A Review on Different Techniques of Mutual Coupling Reduction Between Elements of Any MIMO Antenna. Part 2: Metamaterials and Many More

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Key Points:

- Mutual coupling (MC) reduction among antenna elements is a significant challenge while designing a compact MIMO antenna design
- The negative permittivity and permeability property of Metamaterials helps in suppressing the ground wave propagation
- Some more MC reduction techniques have been discussed thoroughly in this article, like Electromagnetic Band Gap (EBG) structure, Decoupling and Matching network, and Neutralization line

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A Review on Different Techniques of Mutual Coupling Reduction Between Elements of Any MIMO Antenna. Part 2: Metamaterials and Many More

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Abstract This two-part article presents a review of different techniques of mutual coupling (MC) reduction. MC reduction is a primary concern while designing a compact multiple-input-multiple-output (MIMO) antenna where the separation between the antennas is less than $\lambda_0/2$, that is, half of the free-space wavelength. The negative permittivity and permeability of artificially created materials/structures (Metamaterials) significantly help reduce MC among narrow-band compact MIMO antenna design elements. In this part two of the review paper, we will discuss techniques: Metamaterials; Split-Ring-Resonator; Complementary-Split-Ring-Resonator; Frequency Selective Surface, Metasurface, Electromagnetic Band Gap structure, Decoupling and Matching network, Neutralization line, Cloaking Structures, Shorting vias and pins and few more.

1. Introduction

The demand for high-data rate wireless transmission in compact handheld devices like smartphones has revolutionized the importance of compact multiple-input-multiple-output (MIMO) antenna design, which can fulfill the increasing demand without sacrificing the additional bandwidth or increased transmit power (A. Kumar, Ansari, Kanaujia, & Kishor, 2018; A. Kumar, Ansari, Kanaujia, Kishor, & Tewari, 2018) in a rich scattering environment. Along with high-data rates, spatial diversity, and pattern diversity among antenna elements are also required to minimize the power losses and maximize the performance (A. Kumar et al., 2019).

The MIMO antenna should have a common ground embedded on a single substrate and share at least one common resonating frequency. It will ease the integration in monolithic integrated circuits (A. Kumar et al., 2020). We will find many MIMO antennas having no common ground, but such cases should be avoided because of various reasons, as stated by Sharawi (2017).

Compact MIMO antenna results in strong MC among antenna elements that needs to be reduced. Usually, negative permittivity and permeability are not found in naturally occurring materials. Still, they can be produced by some artificial structures like split-ring-resonators (SRRs) (Pendry et al., 1999), which helps in curbing the MC effects. Some periodic structures like electromagnetic band gap (EBG) structures (Kapoor, 2013) are also significant in reducing MC.

This article deals with a thorough description of the existing isolation techniques apart from defected ground structures (DGSs) and Parasitic Structures, which are already discussed in part one of this article for minimizing the MC between patch antennas present until the to date literature. We will also observe and discuss various MC reduction techniques' performance through the comparison tables, highlighting its importance as per the different types of operation bands like narrow-band, wideband, or ultrawideband.

Many review papers (Chouhan et al., 2018; Irene & Rajesh, 2018b; Malviya et al., 2017; Nadeem & Choi, 2019) have been published, citing various techniques of MC reduction but were limited to some specific design and parameters. The main objective is to have closely spaced MIMO antenna elements with high isolation between them. The techniques which we are to discuss in part two of the two-part article are tabulated in Table 1. We will discuss these techniques one by one in detail in the next section.

Besides the techniques, mentioned in Table 1, we can observe that *Frequency Selective Surface (FSS)* (Huang, 2020) and Metasurface (F. Liu et al., 2020; Z. Wang et al., 2020; Yin et al., 2020) are also sometimes useful in suppressing MC along with their many others advantages.

2. Isolation Techniques Discussion

2.1. Metamaterials

Materials which do not exist in nature, but can be artificially designed to have the property of single negative (either ε_r or μ_r is negative) or double negative (DNG) (both ε_r and μ_r are negative) are termed as "Metamaterials (MTMs)". When both the properties are negative, the material is termed as DNG MTM and will act as a black hole where electromagnetic waves cannot propagate. In 1968, V. G. Veselago (1968) was the first one to find the phenomenon of effective negative permeability and permittivity in the artificially created structures, which has changed the outlook for the existing materials in nature. Before that, materials were supposed to always exhibits positive permeability and permittivity. The research has got another dimension when (Pendry et al., 1999) have discovered that the SRR structure will show an effective negative magnetic permeability effect when kept in the proximity of an existing electromagnetic field. These artificial materials may have negative permittivity or permeability, or both. The effective permittivity and permeability of metamaterials can be calculated from its reflection and transmission coefficients. The proposed method has been comprehensively explained by D. R. Smith and S. Schultz (Smith et al., 2002) in 2002.

Similarly, effective permittivity and permeability for a novel V-shaped MTMs have been investigated (Ekmekçi & Turhan-Sayan, 2007) through simulated S-parameters. The Magnetic response of SRR at microwave frequencies and its properties and equivalent circuit diagram has been thoroughly discussed in K. Aydin & Ozbay (2006), Baena et al. (2005), Katsarakis et al. (2004), Koray. Aydin et al. (2005) and Sauviac et al. (2004). The magnetic resonance of the MTM-SRR can be controlled as described in J. Wang et al. (2008), where the inner ring of the SRR has been rotated while in K. Aydin and Ozbay (2007) SRRs loaded with capacitor have been used to shift the magnetic resonance frequency as per the requirements. MTMs have artificial magnetism but can also exhibit negative refractive index–a property not found in any known naturally occurring material; (Padilla et al., 2006; Smith et al., 2004) have shown the remarkable potential of MTMs to explore new horizons in electromagnetism. A review paper has discussed various MTMs based isolation structures in the MIMO antenna field (Gangwar et al., 2014). MTMs are broadly classified into SRR, CSRR, and FSS. We have emphasized on the discussion and observation of some of the novel and famous structures to overview the existing MTMs useful for MC reduction. A square SRR has been placed at the back of the planar antenna (J. Y. Lee et al., 2015) to suppress the MC, as represented in Figure 1a. The SRR has been acting as a wave trap. A pair of SRR has been placed between the rectangular patch antenna (M. U. Khan & Sharawi, 2014; A. Kumar, Ansari, Kanaujia, & Kishor, 2018), while three CSRRs are loaded on its ground plane (Ramachandran et al., 2016), and four SRRs are arranged together to form a ring (Ramachandran et al., 2017) to suppress the MC as represented in Figures 1b–1d respectively. Among many of the popular methods based on MTMs, some are mentioned here: CSRR loaded ground (S. Kumar et al., 2018), three pairs of slotted-CSRRs (Bait-Suwailam, Siddiqui, et al., 2010) as represented in Figure 2a, single-negative magnetic (MNG) MTM (Bait-Suwailam, Boybay, et al., 2010) as described in Figure 2b, square-shaped CSRR (Selvaraju et al., 2018a), Hilbert-shaped magnetic waveguided MTMs (H. X. Xu et al., 2013), three-dimensional (3-D) novel MTM structures (K. Yu et al., 2018), bridge square SRR (Al-fayyadh & Alsabbagh, 2017), MTM-inspired resonators (Hsu et al., 2011; Iqbal et al., 2018), SRR along with DGS (Irene & Rajesh, 2018a), capacitively loaded loop MTM superstrate (Alibakhshikenari, Salvucci, et al., 2018; Jafargholi et al., 2019), epsilon-near-zero metamaterials (Mazaheri & Jafargholi, 2018), two columns of opposite faced CSRR (Selvaraju et al., 2018b),

