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

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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 ~0.65λ 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 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 (SCCSSR) [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

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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 2×1 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]:

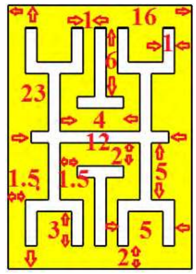
$$k = jk_o\sqrt{|\mu_r|\,|\varepsilon_r|} \tag{1}$$

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

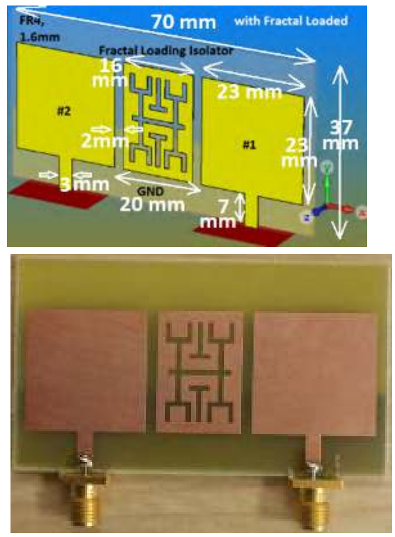
$$A_o e^{jkx}.e^{j\omega t} = A_o e^{-jk_o\sqrt{|\mu_r||\varepsilon_r|}x}.e^{j\omega t} \tag{2}$$

