the outer edge of the patch in the hot state. As illustrated in Fig. 5(b), the conductivity of VO$_2$ does not significantly impact the reflection phase, as long as it is $>3.3 \times 10^4$ S/m. This implies that when the conductivity of VO$_2$ in its hot state exceeds $3.3 \times 10^4$ S/m, VO$_2$ functions like a low-loss conductor, electrically shorting the patches above and below it. The conductivity of the fabricated VO$_2$ in its hot state is $2.5 \times 10^5$, approximately ten times greater than the simulated minimum. On the other hand, in the cold state, the VO$_2$ layer acts as an insulator. As a result, the gap in the patch becomes relatively large, minimizing the capacitance between the two halves of the patch. This configuration causes the unit cell to function similarly to two separate rectangular patches, where the electric field of each half is the most prominent at the edges, as depicted in Fig. 5(a).

**B. Slot-loaded patch unit cell**

The slot-loaded patch unit cell is the inverse of the negative sloped phase element when VO$_2$ is transitioned. As illustrated in Fig. 6(a), this specific unit cell is intended to exhibit a phase of 0° in the cold state and an increased phase of $180^\circ$ when heated. The dimensions of the slot-loaded patch unit cell are as follows: the slot length ($L_s$) is 1.2 mm, the slot width ($W_s$) is 0.1 mm, the patch length ($L_{ps}$) is 1.35 mm, and the patch width ($W_{ps}$) is 0.95 mm. The remaining parameter values, such as the conductor thickness, remain unchanged from the previous unit cell configuration.

At the designated operating frequency of 35 GHz, the EM surface unit cell demonstrates a low reflection coefficient of $-1.9$ dB in the hot state and $-0.25$ dB in the cold state, as depicted in Fig. 6(c). Moreover, the unit cell aims to achieve a phase range spanning from 0° to 180°. As depicted in Fig. 6(d), the actual reflection phase range achieved by the unit cell amounts to $186^\circ$. Specifically, in the hot state, the phase registers at $35^\circ$, while in the cold state, it registers at $-151^\circ$. Operating within a defined bandwidth ranging from 32.3 to 37.1 GHz, the unit cell maintains the desired phase range of $180^\circ \pm 30^\circ$. When the frequency range is narrowed down to 32.8–36.1 GHz, the phase range between the
two operational states becomes constrained, exhibiting a deviation of $180^\circ \pm 10^\circ$.

The introduction of a slot in a patch antenna brings about modifications in the current distribution, therefore influencing the electrical characteristics of the unit cell and inducing a shift in its resonant frequency. The elongated slot between the patches influences the electrical length of the surface current in the $x$ direction in Fig. 6(b). In the hot state, the electrical length stays constant along the $x$ direction, while in the cold state, the central slot acts as a dielectric, compelling the surface current to cross at the edge of the patch. This extension of the electrical length in the cold state leads to a reduced resonant frequency compared to the hot state, as shown in Fig. 6(c).

C. Thermally phase invariant complementary unit cells

The objective of the phase invariant unit cells is to achieve phase values of $0^\circ$ or $180^\circ$ irrespective of temperature variations. These phase requirements are met by defining the 00-patch and 11-patch, which correspond to the reflection phases of $0^\circ$ and $180^\circ$, respectively. The design process incorporates two square patch elements with lengths of $1.55 \text{ mm} (L_{00})$ [Fig. 7(a)] and $1.03 \text{ mm} (L_{11})$ [Fig. 7(b)], while ensuring consistency with the previous unit cell element models in terms of the substrate, ground plane, and...
periodicity. The maximum reflection coefficient is determined to be $-0.02 \, \text{dB}$ for the static 00-patch unit cell and $-0.07 \, \text{dB}$ for the static 11-patch unit cell [see Fig. 7(c)]. Subsequently, this results in a phase of $-162^\circ$ for the static 00-patch unit cell and a phase of $35^\circ$ for the static 11-patch unit cell [refer to Fig. 7(d)].