Table 1
Mutual Coupling Reduction Techniques With References

Techniques	References
Metamaterials (MTMs)-Split-Ring-Resonator (SRR); Complementary-Split-Ring-Resonator (CSRR)	(Al-fayyadh & Alsabbagh, 2017; Alibakhshikenari, Salvucci, et al., 2018; Aydin & Ozbay, 2006, 2007; Koray. Aydin et al., 2005; Baena et al., 2005; Bait-Suwailam, Boybay, et al., 2010; Bait-Suwailam, Siddiqui, et al., 2010; Bilal et al., 2017; Dadgarpour et al., 2017; Ekmekçi & Turhan-Sayan, 2007; Gangwar et al., 2014; Garg & Jain, 2020; Guo et al., 2019; Hsu et al., 2011; Iqbal et al., 2018; Irene & Rajesh, 2018a; Jafargholi et al., 2019; Katsarakis et al., 2004; M. U. Khan & Sharawi, 2014; Krishna et al., 2016; A. Kumar, Ansari, Kanaujia, & Kishor, 2018; A. Kumar, Ansari, Kanaujia, Kishor, & Kandpal, 2018; J. Y. Lee et al., 2015; M. Li et al., 2020; Mark et al., 2020; Mazaheri & Jafargholi, 2018; Najafy & Bemani, 2020; Ntaikos & Yioultsis, 2013; Öznazi & Ertürk, 2008; Padilla et al., 2006; Pendry et al., 1999; Qamar et al., 2016, 2014; Ramachandran et al., 2017, 2016; Sauviac et al., 2004; Selvaraju et al., 2018b, 2018a; Shafique et al., 2015; Smith et al., 2004; 2002; M. C. Tang et al., 2017; Thummaluru & Chaudhary, 2017; Torabi et al., 2016; Veselago, 1968; F. Wang et al., 2018; J. Wang et al., 2008; G. C. Wu et al., 2015; Xu et al., 2013; K. Yu et al., 2018; Zhai et al., 2015; X. Zhu et al., 2017; Ziolkowski & Engheta, 2020)
Electromagnetic Band Gap (EBG)	(Abdelgwad & Ali, 2020; Abedin & Ali, 2005; Abidin et al., 2018; Al-Fayyadh et al., 2017; Alam et al., 2013; Alibakhshikenari, Virdee, et al., 2018; Alibakhshikenari et al., 2019a, 2019b; Chen et al., 2018; Dabas et al., 2018; Ebadi & Semnani, 2014; Exposito-Dominguez et al., 2012; Farahani et al., 2010; Iqbal et al., 2019; Islam & Alam, 2013; J. D. Shumpert, T. J. Ellis, G. M. Rebeiz, 1997; T. T. Jiang et al., 2018; John, 1987; Kapoor, 2013; Kim et al., 2011; J. Kumar, 2016; N. Kumar & Kommuri, 2019; Y. Lee & Sun, 2008; Q. Li et al., 2014; Lu & Lin, 2013; Manimegalai, 2014; Mavridou et al., 2016; Mohamadzade & Afsahi, 2017; Mohamed et al., 2019; Mu'ath J et al., 2014; Payandehjoo & Abhari, 2009, 2014; Qiu-Rong Zheng, Yun-Qi Fu, 2008; Radhi et al., 2019; Rajo-Iglesias et al., 2008; Sharma & Pandey, 2020; Shen et al., 2019; Soliman et al., 2015; Soukoulis, 2002; ; S. D. Assimonis et al., 2012; Suntives & Abhari, 2013; Tan et al., 2019; Thakur et al., 2020; Toolabi et al., 2016; W. Wu et al., 2018; Yablonovitch, 1987; X. M. Yang et al., 2012; A. Yu & Zhang, 2003);
Decoupling and Matching network	(Bilal et al., 2014; Cui et al., 2011; Gong et al., 2011; M. S. Khan et al., 2014; Lin et al., 2012; Malekpour & Honarvar, 2016; Moharram & Kishk, 2013; Piao et al., 2020; Radhi et al., 2018; Shabbir et al., 2020; T. C. Tang & Lin, 2014; Z. Tang et al., 2019; Xu et al., 2018, 2020; Xun et al., 2017; Jianfeng Zhu et al., 2017)
Neutralization line (NL)	(Asadpor & Rezvani, 2018; W. Jiang et al., 2019; Kayabasi et al., 2018; Liu, An, et al., 2020; Luo et al., 2019; Mondal et al., 2018; Ou et al., 2017; Saleh et al., 2017; Su & Lee, 2011; Tiwari, Singh, & Kanaujia, 2019; Tiwari, Singh, & Kanaujia, 2019; H. Wang et al., 2015; S. Wang & Du, 2015; Y. Wang & Du, 2014; Y. Yang et al., 2016; Y. Yu et al., 2016; Zhang & Pedersen, 2016)
Cloaking Structures	(Ahmed & Elwi, 2019; Alù & Engheta, 2005; Bernety & Yakovlev, 2015; Bisht et al., 2020; Z. H. Jiang et al., 2015; J. Li & Pendry, 2008; Moreno et al., 2016; Naqvi et al., 2016; Pendry et al., 2006; Jianfeng Zhu et al., 2016)
Shorting vias and pins	(Abdalla & Ibrahim, 2017; Abdullah et al., 2019; Aliakbari & Lau, 2020; Ling & Li, 2011; Park & Son, 2016; Singh et al., 2013; Sipal et al., 2019; Wong et al., 2017; Zaker, 2018)
Inherent or no isolation techniques	(Abed, 2018; Duan et al., 2019; Ekrami & Jam, 2018; Han et al., 2020; Jehangir & Sharawi, 2017; Jin et al., 2019; L. Liu et al., 2014; X. L. Liu et al., 2014; Malik et al., 2015; Sipal et al., 2018; Sun et al., 2020; H. Wang et al., 2015; S. M. Wang et al., 2015; Zhu & Eleftheriades, 2010)

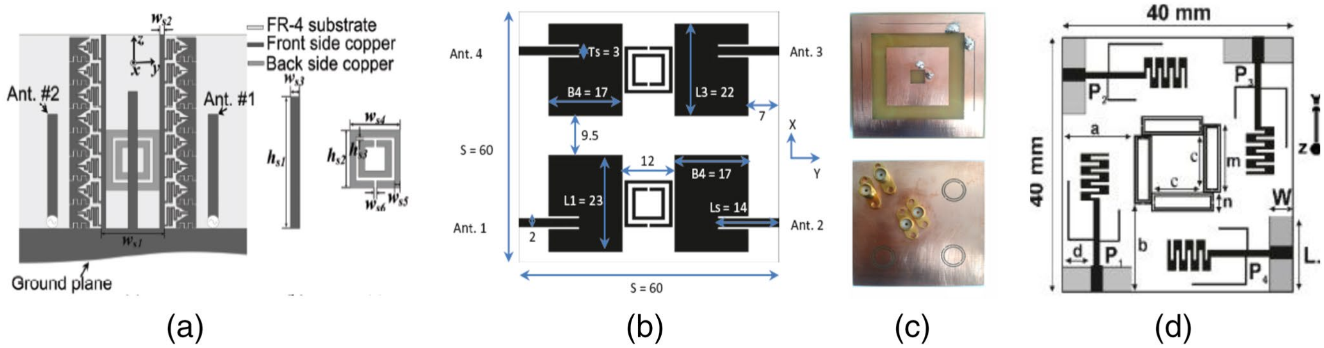

Figure 1. (a) Square SRR at the back (J. Y. Lee et al., 2015) (b) Pair of SRRs between the antenna (A. Kumar, Ansari, Kanaujia, & Kishor, 2018) (c) CSRRs loaded in its ground plane (Ramachandran et al., 2016) (d) A ring of four SRRs (Ramachandran et al., 2017). CSRR, complementary-split-ring-resonator; SRR, split-ring-resonator.

an array of 4 × 2 U-shaped slots resembling CSRRs structure (A. Kumar, Ansari, Kanaujia, Kishor, & Kandpal, 2018), slot combine CSRR on the surface as well as on the ground (Qamar et al., 2014; Shafique et al., 2015) as represented in Figure 3a, modified CSRR based MTM superstrate (Qamar et al., 2016), meta-structures consist π-shaped elements and capacitively grounded elements (M. C. Tang et al., 2017), a filter based on μ negative MTM (Thummaluru & Chaudhary, 2017) as represented in Figure 3b, MTM Labyrinth SRR (Torabi et al., 2016), as described in Figure 3c.

MTM isolator (F. Wang et al., 2018), compact SRR (Ntaikos & Yioultsis, 2013), a double layer MTM mushroom (Zhai et al., 2015), two arrays of square SRR on the top and one array of CSRR loaded ground (Öznazi & Ertürk, 2008), an array of SRRs and a metallic strip (Krishna et al., 2016) have been used to reduce the MC among elements of MIMO antenna. In some research, metasurface (Dadgarpour et al., 2017; Guo et al., 2019; G. C. Wu et al., 2015) has been used to reduce MC. MTM based FSS (Bilal et al., 2017; X. Zhu et al., 2017) has also been useful to minimize the MC.

