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Meta-Surface Wall Suppression of Mutual Coupling between Microstrip Patch Antenna Arrays for THz-Band Applications

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Abstract—This paper presents a novel 2D meta-surface wall to increase the isolation between microstrip patch radiators in an antenna array that is operating in the teraherz (THz) band of 139–141 GHz for applications including communications, medical and security screening systems. The meta-surface unit-cell comprises conjoined twin 'Y-shape' microstrip structures, which are inter-digitally interleaved together to create the meta-surface wall. The proposed meta-surface wall is free of via holes and defected ground-plane hence easing its fabrication. The meta-surface wall is inserted tightly between the radiating elements to reduce surface wave mutual coupling. For best isolation performance the wall is oriented orthogonal to the patch antennas. The antenna array exhibits a gain of 9.0 dBi with high isolation level of less than -63 dB between transmit and receive antennas in the specified THz-band. The proposed technique achieves mutual coupling suppression of more than 10 dB over a much wider frequency bandwidth (2 GHz) than achieved to date. With the proposed technique the edge-to-edge gap between the transmit and receive patch antennas can be reduced to 2.5 mm. Dimensions of the transmit and receive patch antennas are $5 \times 5\,\mathrm{mm}^2$ with ground-plane size of $9 \times 4.25\,\mathrm{mm}^2$ when being constructed on a conventional lossy substrate with thickness of 1.6 mm.

1. INTRODUCTION

Microstrip patch antennas have become popular for applications in wireless communication systems as they possess desirable attributes of low cost, lightweight, planar configuration, and ease of integration. In antenna arrays the radiating elements need to be in close proximity to each other to realise a small form factor, which is highly desirable in modern wireless systems. This requirement however causes significant mutual coupling effects that inevitably degrades the performance of the antenna array. Isolation between neighbouring radiating elements in the antenna can be improved by simply increasing the gap between the elements, but this is at the cost of increased antenna size [1–3]. To overcome the size issue, the patch antenna can be printed on high dielectric substrates, 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 [4, 5]. To date numerous techniques have been explored to improve the radiation performance of patch antennas implemented on substrates [6–8]. This includes incorporating photonic bandgap (PBG) or electromagnetic bandgap (EBG) structures around the radiating elements [9–12]. Another approach to suppress surface waves is to use artificial soft and hard surfaces realized with EBG [13]. The soft surface behaves as a perfect electric conductor

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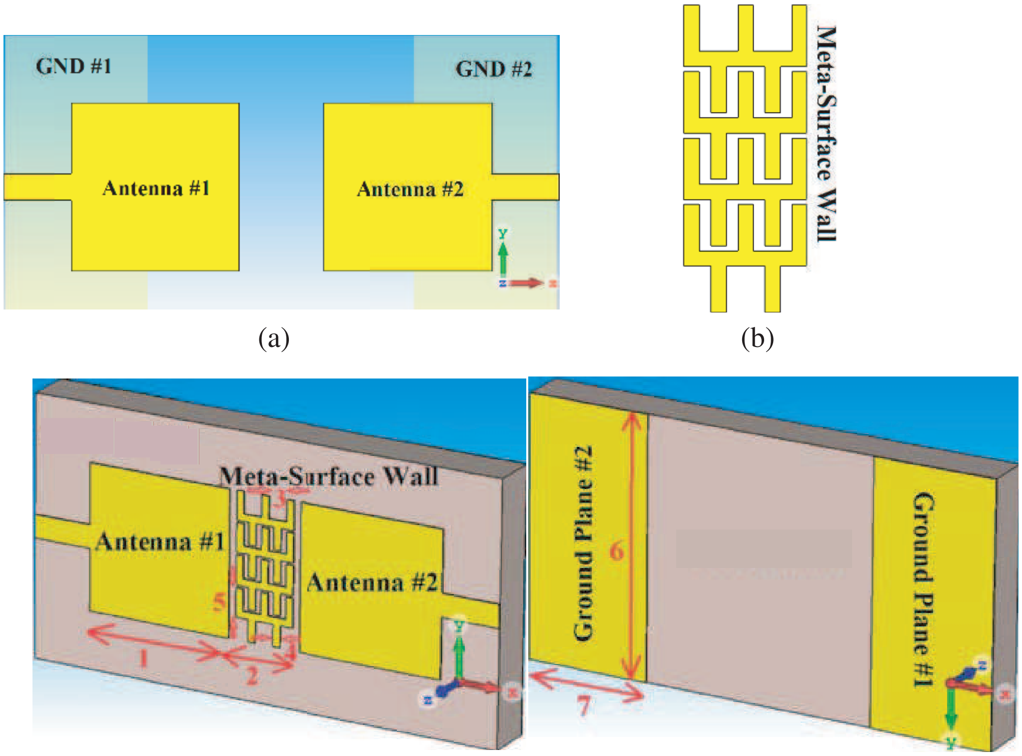
(PEC) in H-plane and as a perfect magnetic conductor (PMC) in E-plane, and visa-versa for the hard surface. Soft surfaces exhibit bandgaps in only one direction and are created on the ground-plane of a microstrip patch antenna. These results show that the presence of a via close to a radiating element can affect its resonant frequency. In addition, a large surface area is required to implement EBG structures.

