Phase Change Material Based Reconfigurable Transmitarray: a Feasibility Study

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***Abstract*—In this paper, we present the design of a reconfigurable transmitarray operating in the D-band (110 – 170 GHz). The transmitarray unit cell has a relatively simple structure with three metal layers and two quartz dielectric substrates. The active transmitting patch of the unit cell ensures a 1-bit phase shift resolution by alternating the states of two innovative switches. Here, we overcome the small dimensions challenge in the D-band by introducing compact switches that are compatible with the dimensions of the proposed unit cell. The switches are made of phase change materials (PCM) that alternate between the amorphous and the crystalline states under the effect of heat. We present a full-wave simulation of the unit cell, which shows an insertion loss that is below 1.5 dB over a relative frequency band of 27%. Furthermore, we synthesize a 16×16 elements transmitarray using an in-house MATLAB tool and compare its theoretical results to a full-wave HFSS simulation. The outcome shows that by integrating the proposed switches into the unit cell, the designed transmitarray can achieve promising reconfiguration results in the D-band.**

***Index Terms*—transmitarray, electronically beamforming, beam scanning, phase change materials.**

I. INTRODUCTION

Transmitarray (TA) antennas gained popularity in various microwave and millimeter-wave applications due to their advantages in terms of high-gain and efficiency compared to classical phased arrays [1]. The most important feature of the TA is the possibility to implement relatively simple and low-loss reconfigurability functions, providing real time beam scanning and beamforming. This is realized generally by integrating elements with tuning properties on the array elements (also indicated as unit cells). Until now, the most popular devices used to control the transmission phase shift of the unit-cells are varactor diodes [2], RF-MEMS [3], and p-i-n diodes [4]. The varactor diodes provide continuous and accurate phase change, but they lack of limited bandwidth (less than 10%). In order to enhance the bandwidth, limited phase resolution of 1- or 2-bit can be implemented using MEMS, p-in diodes, or other switch technologies.

Even if several reconfigurable TA prototypes have been demonstrated in the open literature up to Ka-band (26 – 40 GHz) [3], [4], only preliminary studies have been proposed to achieve electronically beam scanning at higher frequencies [5]. In this paper, we focus on designing a reconfigurable TA at D-band (110 – 170 GHz) for application to the future high-data rate Beyond 5G networks. The investigation on designing TA in this frequency band is still at an early stage and today only fixed-beam solutions have been proposed [6]-[8].The 40×40 element TA at 140 GHz proposed in [6] has a peak gain of 33 dBi and -1 dB gain bandwidth of 10.7%. The stack up of the mentioned TA is made of seven metal layers and thousands of vias, which make it bulky and complex. Another TA design using standard PCB (printed circuit board) technology with two metal layers is presented in [7]. The simplified design comes at the sake of a decreased bandwidth (-1 dB gain bandwidth of 6.8%) and aperture efficiency (32%). A passive TA with a gain higher than 30 dBi and better performances in terms of -1dB gain bandwidth (11.7%) is presented in [8]. The main challenge in designing reconfigurable TA antennas at millimeter-wave frequencies (50 – 300 GHz) is in introducing an active element that is compatible with the small dimensions of the unit cell and presents at same time an acceptable R_{on}/C_{off} ratio.

In this work, in order to overcome the aforementioned challenge, we propose to use a phase change material (PCM) based RF switch. GeTe (Germanium Telluride) is selected due to its advantages at high frequencies such as stability and power handling capabilities. The proposed GeTe switch technology was previously developed in [9]. Here, an optimized design is presented to be compatible with the D-band unit cell requirements. Despite PCMs have been recently proposed to develop reconfigurable antennas [10]- [12], this work represents the first feasibility study of their application to TA antennas. A 1-bit unit cell (i.e. two phase states with 180° of relative phase shift) operating in the D-band is designed and optimized. The reconfiguration is ensured integrating on the radiating element two GeTe switches. The proposed unit cell is used to synthesize a TA composed of 16×16 unit cells. The full antenna has been optimized using an in-hose MATLAB tool. Full-wave simulations have been performed to validate our design.

