Study on Isolation and Radiation Behaviours of a 34×34 Array-Antennas Based on SIW and Metasurface Properties for Applications in Terahertz Band Over 125-300 GHz

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***Abstract*: This paper describes the feasibility of conceptual design of a 34×34 array antenna for operation at Terahertz over a frequency range of 125-300 GHz for S_{11}≤-10dB, which corresponds a fractional bandwidth of 82.35%. Each radiation element constituting the array consists of a square patch of dimensions of 2×2 mm^2 that are excited by a matched microstrip line. Each patch is isolated from each other with metallic via-holes, which are implemented based on the substrate integrated waveguide (SIW) technique. This technique is shown to effectively reduce mutual coupling between adjacent radiation elements that can otherwise undermine the arrays radiation gain and pattern. Periphery of each patch is embedded with circular dielectric slots, which are created based on the metasurface concept to enhance the radiation gain and efficiency performances. With the proposed approaches (1) the mutual coupling is suppressed on average by 25dB over its operating frequency range, and (2) the effective aperture area of the array antenna is extended without increase in the array's physical dimensions. Radiation gain and efficiency of the proposed array antenna over its operating range vary from 7.51 dBi to 40.08 dBi, and from 70.51% to 90.11%, respectively. Improvement in gain and efficiency of approximately 60% and 30%, respectively, is achieved with the inclusion of the metasurafce slots. The proposed 34×34 array antenna is proper candidate for applications in Terahertz wireless communication systems.**

***Keywords*: Array antennas, Terahertz band, mutual coupling suppression, metasurafce, via-holes, microstrip patch, substrate integrated waveguide (SIW).**

I. INTRODUCTION

High-volume data communications, such as 8K HD video and high-resolution audio sources, is anticipated in the very near future. This will require near-instantaneous downloads, which makes a speed increase in wireless communication devices vital. This is only possible at Terahertz band. Terahertz communication systems have been extensively investigated, among various Terahertz applications taking full advantage of ultra-wide bandwidths, which enables high speed communications of above 10 Gbit/s with simple and low spectral efficiency modulation schemes, for example, amplitude shift keying (ASK) or on-off keying (OOK). Studies of prototypes operating at frequencies up to 350 GHz have been reported [1]-[5]. Each of these experimental studies have demonstrated the feasibility of Terahertz communication systems for commercialization. Application of such systems may include fixed wireless access, Terahertz nanocells, WLAN, wireless personal area network, short-range connecting devices, and board-to-board communications [6].

The disadvantage of Terahertz is the signals at these frequencies attenuate sharply when propagating through space, a highly sensitive receiver is necessary to receive data from weak waves. In addition, to boost the gain of Terahertz system will require high-gain antennas. Although, high-gain antennas can be designed with array antennas they are however inflicted with mutual coupling effects between adjacent radiating elements constituting the array that undermines the array's gain performance. The major challenge is therefore to reduce the mutual coupling in Terahertz array antenna.

It has been shown that mutual coupling or isolation among neighbouring radiating elements in the antenna can be improved by increasing the space between the elements, but this is at the cost of increased antenna size [7]. Although the size of the antenna can be reduced by fabricating it on high dielectric substrate, but the resulting surface waves can significantly deteriorate the radiation characteristics of the antenna. This is because on a finite ground-plane the surface waves are reflected and diffracted at the edges of the substrate, which results in a significant amount of energy loss [8]. Many techniques have been investigated to improve the radiation performance of patch antennas implemented on substrates [9], which include using photonic bandgap (PBG) or electromagnetic bandgap (EBG) structures around the radiating elements [10]. Another approach to suppress surface waves is to use artificial soft and hard surfaces realized with EBG [11]. The soft surface behaves as a perfect electric conductor (PEC) in H-plane and as a perfect magnetic conductor (PMC) in E-plane, and visa-versa for the hard surface. Soft surfaces exhibit bandgaps in only one direction and are created on the ground-plane of a microstrip patch antenna. These results show that the presence of a via close to a radiating element can affect its resonant frequency. In addition, a large surface area is required to implement EBG structures.