**D. Unit cell incident angle analysis**

In the case of the EM surfaces, implementing a feed at the broadside can be challenging due to measurement complexities. It is necessary to evaluate the characteristics of unit cells in response to variations in the incident angle. In this study, the EM surface is fed with an open-ended waveguide positioned at $\theta_{\text{offset}} = 15^\circ$ and $\varphi = 180^\circ$. Consequently, the analysis of various incident angles is conducted while assuming $\varphi$ of $180^\circ$. The maximum incident angle expected at any unit cell with this feed configuration and an array diameter of $10 \lambda_0$ is $50^\circ$, so $\theta$ is swept from $0^\circ$ to $50^\circ$.

For the split patch unit cell, the reflection results concerning incident angles are depicted in Figs. 8(a) and 8(b). In the cold state, at 35 GHz, a phase change of $+35^\circ$ is observed as the incident angle increases to $50^\circ$. At frequencies of 33 and...

**FIG. 7.** 3D view of (a) large size (00) patch and (b) small size (11) patch unit cell. (c) $|S_{11}|$ reflection coefficient and (d) $\angle S_{11}$ reflection phase for 00-patch and 11-patch unit cell as a function of frequency.

**FIG. 8.** $\angle S_{11}$ reflection phase of hot and cold states: (a) split patch unit cell and (b) slot-loaded patch unit cell vs incident angle.
37 GHz, the phase increases by 40° (from 60° to 100°) and 20° (from −26° to −6°), respectively, as the incident angle reaches 50°. In the hot state, the variation in the reflection phase increases with a change in the angle of incidence, which is relatively small. At 35 GHz, the phase change remains within 2° as the incident angle increases to 50°, while at frequencies of 33 and 37 GHz, the phase difference reaches up to 6° and 4°. As illustrated in Fig. 8(a), this discrepancy arises due to the steeper slope of the reflection phase in the cold state, compared to the hot state. The large slope of the operating frequency in the cold state results in a resonant frequency change due to variations in the illumination angle, leading to changes in the reflection phase angle. When examining the phase difference between the two states in relation to the incident angle, it is observed that at 35 GHz, a value of 184.1° is observed until an incident angle of 15°, increasing to 214.6° at 50°.

Like the split patch unit cell in the hot state, the slot-loaded patch unit cell in the cold state exhibits at 35 GHz, the phase change remains within 10° as the angle of incidence increases to 50°. In the hot state, at 35 GHz, an increment of 40° in the phase change is observed as the angle of incidence increases to 50°. This characteristic is attributed to the larger slope exhibited by the hot state, compared to the cold state. By analyzing the phase difference between the two states with respect to the incident angle, it is evident that at 35 GHz, a value of 191° is maintained until an incident angle of 15°, and subsequently, increases to 234° at an incident angle of 50°.

The reflection amplitude results are shown as a function of incident angles in Figs. 9(a) and 9(b). Concerning the reflection amplitude analysis, our focus lies within the hot state. This choice is because the loss of the reflection amplitude in both the split and slot-loaded patch is more pronounced in the hot state than in the cold state. Specifically, in the context of the negative sloped phase unit cell shown in Fig. 9(a), as the incident angle increases to 50°, the amplitude enlarges to −0.6 dB at 35 GHz. Similarly, at 37 GHz, an increment in the reflection amplitude from −1.1 to −0.8 dB is represented. As illustrated in Fig. 9(b), for the positive sloped phase load patch, with an increase in the incident angle to 50°, the loss
due to the reflection amplitude reaches 2.1 dB at 35 GHz. Furthermore, at 37 GHz, the reflection amplitude loss increases from 2.7 to 4.2 dB. It can be deduced that the behavior of the individual unit cells exhibits stability under the conditions of open-ended waveguide position of a $\theta_{\text{offset}}$ of 15° and a $\varphi$ of 180°, particularly within the vicinity of 35 GHz.