The paper is organized as follows. In Section II, we present the GeTe switches, the unit-cell architecture, and corresponding simulation results. The optimized TA illuminated by a 10-dBi horn is presented in Section III. We conclude the paper in Section IV with some ideas for future research.

II. UNIT CELL PRINCIPLE, DESIGN, AND SIMULATION RESULTS

A. Germanium telluride (GeTe) switches

The proposed PCM switch technology uses GeTe with direct heating actuation. A PCM changes in nanosecond

timeslots from amorphous to crystalline state following an application of thermal, electrical or optical stimuli, thus changing its electrical properties. For instance, the GeTe is heated at a temperature T_1, that is lower than the fusion temperature and higher than crystallization one, during a period d_1 (between 10 to 100ns) in order to change phase from amorphous to crystalline. For the GeTe to change phase from crystalline to amorphous, it is heated at a temperature T_2, that is higher than the fusion one, and for a duration d_2 in the order of 10ns. This switching phenomenon could be useful to integrate PCM materials in reconfigurable devices and antennas. In Fig. 1, we show the way to deposit the GeTe material and the stack up. A cube of l_s x w_s x h_s of GeTe is placed on the top of a metal alloy aluminum copper (AlCu) (see TABLE I). A gap of w_g separates the two branches of the metal. The metal should be embedded in a layer of an insulator as the silicon dioxide and the GeTe in a layer of silicon nitrate; their properties are depicted in TABLE I.

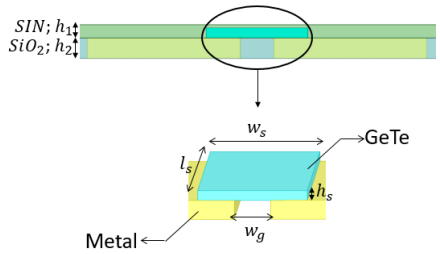


Fig. 1. Proposed GeTe switch technological stack-up.

It is noteworthy to mention that with the presented structure the GeTe changes its electrical properties drastically when changing from amorphous to crystalline state. The geometrical parameters have been defined to achieve the required R_{on}/C_{off}. If we designate the amorphous state as GeTe_OFF (equivalent to a capacitance of C_{off} = *10fF*) and the crystalline state as GeTe_ON (equivalent to a resistance of R_{on} = *1*Ω), it is seen that their resistivity is changing in the order of 10^5(TABLE I).

TABLE I. GETE PROPERTIES

Electrical Constants			
SiO_2	***SiN***	***GeTe_ON***	***GeTe_OFF***
ε_r : 7	ε_r : 4	ε_r: 36 $\boldsymbol{\sigma: 1.85 \cdot 10^5\ S/m}$	ε_r: 36 $\boldsymbol{\sigma: 1.85\ S/m}$

Geometrical Parameters in mm					
$\boldsymbol{w_g}$	$\boldsymbol{w_s}$	$\boldsymbol{l_s}$	$\boldsymbol{h_s}$	$\boldsymbol{h_1}$	$\boldsymbol{h_2}$
$\boldsymbol{1 \cdot 10^{-3}}$	$\boldsymbol{3 \cdot 10^{-3}}$	$\boldsymbol{2 \cdot 10^{-2}}$	$\boldsymbol{3 \cdot 10^{-4}}$	$\boldsymbol{4 \cdot 10^{-4}}$	$\boldsymbol{6 \cdot 10^{-4}}$