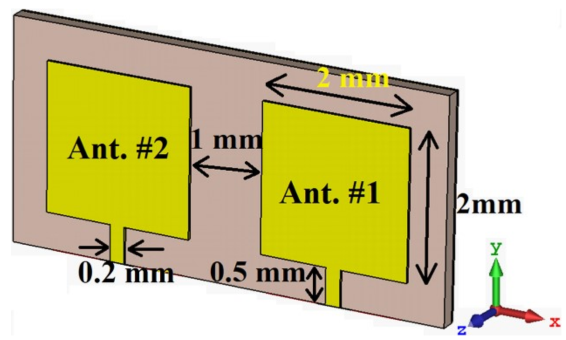
This paper describes two techniques based on substrate integrated waveguide (SIW) and metasurface properties to suppress mutual coupling and increase the radiation performances in a conceptual 34×34 array antenna designed for Terahertz operation over a frequency range of 125-300 GHz. This is achieved by isolating the antennas with metallic via-holes and embedding circular dielectric slots in the periphery of the patch antennas, respectively.

The proposed technique is shown to increase the radiation performance in terms of gain and efficiency over its over working frequency band. Furthermore, the cross-polarization achieved is low demonstrating high isolation between radiating elements in the array. The antenna design was analysed and optimized by full-wave electromagnetic solvers based on Method of Moments (MoM) and Finite Element Method (FEM). Mutual coupling suppression improvement is shown to be on average of 25 dB. Improvement in radiation gain and efficiency are 60% and 30%, respectively. The proposed techniques have no effect on the physical dimensions of the array-antennas.

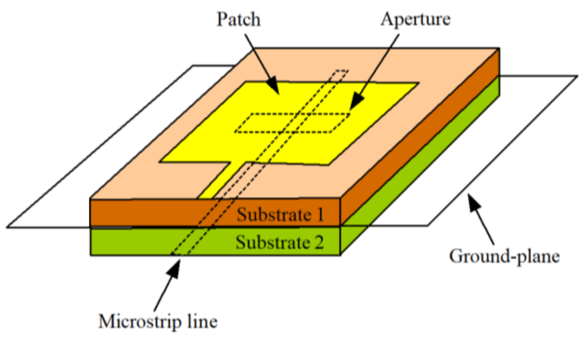
II. 34×34 Array Antenna Design with High Isolation and High Radiation Performances

Common materials used for printed-circuit substrates for high-frequency waves are ceramic, quartz, or Teflon, but when used in the Terahertz band, there is significant signal attenuation and loss of receiving sensitivity. To minimise loss at Terahertz polyimide substrate was employed here. Structure of the 1×2 referenced array-antennas design is shown in Fig. 1(a), where the square metallic patch structures are patterned on the top side of the dielectric substrate. The antenna's elements are excited through standard aperture coupling illustrated in Fig. 1(b). To realize aperture coupling a rectangular aperture was cut out in the ground-plane under each patch, and a microstrip feed-line etched on the bottom of aperture is used to excite the antenna. The amount of coupling from the feed-line to the patch was optimised by controlling the size of the aperture. Each patch is excited through an aperture under it using a common matched microstrip line. The microstrip line under each column of patch in the array, shown in Fig. 1 (b), branches out from a single waveguide port. With this approach the patches are fed in series. We chose the Copper with electric conductivity σ = 5.8×10^7 S/m as metallic pattern and the polyimide with a relative permittivity of ε_r = 3.5 as dielectric layer. Dimension of the patch is 2×2 mm^2 and microstrip line is 0.5×0.2 mm^2. The referenced array antenna was used in the construction of the 34×34 array configuration.

To reduce mutual coupling between adjacent radiating elements it was necessary block surface wave propagation. This was achieved by isolating individual radiating elements with metallic via-holes that were connected directly to the underside ground-plane, as shown in Fig. 2. To realize these metallic via-holes we have utilized the substrate integrated waveguide properties [12]. The radiation gain and efficiency were enhanced by inserting dielectric slots in the periphery of each patch. These slots have realized based on the metasurface technology that by playing the role of the series left-handed capacitances (C_L) actualize the 2-D metamaterial concepts [13, 14]. Dimensions of the via-holes and dielectric slots as well as their separation from each other was determined by numerous simulations using two different 3D full-wave electromagnetic simulation tools (CST Microwave Studio® and HFSS™) on a CPU/GPU with 18 GB RAM. In the simulation process, the propagation wave vector (k) was perpendicular to the structure plane whereas the electric field (E) and magnetic field (H) were parallel to the incident plane. The periodic boundary conditions were set along the x-y plane, while the open boundary conditions were chosen along the z plane.