This paper presents a unique method for enhancing the isolation between microstrip patch radiators for application in antenna arrays, where the transmit/receive bands are very close to each other. Reduction in mutual coupling between adjacent radiating elements that are on the same plane is achieved with a novel 2D meta-surface wall isolator (MSWI) analogous to [14]. In the proposed technique the meta-surface does not require any ground-plane or metallic vias. The proposed MSWI is located between radiating elements. It consists of conjoined twin 'Y-shaped' structures that are inter-digitally interleaved with each other to create a meta-surface wall. A 1×2 microstrip patch antenna array design with the proposed meta-surface wall is investigated in the THz-band from 139 GHz to 141 GHz to demonstrate the feasibility of the proposed technique.

2. META-SURFACE WALL ISOLATOR STRUCTURE

Geometry of the 1×2 microstrip patch antenna array using the proposed meta-surface wall isolator is shown in Fig. 1. The meta-surface consists of inter-digitally coupled unit-cell structures of conjoined twin Y-shaped configurations. The meta-surface wall, shown in Fig. 1(b), comprises several unit-cell structures that are stacked together vertically at regular distances to create the appearance of a different bulk propagation medium. Each conjoined twin Y-shaped structure acts as a resonant circuit. As long as the inserted unit-cell structures are small compared to the propagating wavelength, they create a macroscopic effect (permittivity and permeability) on the electromagnetic wave as it passes through them. The meta-surface is designed to highly impede electromagnetic propagation along the antenna



(a) (b)

(c) (d)

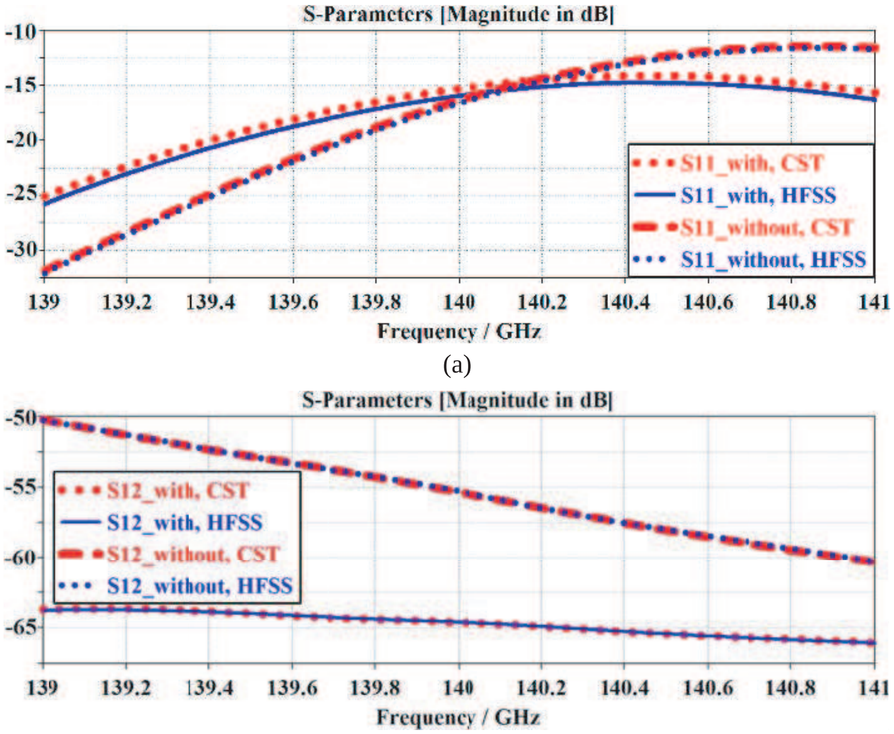
Figure 1. Layout of the antenna array with and without the proposed meta-surface wall isolator. Dimensions of the numerical labels in (c) and (d) are given in Table 1. (a) Top and back view without MSWI. (b) Meta-surface wall isolator. (c) Isometric view with MSWI. (d) Back view with MSWI.