B. Unit cell stack up and simulation results

The proposed transmitarray unit cell (Fig. 2) consists of a wafer-like topology. The unit cell is thus made of three metal layers (passive patch antenna, ground plane, and active patch antennas with PCM switches), which are separated by two quartz glass dielectric with the thickness of h_q and the following electrical properties: ε_r = 3.78 and tan δ = 0.0001. The unit cell is optimized in the D-Band and thus the periodicity P is set to be equivalent to $\lambda/2$ at the central frequency of 140 GHz. The active transmitting rectangular patch is printed on a AlCu layer (w_p x l_p) and placed on the top of the dielectric stack-up. It is loaded by an O-slot, on the left and the right two GeTe switches are inserted respecting the layered stack-up already explained in Section II.A and shown in Fig. 1. This configuration of the GeTe switches allows obtaining a symmetrical behavior of the scattering parameter magnitudes with a 180° degrees phase shift while alternating the ON (crystalline) and the OFF (amorphous) states. In this way a 1-bit unit-cell design is achieved. The transmitting patch is connected by a metalized via hole (diameter of $\emptyset_v$) to a passive receiving patch printed on the bottom layer. The passive patch antenna is rectangular (w_p x l_p) and is loaded by a U-slot. It is connected to the ground plane, which is placed in the intermediate layer, with two vertical via holes (diameter of $\emptyset_v$) for biasing purposes. The detailed structure geometrical parameters of the unit cell are summarized in TABLE II.

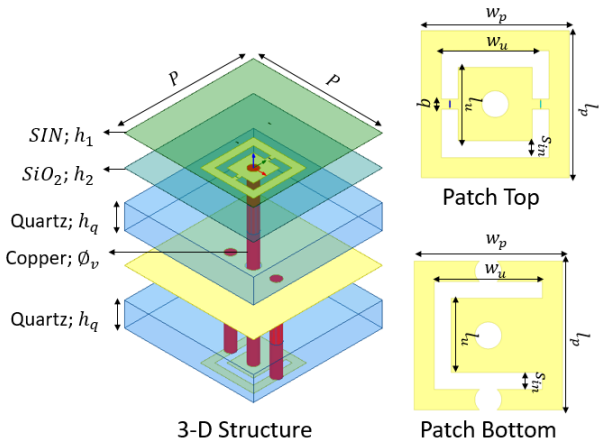


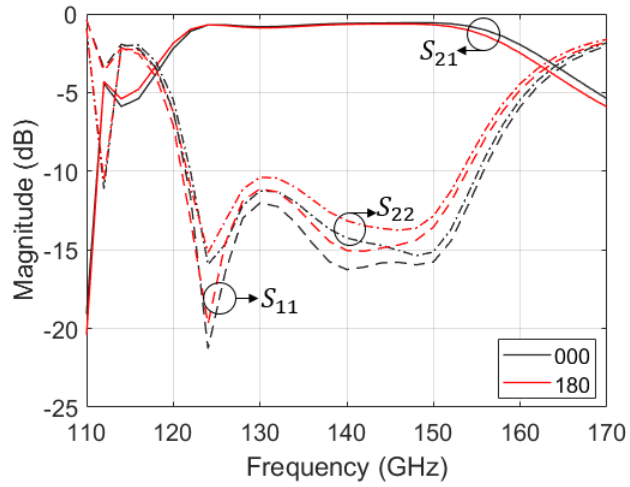
Fig. 2. 1-bit electronically reconfigurable unit-cell, the transmitting and the receiving patche designs.

