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# Mutual Coupling Suppression Between Two Closely Placed Microstrip Patches Using EM-Bandgap Metamaterial Fractal Loading

MOHAMMAD ALIBAKHSHIKENARI<sup>ID1</sup>, (Student Member, IEEE),

MOHSEN KHALILY<sup>ID2</sup>, (Senior Member, IEEE), BAL SINGH VIRDEE<sup>3</sup>, (Senior Member, IEEE),

CHAN HWANG SEE<sup>4,5</sup>, (Senior Member, IEEE),

RAED A. ABD-ALHAMEED<sup>ID6,7</sup>, (Senior Member, IEEE), AND ERNESTO LIMITI<sup>ID1</sup>

<sup>1</sup>Electronic Engineering Department, University of Rome “Tor Vergata,” 00133 Rome, Italy

<sup>2</sup>Institute for Communication Systems, Home of 5G Innovation Centre (5GIC), University of Surrey, Guildford GU2 7XH, U.K.

<sup>3</sup>Center for Communications Technology and Mathematics, School of Computing and Digital Media, London Metropolitan University, London N7 8DB, U.K.

<sup>4</sup>School of Engineering, University of Bolton, Bolton BL3 5AB, U.K.

<sup>5</sup>School of Engineering and the Built Environment, Edinburgh Napier University, Edinburgh EH10 5DT, U.K.

<sup>6</sup>School of Electrical Engineering and Computer Science, University of Bradford, Bradford BD71DP, U.K.

<sup>7</sup>College of Science and Technology, Basra University, Basra 61004, Iraq

Corresponding author: Mohsen Khalily (m.khalily@surrey.ac.uk)

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**ABSTRACT** An approach is proposed to reduce mutual coupling between two closely spaced radiating elements. This is achieved by inserting a fractal isolator between the radiating elements. The fractal isolator is an electromagnetic bandgap structure based on metamaterial. With this technique, the gap between radiators is reduced to  $\sim 0.65\lambda$  for the reduction in the mutual coupling of up to 37, 21, 20, and 31 dB in the X-, Ku-, K-, and Ka-bands, respectively. With the proposed technique, the two-element antenna is shown to operate over a wide frequency range, i.e., 8.7–11.7, 11.9–14.6, 15.6–17.1, 22–26, and 29–34.2 GHz. Maximum gain improvement is 71% with no deterioration in the radiation patterns. The antenna’s characteristics were validated through measurement. The proposed technique can be applied retrospectively and is applicable in closely placed patch antennas in arrays found in multiple-input multiple-output and radar systems.

**INDEX TERMS** Fractal, EM bandgap, two-element patch antenna, mutual coupling reduction, metamaterials,multiple-input multiple-output (MIMO), radar.

## I. INTRODUCTION

Multi-antenna systems such as MIMO are plagued with mutual coupling effects that can severely degrade the system’s performance because of increased unwanted near-field EM coupling that adversely disfigures the system’s radiation pattern. The magnitude of the coupling between two adjacently placed patch antennas is a function of position of one antenna relative to other [1]. In fact, mutual coupling is exacerbated when the antennas are very close to each other. Reduction of mutual coupling in antennas is therefore highly desirable, and many techniques have been previously investigated to reduce this phenomenon [2]–[6]. In [7], a slot is embedded in the ground plane to decrease mutual coupling between radiating elements. The slot however adversely

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affects the radiation pattern of the antenna, which can be avoided by using a mushroom type EBG structure reported in [8] and [9]. This involves using plated through hole (vias) that introduce additional loss and complicates the fabrication of the antenna. Vias can be eliminated by using a uni-planar compact electromagnetic bandgap (UC-EBG) structure proposed in [10]. Main disadvantage of UC-EBG is its design complexity. Other techniques to reduce mutual coupling use slotted complementary split ring resonator (SCSRR) [11] and slot combined complementary split ring resonator (SCCSR) [12] structure. In [13], mutual coupling is reduced at the expense of gain and side-lobe level. In [14], isolation between the radiating elements is improved by inserting a meander line resonator between the radiating elements. With this technique the isolation is increased by 8-10 dB between microstrip antennas with edge-to-edge

separation of  $\lambda/18$  over the antenna's 10 dB impedance bandwidth.

In this paper, mutual coupling reduction is demonstrated using fractal isolation which is based on metamaterial EM bandgap structure that is inserted between two closely spaced patch antennas. Compared with other methodologies the proposed technique covers multiple resonant bands, i.e. between 8.7 – 11.7 GHz (X-band), 11.9 – 14.6 GHz (X- and Ku-bands), 15.6 – 17.1 GHz (Ku-band), 22 – 26 GHz (K-band), and 29 – 34.2 GHz (Ka-band). Measured results confirm that with the proposed EMBG-MTM structure the average and maximum suppression on mutual coupling is 15 dB & 37 dB in X-band, 11 dB & 21 dB in Ku-band, 10 dB & 20 dB in K-band, and 18 dB & 31 dB in Ka-band.

## II. PROPOSED COUPLING SUPPRESSION TECHNIQUE

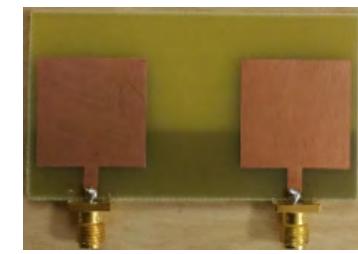
Two identical and standard patch antennas, shown in Fig. 1, were used to demonstrate the proposed mutual coupling reduction technique. Fig. 1(a) is the reference  $2 \times 1$  patch antenna with no isolation. Fig. 1(b) shows the proposed fractal isolator, which is based on EBG-MTM structure that is placed between the two antennas, as shown in Fig. 1(c). The fractal etched in the microstrip patch are constituted from four interconnected 'Y-shaped' slots that are separated with an inverted 'T-shaped' slot. This slot configuration was determined through investigation of numerous fractal curves. This fractal configuration was chosen as it had minimal effect on the antenna's bandwidth and radiation gain characteristics. The ground plane was truncated to realize a wide impedance bandwidth.