array's surface within the specified THz frequency band of operation. It is an effective artificial high-impedance surface that blocks current from flowing in the specified THz frequency band. Hence, the proposed structure is used here as an effective isolator that suppresses mutual coupling between the two radiators, as shown in Fig. 1(c). MSWI is oriented orthogonal to the radiators for effective suppression of mutual coupling between the Tx and Rx. The physical dimensions of the structure are listed in Table 1. Antenna#1 is used for transmitting (Tx) and Antenna#2 receiving (Rx). A 1 × 2 array is implemented on a single layer of commercially available dielectric substrate with thickness of 1.6 mm, dielectric constant of 4.3, and $\tan\delta = 0.025$. In this theoretical study the loss was not the main concern as we wanted to demonstrate the concept of meta-surface wall isolator. In practice, a low loss substrate would be employed at THz. The two square microstrip patches are excited through 50 Ω microstrip lines as shown in Fig. 1. The meta-surface wall isolator structure was determined from extensive simulation analysis. MSWI is placed between the radiating patches designed to operate in the THz-band from 139 GHz to 141 GHz.

Table 1. Structural parameters of the antenna array and MSWI defined in Fig. 1.

#1	#2	#3	#4	#5	#6	#7
5 mm	2.5 mm	0.625 mm	0.25 mm	1.0 mm	9 mm	4.25 mm

S-parameter responses of the proposed antenna array without and with the proposed MSWI are shown in Fig. 2. It is clear from this graph that mutual coupling is dramatically reduced after applying MSWI. With MSWI, mutual coupling is suppressed by −63.5 dB at 139 GHz, by −65 dB at 140 dB, and by −66.5 dB at 141 GHz. Compared with no MSWI the maximum, minimum and average reductions in mutual coupling are 13.5 dB, 10 dB, and 6.5 dB, respectively. The results were obtained from 3D full-wave EM simulators of CST Microwave Studio and HFSS. The two EM tools use very different



(a)

(b)

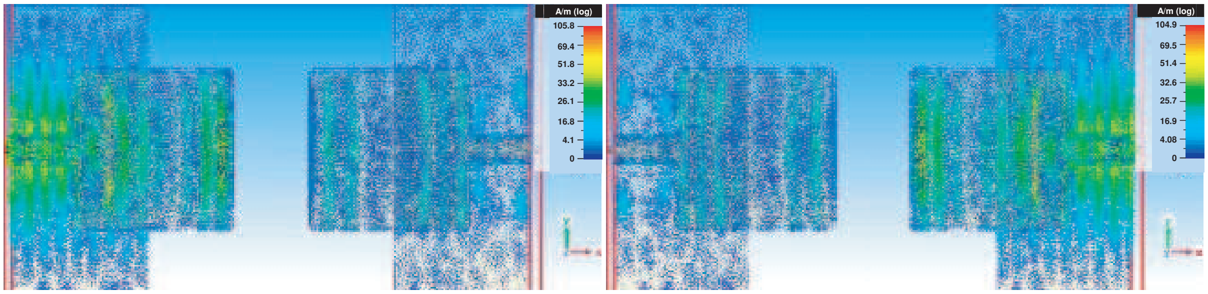
Figure 2. Reflection (S_{11}) and transmission-coefficient (S_{12}) response of the proposed antenna array before and after implementing MSWI. (a) Reflection-coefficient. (b) Transmission-coefficient.

techniques to analyse the proposed structure. In fact, CST Microwave Studio uses Method of Moments discretization with a surface integral formulation of the electric and magnetic field, and HFSS uses Finite Element Method to arrive at frequency domain solution. There is excellent coherency in the results of the two very different techniques which validates the proposed technique. Salient results are summarized in Table 2.

Table 2. Isolation between Tx/Rx antennas.

$\|S_{11}\| \leq -10\,\text{dB}$	139–141 GHz (BW: 2 GHz)		
S_{12}	Minimum	Maximum	Average
Without MSWI	−50 dB @ 139 GHz	−60 dB @ 141 GHz	−55 dB @ 140 GHz
With MSWI	−63.5 dB @ 139 GHz	−66.5 dB @ 141 GHz	−65 dB @ 140 GHz
Improvement	13.5 dB	6.5 dB	10 dB