TABLE II. UNIT CELL STRUCTURE

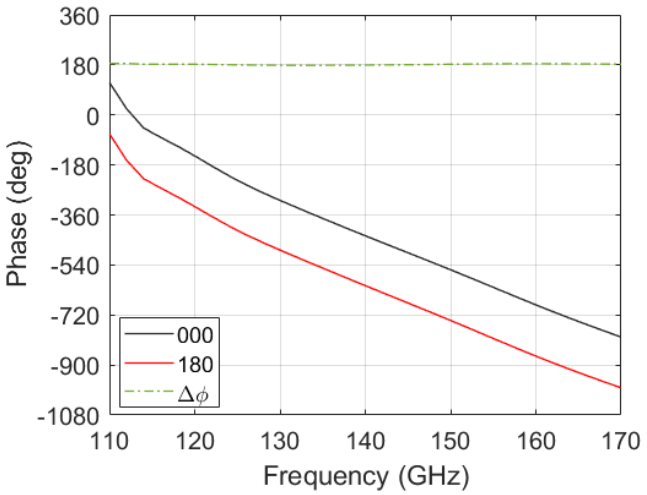
Geometrical Parameters in mm								
$\boldsymbol{h_q}$	$\boldsymbol{\emptyset_v}$	$\boldsymbol{P}$	$\boldsymbol{w_p}$	$\boldsymbol{l_p}$	$\boldsymbol{w_u}$	$\boldsymbol{l_u}$	$\boldsymbol{s_{in}}$	$\boldsymbol{b}$
0.2	0.08	1.07	0.44	0.44	0.32	0.22	0.05	0.03

The proposed unit-cell performances are studied using full-wave simulations (Ansys-HFSS) with periodic boundary conditions and Floquet ports. The purpose of the simulation is to demonstrate the capacity of the unit cell with GeTe switches to reconfigure in two different phase states (called 000 and 180). The transmission (S_{21}) and reflection (S_{11} and S_{22}) coefficient magnitudes for the phase states 000 (black plots) and 180 (red plots) are presented in Fig. 3(a). This figure shows that the cell exhibits 0.69 dB insertion loss at 140 GHz. The insertion losses are lower than 1.5 dB over a 27% bandwidth. In TABLE III, the performances of the unit cell in terms of insertion losses are detailed. In Fig. 3(b), the phases

of S_{21} for the two unit cell states and the phase difference ($\Delta\phi$) are shown. It is seen from the plots that the unit cell can produce two phase states with low insertion losses and a phase difference of 180° over a relatively large frequency range.



(a)



(b)

Fig. 3. Simulated scattering parameters of the proposed reconfigurable unit cell with PCM RF switches. Magnitude of the transmission and reflection coefficients (a) and phase of the transmission coefficients (b) for the phase states 000 and 180. The achieved relative phase shifter ($\Delta\phi$) is also reported in (b).

TABLE III. UNIT CELL PERFORMANCES

At the central frequency (140*GHz*)			
in *dB*	S_{21}	S_{11}	S_{22}
	-0.69	-16.25	-14.25
Bandwidths			
S_{21}: $-1dB$		S_{21}: $-3dB$	S_{11}: $-10dB$
24.5%		32%	26%

III. ELECTRONICALLY RECONFIGURABLE TRANSMITARRAY SYNTHESIS AND SIMULATION RESULTS

A transmitarray of 16×16 elements is synthesized using an in-house MATLAB tool. The building block of the transmit-array is the electronically reconfigurable unit cell proposed in Section IIII.B. The tool generates the phase distribution starting from the full-wave HFSS simulation of each state of the unit cell (000 and 180) and using a ray-tracing solver. In order to collimate the beam towards a specific direction, theoretically, a 360° phase range tuning is preferable for each unit cell on the aperture of the TA. Since the designed unit cell provides two phase states (0° and 180°), thus a discrete phase quantization is used to approximate the ideal phase distribution, and then the array layout is defined accordingly. The quantization rule Q is expanded in (1)

$$Q(\angle S_{21}^{j}) = \begin{cases} 0°, & if \ -\frac{\pi}{2} \le \angle S_{21}^{j} < \frac{\pi}{2} \\ 180°, & otherwise \end{cases} \quad (1)$$

where $\angle S_{21}^{j}$ is the required phase shift for the j cell of the transmit-array.