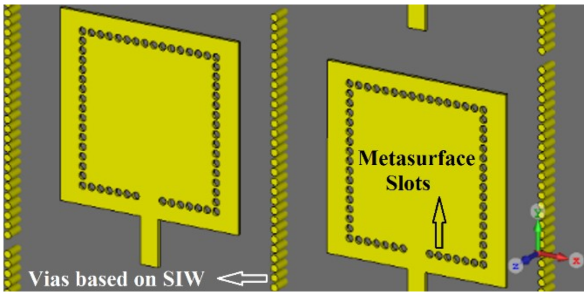
(a)



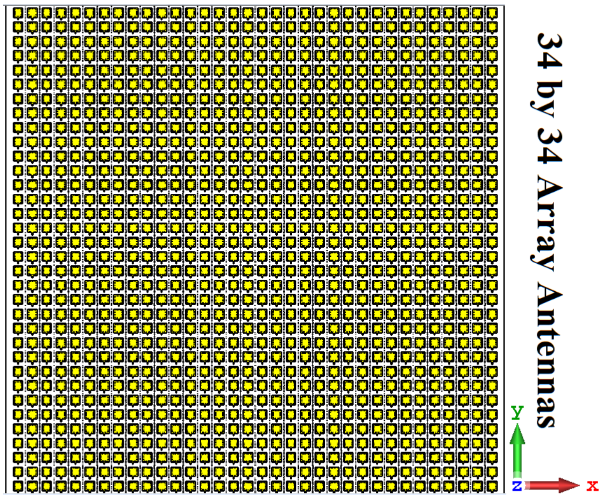
(b)

Fig.1. (a) Reference 1×2 array antenna with structural parameters, and (b) feed mechanism based on the standard aperture coupling.

Configuration of the proposed 34×34 array antenna based on the SIW and metasurface technologies is shown in Fig.2. For more clarity, Fig. 2(a) shows a zoomed view of the 34×34 array located in center of the structure. The optimized separation between each via-holes is 0.1 mm. In the simulation the antennas are fed through a waveguide port. The overall structure of the 34×34 array antennas is shown in Fig. 2(b). As the array is a symmetrical structure the symmetry option in the solvers was used to decrease computational time.



(a) Zoomed view of 34×34 array antennas to show 1×2 array elements located in the center



(b) Layout view of whole 34×34 array antennas

Fig.2. Configuration of the proposed 34×34 array antennas.

Fig.3 shows the S-parameter responses of the referenced and proposed 34×34 array antennas without and with metallic the via-holes. This graph shows the proposed array operates over a very wide Terahertz band from 125 GHz to 300 GHz for S_{11}≤-10dB, which corresponds to 82.35% bandwidth. It also clearly shows dramatic improvement in isolation with the via-holes. After implementing the via-holes the minimum, average, and maximum improvement in mutual coupling suppression between the array elements is 5 dB, 25 dB, and 50 dB, respectively. There is excellent correlation between CST Microwave Studio® and HFSS™ results. CST Microwave Studio® uses Method of Moments (MoM) to arrive at the solution whereas HFSS™ uses Finite Element Method (FEM).

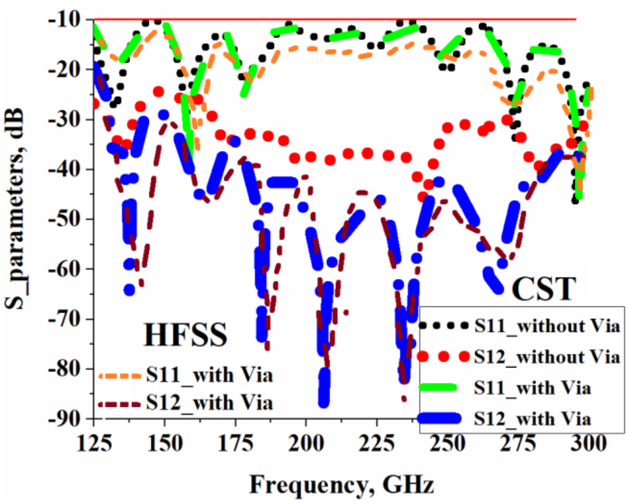


Fig.4. S-parameter responses of the referenced and proposed 34×34 array antennas with no and with metallic via-holes using two different commercially available 3D full wave electromagnetics simulation tools (CST Microwave Studio® and HFSS™).