From the comparison made in Table 2, it results that the MTMs help in achieving the isolation above 45 dB, better Envelop Correlation Coefficient (ECC), and works primarily for narrow-band MIMO antenna. MTMs generally require more area to be placed between the antenna's elements and mostly work in narrow-band antenna. MTMs are more useful in designing band-stop filters and achieving very high isolation among narrow-band MIMO antennas' elements.

One more thing we can observe that ECC calculated using S-parameters (A. Kumar, Ansari, Kanaujia, Kishor, et al., 2018) has lower values around 0.01 than the ECC < 0.036 calculated using far-field radiation pattern (A. Kumar et al., 2019). The far-field based computational ECC is more reliable as it considers

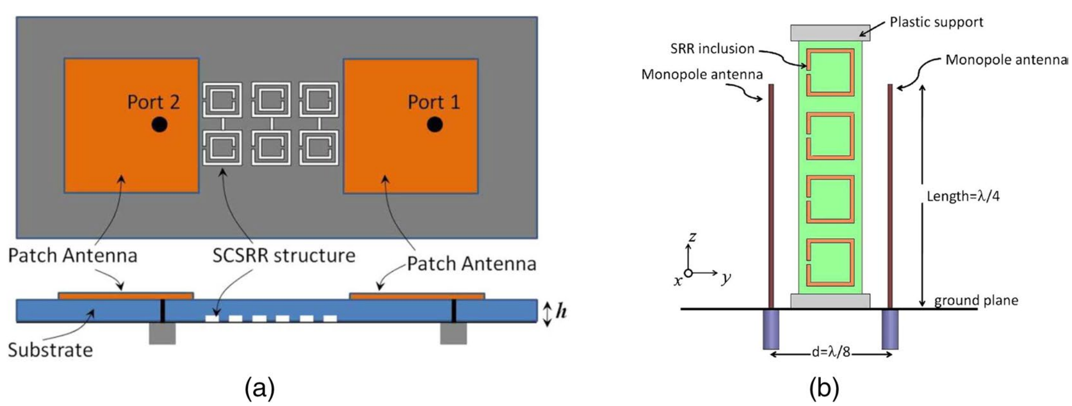

Figure 2. (a) Slotted CSRRs (Bait-Suwailam, Siddiqui, et al., 2010) (b) Single negative (MNG) MTMs (Bait-Suwailam, Boybay, et al., 2010). CSRR, complementary-split-ring-resonator; MTMs, Metamaterials.

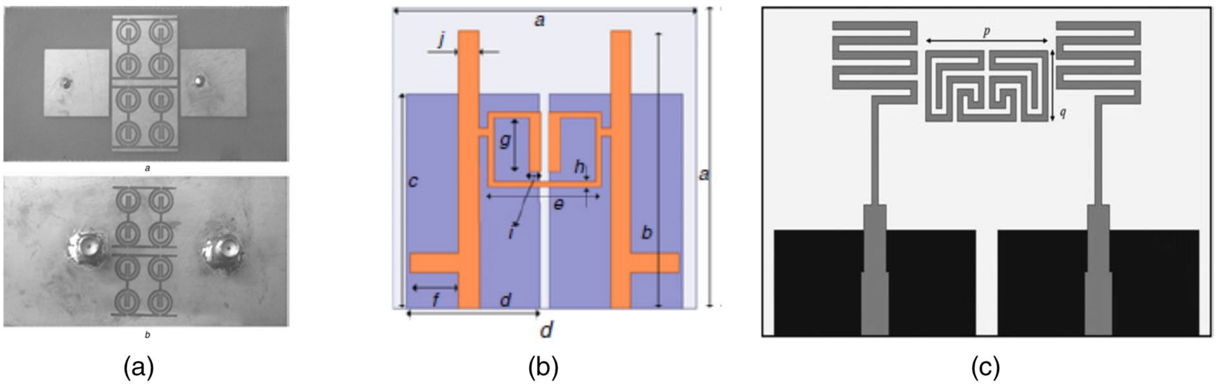

Figure 3. (a) Slot combine CSRR on surface and ground (Qamar et al., 2014) (b) μ negative MTM filter (Thummaluru & Chaudhary, 2017) (c) Labyrinth SRR (Torabi et al., 2016). CSRR, complementary-split-ring-resonator; MTM, Metamaterials.

the radiation pattern spatial diversity into consideration, unlike port isolation only in S-parameters-based computation.

2.2. Electromagnetic Band Gap Structures

EBG structures provide a high impedance path to surface wave propagation at specific operational frequencies and suppress the MC. EBG structures are periodic structures that avert or assist the propagation of electromagnetic waves in a specified band of frequencies irrespective of the angle of incident and polarization

Table 2
Comparison of MIMO Antenna Based on Metamaterials

Ref.	Substrate area (l × b) mm², $\lambda_0 \times \lambda_0 = \lambda_0^2$	Min. isolation (dB)	Max. ECC value and computation approach	Type of metamaterials	No. of elements	Narrowband/ Wideband/ UWB
(A. Kumar, Ansari, Kanaujia, & Kishor, 2018)	60 × 60, 0.35 × 0.35 = 0.12	17	0.024, S-parameters	Pair of square SRR	4	Narrowband (Multi-band)
(J. Y. Lee et al., 2015)	60 × 57, 0.49 × 0.46 = 0.23	30	0.002, Far-field	1 D EBG and square SRR	2	Narrowband
(Ramachandran et al., 2016)	60 × 60, 0.49 × 0.49 = 0.24	22	0.4, Far-field	CSRRs loaded ground	4	Narrowband
(Ramachandran et al., 2017)	40 × 40, 0.26 × 0.26 = 0.07	22	0.3, Far-field	A ring of four SRRs	4	Multi-band
(Qamar et al., 2014)	84 × 44, 1.04 × 0.54 = 0.56	42	–	Slot combine CSRR on surface and ground	2	Narrowband
(Thummaluru & Chaudhary, 2017)	45.5 × 45.5, 0.40 × 0.40 = 0.16	35	~0, S-parameters	μ negative MTM filter	2	Narrowband
(Torabi et al., 2016)	24.3 × 42.9, 0.19 × 0.33 = 0.06	45	0.0018, S-parameters	Labyrinth SRR	2	Narrowband
(Al-fayyadh & Alsabbagh, 2017)	60 × 60, 0.47 × 0.47 = 0.22	18	~0, S-Parameters	A 3-D metamaterial structure	2	Narrowband
(Irene & Rajesh, 2018a)	37 × 44, 0.69 × 0.82 = 0.57	20	0.1, Far-field	Clip shaped MTM	2	Narrowband
(Zhai et al., 2015)	119 × 119, 0.96 × 0.96 = 0.92	42	0.02, Far-field	Double-layer mushroom structure	4	Narrowband

Abbreviations: CSRR, complementary-split-ring-resonator; EBG, electromagnetic band gap; ECC, envelop correlation coefficient; MIMO, multiple-input-multiple-output; MTM, Metamaterials; SRR, split-ring-resonator.

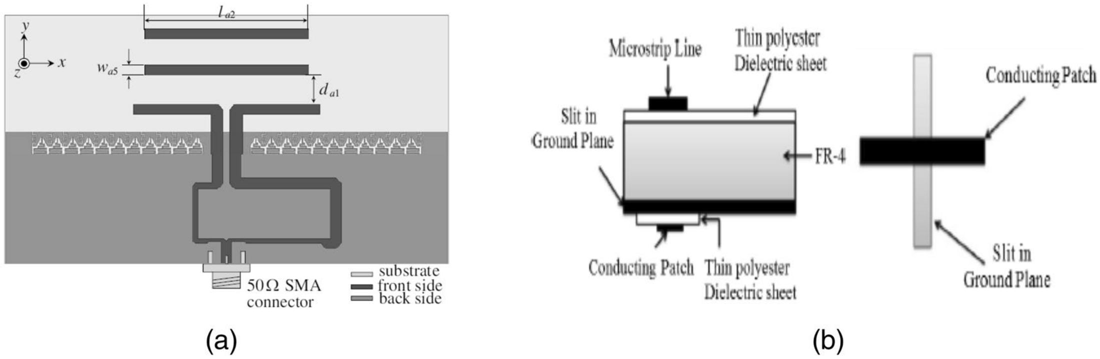

Figure 4. (a) 1-D EBG ground plane (Kim et al., 2011) (b) 2-D EBG comprises of patch and slit (Q. Li et al., 2014). EBG, electromagnetic band gap.

states of EM waves (Kapoor, 2013). EBG structures help in improving the radiation/gain patterns and decreasing the noise/losses in transmissions. The EBG structure concept has been originated by John (1987) and Yablonovitch (1987). When a bandgap or a frequency gap exists in a periodic dielectric substrate, then the EM wave with frequencies belonging to the gap cannot propagate in any direction inside the material. EBG structures may be formed on the metal or dielectric substrates and can be one dimensional (1-D), two dimensional (2-D), or three dimensional (3-D) depending upon the dimensions which satisfy the Bragg's conditions, which states that the inter-cell separation (period) is close to half guided wavelength (λg/2) and are capable of averting EM propagation in either all or selected directions (J. D. Shumpert, et al., 1997; Soukoulis, 2002).