IV. EM SURFACE DESIGN AND INITIAL SIMULATION

To create beam-switching EM surface between the hot and cold states, phase maps were designed denoting the required phase for each element. The angles $\theta_o = \theta'$ and $\varphi = 90^\circ$, and $\theta_o = \theta'$ and $\varphi = 270^\circ$ were set in the VO$_2$-integrated EM surface for the cold and hot states, respectively, with $\theta_o$ values of 5° and 10°. As illustrated in Figs. 10(a) and 10(b), a Ka-band open-ended waveguide probe (SAP-28KF-E2) with $\theta_{\text{offset}}$ of 15° and $\varphi$ of 180° was used to excite the EM surface. The feed probe was positioned 44 mm from the EM surface phase center with a ratio of focal length to aperture size ($F/D$ ratio) of 0.54.

To realize both phase maps of Fig. 2(b) in the cold state and Fig. 2(c) in the hot state, a new phase distribution was created by combining the two individual maps. This concept is illustrated in Figs. 10(c) and 10(d). It is observed that in this scenario, all complementary unit cells described in Sec. III are necessary. For achieving a phase of 180° in the hot state and a phase of 0° in the cold state, the slot-loaded unit cell is allocated and highlighted in gray. Conversely, the split patch unit cell can be utilized and highlighted in yellow. Additionally, a 00-patch unit cell is employed to maintain 0° in both states, while a patch with a 11-patch unit cell is allocated for maintaining a phase of 180°. Observing the phase map shows a symmetrical distribution along the $x$-axis and an inverted distribution along the $y$-axis, which is the result of adjusting the constant reference phase $\Delta \phi$.

The finite array was simulated in CST Studio Suite as an impedance surface (Appendix), yielding the results as shown in Fig. 11. The beams generated in both the cold and hot states exhibit symmetrical characteristics, with gain performance within a 1 dB margin, leading to comparable sidelobe levels (SLLs). The simulation results indicate that for conditions $\theta_o = 5^\circ$ and $\varphi = 90^\circ$, the reflection coefficient is simulated at 20.0 dB, while for $\theta_o = 5^\circ$ and $\varphi = 270^\circ$, it is simulated at 20.1 dB. The corresponding SLLs
are found to be $-17.8$ and $-17.9$ dB, respectively. In the case of $\theta_o = 10^\circ$ and $\varphi = 90^\circ$, the reflection coefficient is determined to be $19.7$ dB, while for $\theta_o = 10^\circ$ and $\varphi = 270^\circ$, it is determined to be $20.1$ dB. The SLL values exhibit $-19.1$ and $-17.1$ dB, respectively.

Figure 12 illustrates a scenario without the complementary method, where beam steering is observed at $-10^\circ$, yet no beam forms with state changes, indicating the ineffectiveness of beam formation without employing the complementary approach. Following the impedance surface simulations, we carried out a more accurate full-wave simulation of the finite array, which will be compared to the measurement results in Sec. VI.

A steady-state thermal simulation was performed in ANSYS ICEPAK with a wafer placed on a constant power source as shown in Fig. 13(a). The steady-state temperature on the top surface of the wafer is shown, demonstrating the complete transition of VO$_2$ over the wafer with a maximum temperature of 75 °C for an input power of 60 W. The input power is swept in Fig. 13(b) to obtain the maximum steady-state temperature as a function of the dimming range of the source. Using a 60 W infrared (IR) source, we measured a VO$_2$ sapphire wafer and observed a transition to 70 °C in 42 s and saturation within 90 s.

V. VO$_2$-INTEGRATED EM SURFACE FABRICATION
A. VO$_2$ layer

The fabrication process of the VO$_2$-based EM surface starts with a 100-mm-diameter C-plane sapphire wafer. VO$_2$ deposition is a critical step. The deposition of VO$_2$ material was carried out under controlled conditions following the procedure detailed in our prior work. To achieve the desired deposition, a mixture of Ar$^+$ and O$_2$ gases was introduced into the chamber at specific flow rates. These gases were introduced along with the vanadium target. As illustrated in Fig. 14(a), to achieve a total deposited thickness of 100 nm, the deposition process was carried out for a total duration of 20 s.