3D radiation-gain plots of the proposed 1×2 array antennas shown in Fig. 2(a) at various operating frequencies after applying the metasurface slots is exhibited in Fig.4. It shows that at lower frequency range between 125 GHz and 200 GHz the beamwidth of the array is much larger than at higher frequencies between 250 GHz and 300 GHz where array is more unidirectional.

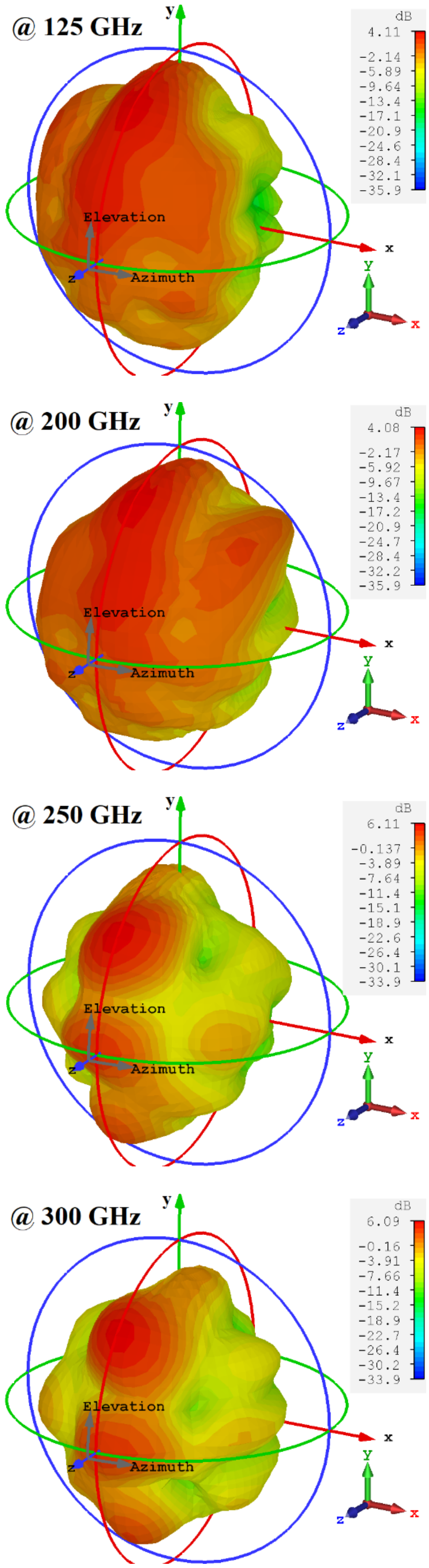
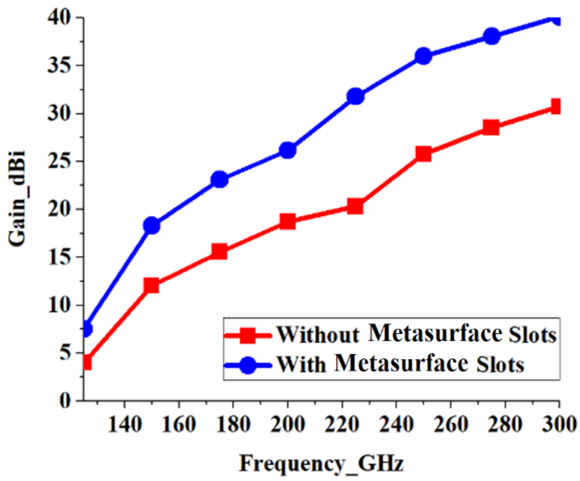


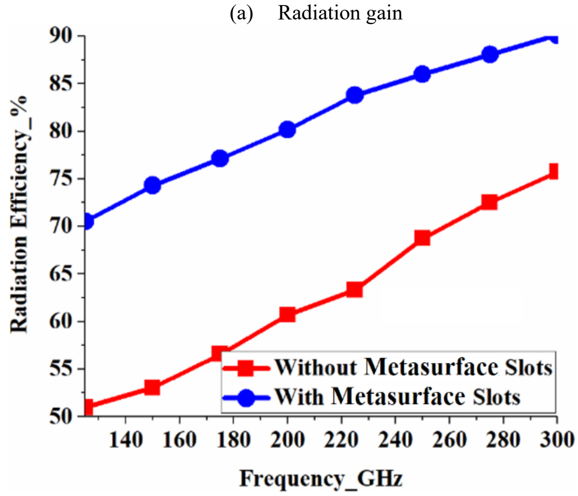
Fig.4. 3-D radiation polar gain plots of the 1×2 array antenna shown in Fig. 2(a) at various operational frequencies of 125, 200, 250, and 300 GHz.