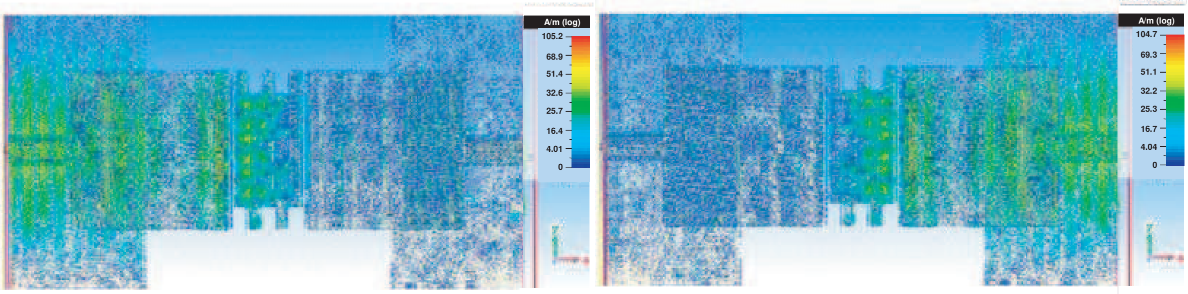
The decoupling effects can also be observed by visualizing the surface current plots over the 1 × 2 antenna array, as shown in Fig. 3. The surface current density distributions in Fig. 3 show that with no MSWI and when Antenna#1 is excited the electromagnetic energy is coupled to Antenna#2, and vice versa. However, when MSWI is placed between the two antennas, it significantly chokes electromagnetic energy from Antenna#1 being coupled to Antenna#2.



Left-hand Antenna#1 is excited

Right-hand Antenna#2 is excited

(a)



Left-hand Antenna#1 is excited

Right-hand Antenna#2 is excited

(b)

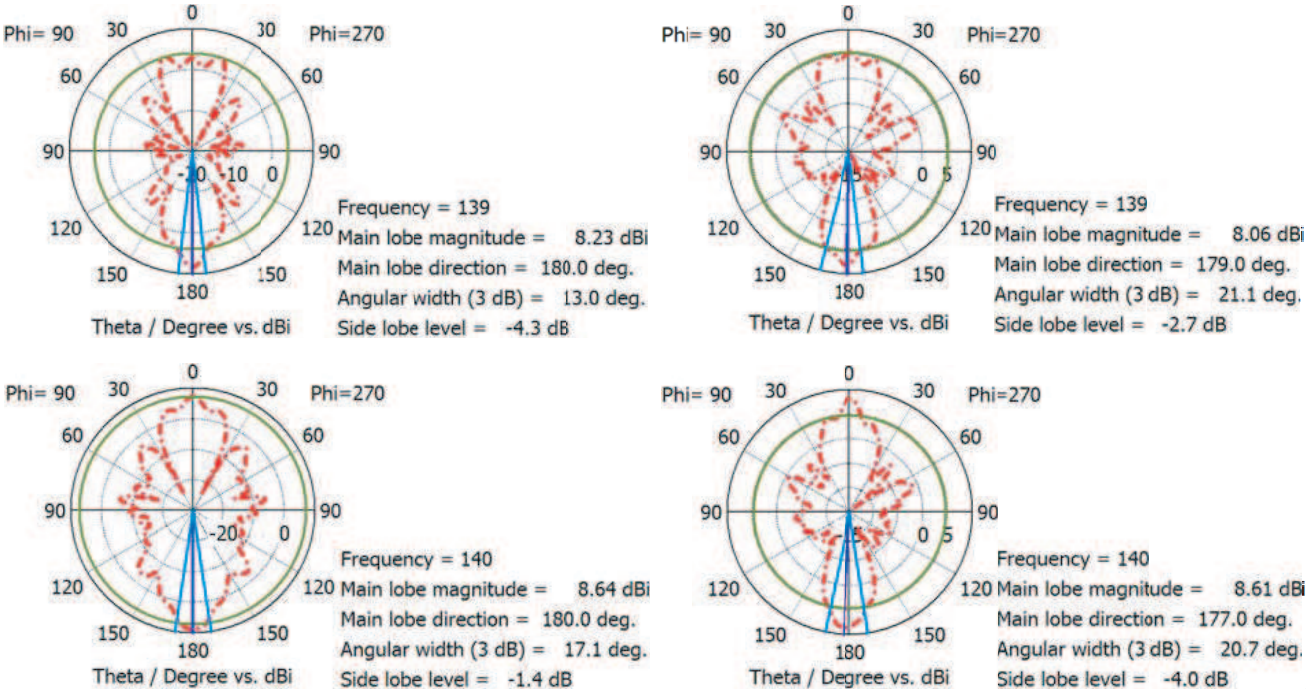
Figure 3. Surface current density distributions over the antenna array at 140 GHz. (a) Without MSWI. (b) With MSWI.