[Diagram of microfabrication process to fabricate VO$_2$-integrated EM surface: (a) VO$_2$ deposition on the sapphire wafer, (b) photoresist spinning, (c) first photolithography for patterning VO$_2$, (d) VO$_2$ etching, (e) second photoresist spinning, (f) second photolithography to define copper structure, and (g) copper deposition and lift-off process.]
of 15 min. To assess the electrical properties of the fabricated VO₂ samples, the sheet resistance of each sample was characterized using a four-point probe measurement. Additionally, the average contrast ratio, calculated as the ratio of the maximum to minimum reflectivity values among the samples, was determined to be 4.3 × 10⁵ (see Table I).

Following the deposition process, a 25-min treatment using hexamethyldisilazane (HMDS) and a 5-min dehydration bake were performed. Subsequently, a 1.5 μm layer of S1813 positive resist was deposited on both samples using a standard process in Fig. 14(b). The test vehicles were then exposed using a Heidelberg maskless aligner (MLA) [Fig. 14(c)]. To etch the VO₂ thin film, reactive ion etching (RIE) was employed, and afterward, the resist was removed using a solution of N-methyl-2-pyrrolidone (NMP) [Fig. 14(d)].

B. Copper layer

To obtain the copper pattern, AZNLOF2070 resist is deposited on both test vehicles as in Fig. 14(e). The samples underwent secondary exposure and patterning process utilizing an MLA shown in Fig. 14(f). The sample was exposed for a total of 50 min with a 375 nm laser and a dose of 475 mJ/cm². Copper was deposited through the E-beam evaporator. After deposition, the underlying resist is removed. The metal thickness was set to 700 nm in Fig. 14(g). The correct designs were confirmed by comparing the copper pattern to the designed EM surface mask. In Fig. 15(a), a micrograph depicting the individual unit cells is displayed. Figures 15(b) and 15(c) showcase two specific complementary EM surface designs intended to target θ₀ = 5° and θ₀ = 10°, respectively.

VI. EM SURFACE MEASUREMENT

After on-wafer fabrication of the array, radiation pattern measurement was carried out in an anechoic chamber. Because the EM surface shifts the beam between hot and cold states, the pattern measurements required additional instrumentation (Fig. 16). To facilitate the measurement of the EM surface, a measurement setup was fabricated using 3D printing. The heat required for the reconfigurable EM surface was provided by an external 60 W ceramic IR source. This ceramic IR source, with dimensions of 100 × 75 mm², demonstrated uniform heating characteristics. The corresponding visual representations, shown in Figs. 16(b) and 16(c), illustrate the deactivated and activated states of the source. To mitigate the potential structural deformation, the EM surface wafer was directly placed on the ceramic IR source, therefore minimizing the number of plastic components in contact with the heat source, as depicted in Figs. 17(a) and 17(b). To secure the sample in place, self-adhering high-temperature silicone tape was used to attach it to the IR source. To support the feed, in place of the primary backplate, a secondary fixture is 3D printed to attach to the original feed fixture to provide structural stability shown in Fig. 17(c). The waveguide probe holder consists of a 3D printed wrap around enclosure where the probe is inserted.

The EM surface was excited using an open-ended waveguide probe with an angle θ_offset of 15° and φ of 180°, considering the same conditions as in the full-wave simulation shown in Figs. 17(d) and 17(e). For the full-wave simulation EM surface, a comprehensive EM surface model encompassing four unit cells is generated through an automated process [Fig. 17(c)]. The EM surface was positioned within an anechoic chamber to facilitate precise measurements within the range of −90° ≤ θ ≤ 90°, each measurement with a 1° increment. To validate the intended EM surface performance, measurements were conducted both in the absence of thermal actuation, representing the EM surface’s cold state, and with the activation of the heating bulb for the hot state.