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

(a) Two-element patch antenna without fractal isolator



(b) EM bandgap fractal isolator



(c) Two-element antenna with fractal isolator

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

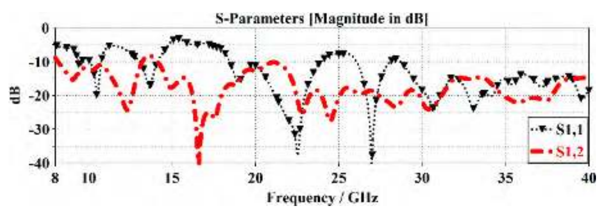


FIGURE 2. **S-parameter response of the EM bandgap fractal isolator.**

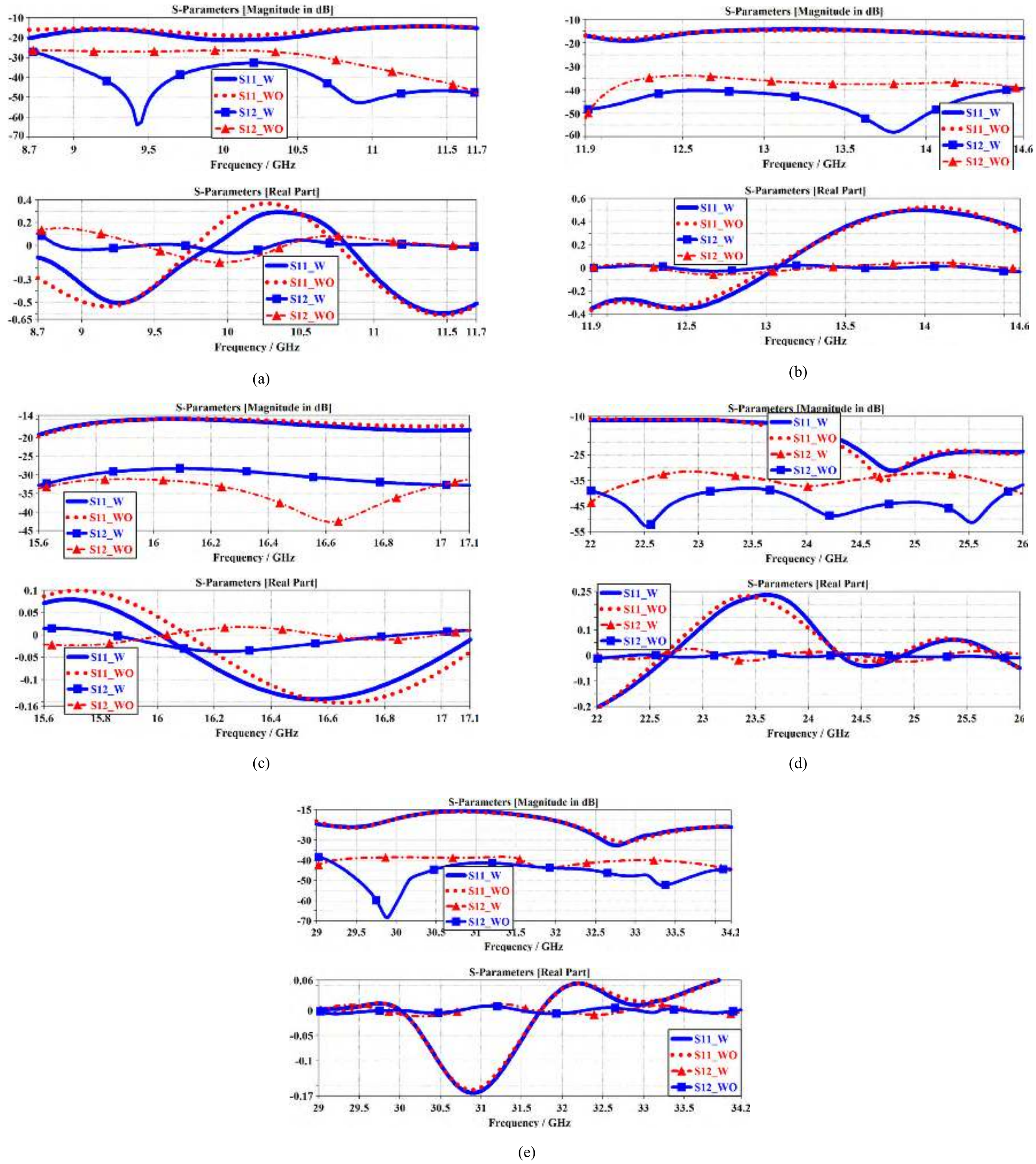


FIGURE 3. Measured reflection (S_{11}) and transmission (S_{12}) coefficients of the proposed 2×1 antenna 'with' and 'without' fractal isolator. Note, "W" denotes 'with' fractal isolator, and "WO" denotes 'without' fractal isolator. (a) First working band from 8.7 to 11.7 GHz (X-band). (b) Second working 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 $\varepsilon_r = 4.3$, 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_1	83.4 Ω

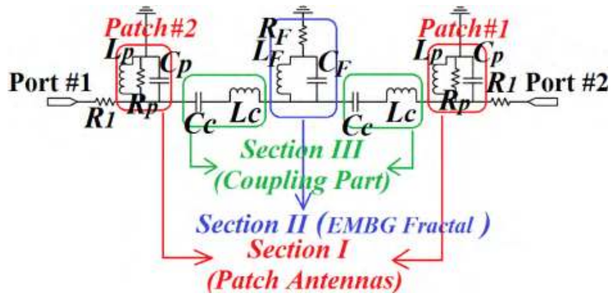


FIGURE 4. Equivalent circuit diagram of the proposed 2×1 antenna.

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, 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 2×1 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	15.5×15.5 mm^2	40 dB	Single, Narrow-band	Yes
[8]	EBG/ No symmetry	27.2×20 mm^2	4 dB	Single, Narrow-band	Yes
[10]	Compact EBG/ No symmetry	24.25×18.2 mm^2	17 dB	Single, Narrow-band	Yes
[11]	SCSRR/ No symmetry	15×15 mm^2	10 dB	Single, Narrow-band	Yes
[12]	SCSSRR/ No symmetry	20×20 mm^2	14.6 dB	Single, Narrow-band	Yes
[13]	Meander line resonator/ No symmetry	24.8×24.6 mm^2	10 dB	Single, Narrow-band	No
[14]	DGS/ No symmetry	20×8 mm^2	17.43 dB	Single, Narrow-band	Yes
[17]	Waveguide MTM/ No symmetry	40.34×40.34 mm^2	18 dB	Single, Narrow-band	No
[18]	Fractal load with DGS/ No symmetry	17.6×17.0 mm^2	16 dB	Single, Narrow-band	No
[19]	U-shaped resonator/ No symmetry	46.82×38.96 mm^2	10 dB	Single, Narrow-band	Yes
[20]	Slotted meander line resonator/ No symmetry	16.86×13.4 mm^2	16 dB	Single, Narrow-band	Yes
[21]	I-shaped resonator/ No symmetry	18.35×30.0 mm^2	30 dB	Single, Narrow-band	Yes
This work	**Fractal load/ Yes symmetry**	**23×23 mm^2**	**37 dB**	**Five, Wideband**	**No**