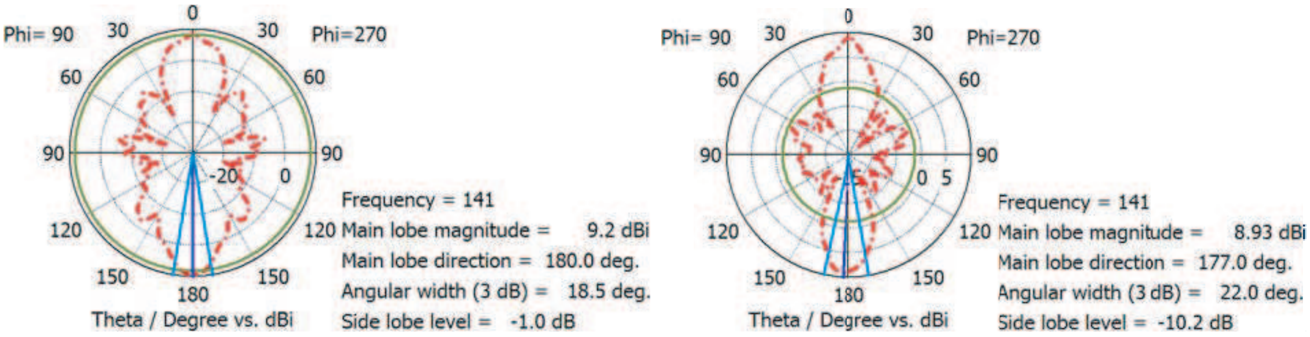
The antenna array's radiation patterns for both cases of without and with MSWI structure at the mid-band frequency of 140 GHz are plotted in Fig. 4. These results show no obvious degradation in the radiation characteristics of the array radiation without and with the isolation wall. In fact, it is evident that with MSMI the radiation becomes more directive. The MSWI could be inserted retrospectively to reduce mutual coupling in planar antennas. The array antenna's radiation gain without and with the isolation wall varies from 8.06 dBi to 9.20 dBi, and from 8.06 dBi to 8.99 dBi, respectively.

Table 3. Comparison of the proposed antenna array characteristics with recent works.

Refs.	Method	Max. isolation improvement	Edge-to-edge separation (mm)	Freq. range (Bandwidth)	Rad. pattern deterioration	Simplicity of Design
[14]	EBG	4 dB	45 mm	Narrow 5.55–5.7 GHz (150 MHz)	Yes	Low
[15]	UC-EBG	10 dB	25 mm	Narrow 5.65–5.75 GHz (100 MHz)	Yes	Low
[16]	U-shaped resonator	10 dB	25 mm	Narrow 2.38–2.5 GHz (120 MHz)	Yes	Moderate
[17]	SCSRR	10 dB	15 mm	Narrow 4.9–5.1 GHz (200 MHz)	Yes	Low
[18]	Meander-line resonator	10 dB	6 mm	Narrow 2.7–2.83 GHz (130 MHz)	No	Low
This work	MSWI	13.5 dB	2.5 mm	Wide 139–141 GHz (2 GHz)	No	High

In Table 3, the proposed technique is compared with other techniques reported to date. The results show that the proposed mutual coupling reduction technique permits operation over a wide frequency bandwidth of 2 GHz from 139–141 GHz. The results show that with the proposed MSWI higher isolation is observed between antennas, which does not degrade the antenna array's radiation pattern. The proposed MSWI is of a simple 2D construction, which can be applied retrospectively to





(a) (b)

Figure 4. Radiation patterns of the antenna array in the H-plane without and with MSWI at 139 GHz, 140 GHz, and 141 GHz. (a) Without MSWI. (b) With MSWI.

existing planar array antennas subject to sufficient space between the radiators. With the proposed technique the edge-to-edge gap between the transmit and receive patch antennas can be reduced to 2.5 mm. In addition, unlike other techniques the proposed technique does not require any via holes and/or defected ground-plane.

3. CONCLUSION

A novel meta-surface wall is shown to reduce mutual coupling between adjacent microstrip patch antennas implemented on the same substrate and operating in the THz-band of 139–141 GHz. This is achieved by inserting a meta-surface wall between the radiating elements. The meta-surface wall essentially blokes the propagation of surface waves. The meta-surface wall is constructed with unit-cells comprising conjoined twin Y-shaped structured that are inter-digitally coupled to each other to create a vertical stack. With the proposed technique the isolation level of less than −63 dB is achieved between antennas. This technique can be applied to densely packed antennas in antenna arrays where the effect of mutual coupling can severely affect the array's performance.

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