For the complementary EM surfaces, the results obtained for θ₀ = 5° and φ of 90°, as well as θ₀ = 5° and φ of 270°, verify beam steering capacity in the yz-plane, as depicted in Fig. 18(a). The maximum simulation gains achieved in the hot and cold states were reported as 20.2 and 20.7 dB, respectively. In contrast, the measured results yielded gains of 19.1 and 19.8 dB, respectively, indicating a close agreement within a 1 dB deviation from the expected outcomes. The simulated half-power beamwidth (HPBW) for both states was determined to be 6.2°. However, the measured beam exhibited a slightly wider
beamwidth of 8° in both the cold and hot states. The corresponding SLLs are found to be −15.8 and −16.2 dB, respectively. Expanding the scope of beam switching to encompass a total of 20°, the measured gain in the cold and hot states reached 19.4 and 20.3 dB, respectively in Fig. 18(b). These measured results, when compared to the simulated gains of 20.9 and 21.5 dB, exhibit a reasonable alignment. The SLL values exhibit −14.6 and −12.9 dB, respectively. The relatively higher SLL of the measured values can be interpreted as the result of a combination of pattern distortion through feed shifting by cable tension and the effects of fabrication defects, which will be discussed in Sec. VII.

For θ_0 = 5° and 10°, all measured cross-polarization levels in both the cold and hot states exhibited a performance of 20 dB lower than the maximum gain. Additionally, we have included results for the non-complementary EM surface in Fig. 19, which fails to operate in the cold state, in contrast to Fig. 18. There is good agreement between the measurement and simulation results with a peak gain of 15.1 and 16.4 dB, respectively, at the hot state. In the hot state, the cross-polarization levels are 20 dB lower than copolarization. The measured sidelobe levels are 2.1 dB higher than the simulated design, resulting in levels −10.3 dB below the main beam in the hot state. This increase is due to undesirable reflections from the measurement setup not included in the simulation model. In terms of beam width, the measured results also yielded a strong alignment to the simulation. The HPBW is 6.8° and 8.1° for simulation and measurements, respectively.

VII. DISCUSSION

As shown in Table II, the VO_2-based EM surface exhibited a simulated gain of 21.5 dB and an aperture efficiency of 14.1%. Spillover loss of 3.68 dB and illumination loss of 0.24 dB are calculated for an open-ended waveguide configuration characterized by a gain of 6.5 dB and an F/D ratio of 0.54. The open-ended waveguide has HPBW values of 60° in the H-plane and 110° in the E-plane, resulting in an almost uniform illumination and a high spillover loss. By optimizing the F/D ratio, the spillover loss can be reduced in Fig. 20. A quantization error of −3 dB for a 1-bit unit cell, a theoretical gain of 22.0 dB, and an aperture efficiency of 16.1% is calculated. The same EM surface configuration demonstrated a measured gain of 20.3 dB and an aperture efficiency of 10.9%. With improved feed placement to minimize illumination and spillover losses, the maximum achievable efficiency is 20.2%. We note that the 1-bit quantization fundamentally imposes a limit on efficiency of 50% as a trade-off for a simplified design. A comprehensive efficiency analysis is presented in Table II, revealing additional gain losses of 1.2 dB from the simulated peak gain attributable to three factors including complementary phase (α_1), fabrication defects (α_2), and thermal actuation.

The first factor is related to the complementary phase. In the case of the negative sloped phase unit cell structure, the reflection phase is 20° in the cold state and −161° in the hot state, resulting in a phase difference of 181°. The other two unit cells exhibit phase differences of 186° and 197° between −151° to 35° and −162° to 35°, respectively. These deviations from the ideal phase difference and incomplete complementarity contribute to a decrease in the overall aperture efficiency of the EM surface. In addition to the inherent 1-bit quantization loss, the presence of an imperfect complementary phase will introduce additional losses denoted as α_1.

Additionally, the second contributing factor relates to fabrication defects. During the lift-off process, we found that less than 5% of the unit cell was over-lifted, leading to the disappearance of the copper region within those unit cells. Consequently, when the area is illuminated with an electromagnetic wave, a reflection phase distribution different from the desired phase is formed, which impacts
higher unit cell phase losses. The occurrence of a fabrication defect will result in an additional loss attributed to the unit cell, denoted as the $\alpha_2$ term.