Radiation characteristics of the array antennas were improved by inserting circular dielectric slots in the periphery of each patch, as shown in Fig. 2(a). Slots in the patch structure essentially create series left-handed capacitances (C_L) as one of the main structural components of the 2-D metamaterial transmission-lines so-called as "metasurface". By optimizing the number of slots, their diameter, and separation from each other is shown below to effectively increase the array's aperture and hence gain and efficiency performance. This is achieved without enlarging the size of the antenna.

Radiation gain and efficiency responses of the referenced and proposed 34×34 array antennas with no and with dielectric slots at an angle normal to the plane of the array are shown in Fig.5 in the direction of the main beam. Without the metasurface slots the gain varies from 3.96 dBi to 30.71 dBi, and the efficiency from 50.96% to 75.71%. With application of the metasurface slots the gain now varies from 7.51 dBi to 40.08 dBi and the efficiency from 70.51% to 90.11%. These results are summarized in Table I, which reveal with metasurface slots minimum gain and efficiency improvements are 90% and 40%, respectively; and maximum improvements are ~35% and 20%, respectively.



(a) Radiation gain



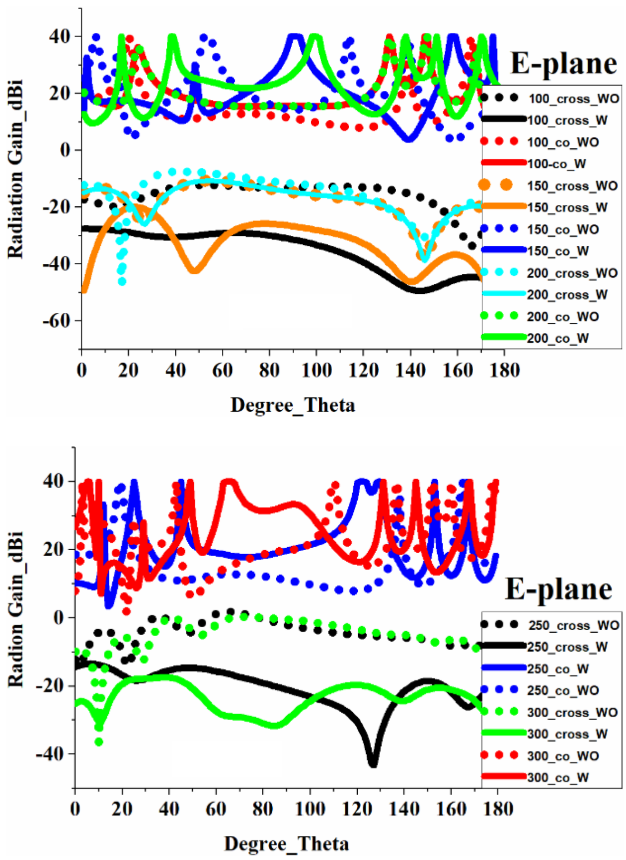
(b) Radiation efficiency

Fig.5. Radiation gain and efficiency of the referenced and proposed 34×34 array antennas before and after applying the dielectric metasurface slots at the broadside angle.

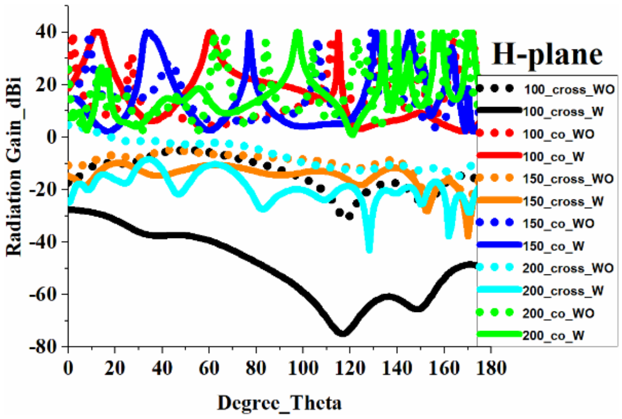
TABLE I. Radiation Gain and Efficiency With and Without Slots