Two patch antennas are electromagnetically coupled through the substrate media and space above and below it. Coupling on the substrate layer is due to surface waves, and the coupling through the air is the through direct patch-to-patch near-field. One of the two coupling is more dominant, which depends on the spatial geometry of the antenna structure. Direct mutual coupling between the patch elements can be controlled by adding an extra indirect coupling path using the proposed EBG-MTM isolation structure. The main aim of this work was to create a suitable coupling path that opposes the signal interacting between the two adjacent radiating elements, and at the same time not adversely affect the radiation pattern of the overall antenna.

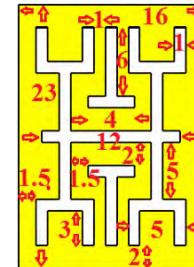
With no fractal isolator when antenna#1 is excited the stray coupling component  $A_o e^{jkx}$  of the electromagnetic waves, which travels along the minus  $x$ -direction, will induce current on antenna#2 thereby creating mutual coupling between the two antennas. When the fractal structure is placed between the two antennas it creates a region with negative permeability yet positive permittivity ( $\mu_r < 0$ ,  $\epsilon_r > 0$ ), where the wavenumber can be expressed as [15]:

$$k = jk_o \sqrt{|\mu_r| |\epsilon_r|} \quad (1)$$

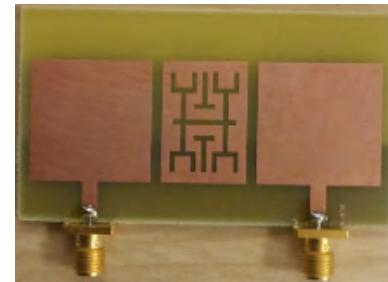
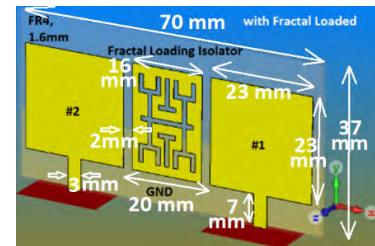
In this case, the corresponding  $x$ -component of the electric field traveling along the negative  $x$ -direction,  $A_o e^{jkx}$  can be



(a) Two-element patch antenna without fractal isolator

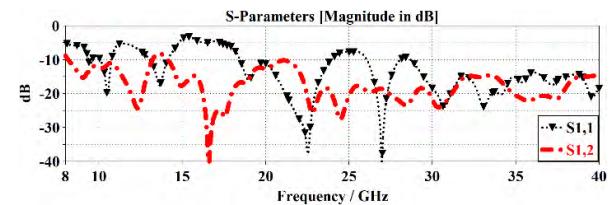


(b) EM bandgap fractal isolator



(c) Two-element antenna with fractal isolator

**FIGURE 1.** (a) Reference  $2 \times 1$  antenna, (b) EM bandgap fractal isolator (annotated dimensions in mm), and (c) Proposed  $2 \times 1$  antenna with EM bandgap isolator.