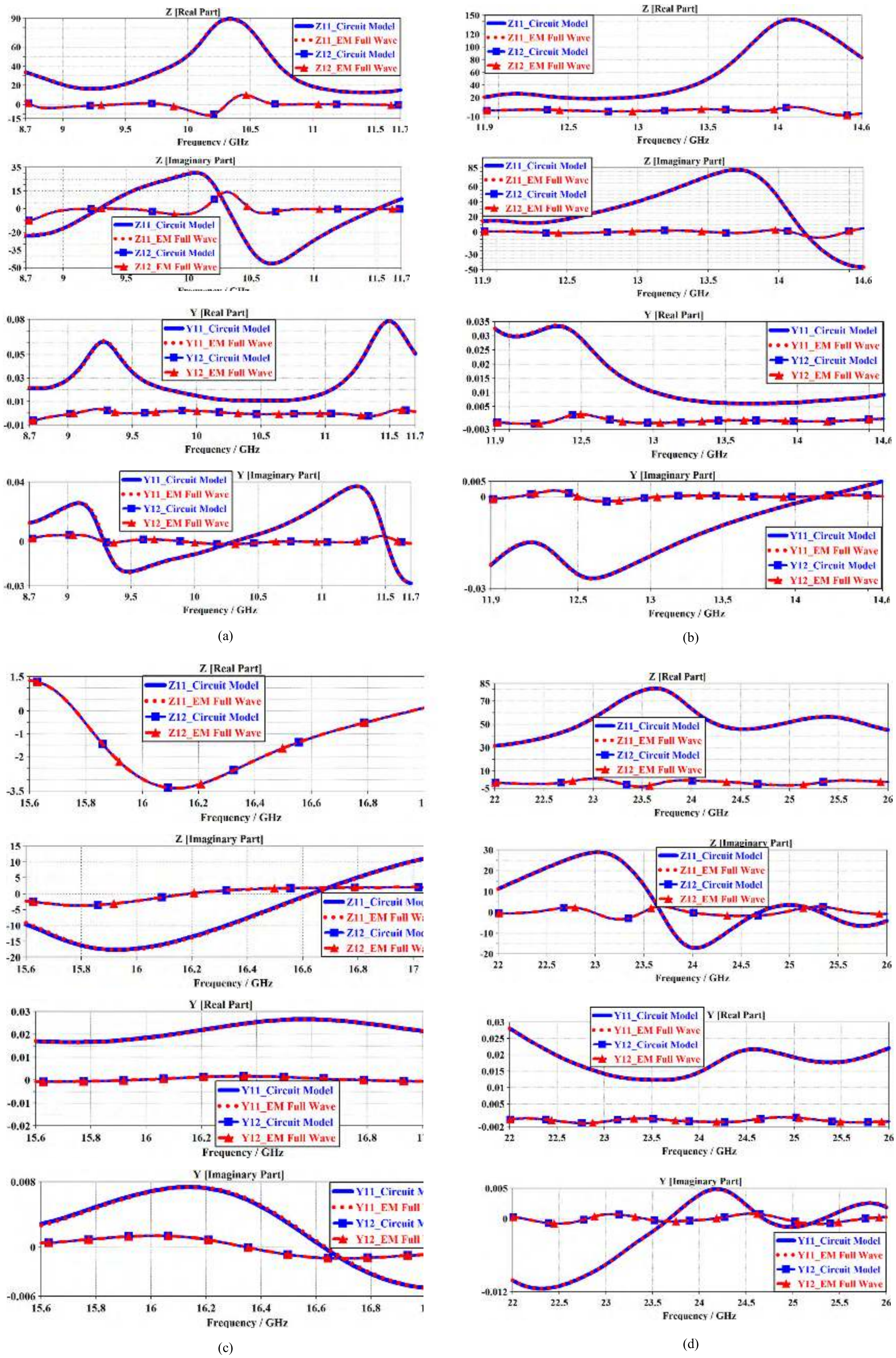
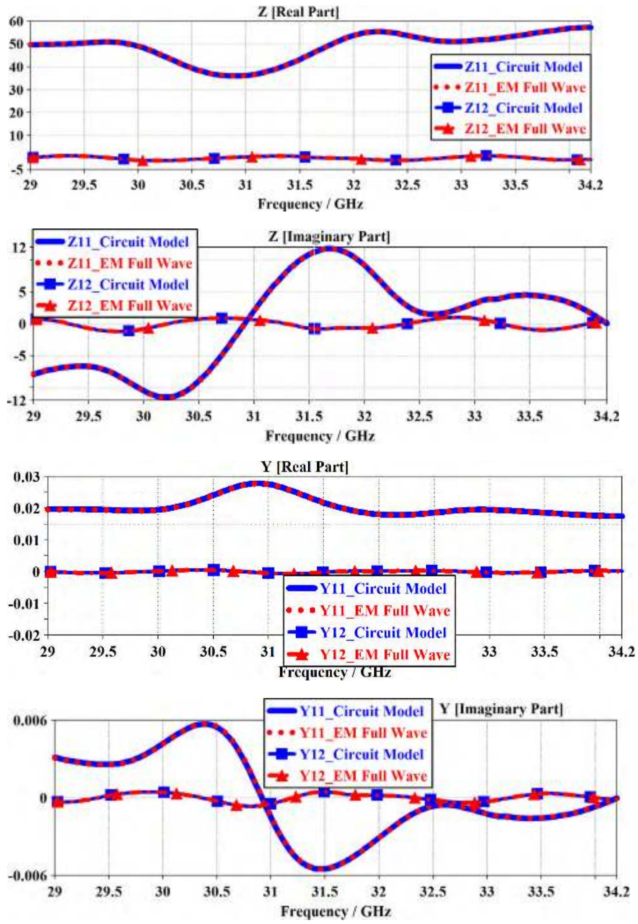