A dipole antenna designed with the 1-D EBG ground plane, as represented in Figure 4a, has higher directivity and a better FB (front-to-back) ratio (Kim et al., 2011). While 1-D EBG structure, inserted between two closely located monopole antenna, has suppressed MC (J. Y. Lee et al., 2015). A planar EBG structure has been printed on the high permittivity substrate in a multilayer patch antenna for suppressing MC (Rajo-Iglesias et al., 2008). A 2-D EBG structure employs two tightly coupled arrays, one comprising of conducting patch. The other is the slits in the ground plane as represented in Figure 4b to reduce the MC between two monopoles UWB-MIMO antenna (Q. Li et al., 2014). Similarly, many EBG structures have been studied in the literature, among them, few are going to be discussed here: 1-D EBG structure comprises of patterns of grids on the top patch with a metallic ground plane, and both are shorted by several vias (W. Wu et al., 2018); conventional mushroom EBG structure loaded with slots (Lu & Lin, 2013); 4 × 1 array configuration of a unit cell size (6.8 × 6.8 mm) unipolar EBG (Dabas et al., 2018); multi-layered EBG structure (T. Jiang et al., 2018); a novel uni-conductor EBG placed between patch antenna as represented in the Figure 5a (Mohamed et al., 2019); EBG structure based on MTM (Alibakhshikenari et al., 2019b); waveguided MTM realized by crossed-meander-line slits exhibit magnetic resonance as well as the bandgap property (X. M. Yang et al., 2012); another EBG ground structure can be viewed in Figure 5b (Shen

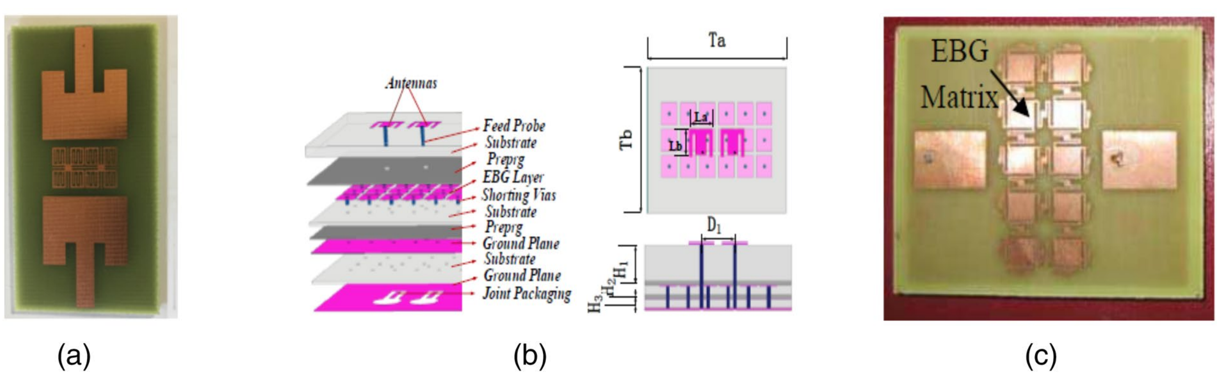

Figure 5. (a) A novel uni-conductor EBG placed between patch antenna (Mohamed et al., 2019) (b) a novel EBG ground (Shen et al., 2019) (c) 2 × 5 EBG structure (Islam & Alam, 2013). EBG, electromagnetic band gap.

Table 3
Comparison of MIMO Antenna Based on EBG

Ref.	Substrate area (l × b) mm^2, $\lambda_0 \times \lambda_0 = \lambda_0^2$	Min. Isolation (dB)	Max. ECC value and computation approach	Type of EBG	No. of elements	Narrowband/ Wideband/ UWB
(Q. Q. Li et al., 2014)	50 × 60, 0.50 × 0.50 = 0.25	13	–, –	2-D EBG comprises of patch and slit	2	Wideband
(W. W. Wu et al., 2018)	60 × 60, 0.60 × 0.60 = 0.36	17.5	0.3, Far-field	Patterns of grids shorted to the ground plane through vias	4	UWB
(Dabas et al., 2018)	27.2 × 46, 0.27 × 0.46 = 0.12	18	0.018, S-parameters	Uniplanar EBG	2	UWB
(Mohamed et al., 2019)	49 × 24, 0.95 × 0.46 = 0.44	35	0.03, Far-field	Novel uni-conductor EBG	2	Narrowband
(Alibakhshikenari et al., 2019b)	37 × 70, 1.07 × 2.03 = 2.17	20	–, –	EM-Bandgap Metamaterial Fractal Loading	2	Wideband (Multi-band)
(X. M. X. M. Yang et al., 2012)	76.4 × 91, 0.78 × 0.93 = 0.73	16	–, –	Crossed-meander-line slits	2	Narrowband
(Tan et al., 2019)	44 × 58, 0.50 × 0.66 = 0.33	26	0.089, Far-field	Split Uniplanar EBG	2	Narrowband (Multi-band)
(Al-Fayyadh et al., 2017)	34.5 × 60, 0.40 × 0.70 = 0.28	21.6	0.001, S-parameters	Uniplanar EBG	2	Narrowband
(Mohamadzade & Afsahi, 2017)	45 × 90, 0.84 × 1.68 = 1.41	33.06	–	4 × 2 Compact EBG cells	2	Narrowband
(Radhi et al., 2019)	68 × 40, 0.60 × 0.35 = 0.21	27	0.0003, S-parameters	Fractal based EBG	2	Narrowband

Abbreviations: EBG, electromagnetic band gap; ECC, envelop correlation coefficient; MIMO, multiple-input-multiple-output.

et al., 2019); a 2 × 5 EBG structure as represented in Figure 5c (Islam & Alam, 2013); split EBG structure (Tan et al., 2019); a novel and compact spiral EBG (Qiu-Rong Zheng, Yun-Qi Fu, 2008); EBG based corrugated structure (Lu & Lin, 2013); Tunable Double-Layer EBG structures (Mavridou et al., 2016); some famous uniplanar EBG structure (Abedin & Ali, 2005; Abidin et al., 2018; Al-Fayyadh et al., 2017; Alibakhshikenari, Virdee, et al., 2018; Farahani et al., 2010; Iqbal et al., 2019; Mohamadzade & Afsahi, 2017; Mu'ath J et al., 2014; Payandehjoo & Abhari, 2009; Soliman et al., 2015; Toolabi et al., 2016); dumbbell-shaped EBG structure (A. Yu & Zhang, 2003); electromagnetic soft surfaces realized by metal strips loaded with C-shaped slots (Chen et al., 2018); multilayer EBG structure (Exposito-Dominguez et al., 2012); MTM inspired EBG structure (Alibakhshikenari et al., 2019a) mushroom type EBG structure (J. Kumar, 2016); high impedance ground plane (Y. Lee & Sun, 2008); multilayer mushroom type EBG (Payandehjoo & Abhari, 2014); EBG structure introduced at superstrate level (Suntives & Abhari, 2013) and a novel Fractal based uniplanar EBG (Radhi et al., 2019) have been used to suppress the surface wave propagation hence reduce the MC among microstrip antennas. Many more EBG structures and their optimization have been discussed in Alam et al. (2013) and S. D. Assimonis et al. (2012) and Ebadi and Semnani (2014).

Table 3 indicates that EBG based MIMO antennas are generally bulky, and EBG structures help minimize the MC for MIMO antennas working in a specific range. Uniplanar EBG structures were the most common of all the designs.