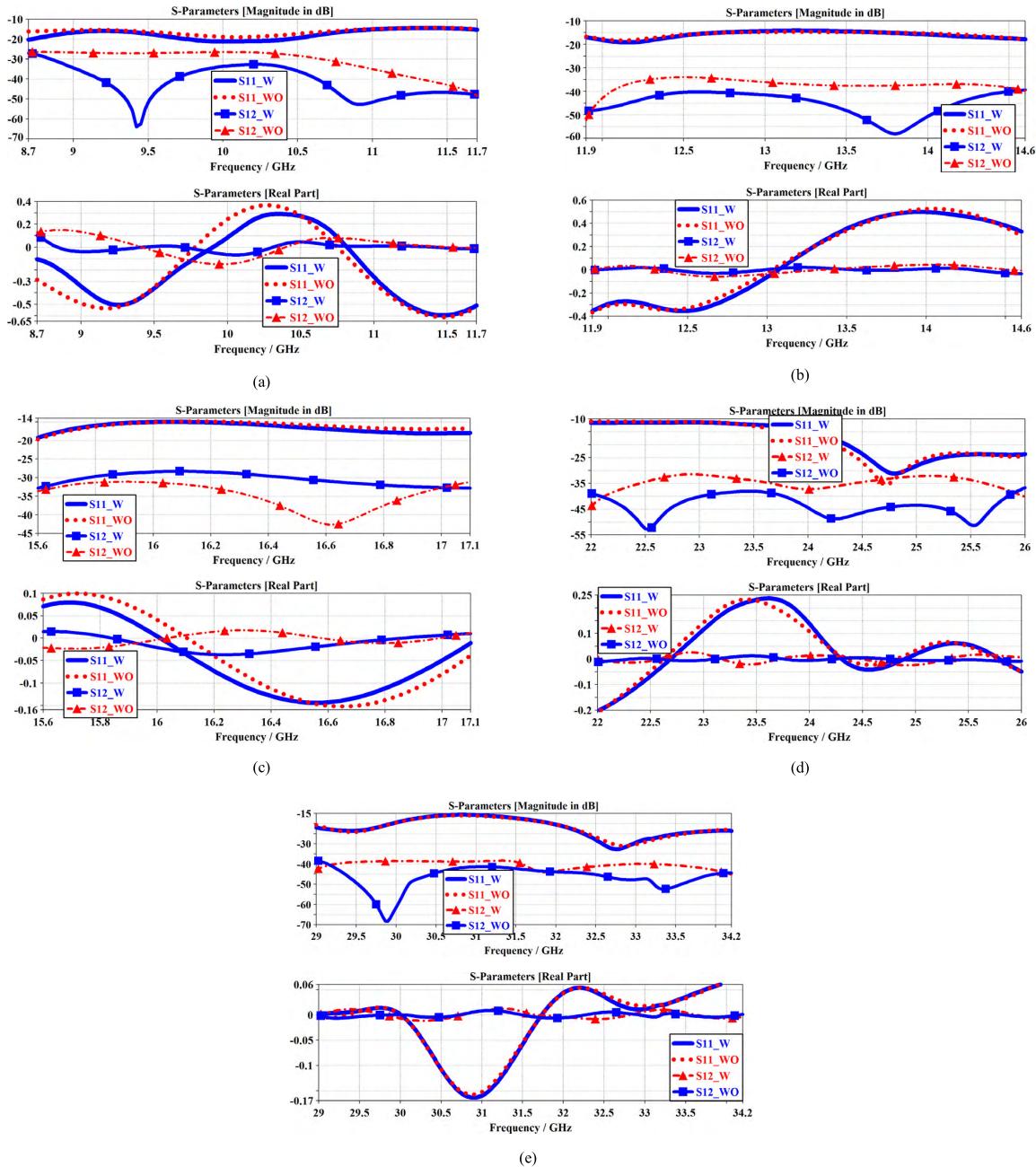


**FIGURE 2.** S-parameter response of the EM bandgap fractal isolator.

further expressed as:

$$A_o e^{jkx} \cdot e^{j\omega t} = A_o e^{-jk_o \sqrt{|\mu_r| |\epsilon_r|} x} \cdot e^{j\omega t} \quad (2)$$

Eqn (2) shows that electromagnetic wave traveling along minus  $x$ -direction of the EBG-MTM surface is evanescent.



**FIGURE 3.** Measured reflection ( $S_{11}$ ) and transmission ( $S_{12}$ ) coefficients of the proposed  $2 \times 1$  antenna ‘with’ and ‘without’ fractal isolator. Note, ‘W’ denotes ‘with’ fractal isolator, and ‘WO’ denotes ‘without’ fractal isolator. (a) First working band from 8.7 to 11.7 GHz (X-band). (b) Second working band from 11.9 to 14.6 GHz (X- and Ku-bands). (c) Third working band from 15.6 to 17.1 GHz (Ku-band). (d) Fourth working band from 22 to 26 GHz (K-band). (e) Fifth working band from 29 to 34.2 GHz (Ka-band).

In this way, the wave creating mutual coupling between the two antennas is rejected. When the wave radiated by antennas propagate along  $z$ -direction, while the magnetic field component is in the  $x$ -direction, radiation is assured by the anisotropic nature of the EBG-MTM structure. The fractal slots behave as electromagnetic band-gap structure that prevent propagation in certain frequency bands. Detailed explanation and analysis is given in [16].

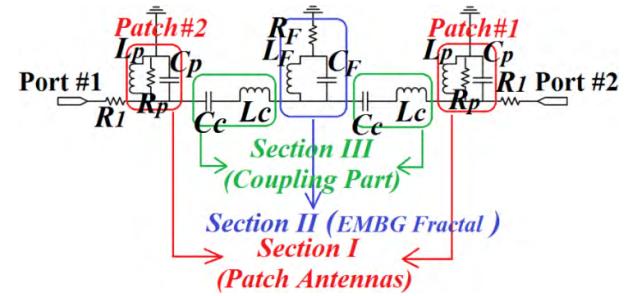
The antenna was fabricated on FR-4 lossy dielectric substrate with dielectric constant of  $\epsilon_r = 4.3$ , thickness of  $h = 1.6$  mm, loss tangent of  $\tan \delta = 0.025$ . Although FR4 dielectric substrate is not an appropriate medium for millimeter-wave circuits however it was used in this study to demonstrate proof-of-concept of using fractal inclusion for reducing mutual coupling between adjacent radiating elements. FR4 had a measured loss of 0.315 dB/cm at 30 GHz.

**TABLE 1.** Optimized values of the equivalent model representing the proposed structure at 10 GHz.

$C_P$	2.5 pF
$L_P$	10 nH
$R_P$	50 Ω
$C_F$	0.12 pF
$L_F$	2.1 nH
$R_F$	76.5Ω
$C_C$	1.3 pF
$L_C$	0.19 nH
$R_I$	83.4 Ω

This loss is too great for practical applications. In this study the high loss was compensated by increasing the transmit power to +23 dBm. Length ( $L$ ) and the width ( $W$ ) of the patch antenna are 23 mm and 23 mm, respectively. Edge-to-edge gap between the two patch antennas ( $g$ ) is 20 mm. The unit of structural dimensions in Fig. 1 are in millimeters.

The proposed array antenna, shown in Fig. 1, was investigated using CST Microwave Studio. Dimensions of the fractal EMBG-MTM structure are shown in Fig. 1(b). The transmission and reflection coefficient plots of the proposed EM bandgap fractal isolator is shown in Fig. 2. It shows attenuation exceeding 10 dB over a wide bandwidth. Measured results in Fig. 3 reveal that in addition to mutual coupling reduction the distinguishing feature of the fractal EMBG-MTM structure is its ability to support radiation in five frequency bands, namely X-, Ku, K-, and Ka-bands. These results show that with the proposed fractal loading the average and maximum suppression on mutual coupling,