FIGURE 5. Input impedance (Ω) and admittance (1/Ω) of the proposed 2×1 antenna. (a) First operating band from 8.7 to 11.7 GHz (X-band). (b) Second operating band from 11.9 to 14.6 GHz (X- and Ku-bands). (c) Third operating band from 15.6 to 17.1 GHz (Ku-band). (d) Fourth operating band from 22 to 26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



(e)

FIGURE 5. ***(Continued.)*** **Input impedance (Ω) and admittance (1/Ω) of the proposed 2×1 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:

$$f_r = \frac{1}{2\pi\sqrt{L_F C_F}} \tag{3}$$

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 2×1 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 fractal EMBG-MTM structure acts as an effective decoupling structure.

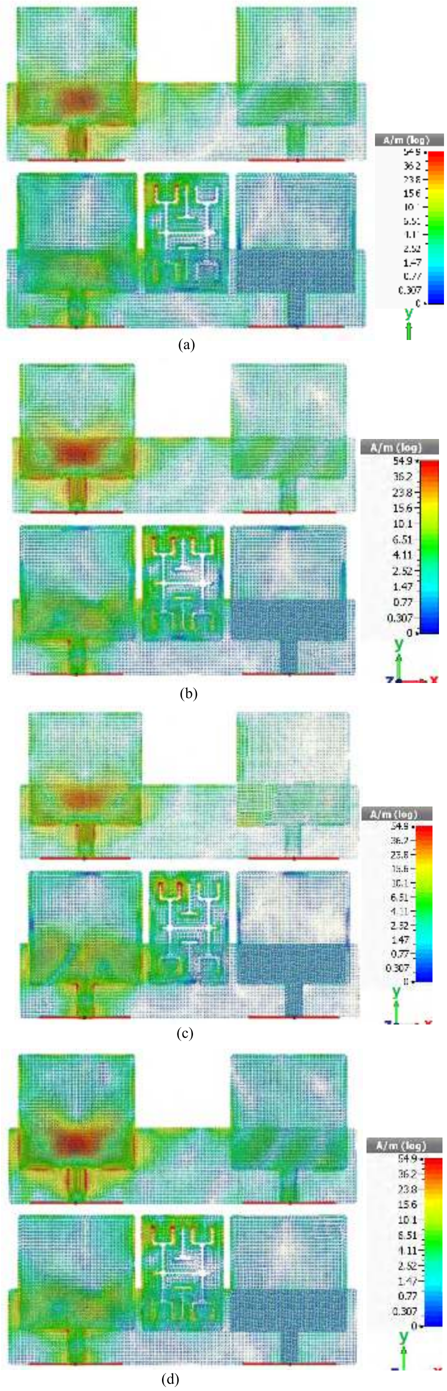


FIGURE 6. **Surface current distributions at various spot frequencies. (a) Without and with fractal isolator @ 9.42 GHz (X-band). (b) Without and with fractal isolator @ 13.8 GHz (Ku-band). (c) Without and with fractal isolator @ 22.55 GHz (K-band). (d) Without and with fractal isolator @ 29.9 GHz (Ka-band).**