2.3. Decoupling and Matching Network

Sometimes decoupled and matched network between the patch antenna helps to cater away the coupled field and hence suppress the MC. Two π-shaped decoupling strip structures were introduced between the patch antenna to suppress the MC (J. Zhu et al., 2017). Xun et al. have used a compact planar spiral line structure to decouple the MC, as represented in Figure 6a (Xun et al., 2017). A decoupling structure comprised metalized via walls, and short-circuited stepped-impedance designs have been used to suppress MC (K. Da Xu et al., 2018) as represented in Figure 6b. A decoupling path is provided by the strips which are

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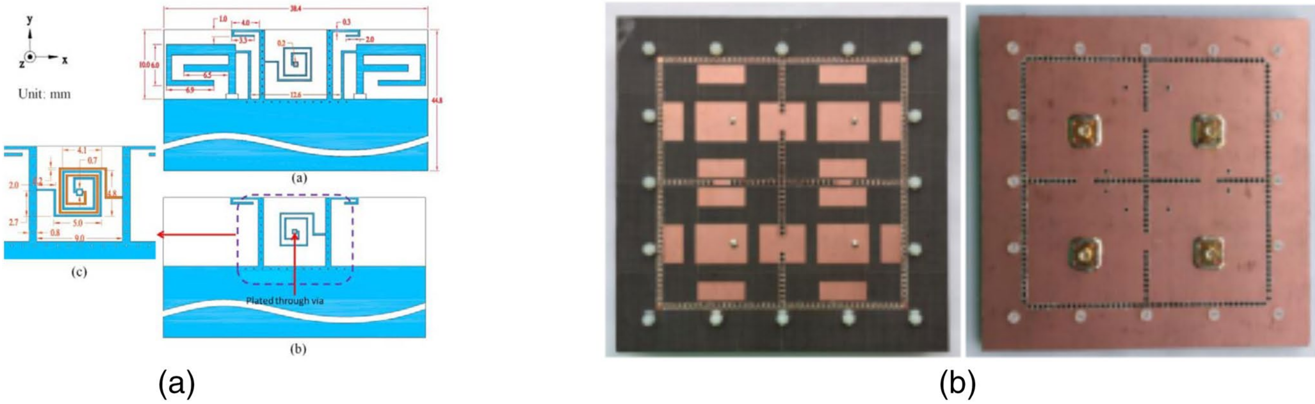

Figure 6. (a) Compact planar spiral line (PSL) structure (Xun et al., 2017) (b) metalized via walls and short-circuited stepped-impedance structures (K. Da Xu et al., 2018).

placed beneath the patch antenna and are shorted by the vias (T. C. Tang & Lin, 2014). Some parasitic type-decoupling structures like a floating parasitic digitated decoupling structure (M. S. Khan et al., 2014), a comb-like decoupling structure on the ground plane (Malekpour & Honarvar, 2016) and a novel decoupling structure (Radhi et al., 2018) as represented in Figures 7a–7c respectively have been used for reducing the MC.

A novel and general decoupling network has been proposed using a single transmission line connected between the input ports of the antenna (Moharram & Kishk, 2013), as represented in Figure 8a. A sinusoidal decoupling structure (Bilal et al., 2014) and a novel decoupling along with DGS, slots, and slits (Z. Tang et al., 2019) have been used in a UWB-MIMO antenna as represented in Figures 8b and 8c, respectively.

Two transmission lines (TLs) are connected to two closely spaced antennas. Their lengths are designed so that the trans-admittance between the port changes from complex to imaginary only. A reactive shunt component is then attached to cancel the imaginary part and cancels any coupling between the antenna (Lin et al., 2012) as represented in Figure 9a. In another case, a decoupling network has been assigned between the antenna along with a slot cut in the ground plane (Cui et al., 2011) while, in another example, a hybrid ring of arbitrary power division has been implemented as an orthogonal feeding network (Gong et al., 2011) as represented in Figures 9b and 9c, respectively, to improve the isolation between the two monopole antennas.

As shown in Table 4, the decoupling and matching network is ideally suitable for narrow-band MIMO antenna with the compactness of around 0.06 λ_0^2 (Cui et al., 2011). Although the authors claim in some of the proposed works (Bilal et al., 2014; M. S. Khan et al., 2014; Malekpour & Honarvar, 2016; Radhi et al., 2018; Z. Tang et al., 2019) as decoupling isolation structure but the MIMO antenna having a decoupling network

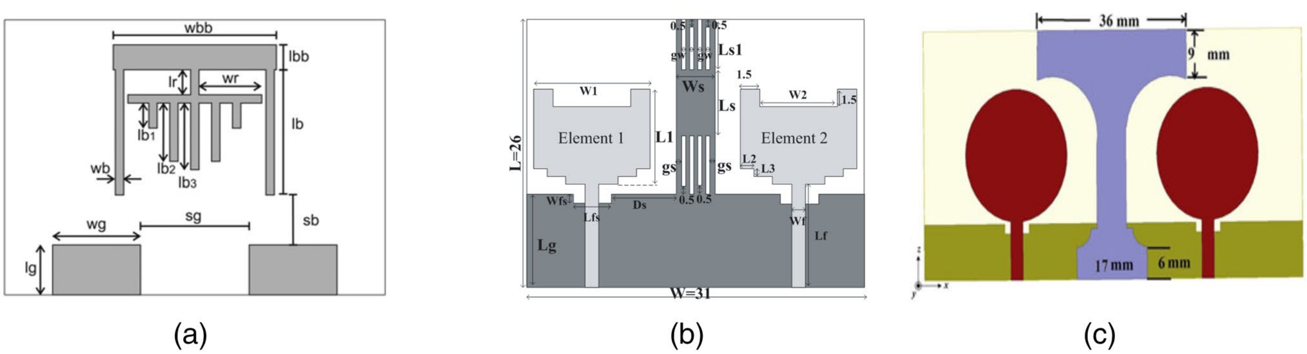

Figure 7. (a) Floating parasitic structure (M. S. Khan et al., 2014) (b) comb-like (Malekpour & Honarvar, 2016) (c) partial ground (Radhi et al., 2018).

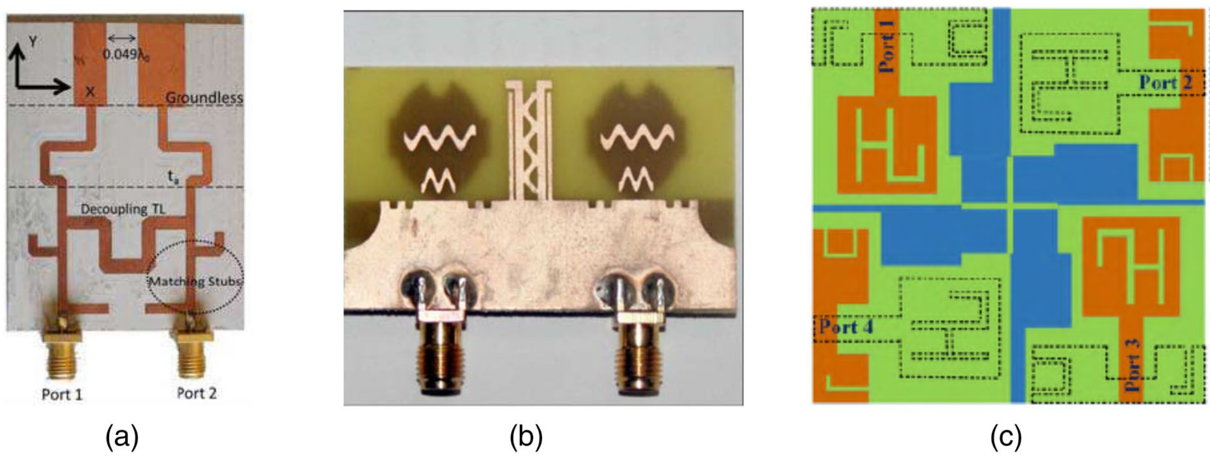

Figure 8. (a) A novel and general decoupling network (Moharram & Kishk, 2013) (b) sinusoidal decoupling structure (Bilal et al., 2014) (c) a novel decoupling structure along with DGS, slots & slits (Z. Tang et al., 2019). DGS, defected ground structures.

is more like parasitic structure, protruding ground stub and slots/slits-etching which results in high isolation among the compact UWB-MIMO antenna.