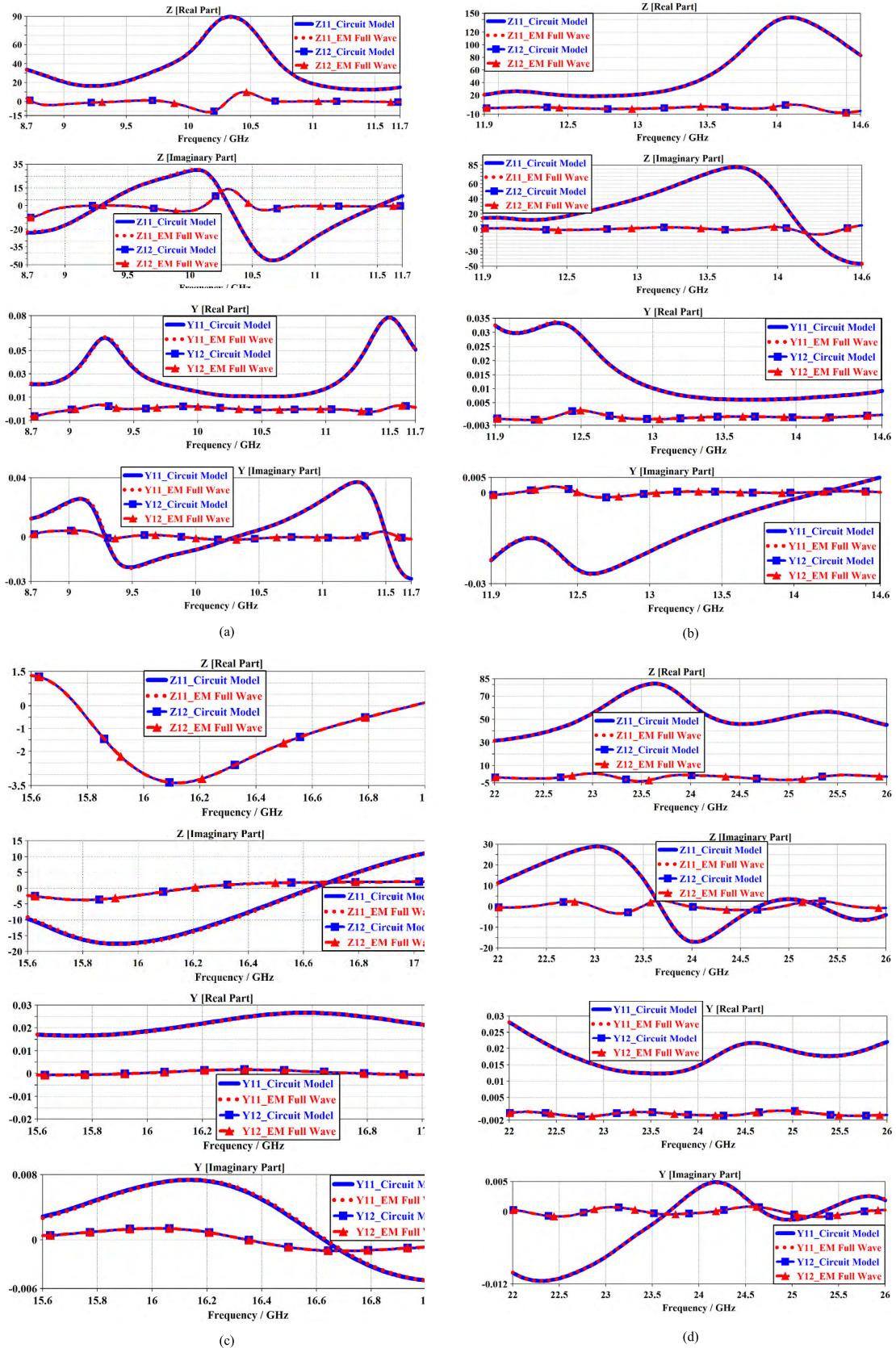
**FIGURE 4.** Equivalent circuit diagram of the proposed  $2 \times 1$  antenna.

respectively, are: 15 dB & 37 dB in the X-band (8.7 – 11.7 GHz); 11 dB & 21 dB in the X- and Ku-bands (11.9 – 14.6 GHz); 10 dB & 12 dB in the Ku-band (15.6 – 17.1 GHz); 10 dB & 20 dB in the K-band (22 – 26 GHz); and 18 dB & 31 dB in the Ka-band (29 – 34.2 GHz). Also, the reflection coefficient remains virtually unaffected.

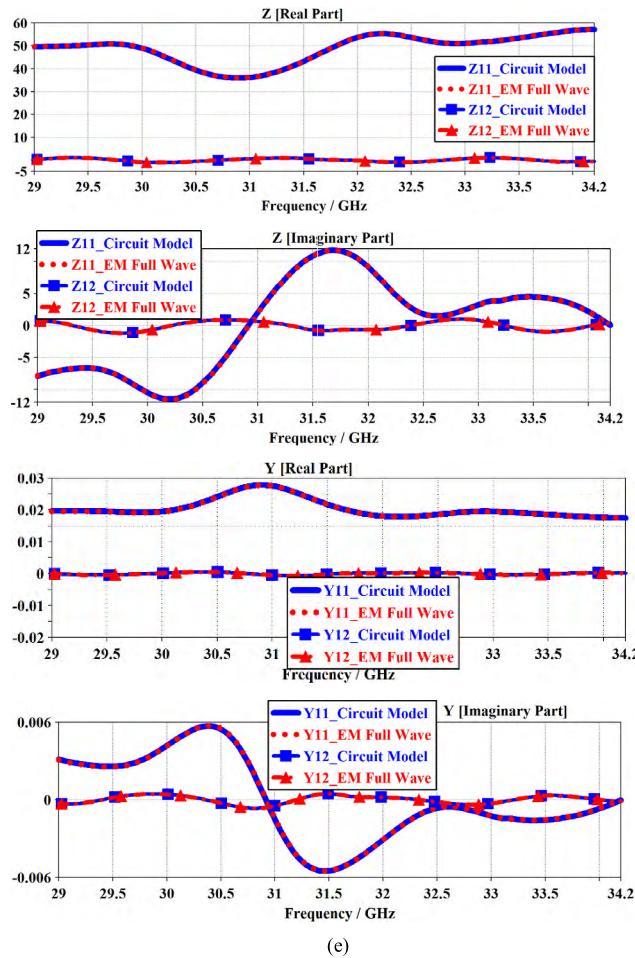
Equivalent electrical circuit model of the  $2 \times 1$  antenna loaded with the fractal isolator is shown in Fig. 4, where the patch radiators are represented with a resonant circuit comprising inductance  $L_P$ , capacitance  $C_P$ , and the Ohmic and dielectric loss represented by resistance  $R_P$ . Similarly, the equivalent circuit of the fractal EMBG-MTM isolator is represented by inductance  $L_F$ , capacitance  $C_F$ , and resistance  $R_F$ . Coupling between patch and fractal isolator is through a combination of inductance  $L_C$  and capacitance  $C_C$ . Inductance  $L_C$  is more dominant because the fractal isolator is coupled via non-radiating edge of the patch antenna.

