Study on Antenna Mutual Coupling Suppression Using Integrated Metasurface Isolator for SAR and MIMO Applications

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Abstract- **A metasurface based decoupling structure that is composed of a square-wave slot pattern with exaggerated corners that is implemented on a rectangular microstrip provides high-isolation between adjacent patch antennas for Synthetic Aperture Radar (SAR) and Multi-Input-Multi-Output (MIMO) systems. The proposed 1×2 symmetric array antenna integrated with the proposed decoupling isolation structure is designed to operate at ISM bands of X, Ku, K, and Ka. With the proposed mutual coupling suppression technique (i) the average isolation in the respective ISM bands listed above is 7 dB, 10 dB, 5 dB, and 10 dB; and (ii) edge-to-edge gap between adjacent radiation elements is reduced to 10 mm (0.28λ). The average antenna gain improvement with the metasurface isolator is 2 dBi.**

Keywords- **Mutual coupling suppression, decoupling, metasurface, synthetic aperture radar (SAR), MIMO.**

I. INTRODUCTION

Wireless communications systems using single channel full-duplex (SCFD) simultaneously transmit and receive radio-signals on the same frequency channel. Although SCFD is more efficient than time-division and frequency-division duplexing systems it's not popular because of self-interference resulting from leaked signals at the receiver from its own transmitter. This can be seriously debilitating especially in low-power systems with sensitive receivers [1]. To enable the widespread use of SCFD it is therefore important to reduce or mitigate the effects of self-interference.

Techniques to suppress self-interference include antenna cancellation, radio-frequency/analogue cancellation, and digital base-band cancellation. Antenna cancellation is considered essential as analogue cancellation is not effective by itself to prevent saturation low-noise amplifier and analog-to-digital converter prior to a digital base-band cancellation. Antenna spacing is one means of minimising the effects of self-interference, however it requires multiple antennas and greater space [1–2]. Other cancellation techniques investigated to date include (i) orthogonal polarized antennas [3, 4]; (ii) co-located antennas with a beamforming feed network [5, 6];

orthogonal polarized planar array antennas [7–9]; and self-induced destructive interference [1–9]. Array and co-located antennas in [5–9] perform self-cancellation recursively as array size gets bigger.

In this paper, a unique decoupling structure is shown to provide high-isolation between nearby patch antennas. The decoupling structure is located between the two antennas to cancel self-interference. It is essentially a metasurface that consists of a square-wave slot pattern with exaggerated corners etched on a rectangular microstrip. This technique is shown to offer an average of 10 dB of mutual coupling suppression.

II. PROPOSED 1×2 SYMMETRIC ARRAY ANTENNA WITH THE PROPOSED DECOUPLING ISOLATOR

Self-interference between the transmit and receive (TRx) array antenna results from insufficient TRx isolation characteristic of an array element and the mutual couplings between the array elements. Strength of spatial couplings in the array antenna is determined by the spacing between the array elements and geometry of the antenna, whereas the TRx isolation of the array element determines the direct coupling.

It is necessary to effectively suppress self-interference at each Rx-port of the array elements to realize acceptable-isolation. A symmetric array is preferred because each coupled signal has its counterpart (a signal with same power and/or same phase) at other ports, and simply adding them destructively in an Rx using the decoupling structure would result in higher isolation. Fig. 1(a) depicts a symmetric layout for a 1×2 array, where each radiation element is excited separately. Fig. 1(b) shows the proposed decoupling structure or metasurface that is composed of a square-wave slot pattern with exaggerated corners that is implemented on a rectangular microstrip. The corners were exaggerated to enhance the isolation. This decoupling structure is integrated between the antennas in the array as shown in Fig. 1(c) to reduce self-interference. The array was designed to operate at ISM bands of X, Ku, K, and Ka, and constructed on FR-4 lossy substrate with dielectric

constant of $\varepsilon_r = 4.3$, $tan\delta = 0.025$, and thickness of 1.6 mm. Each element in the array was directly fed with a required current (amplitude and phase) to achieve a high-gain directional beam at the boresight.