2.4. Neutralization Line

Neutralization line (NL) is one of the unconventional techniques popular because of its simplicity and compactness, which suppresses the MC. Unlike the parasitic elements/structures, NL feeds the passive antenna with the EM wave of the same phase, which NL receives from the active antenna to cancel out the EM signal, induced from the active to the passive antenna. Always a low impedance area of the antenna is preferred to connect the NL.

Along with four cuts on the ground, the NL connecting both the symmetrical radiating element (Y. Yang et al., 2016), as represented in Figure 10a, helps minimize the MC. A similar structure of NL likes above, but now with a matrix of 3 × 3 CSRRs loaded ground (Asadpor & Rezvani, 2018) has been used for MC reduction.

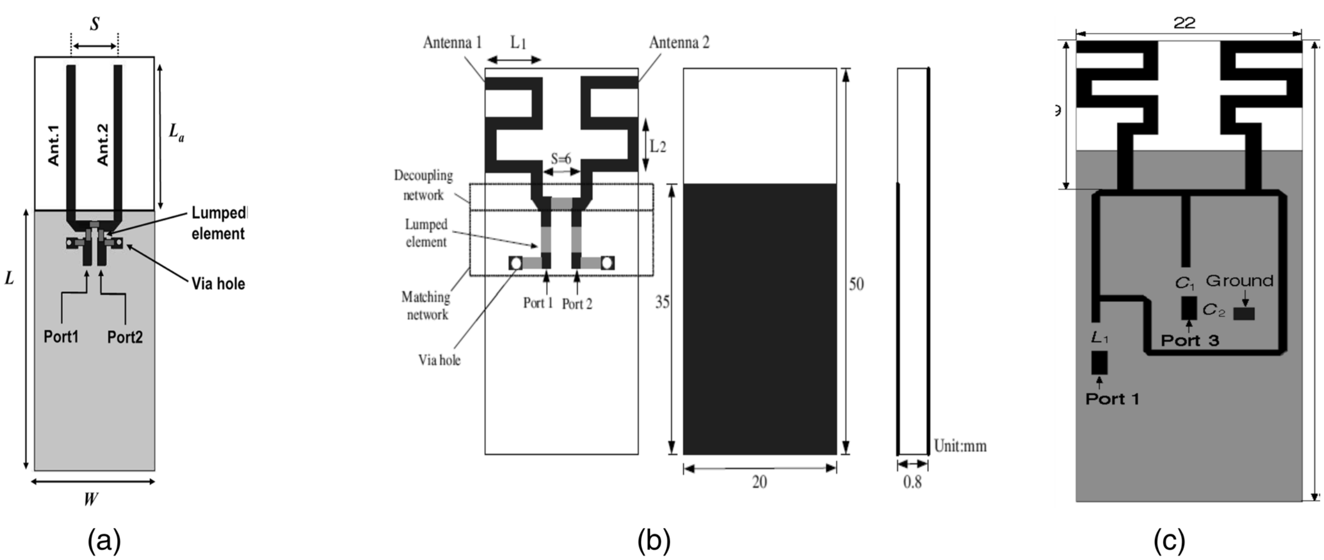

Figure 9. (a) Two TLs with reactive shunt component (Lin et al., 2012) (b) decoupling network along with a lumped element (Cui et al., 2011) (c) hybrid ring of arbitrary power division (Gong et al., 2011).

Table 4
Comparison of MIMO Antenna Based on Decoupling and Matching Network

Ref.	Substrate area (l × b) mm^2, $\lambda_0 \times \lambda_0 = \lambda_0^2$	Min. Isolation (dB)	Max. ECC value and computation approach	Type of network	No. of elements	Narrowband/ Wideband/ UWB
(Xun et al., 2017)	44.8 × 38.4, 0.36 × 0.31 = 0.11	20.3	–	Compact planar spiral line (PSL) structure	2	Narrowband (Multi-band)
(K. Da Xu et al., 2018)	160 × 160, 1.79 × 1.79 = 3.20	28	–	Metalized via walls and short-circuited stepped-impedance structures	4	Narrowband
(M. S. Khan et al., 2014)	33 × 45.5, 0.34 × 0.47 = 0.16	20	0.3, Far-field	Floating parasitic digitated decoupling structure	2	UWB
(Malekpour & Honarvar, 2016)	26 × 31, 0.27 × 0.32 = 0.09	25	0.001, S-parameters	Comb-like decoupling structure	2	UWB
(Radhi et al., 2018)	47 × 93, 0.49 × 0.96 = 0.47	31	0.035, S-parameters	Wideband planar decoupling structure	2	UWB
(Moharram & Kishk, 2013)	42 × 45, 0.34 × 0.37 = 0.13	15	~0, S-parameters/ Far-field	Inverted ohm-shaped connecting transmission line	2	Narrowband
(Bilal et al., 2014)	30 × 50.5, 0.30 × 0.51 = 0.15	20	0.53, S-parameters	Sinusoidal Decoupling Structure	2	UWB
(Z. Z. Tang et al., 2019)	39 × 39, 0.30 × 0.30 = 0.09	22	0.02, Far-field	A novel decoupling structure along with DGS, slots & slits	2	UWB
(Lin et al., 2012)	45 × 22, 0.37 × 0.18 = 0.07	20	–	Two TLs with shunt reactive component	2	Narrowband
(Cui et al., 2011)	50 × 20, 0.40 × 0.16 = 0.06	35	0.1, S-parameters	Decoupling network along with a lumped element	2	Narrowband
(Gong et al., 2011)	70 × 22, 0.56 × 0.18 = 0.10	23	0.1, S-parameters	Hybrid ring of arbitrary power division	2	Narrowband

Abbreviations: ECC, envelop correlation coefficient; MIMO, multiple-input-multiple-output.

A wideband NL comprises two metal strips and one circular disc (Zhang & Pedersen, 2016), as represented in Figure 10b; the circular disc provides multiple decoupling current paths that help achieve wideband decoupling. A simple meandered-shaped metallic stripline (Y. Yu et al., 2016) has been used as NL to cancel coupling between circular rings shaped radiating patch antennas as represented in Figure 11a. An NL comprises two metallic strips and a rectangular patch (Tiwari, Singh, & Kanaujia, 2019; Tiwari, Singh, & Kanaujia, 2019), as described in Figure 11b has been used between the UWB-MIMO antenna elements. A simple metallic strip was connecting the feedline (Luo et al., 2019; Ou et al., 2017); triple branch NL along

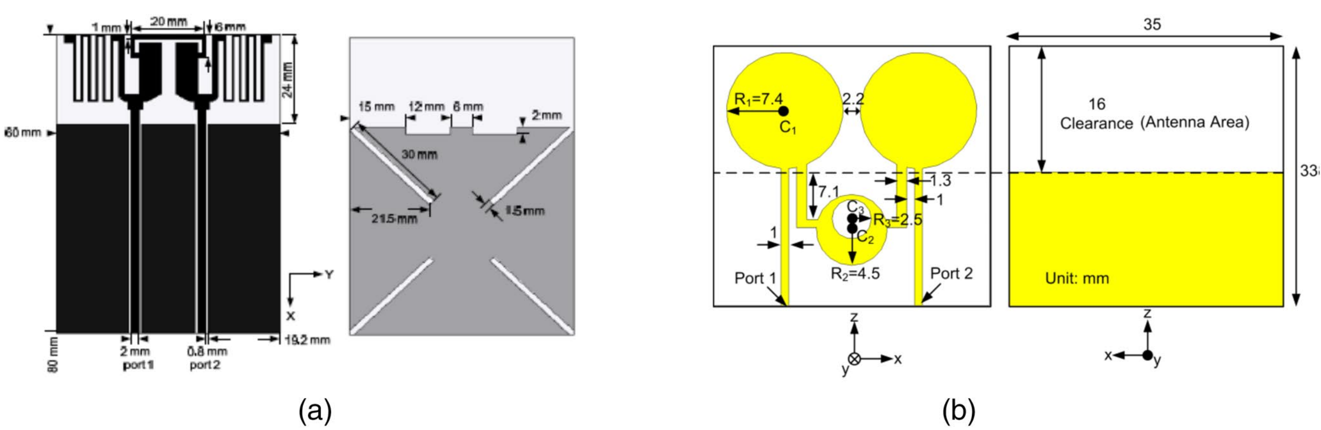

Figure 10. (a) NL along with four cuts in the ground plane (Y. Yang et al., 2016) (b) NL comprises two metal strips and one circular disc (Zhang & Pedersen, 2016).NL, neutralization line.