The final factor impacting the EM surface performance is thermal actuation. During the experiment, the EM surface was subjected to heat primarily from the bottom surface, which required the heat to propagate through the ground plane and substrate to reach the aperture surface. As a result of this heating arrangement, the ground plane was consistently exposed to high temperatures, resulting in minor burn marks on the back surface.

The significance of this paper lies in its achievement of successfully demonstrating the comprehensive process of designing, fabricating, and measuring an EM surface using a complementary method capable of beam switching through the thermal actuation of VO$_2$. Table III offers a comparative overview of various types of EM surfaces. Notably, there is a case of a graphene integrated EM surface designed for operation at 1.3 THz, leveraging the unique surface plasmonic properties, thereby changing the complex permittivity of graphene. It is interesting to highlight that cases using VO$_2$ exhibit low unit cell losses, suggesting better performance at the mmWave band than other approaches, such as LC and BST. Additionally, it is worth noting that the proposed EM surface exhibits ease of manufacturing facilitated by the batch fabrication process enabled by VO$_2$ thin film deposition on a wafer. In conclusion, the integration of VO$_2$ as a mmWave reconfigurable device offers several notable advantages. VO$_2$ exhibits a loss ranging from 2 to 3 dB at the mmWave band. Additionally, the EM surface incorporates VO$_2$ to enable simplified thermal tuning.
VIII. CONCLUSION

We propose a complementary unit cell design enabling beam steering with single excitation. This study verified a novel application of low-loss VO$_2$ in the design of a complementary EM surface operating at a frequency of the mmWave band. The EM surface design includes increasing and decreasing phase variants, as well as two temperature-independent phase unit cells. This study is the first demonstration of the design, fabrication, and measurement of a thermally actuated, globally reconfigurable EM surface integrated with VO$_2$ with beam steering. Fabrication of the EM surface utilizes lithography techniques. Measurements are conducted for two cases: $\theta_o = 5^\circ$ and $\theta_o = 10^\circ$. The measured gains, at $\theta_o = 5^\circ$ and $\varphi = 90^\circ$, and when the beam is steered to $\theta_o = 5^\circ$ and $\varphi = 270^\circ$, align with the simulation results, achieving measured gains of 19.1 and 19.8 dB, respectively. Additionally, when the total beam steering is increased to $20^\circ$, the measured gain at $\theta_o = 5^\circ$ and $\varphi = 90^\circ$ reaches 19.4 dB, and when the EM surface is actuated to steer the beam to $\theta_o = 10^\circ$ and $\varphi = 270^\circ$, the measured gain is 20.3 dB. These measured results align reasonably well with the simulated gains of 20.9 and 21.5 dB. The successful development of a mmWave EM surface incorporating VO$_2$ technology establishes a solid foundation for future applications at the mmWave band. With its inherently

### TABLE II. VO$_2$ EM surface gain budget at 35 GHz.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum efficiency</td>
<td>50% Calculated</td>
</tr>
<tr>
<td>Theoretical directivity</td>
<td>29.9 dB Calculated</td>
</tr>
<tr>
<td>Illumination loss</td>
<td>0.24 dB Calculated</td>
</tr>
<tr>
<td>Spillover loss</td>
<td>3.68 dB Calculated</td>
</tr>
<tr>
<td>1-bit quantization loss$^a$</td>
<td>$3 + \alpha_1$ dB Calculated</td>
</tr>
<tr>
<td>Unit cell losses (mag., phase)$^a$</td>
<td>$2 + \alpha_2$ dB Calculated</td>
</tr>
<tr>
<td>Peak gain</td>
<td>22.0 dB Calculated</td>
</tr>
<tr>
<td>Peak gain</td>
<td>21.5 dB Simulated</td>
</tr>
<tr>
<td>Efficiency</td>
<td>14.1% Simulated</td>
</tr>
<tr>
<td>Peak gain</td>
<td>20.3 dB Measured</td>
</tr>
<tr>
<td>Efficiency</td>
<td>10.9% Measured</td>
</tr>
<tr>
<td>Achievable efficiency</td>
<td>20.2% Simulated</td>
</tr>
</tbody>
</table>

$^a$Estimated gain calculation is carried out with $\alpha_1 = 0$ and $\alpha_2 = 0$. 