S-parameters including reflection coefficient ($|S_{11}| \leq -10dB$) and mutual coupling (S_{12}) were obtained using 3D full-wave simulators (CST Microwave Studio™ and HFSS). The results of the simulation in Fig. 2 show the reference array with no decoupling structure in the four frequency bands (X, Ku, K, and Ka) has maximum and average isolation values of -26 dB & -25.5 dB, -27.13 dB & -23.5 dB, -25 dB & -23 dB, and -46.5 dB & -35 dB, respectively. The S-parameters are listed in Table I.

(a)

a, b, c, d, and e are 8, 2, 1, 2, and 1 mm, respectively

(b)

(c)

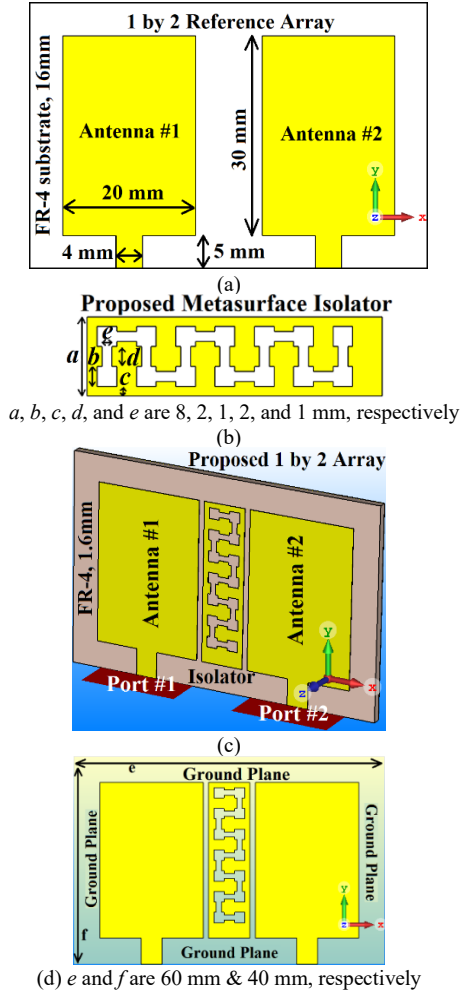(d) e and f are 60 mm & 40 mm, respectively

Fig. 1. Configuration of (a) reference array antennas, (b) proposed integrated closed isolator based on metasurface, (c) proposed array antennas applying the proposed decoupling slab, and (d) ground-plane of both structures.

With the metasurface decoupling structure the array covers X-band (8.41-8.7 GHz) with bandwidth (Δf) of 290 MHz corresponding to a fractional bandwidth (FBW) of 3.4%; Ku-band (13.8-14.6 GHz) with Δf of 800 MHz and FBW of 5.63%; Ku-band (15.6-17.07 GHz) with Δf of 1.45 GHz and FBW of 8.88%; and bands Ku, K, & Ku (17.5-30.0 GHz) with Δf of 12.5 GHz and FBW of 52.63%. The maximum and average isolation values in the respective band (Ku, K, & Ku) are -33.6 dB & -32.5 dB; -36.45 dB & -33 dB; -30 dB & -27.5 dB; and -55.3 dB & -44 dB. By comparing the results with the reference array, it is

apparent that after applying the proposed integrated decoupling structure the maximum and average suppression in mutual coupling is 7.6 dB & 7 dB in the first band; ~10 dB & ~10 dB in the second band; 5 dB & 4.5 dB in the third band; and ~10 dB and ~10 dB in the fourth band. S-parameters characteristics of the proposed array antennas are summarized in Table I.
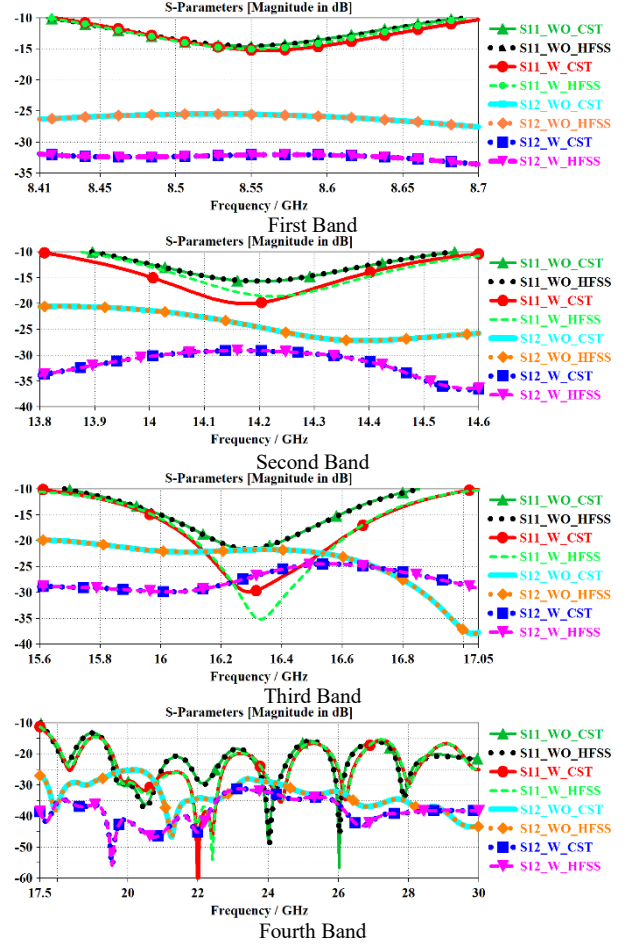