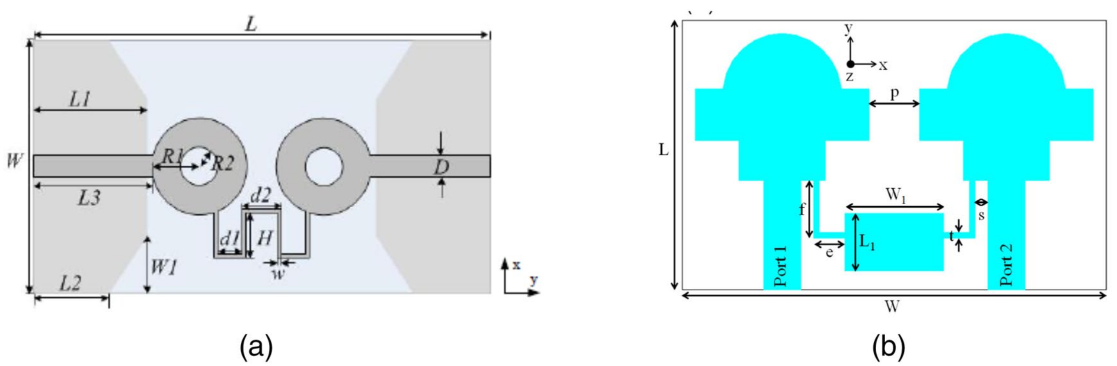

Figure 11. (a) Meandered-shaped metallic NL (Y. Yu et al., 2016) (b) NL comprises of two metallic strips and a rectangular patch (Tiwari, Singh, & Kanaujia, 2019; Tiwari, Singh, & Kanaujia, 2019). NL, neutralization line.

with DGS (Mondal et al., 2018), as represented in Figure 12a; a microstrip neutralization network (H. Wang et al., 2014) as depicted in Figure 12b; NL along with inverted I-ground slots (W. Jiang et al., 2019); a simple NL connecting the ground of CPW-Fed tri-band MIMO antenna (Saleh et al., 2017); crossed NL (S. Wang & Du, 2015); typical NL (Su & Lee, 2011); a neutralization ring (Kayabasi et al., 2018) and a group of three NLs (Y. Wang & Du, 2014) have been used to cancel the coupling from one antenna to another radiating patch antenna.

Table 5 represents that just like parasitic structures, NLs are useful for all the cases: narrow-band, wideband, UWB-MIMO antennas.

2.5. Cloaking Structures

This method deals with electromagnetic invisibility where the bistatic scattering width of a given object is suppressed independent of the angle of incidence and observations.

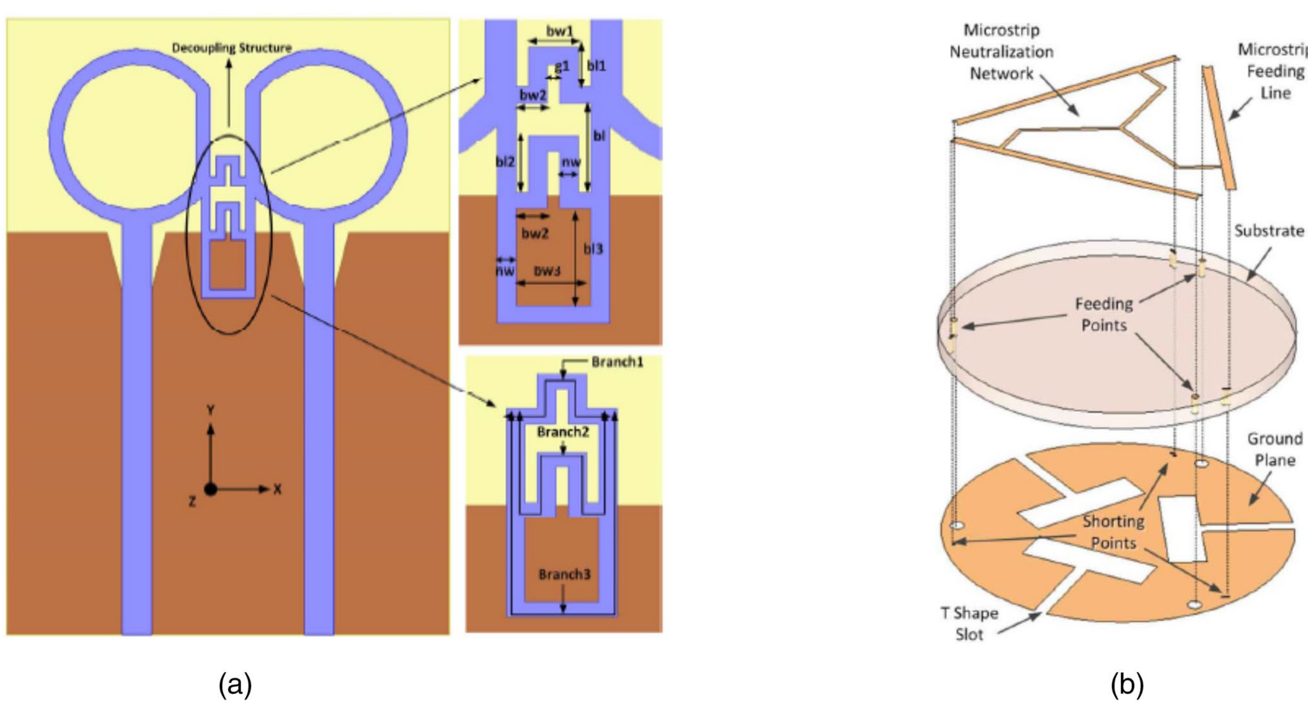

Figure 12. (a) Triple branch NL along with DGS (Mondal et al., 2018) (b) microstrip neutralization network (H. Wang et al., 2014). DGS, defected ground structures; NL, neutralization line.

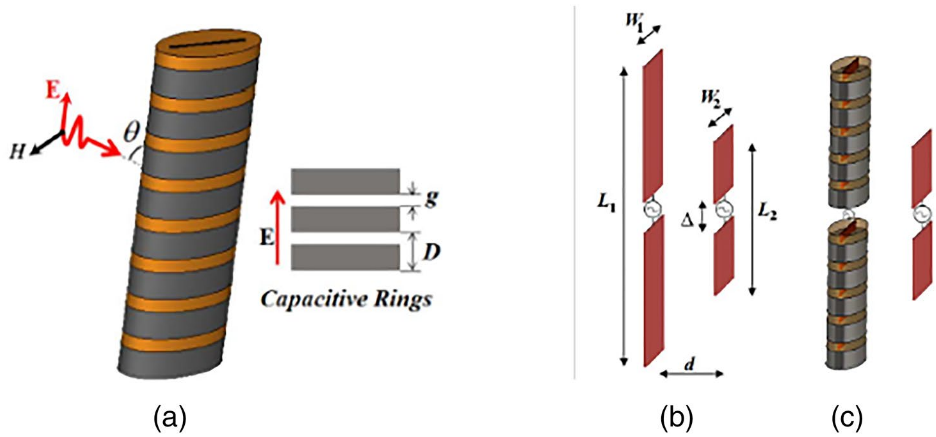

Figure 13. (a) Confocal elliptical metasurface cloaks (b) Two strip dipole antenna (c) One strip dipole cloaked from another (Bernety & Yakovlev, 2015).

Some cloaked structures are based on the principle of bending EM waves around the object (J. Li & Pendry, 2008; Pendry et al., 2006) to be cloaked, while in some cases, bulk isotropic low or negative index materials (Alù & Engheta, 2005) is used to suppress the dominant scattering mode. The confocal elliptical metasurface consists of periodic sub-wavelength elements (Bernety & Yakovlev, 2015) used to cloak the one strip dipole antenna from the firmly placed other dipole antenna as represented in Figure 13a-13c. The similar design process of cloaking one strip dipole antenna from another has been followed at terahertz frequencies with an elliptically shaped graphene monolayer (Moreno et al., 2016).