**TABLE 2.** Mutual coupling isolation comparison.

References	Technique/ Symmetry	Antenna Dimensions	Max. Isolation Improvement	Band coverage	Radiation pattern deterioration
[7]	Slot in ground plane/ No symmetry	$15.5 \times 15.5 \text{ mm}^2$	40 dB	Single, Narrow-band	Yes
[8]	EBG/ No symmetry	$27.2 \times 20 \text{ mm}^2$	4 dB	Single, Narrow-band	Yes
[10]	Compact EBG/ No symmetry	$24.25 \times 18.2 \text{ mm}^2$	17 dB	Single, Narrow-band	Yes
[11]	SCSRR/ No symmetry	$15 \times 15 \text{ mm}^2$	10 dB	Single, Narrow-band	Yes
[12]	SCSSRR/ No symmetry	$20 \times 20 \text{ mm}^2$	14.6 dB	Single, Narrow-band	Yes
[13]	Meander line resonator/ No symmetry	$24.8 \times 24.6 \text{ mm}^2$	10 dB	Single, Narrow-band	No
[14]	DGS/ No symmetry	$20 \times 8 \text{ mm}^2$	17.43 dB	Single, Narrow-band	Yes
[17]	Waveguide MTM/ No symmetry	$40.34 \times 40.34 \text{ mm}^2$	18 dB	Single, Narrow-band	No
[18]	Fractal load with DGS/ No symmetry	$17.6 \times 17.0 \text{ mm}^2$	16 dB	Single, Narrow-band	No
[19]	U-shaped resonator/ No symmetry	$46.82 \times 38.96 \text{ mm}^2$	10 dB	Single, Narrow-band	Yes
[20]	Slotted meander line resonator/ No symmetry	$16.86 \times 13.4 \text{ mm}^2$	16 dB	Single, Narrow-band	Yes
[21]	I-shaped resonator/ No symmetry	$18.35 \times 30.0 \text{ mm}^2$	30 dB	Single, Narrow-band	Yes
<b>This work</b>	<b>Fractal load/ Yes symmetry</b>	<b><math>23 \times 23 \text{ mm}^2</math></b>	<b>37 dB</b>	<b>Five, Wideband</b>	<b>No</b>



**FIGURE 5.** Input impedance ( $\Omega$ ) and admittance ( $1/\Omega$ ) of the proposed  $2 \times 1$  antenna. (a) First operating band from 8.7 to 11.7 GHz (X-band). (b) Second operating band from 11.9 to 14.6 GHz (X- and Ku-bands). (c) Third operating band from 15.6 to 17.1 GHz (Ku-band). (d) Fourth operating band from 22 to 26 GHz (K-band).



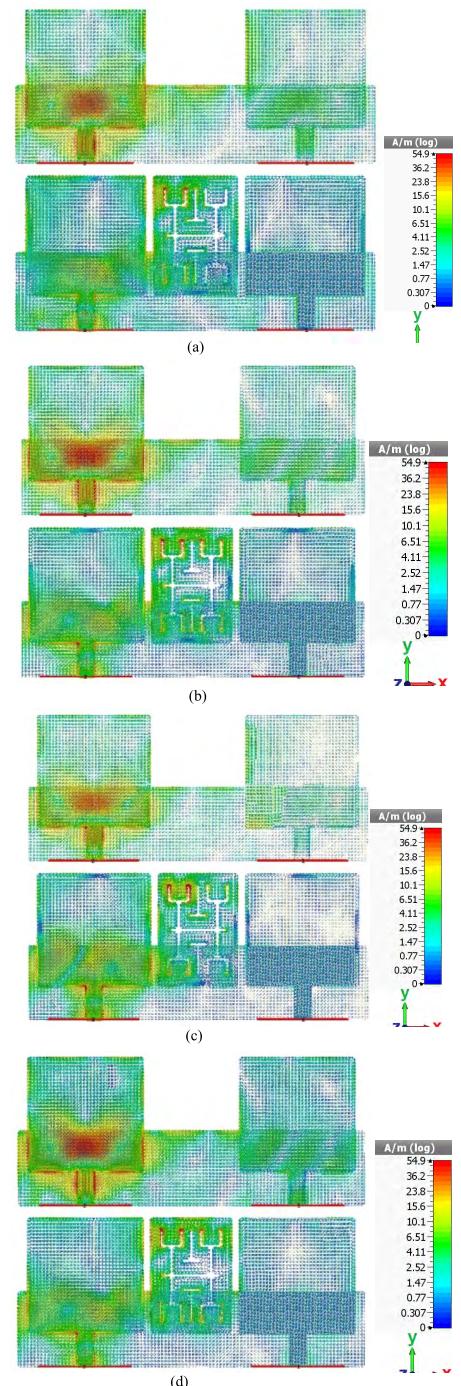
**FIGURE 5. (Continued.)** Input impedance ( $\Omega$ ) and admittance ( $1/\Omega$ ) of the proposed  $2 \times 1$  antenna. (e) Fifth operating band from 29 to 34.2 GHz (Ka-band).