Fig. 2. S-parameters of the reference and proposed array antennas. WO and W represent without and with metasurface isolator, respectively.

TABLE I. SUPPRESSION OF THE REFERENCE AND PROPOSED ARRAYS WITH NO AND WITH METASURFACE DECOUPLING SLAB

First band→ 8.41 – 8.7 GHz (Δf=290 MHz, FBW=3.4%
Average suppression after applying metasurface isolator: 7dB
Second band→ 13.8 – 14.6 GHz (Δf=800 MHz, FBW=5.63%
Average suppression after applying metasurface isolator: ~10dB
Third band→ 15.6 – 17.05 GHz (Δf=1.45 GHz, FBW=8.88%
Average suppression after applying metasurface isolator: ~5dB
Fourth band→ 17.5 – 30 GHz (Δf=12.5 MHz, FBW=52.63%
Average suppression after applying metasurface isolator: ~10dB

The equivalent electrical circuit model of the antenna array loaded with the integrated metasurface isolator is shown in Fig. 3, where the patch radiator is represented with a resonant circuit comprising inductance L_P, capacitance C_P, and resistance R_P. Equivalent circuit of the metasurface isolator is represented by inductance L_M and the capacitance C_M, whose magnitude depend on the gap between the radiators. Coupling between patch and metasurface isolator is through a combination of inductance L_C and capacitance C_C. Inductance L_C is more

dominant because the integrated metasurface isolator is coupled via non-radiating edge of the patch antenna. Ohmic and dielectric loss associated with the metasurface isolator are modelled by resistance R_M. The resonance frequency (f_r) of the decoupling slab is dependent on the magnitude of inductance (L_M) and capacitance (C_M) given by:
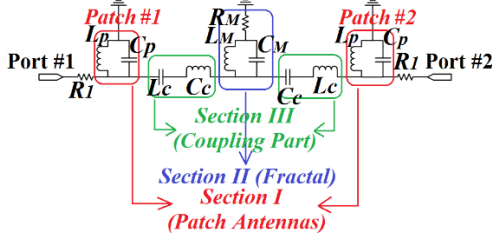
$$f_r = \frac{1}{2\pi\sqrt{L_M C_M}} \qquad (1)$$

Fig. 3. Equivalent circuit diagram of the proposed 1×2 array antenna.

Optimised values of the equivalent circuit model were extracted using Keysight's ADS software tool and are given in Table II. The simplified equivalent circuit model is used to determine the effectiveness of the integrated metasurface isolator on the antenna array's return-loss and isolation performance. Input impedance and admittance of the proposed antenna arrays computed using CST are shown in Fig. 4. There is very good correlation in input impedance and admittance response between the circuit model and CST.