Using the aforementioned tool, the phase distributions for two steering angles are generated: i) broadside transmission, ii) transmission towards 30°. The directivity and the gain of the TA radiating at broadside and calculated using the MATLAB tool are presented in Fig. 4. The gain at the central frequency is equal to 21.5 dBi and the directivity is 24.2 dBi. The peak gain is of 22 dBi at 150 GHz, and the -1 dB bandwidth is of 16% (24 GHz).

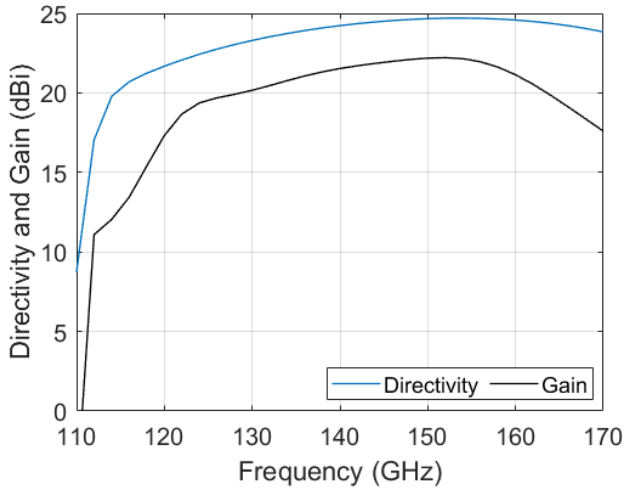


Fig. 4. Directivity and the gain (dBi) of the reconfigirable calculated at braodside using the MATLAB numerical tool.

The full TA considering the two phase distribution is then simulated in HFSS (Fig. 5) with the Finite Element Boundary Integral (FE-BI) solver. The TA is illuminated using a standard 10-dBi horn placed at a focal distance F = 13 mm (F/D = 0.81).

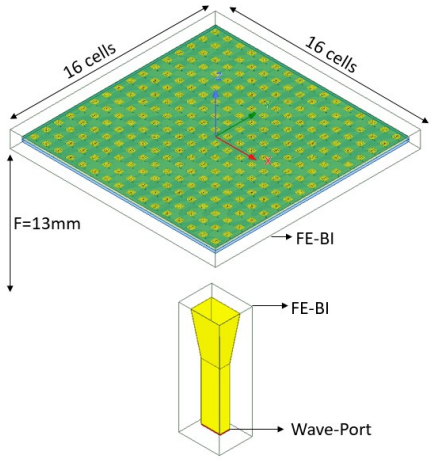


Fig. 5. The full-wave simulation of the 16×16 unit-cells transmitarray.

The simulation results are then compared to the MATLAB theoretical results. In Fig. 6, the normalized pattern for the two transmission cases (0° and 30°) are shown with the corresponding phase distribution. The plots shows good agreement between the full-wave simulations and the theoretical results especially in the main beam. These patterns demonstrate the feasibility of reconfigurable TA using the developed unit-cell.

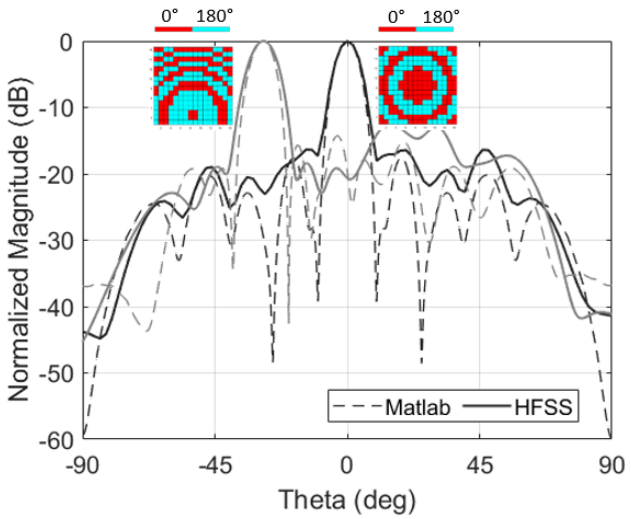


Fig. 6. The normalized patterns of the transmit-array in broadside and 30° transmission.