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

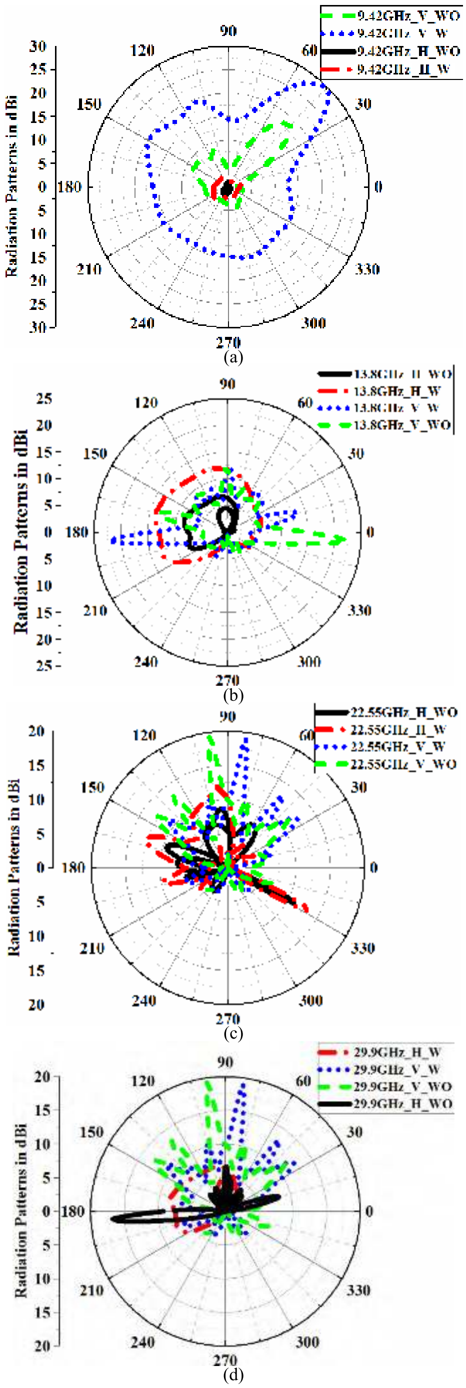


FIGURE 7. Measured radiation patterns (normalized) when the antenna is loaded (W) and un-loaded (WO) with the fractal isolator in the horizontal-plane (H) and vertical-plane (V).

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.

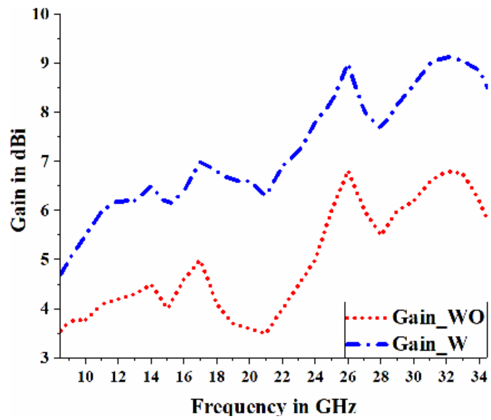


FIGURE 8. Measured radiation gain response without (WO) and with (W) the proposed fractal load at angular positions where the gain is optimum.

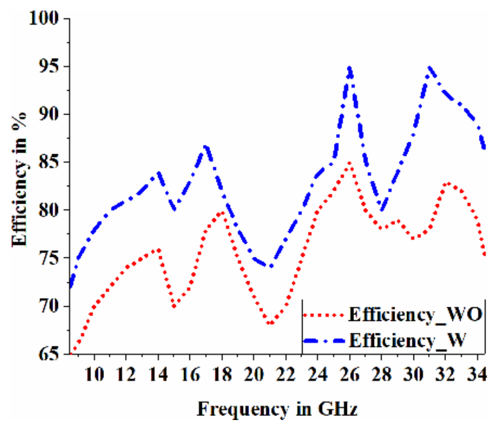


FIGURE 9. Measured radiation efficiency plots without (WO) and with (W) the proposed fractal isolator at angular positions where the efficiency is optimum.

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 0.65λ whereas other techniques it's 1.4λ.

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 0.65λ, 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.

REFERENCES

[1] C. Balanis, *Antenna Theory: Analysis and Design*. Hoboken, NJ, USA: Wiley, 2005.

[2] Y.-F. Cheng, X. Ding, W. Shao, and B.-Z. Wang, "Reduction of mutual coupling between patch antennas using a polarization-conversion isolator," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1257–1260, 2016.

[3] K. S. Vishvaksenan, K. Mithra, R. Kalaiarasan, and K. S. Raj, "Mutual coupling reduction in microstrip patch antenna arrays using parallel coupled-line resonators," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2146–2149, 2017.

[4] Q. Li *et al.*, "Mutual coupling reduction in patch antenna arrays," in *Proc. IEEE Int. Vac. Electron. Conf.*, Apr. 2018, pp. 209–210.