TABLE II. OPTIMIZED VALUES OF THE EQUIVALENT MODEL REPRESENTING THE PROPOSED STRUCTURE

C_P	L_P	C_M	L_M	R_M	C_C	L_C	R_l	R_P
2.2 pF	11.5 nH	10 pF	2.6 nH	75.0 Ω	14.1 pF	1.3 nH	85.05 Ω	50 Ω

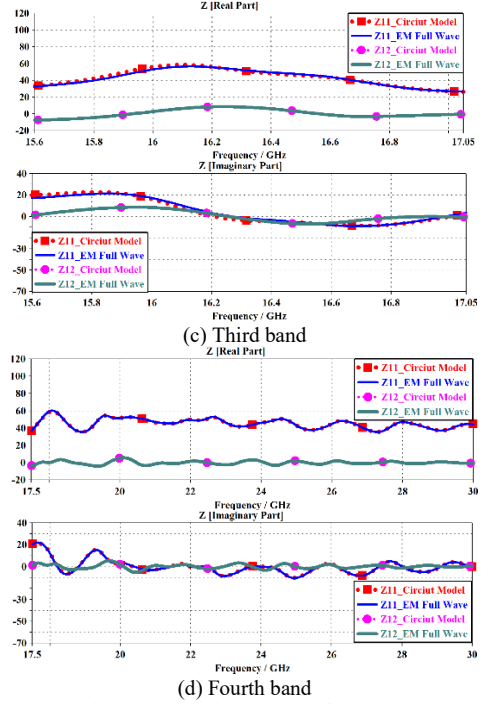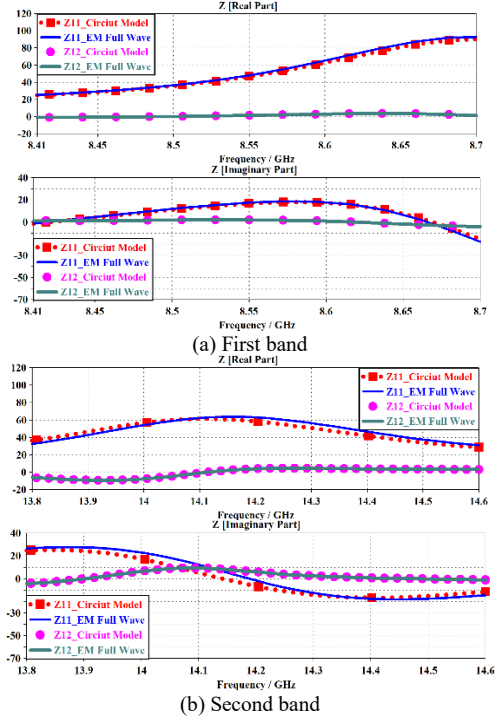(a) First band

(b) Second band

(c) Third band

(d) Fourth band

Fig. 4. Input impedance (Ω) & admittances (1/Ω) of the proposed array.

The surface current distributions and radiation properties of the reference and proposed array antenna are plotted in Figs. 5 and 6, respectively. It is evident from these plots the decoupling structure composed of the square-wave slot soaks up the surface waves that would otherwise couple with the adjacent radiating elements. After applying the proposed isolator based on metasurface the radiation patterns have not been compromised destroyed. In addition, it is observed the radiation patterns with the metasurface decoupling structure approximates the original reference antenna, and over certain angular directions it exhibits better gain performance. The maximum gain of the array antenna with the decoupling slab increased from 5.8 dBi to 7.9 dBi corresponding to 36.2% improvement. The gain of the reference and proposed array antennas with no and with metasurface decoupling structure varies from 2 dBi to 5.8 dBi, and from 3.5 dBi to 7.9 dBi, respectively.

Table II compares the maximum isolation of the proposed technique with previously published work. Defected ground structure (DGS) and ground-plane slot [10, 11] techniques report good improvement in isolation between two antenna elements, however their radiation pattern is significantly deteriorated. Meander line resonator [12] is an appealing choice to reduce surface wave coupling between two elements, without affecting radiation pattern, but these techniques are more complex to design and implement in practice. In [13] the authors have used an electromagnetic band gap (EBG) along with DGS techniques to increase isolation between the radiation elements but this design is also complex to design and fabricate. Besides complexity, acceptable isolation has not achieved. The minimum edge-to-edge gap between the antennas with the proposed technique is 0.28λ but it is more than two times with previously reported techniques.