IV. Conclusion

An electronically reconfigurable unit-cell design is proposed in this paper. A 1-bit phase shift is ensured by alternating the states of two PCM based GeTe switches. The simulation of a 16×16-element transmitarray is performed and validate in full-wave simulation. The normalized patterns for 0° and 30° pointing demonstrate the feasibility of reconfigurable transmitarray using PCM switches. The results of the study are promising for further investigation especially on the activation process of the switches. For the best of our knowledge, this is a first study on reconfigurable transmitarray with steering beam capabilities in the D-band using switches based on PCM.

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References

[1] J. R. Reis, M. Vala, and R. F. S. Caldeirinha, “Review paper on transmitarray antennas,” *IEEE Access*, vol. 7, pp. 94171-94188, 2019.

[2] J. Y. Lau and S. V. Hum, “Reconfigurable transmitarray design approaches for beamforming applications,” *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 5679-5689, Dec.2012.

[3] C. Cheng, B. Lakshminarayanan, and A. Abbaspour-Tamijani, “A programmable lens-array antenna with monolithically integrated MEMS switches,” *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 8, pp. 1874-1884, Aug. 2009.

[4] F. Diaby, A. Clemente, R. Sauleau, K. T. Pham, and L. Dussopt, “2 bit reconfigurable unit-cell and electronically steerable transmitarray at Ka-band,” *IEEE Trans. Antennas Propag.*, vol. 68, no. 6, pp. 5003-5008, June 2020.

[5] X. Li, Z. Li, C. Wan, and S. Song, “Design and analysis of terahertz transmitarray using 1-bit liquid crystal phase shifter,” in *9th Asia-Pac. Conf. Antennas Propag. (APCAP)*, Xiamen, China, Aug.2020, pp. 1-2.

[6] Z. Miao et al., “140 GHz high-gain LTCC-integrated transmit-array antenna using a wideband SIW aperture-coupling phase delay structure,” *IEEE Trans. Antennas Propag.*, vol. 66, no. 1, pp. 182-190, Jan. 2018.

[7] H. Yi, S.-W. Qu, and C. H. Chan, “Low-cost two-layer terahertz transmit array,” *Electron. Lett.*, vol. 53, no. 12, pp. 789–791, Jun. 2017.

[8] F. Foglia Manzillo, A. Clemente, and J. L. González-Jiménez, “High-gain D-band transmitarrays in standard PCB technology for beyond-5G communications,” *IEEE Trans. Antennas Propag.*, vol. 68, no. 1, pp. 587-592, Jan. 2020.

[9] A. Léon, B. Reig, V. Puyal, E. Perret, P. Ferrari, and F. Podevin, “High performance and low energy consumption in phase change material RF switches,” in *48th Eur. Microw. Conf. (EuMC)*, Madrid, Spain, Sept.2018, pp. 491-494.

[10] L. M. De La Cruz, S. Hawasli, T. G. Ivanov, T. K. Anthony, and M. Zaghloul, “Germanium telluride reconfigurable antennas,” in *IEEE Int. Symp. Antennas Propag. (APS/URSI),* Puerto Rico, Jul.2016, pp. 1053-1054.

[11] J. Leon-Valdes, L. Huitema, E. Arnaud, D. Passerieux, and A. Crunteanu, “Polarization reconfiguration of a millimeter-waves antenna using the optical control of phase change materials,”in *14th Eur. Conf. Antennas Propag. (EuCAP)*, Copenhagen, Denmark, Mar.2020, pp. 1-4.

[12] D. E. Anagnostou, G. Goussetis, D. Torres, and N. Sepulveda, “Ultra-fast reconfigurable antennas with phase change materials,” in *Int. Workshop Antenna Technol. (iWAT)*, Athens, Greece, Mar.2017, pp. 146-147.