[5] S. Maddio, G. Pelosi, M. Righini, S. Selleri, and I. Vecchi, "Mutual coupling reduction in multilayer patch antennas via meander line parasites," *Electron. Lett.*, vol. 54, no. 15, pp. 922–924, 2018.

[6] M. Kiani-Kharaji, H. R. Hassani, and S. Mohammad-Ali-Nezhad, "Wide scan phased array patch antenna with mutual coupling reduction," *IET Microw., Antennas Propag.*, vol. 12, no. 12, pp. 932–1938, 2018.

[7] J. OuYang, F. Yang, and Z. M. Wang, "Reduction of mutual coupling of closely spaced microstrip MIMO antennas for WLAN application," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 310–312, 2011.

[8] A. Yu and X. Zhang, "A novel method to improve the performance of microstrip antenna arrays using a dumbbell EBG structure," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, no. 1, pp. 170–172, 2003.

[9] A. Suntives and R. Abhari, "Miniaturization and isolation improvement of a multiple-patch antenna system using electromagnetic band gap structures," *Microw. Opt. Technol ., Lett.*, vol. 55, no. 7, pp. 1609–1612, 2013.

[10] M. T. Islam and M. S. Alam, "Compact EBG structure for alleviating mutual coupling between patch antenna array elements," *Prog. Electromagn. Res.*, vol. 137, pp. 425–438, May 2013.

[11] M. M. B. Suwailam, O. F. Siddiqui, and O. M. Ramahi, "Mutual coupling reduction between microstrip patch antennas using slotted-complementary split-ring resonators," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 876–878, 2010.

[12] M. F. Shafique, Z. Qamar, L. Riaz, R. Saleem, and S. A. Khan, "Coupling suppression in densely packed microstrip arrays using metamaterial structure," *Microw., Opt. Techanol. Lett.*, vol. 57, no. 3, pp. 759–763, 2015.

[13] J. Ghosh, S. Ghosal, D. Mitra, and S. R. B. Chaudhuri, "Mutual coupling reduction between closely placed microstrip patch antenna using meander line resonator," *Prog. Electromagn. Res. Lett.*, vol. 59, pp. 115–122, 2016.

[14] F.-G. Zhu, J.-D. Xu, and Q. Xu, "Reduction of mutual coupling between closely-packed antenna elements using defected ground structure," *Electron. Lett.*, vol. 45, no. 12, pp. 601–602, 2009.

[15] A. Grbic and G. V. Eleftheriades, "Periodic analysis of a 2-D negative refractive index transmission line structure," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, pp. 2604–2611, Oct. 2003.

[16] C. L. Holloway, E. F. Kuester, J. A. Gordon, J. O'Hara, J. Booth, and D. R. Smith, "An Overview of the theory and applications of metasurfaces: The two-dimensional equivalents of metamaterials," *IEEE Antennas Propag. Mag.*, vol. 54, no. 4, pp. 10–35, Jul. 2012.

[17] Z. Qamar and H. C. Park, "Compact waveguided metamaterials for suppression of mutual coupling in microstrip array," *Progr. Electromagn. Res.*, vol. 149, pp. 183–192, 2014.

[18] X. Yang, Y. Liu, Y.-X. Xu, and S.-X. Gong, "Isolation enhancement in patch antenna array with fractal UC-EBG structure and cross slot," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2175–2178, 2017.

[19] S. Farsi, D. Schreurs, and B. Nauwelaers, "Mutual coupling reduction of planar antenna by using a simple microstrip U-section," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 1501–1503, 2012.

[20] M. G. Alsath, M. Kanagasabai, and B. Balasubramanian, "Implementation of slotted meander-line resonators for isolation enhancement in microstrip patch antenna arrays," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 15–18, 2013.

[21] C. K. Ghosh and S. K. Parui, "Education of mutual coupling between E-shaped microstripantennas by using a simple microstrip I-section," *Microw., Opt. Technol. Lett.*, vol. 55, no. 11, pp. 2544–2549, 2013.

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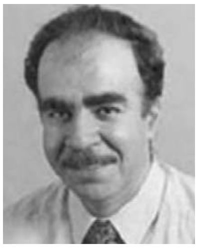

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Dr. Abd-Alhameed is a Fellow of the Institution of Engineering and Technology, U.K., and the Higher Education Academy. He is a Chartered Engineer in U.K. He received the Business Innovation Award for his successful KTP with Pace and Datong companies 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_2 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.