FIG. 19. Measurement and simulation gain results of the EM surface without a complementary design for no radiation (blue line) and in the $\theta_o = 10^\circ$ and $\varphi = 270^\circ$ directions (red line).

FIG. 20. Calculated efficiencies as a function of $F/D$. 

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low-loss characteristics compared to conventional reconfigurable technologies such as PIN diodes and MEMS switches, VO$_2$ is a suitable technology up to sub-THz frequencies. Reducing the thermal transmission time will further enable VO$_2$-based smart EM surfaces to be used in smart factories or CubeSats, where millisecond beamsteering can be utilized.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

J. A. Ramsey and S. Y. Lee contributed equally to this work.

J. A. Ramsey: Data curation (lead); Formal analysis (equal); Methodology (lead); Writing – original draft (equal); Writing – review & editing (equal). S. Y. Lee: Formal analysis (equal); Writing – original draft (equal); Writing – review & editing (equal). W. R. Disharoon: Writing – review & editing (supporting). D. L. West: Writing – review & editing (supporting). N. Ghalichechian: Conceptualization (lead); Funding acquisition (lead); Supervision (lead); Writing – original draft (supporting); Writing – review & editing (supporting).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

APPENDIX: SURFACE IMPEDANCE SIMULATION

Simulating large-scale structures with small feature sizes as compared to $\lambda_o$, including 100 nm thickness of VO$_2$, becomes computationally expensive. Scaling large structures into a variation more computationally manageable allows for design flexibility and a reduction in the simulation time. In this case, the EM surface with a total of 10$\lambda_o$ diameter and 1248 elements having over 400 $\times$ 10$^6$ mesh cells would require heavy computational power. Upon design improvement, the simulation would have to be repeated, increasing the time spent in the design process.

For this reason, to simplify initial simulations, we converted the EM surface into an impedance surface. Described as a relation of the tangential electric and magnetic fields at the surface of conductors. These models enable fast computation by establishing a impedance surface models is used to analyze propagation and scattering phenomena associated with lossy dielectric objects or imperfect conductors. These models enable fast computation by establishing a relationship between the electric and magnetic fields on the surface of an impedance model is described by\(^{34}\)

\[
\vec{E}_t(\omega) = Z(\omega) \left[ \n \times \vec{H}_t(\omega) \right], \tag{A1}
\]

where

\[
Z(\omega) = \frac{\sqrt{\omega \varepsilon_2}}{\sqrt{\sigma + \omega \varepsilon_2}}. \tag{A2}
\]

$\vec{E}_t(\omega)$ and $\vec{H}_t(\omega)$ are the tangential field components, $Z(\omega)$ is the surface impedance, and $\n$ is the normal vector pointing from medium 2 to medium 1. The intrinsic impedance can be approximated along the real axis, removing a medium dependency. $Z(\omega)$ is employed to define a normalized impedance function $Z_N(\sigma')$, producing a simplified approximation by replacing $\omega$ by the transform variable $s$. $Z_N(\sigma')$ is expressed as

\[
Z_N(\sigma') = \frac{1}{\eta_s} Z(\omega s'), \tag{A3}
\]
where

\[ a = \frac{\sigma}{\varepsilon}. \]  

(A4)

Initially, the unit cell is designed and simulated following the guidelines presented in Sec. III. Subsequently, Z-parameters are computed, and an impedance model is assigned to the material under consideration. The surface impedance is provided in the form of a table, where the resistance and reactance as a function of frequency are described as input from the original full model. The representative model is treated as volumeless with the electromagnetic characteristics of the original simulated model applied. The data are then interpolated to create a full representation of the surface impedance boundary conditions, eliminating the need for volume meshing and substantially reducing the simulation time. This impedance surface, which incorporates an open-ended waveguide source, serves as preliminary validation for the gain value of the EM surface in Sec. IV.

REFERENCES