Port #1   Port #2
With no Isolator

Port #1   Port #2
With Isolator @ 8.5 GHz

Port #1   Port #2
With no Isolator

Port #1   Port #2
With Isolator @ 16.0 GHz

Port #1   Port #2
With no Isolator

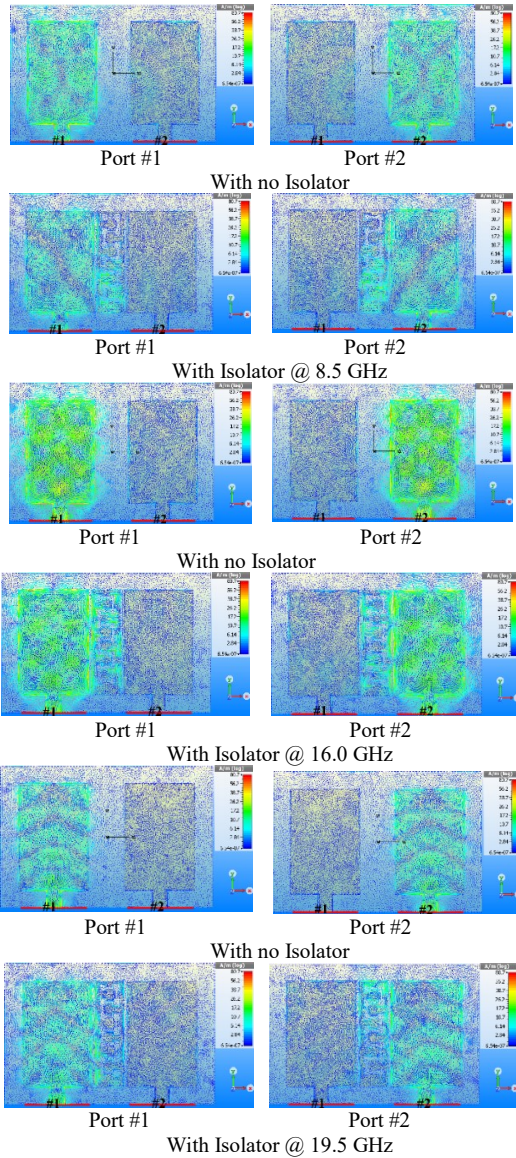Port #1   Port #2
With Isolator @ 19.5 GHz

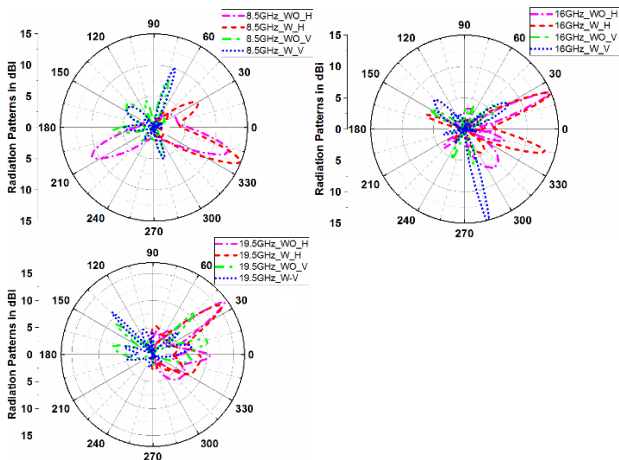Fig. 5. Surface current distribution simulations over the array at various operational frequencies.

Fig. 6. Radiation patterns of the reference and proposed array antennas without (WO) and with (W) metasurface isolator in the horizontal (H) and vertical (V) planes at various operational frequencies.

TABLE II. Mutual Coupling Isolation Comparison

Ref.	Technique	Max. Isolation Improvement	Bands	Radiation pattern deterioration
[10]	SCSRR	10 dB	Single	Yes
[11]	U-shaped resonator	10 dB	Single	Yes
[12]	Meander line resonator	10 dB	Single	No
[13]	EBG	4 dB	Single	Yes
This work	Metasurface	10 dB	Fourth	No

III. CONCLUSION

A unique isolation structure is shown to suppress self-interference in 1×2 array antenna. The isolation structure is essentially a metasurface that consists of a square-wave slot pattern with exaggerated corners implemented on a rectangular microstrip patch. When this structure is integrated between the neighbouring two antennas the resulting mutual coupling is suppressed by average of 10 dB with minimal effect on the radiation characteristics of the array. This technique allows the edge-to-edge gap between the antennas to be reduced to 0.28λ. Also, the gain is improved by 36%. The proposed technique is cost effective, simple to implement and can be retrofitted. It should be suitable for low-power synthetic aperture radars (SAR) and MIMO systems.

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