Resonance frequency ( $f_r$ ) of the decoupling slab is dependent on the magnitude of inductance ( $L_F$ ) and capacitance ( $C_F$ ) given by:

$$f_r = \frac{1}{2\pi\sqrt{L_F C_F}} \quad (3)$$

Optimized values of the equivalent circuit model were extracted using Keysight's ADS software tool and are given in Table 1 for a spot frequency. The simplified equivalent circuit model was used to determine the effectiveness of the fractal EMBG-MTM isolator on the two-element antenna's return-loss and isolation performance. Input impedance and admittance of the proposed  $2 \times 1$  antenna computed using CST Microwave studio and the equivalent electrical circuit model are shown in Fig. 5. There is very good correlation in input impedance and admittance response obtained with the circuit model and CST Microwave Studio.

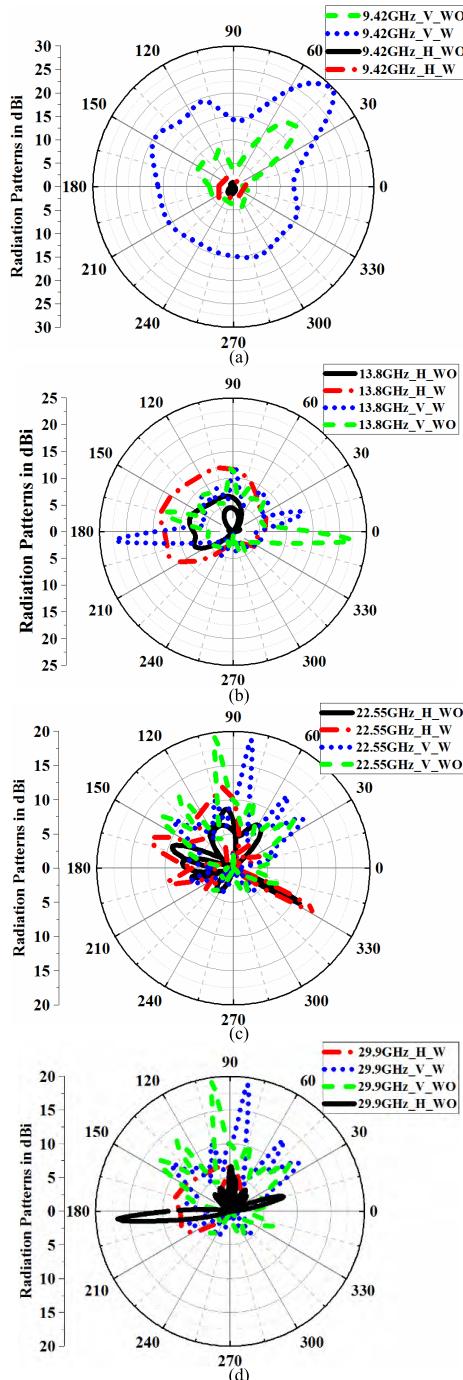
Current density distribution over the two patch antennas with no fractal load and with fractal load at various spot frequencies are shown in Fig. 6. It is evident that surface current is suppressed by introducing the fractal load between the neighboring antennas. This confirms the proposed



**FIGURE 6. Surface current distributions at various spot frequencies.** (a) Without and with fractal isolator @ 9.42 GHz (X-band). (b) Without and with fractal isolator @ 13.8 GHz (Ku-band). (c) Without and with fractal isolator @ 22.55 GHz (K-band). (d) Without and with fractal isolator @ 29.9 GHz (Ka-band).

fractal EMBG-MTM structure acts as an effective decoupling structure.

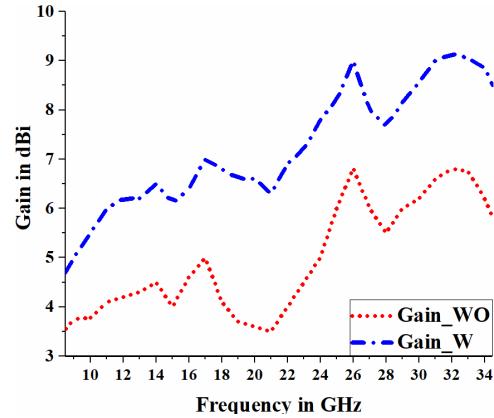
The normalized measured radiation patterns of the two-element antenna with the fractal isolator are shown in the Fig. 7. These results show with fractal isolation coverage and gain performance is generally much better than the unloaded case. Generally, there is significant gain improvement over



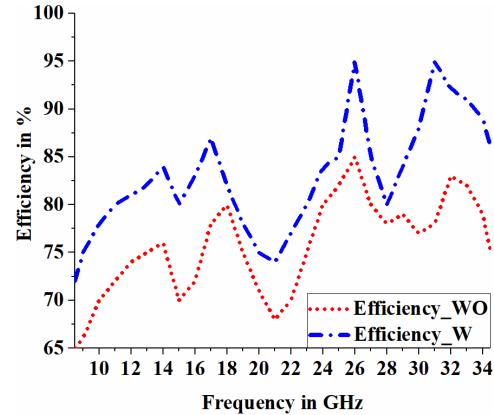
**FIGURE 7.** Measured radiation patterns (normalized) when the antenna is loaded (W) and un-loaded (WO) with the fractal isolator in the horizontal-plane (H) and vertical-plane (V).

certain directions in the horizontal and vertical planes. Grating lobe phenomenon is observed when the inter-element spacing is greater than half a wavelength. However, in the proposed case the periodicity in the array is disrupted with fractal isolators which mitigates grating lobes. Fig. 8 shows the measured gain of the antenna with no fractal loading varies from 3.55 dBi to 6.82 dBi over the specified frequency range. With fractal loading the antenna gain varies between 4.7 dBi to 9.15 dBi. Maximum gain with the fractal load is

9.15 dBi and without the load is 6.82 dBi, which corresponds to an improvement of 71%. Radiation efficiency without and with the fractal load is shown in Fig. 9. The radiation efficiency without the fractal isolator varies from between 65% to 85% over the specified frequency range, however the efficiency improves with insertion of the fractal load. In this case the radiation efficiency varies between 72% to 95% over the specified frequency range. It should be noted that these measurements were made at angular positions where the magnitude of the gain and efficiency were optimum.