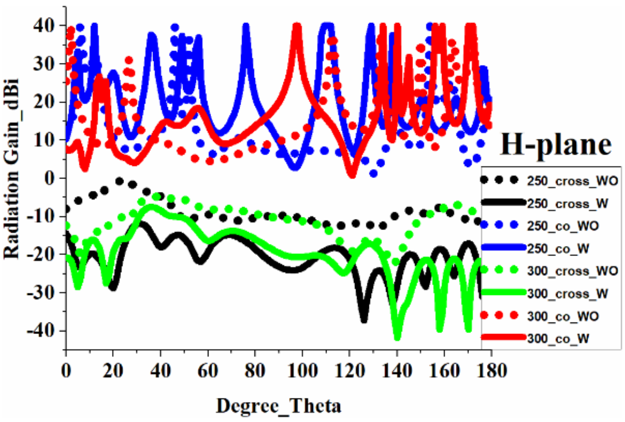
Gain	
Minimum without MTM slots	3.96 dBi
Minimum with MTM slots	7.51 dBi
Improvement	**3.55 dBi**
Gain	
Maximum without MTM slots	30.71 dBi
Maximum with MTM slots	40.08 dBi
Improvement	**9.37 dBi**
Efficiency	
Minimum without MTM slots	50.96%
Minimum with MTM slots	70.51%
Improvement	**19.55%**
Efficiency	
Maximum without MTM slots	75.71%
Maximum with MTM slots	90.11%
Improvement	**14.40%**

The co- and cross-polarized radiation gain patterns of the referenced and proposed 34×34 array antennas without (WO) and with (W) dielectric metasurafce slots in E- and H-planes as a function of broadside angle (z-x) with reference to normal to the plane of the array at the operational frequencies are plotted in Fig.6. It is evident that after applying the metasurface slots the cross-polarization levels significantly drop and co-polarization patterns improve. The gain variation is attributed to phase variation between the elements in the array.



(a) E-plane





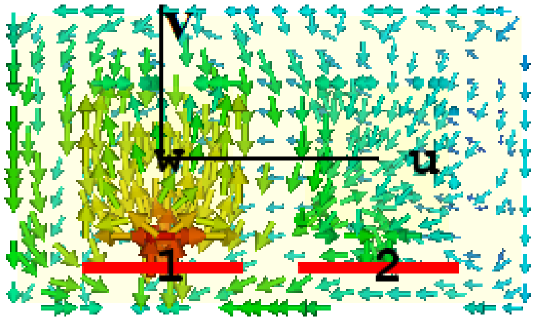
(b) H-plane

Fig.6. Co- and Cross-polarized radiation gain patterns of the referenced and proposed 34×34 array antennas without (WO) and with (W) metasurface slots in E- and H-planes as a function of broadside angle (*z*-*x*) normal to the plane of the array at various operating frequencies.

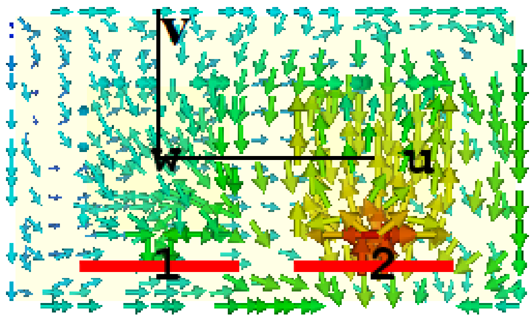
Surface current density distributions of the referenced and proposed 1×2 array antennas shown in Figs. 1(a) and 2(a) without and with metal via-holes are shown in Fig. 7. This figure shows that the via-holes are an effective EM band-gap structure to significantly block surface currents interacting with adjacent radiation elements and thereby effecting the far-field of the antenna array.

III. Comparison of the Proposed Decoupling Method with the Recent Mutual Coupling Suppression Thecniques

The proposed isolation method is compared with the recent publications employing various mutual coupling suppression techniques. Most of the arrays listed in Table II employ defected ground structures (DGS) to complement their suppression technique to increase isolation between the radiation elements. The radiation pattern of prior techniques is distorted. Here, the array antenna with the proposed isolation method based on SIW and dielectric metasurface slots in each patch has advantage the of: (i) symmetry; (ii) simple design; (iii) improved radiation patterns; (iv) enhanced radiation gain and efficiency; (vi) low cross-polarization levels; and (vii) mutual coupling suppression on average of 25 dB over its operating band.