**FIGURE 8.** Measured radiation gain response without (WO) and with (W) the proposed fractal load at angular positions where the gain is optimum.



**FIGURE 9.** Measured radiation efficiency plots without (WO) and with (W) the proposed fractal isolator at angular positions where the efficiency is optimum.

Table 2 compares the maximum isolation improvement of the proposed technique with previously published works. Defected ground structure (DGS) [14] and ground plane slot [7] techniques report impressive improvement in isolation between two antenna elements however their radiation pattern is significantly deteriorated. EBG [8], UC-EBG [10] and WGMTM [17] are the most 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. Yang *et al.* [18] have used a fractal and DGS techniques to increase isolation between the radiation elements, but this design too is complex to design and fabricate. The advantages of the

proposed approach are: (i) simple planar symmetrical geometry; (ii) wide band operation; (iii) excludes metallic vias which simplifies manufacturing costs; (iv) excludes the inclusion of defected the ground structures; (v) yields higher isolation between the array elements; and (vi) reduces edge-to-edge gap between the antennas to  $0.65\lambda$  whereas other techniques it's  $1.4\lambda$ .

### III. CONCLUSIONS

Effectiveness of the proposed fractal structure based on EMBG-MTM to suppress mutual coupling between two patch antennas has been demonstrated. With the proposed technique the edge-to-edge gap between the antennas can be reduced to  $0.65\lambda$ , and the optimum measured isolation enhancement is 37 dB, 21 dB, 20 dB, and 31 dB in the X-, Ku-, K-, and Ka-bands. The proposed technique can be applied in two-element antenna for various applications such as MIMO, RFID technology and Radar.

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Prof. E. Limiti.

In 2018, he joined the Antenna System Division, Department of Electrical Engineering, Chalmers University of Technology, Gothenburg, Sweden, as a Ph.D. Visiting Researcher, where is involved in doing research activities. He is currently a member of the Microwave Engineering Center for Space Applications, where Prof. E. Limiti is the Head of the Department. His research interests include array antennas, synthetic aperture radars, multiple input multiple output systems, waveguide slotted antenna arrays, substrate integrated waveguides, microwave and millimeter waves, antennas and wave propagations, metamaterials, electromagnetic-waves applications, on-chip antenna, and millimeter-waves and terahertz applications. The above-mentioned research areas have produced more than 60 publications on refereed international journals and presentations within international conferences. He acts as a Referee for international journals of the microwave, antenna and propagation sector. He is with the Steering Committee of international conferences and workshops.



**MOHSEN KHALILY** (M'13–SM'18) was a Senior Lecturer and a Postdoctoral Research Fellow with the Wireless Communication Center, Universiti Teknologi Malaysia, from 2012 to 2015. He has been a Research Fellow of antenna and propagation with the Home of 5G Innovation Centre, Institute for Communication Systems, University of Surrey, U.K., since 2015. He has published almost 80 academic papers in international peer-reviewed journals and conference proceedings. His research interests include dielectric resonator antennas, multiple-input multiple-output antennas, phased array antennas, hybrid beamforming, and millimeter-wave antennas and propagation. He is a member of the IEEE Antennas and Propagation Society, the IEEE Communication Society, and the IEEE Microwave Theory and Techniques Society, and an Associate Editor of the IEEE Access.



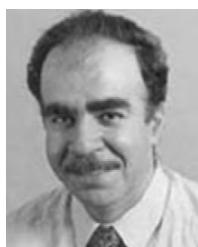
**BAL SINGH VIRDEE** (SM'08) received the B.Sc. and M.Phil. degrees in communications engineering from the University of Leeds, U.K., and the Ph.D. degree in electronic engineering from the University of London, U.K. He was with the industry for various companies including Philips, U.K., as a Research and Development Engineer and Filtronic Components Ltd., as a Future Products Developer in the area of RF/microwave communications. He has taught in several academic institutions. He is currently a Professor of microwave communications with

the School of Computing and Digital Media, London Metropolitan University, where he is the Head of the Center for Communications Technology and the Director of London Metropolitan-Microwaves. He has published numerous research-papers. His research, in collaboration with industry and academia, is in the area of microwave wireless communications encompassing mobile phones to satellite technology. He is an Executive Member of the IET's Technical and Professional Network Committee on RF/Microwave-Technology. He is a Fellow of the IET. He has chaired technical sessions at the IEEE international conferences.



**CHAN HWANG SEE** (M'14-SM'15) received the B.Eng. degree (Hons.) in electronic, telecommunication, and computer engineering and the Ph.D. degree in computational bioelectromagnetics from the University of Bradford, Bradford, U.K., in 2002 and 2007, respectively.

He was a Senior Research Fellow with the Antennas and Applied Electromagnetics Research Group, University of Bradford. He is currently a Senior Lecturer (Program Leader) of electrical and electronic engineering with the School of Engineering, University of Bolton, Bolton, U.K. He is also a Visiting Research Fellow with the School of Engineering and Informatics, University of Bradford. He has published more than 160 peer-reviewed journal articles and conference papers. He has co-authored one book and five book chapters. His research interests include wireless sensor networks' system design, computational electromagnetism, antennas, and acoustic sensor design. He is a member of the Institution of Engineering and Technology, U.K. He is also a Fellow of the Higher Education Academy and an Associate Editor of the IEEE ACCESS. He received two Young Scientist Awards from the International Union of Radio Science and the Asia-Pacific Radio Science Conference, in 2008 and 2010, respectively. He was a recipient of the Certificate of Excellence for his successful Knowledge Transfer Partnership with Yorkshire Water on the design and implementation of a wireless sensor system for sewerage infrastructure monitoring, in 2009. He is a Chartered Engineer in U.K.



**RAED A. ABD-ALHAMEED** (M'02-SM'13) received the B.Sc. and M.Sc. degrees in electrical engineering from Basrah University, Basrah, Iraq, in 1982 and 1985, respectively, and the Ph.D. degree in electrical engineering from the University of Bradford, Bradford, U.K., in 1997.

He has also been a Research Visitor with Glyndwr University, Wrexham, U.K., since 2009, covering the wireless and communications research areas. He is currently a Professor of electromagnetic and radio frequency engineering with the University of Bradford. He is the Leader of radio frequency, propagation, sensor design, and signal processing. He leads the Communications Research Group, School of Engineering and Informatics, Bradford University, for years. He is a Principal Investigator of several funded applications to EPSRCs and a Leader of several successful Knowledge Transfer Programmes (KTPs) with Arris, Yorkshire Water plc, Harvard Engineering plc, IETG Ltd., Seven Technologies Group, Emkay Ltd., and Two World Ltd. He is also a Co-Investigator of several funded research projects including: H2020 MARIE Skłodowska-CURIE ACTIONS: Innovative Training Networks Secure Network Coding for Next Generation Mobile Small Cells 5G-US, nonlinear and demodulation mechanisms in biological tissue (Department of Health, Mobile Telecommunications and Health Research Programme, and Assessment of the Potential Direct Effects of Cellular Phones on the Nervous System) (EU: collaboration with six other major research organizations across Europe). He has published more than 500 academic journal and conference papers. He has co-authored three books and several book chapters. He has long years' research experience in the areas of radio frequency, signal processing, propagations, antennas, and electromagnetic computational techniques. His research interests include computational methods and optimizations, wireless and mobile communications, sensor design, EMC, beam steering antennas, energy-efficient PAs, and RF predistorter design applications.

Dr. Abd-Alhameed is a Fellow of the Institution of Engineering and Technology, U.K., and the Higher Education Academy. He is a Chartered Engineer in U.K. He received the Business Innovation Award for his successful KTP with Pace and Datong companies on the design and implementation of multiple-input multiple-output sensor systems and antenna array design for service localizations. He is the Chair of several successful workshops on energy efficient and reconfigurable transceivers: approach toward energy conservation and CO<sub>2</sub> reduction that addresses the biggest challenges for future wireless systems. He was also appointed as a Guest Editor for *IET Science, Measurements and Technology*, in 2009 and 2012.



**ERNESTO LIMITI** was elected to represent the Industrial Engineering Sector in the academic senate of the University of Roma Tor Vergata, from 2007 to 2010 and from 2010 to 2013. He has been a Research and Teaching Assistant with the University of Roma Tor Vergata, since 1991, where he has been an Associate Professor, since 1998, and a Full Professor of electronics with the Engineering Faculty, since 2002. He represents the University of Roma Tor Vergata in the governing body of the

Microwave Engineering Center for Space Applications, an inter-university center among several Italian universities. He is currently the President of the Consortium Advanced Research and Engineering for Space formed between the university and two companies. He is the President of the Laurea and Laurea Magistrale degrees in electronic engineering of the University of Roma Tor Vergata. His research activity focused on three main lines, all of them belonging to the microwave and millimeter-wave electronics research area. The first one is related to characterization and modeling for active and passive microwave and millimeter-wave devices. Regarding active devices, the research line is oriented to the small-signal, and noise and large signal modeling. Regarding passive devices, equivalent-circuit models have been developed for interacting discontinuities in microstrip, for typical monolithic microwave integrated circuit passive components (MIM capacitors) and to waveguide/coplanar waveguide transitions analysis and design. For active devices, new methodologies have been developed for the noise characterization and the subsequent modeling, and equivalent-circuit modeling strategies have been implemented both for small and large-signal operating regimes for GaAs, GaN, SiC, Si, and InP MESFET/HEMT devices. The second line is related to design methodologies and characterization methods for low-noise circuits. The main focus is on cryogenic amplifiers and devices. Collaborations are currently ongoing with the major radioastronomy institutes all around Europe within the frame of FP6 and FP7 programs (RadioNet). Finally, the third line is in the analysis methods for nonlinear microwave circuits. In this line, novel analysis methods (Spectral Balance) are developed together with the stability analysis of the solutions making use of traditional (harmonic balance) approaches. The above research lines have produced more than 250 publications on refereed international journals and presentations within international conferences. He is actively involved in research activities with many research groups, both European and Italian, and he is in tight collaborations with high-tech Italian (Selex SI, Thales Alenia Space, Rheinmetall, Elettronica S.p.A., and Space Engineering) and foreign (OMMIC, Siemens, and UMS) companies. He contributed, as a Researcher and/or as a Unit Responsible, to several national (PRIN MIUR, Madess CNR, and Agenzia Spaziale Italiana) and international (ESPRIT COSMIC, Manpower, Edge, Special Action MEPI, ESA, EUROPA, Korrigan, RadioNet FP6, and FP7) projects. Regarding teaching activities, he teaches, over his institutional duties in the frame of the Corso di Laurea Magistrale in Ingegneria Elettronica, elettronica per lo spazio within the master course in sistemi avanzati di comunicazione e navigazione satellitare.

He is a member of the committee of the Ph.D. program in telecommunications and microelectronics with the University of Roma Tor Vergata, tutoring an average of four Ph.D. candidates per year. He acts as a Referee for international journals of the microwave and millimeter wave electronics sector. He is with the Steering Committee of international conferences and workshops.