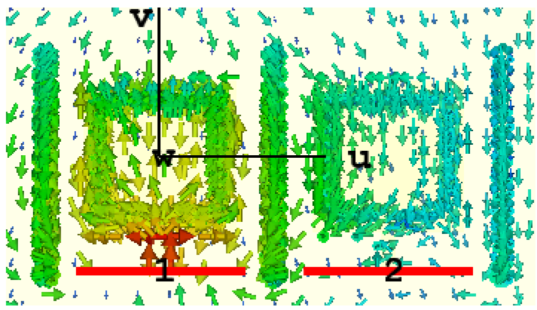


Port#1 is excited and port#2 terminated in 50Ω load.

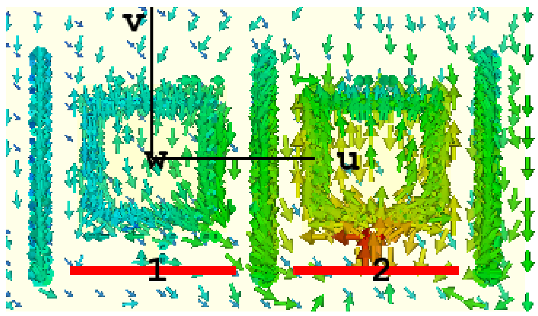


Port#2 is excited and port#1 terminated in 50Ω load.

(a) Without metallic via-holes



Port#1 is excited and port#2 terminated in 50Ω load.



Port#2 is excited and port#1 terminated in 50Ω load.

(b) With metallic via-holes

Fig.7. Surface current density distributions of the referenced and proposed array antennas without and with metal via-holes at 250 GHz for 1×2 array antennas located in middle of 34×34 array structure.

TABLE II. Comparison between the proposed decoupling method with other techniques in literature

Ref.	Method	Max. isolation improvement	Rad. gain pattern deterioration	Application of DGS	Edge-to-Edge Gap	Symmetry and Simplicity
[15]	SCSRR	10 dB	Yes	Yes	$0.25\lambda_0$	No
[16]	SCSSRR	14.6 dB	Yes	Yes	$0.125\lambda_0$	No
[17]	Compact EBG	17 dB	Yes	Yes	$0.8\lambda_0$	No
[18]	Fractal MTM-EMBG	37 dB	No	No	$0.5\lambda_0$	Yes
[19]	Meander Line	10 dB	No	Yes	$0.055\lambda_0$	No
[20]	EBG	8.8 dB	-	Yes	$0.75\lambda_0$	No
[21]	EBG	13 dB	Yes	Yes	$0.5\lambda_0$	No
[22]	MTM-DS	57 dB	No	No	$0.66\lambda_0$	Yes
[23]	Fractal load + DGS	16 dB	No	Yes	$0.22\lambda_0$	No
[24]	Slotted Meander-Line	16 dB	Yes	Yes	$0.11\lambda_0$	No
[25]	Slots	>26 dB	No	No	$0.37\lambda_0$	Yes
[26]	I-Shaped Resonator	30dB	Yes	Yes	$0.45\lambda_0$	No
[27]	W/g MTM	18 dB	No	Yes	$0.093\lambda_0$	No
[28]	MSWI	13.5 dB	No	No	$1.167\lambda_0$	Yes
This work	**SIW & Metasurface**	**50 dB**	**No**	**No**	**$0.41\lambda_0$**	**Yes**

IV. Conclusion

Simple and effective technique based on the substrate integrated waveguide (SIW) has been presented to reduce unwanted mutual coupling between the radiating elements in 34×34 array antennas operating at Terahertz band. This is realized by inserting metallic via-holes between the radiating elements to block propagating surface waves. Also, described is a technique utilizing the metasurafce properties to enhance the array's radiation gain and efficiency performances. This was achieved by embedding circular dielectric slots in the periphery of the radiating structure. The proposed techniques do not compromise the antenna size. The proposed array with high isolation and enhanced radiation gain and efficiency performances should facilitate Terahertz communications.

Acknowledgments

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