Two reject band filter (RBF) cells placed adjacently have resulted in a zero refractive index at 2.5 GHz (Ahmed & Elwi, 2019), as represented in Figure 14a-14b and thus suppressing the MC between monopole antennas. The use of metasurfaces, which is quasi-2D, which consists of arrays of the sub-wavelength environment (Z. H. Jiang et al., 2015), as represented in Figure 15, exhibits dispersive properties.

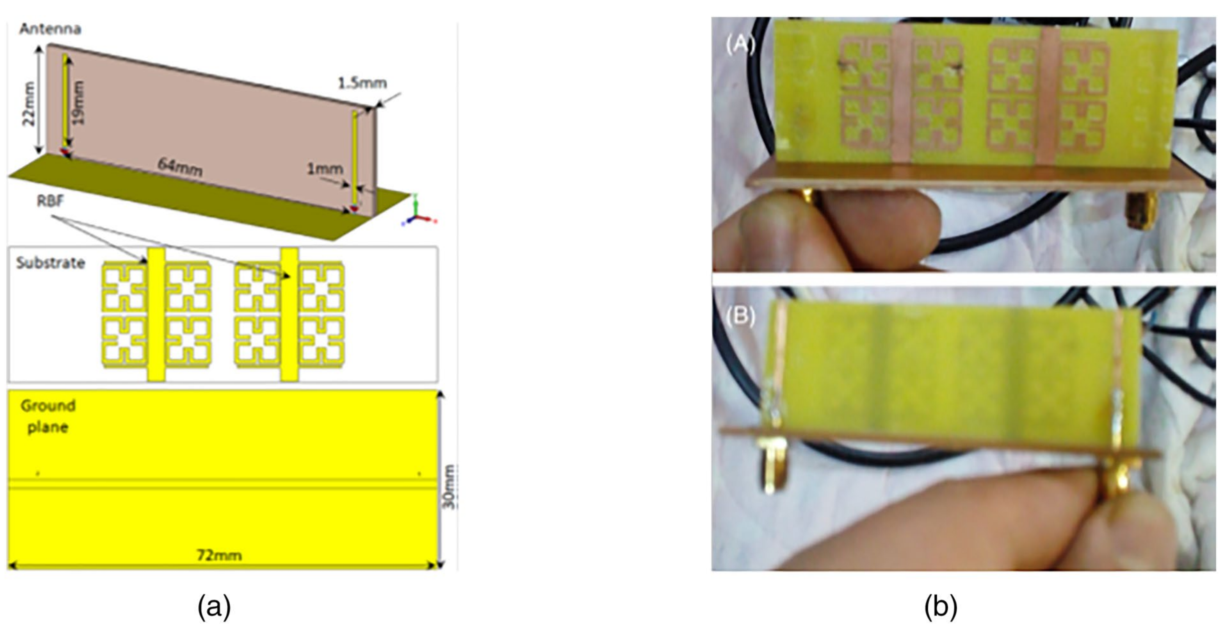

Figure 14. (a) Designed two RBF (b) Fabricated monopole MIMO antenna with the two RBF (Ahmed & Elwi, 2019). MIMO, multiple-input-multiple-output; RBF, reject band filter.

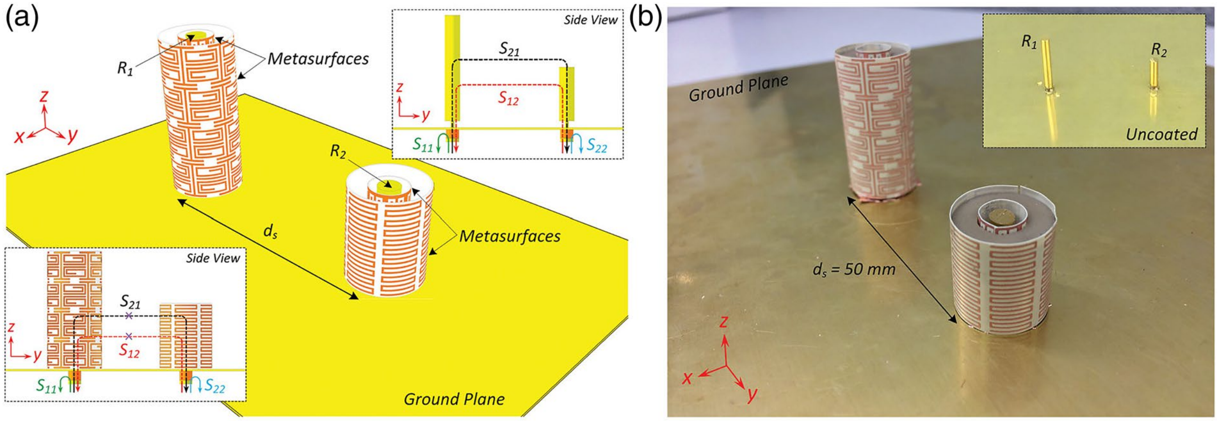

Figure 15. Quasi-2D functional metasurfaces (Z. H. Jiang et al., 2015).

In another case, the cylindrical-shaped cloaking-based surface comprises several interconnected 2-port microstrips (2-PM) (Jianfeng. Zhu et al., 2016), and interconnected 2-port reconfigurable microstrip (2-PFRM) (Naqvi et al., 2016) have been illustrated in Figures 16a and 16b, respectively, which helps in reducing MC.

Table 5
Comparison of MIMO Antenna Based on NL

Ref.	Substrate area (l × b) mm^2, $\lambda_0 \times \lambda_0 = \lambda_0^2$	Min. Isolation (dB)	Max. ECC value and computation approach	Type of NL	No. of elements	Narrowband/ Wideband/ Multi-band/UWB
(Y. Y. Yang et al., 2016)	80 × 60, 0.24 × 0.18 = 0.04	30	–	Simple rectangular NL	2	Narrowband (Multi-band)
(Zhang & Pedersen, 2016)	33 × 35, 0.31 × 0.36 = 0.11	22	0.1, Far-field	NL comprises two metal strips and one circular disc	2	Wideband
(Y. Yu et al., 2016)	40 × 80, 0.41 × 0.83 = 0.34	15	–	Meandered-shaped metallic NL	2	UWB
(Tiwari, Singh, & Kanaujia, 2019)	21 × 34, 0.25 × 0.40 = 0.10	22	0.005, S-parameters	NL comprises of two metallic strips and a rectangular patch	2	UWB
(Ou et al., 2017)	50 × 40, 0.41 × 0.33 = 0.14	20	0.005, S-parameters	Simple metallic strip connecting the feedline	2	Narrowband (Multi-band)
(Mondal et al., 2018)	22 × 15, 0.65 × 0.45 = 0.30	20	0.001, S-parameters	Triple branch NL	2	Wideband
(H. Wang et al., 2014)	π16 × 16, 0.40 × 0.13 = 0.05	15	0.029, Far-field	Microstrip neutralization network	3	Narrowband
(W. Jiang et al., 2019)	124 × 74, 1.36 × 0.81 = 1.10	15	0.15, Far-field	Simple Rectangular NL	8	Narrowband
(Saleh et al., 2017)	36 × 47, 0.29 × 0.38 = 0.11	18	0.08, S-parameters	Simple Rectangular NL	2	Wideband (Multi-band)
(S. Wang & Du, 2015)	135 × 80, 0.34 × 0.20 = 0.07	10	0.283, Far-field	Crossed NL	2	Narrowband (Multi-band)
(Su & Lee, 2011)	65 × 35, 0.52 × 0.28 = 0.15	18	–	Normal NL	2	Narrowband
(Kayabasi et al., 2018)	75.19 × 75.19, 0.78 × 0.78 = 0.61	13	0.1, –	Neutralization ring	4	UWB
(Y. Wang & Du, 2014)	115 × 60, 0.62 × 0.32 = 0.20	15	0.053, S-parameters	Three NLs	2	Wideband

Abbreviations: ECC, envelop correlation coefficient; MIMO, multiple-input-multiple-output; NL, neutralization line.

Figure 16. Cylindrical cloaking surface (a) interconnected 2-port microstrip (2-PM) (Jianfeng. Zhu et al., 2016) (b) interconnected 2-port reconfigurable microstrip (2-PFRM) (Naqvi et al., 2016).

2.6. Shorting Vias and Pins

Another prevalent method is shorting any parasitic elements/structures through metallic vias and pins to provide an additional decoupling path for the coupled fields before it reaches the other antenna placed in closer proximity. Six metallic pins (Abdullah et al., 2019) have been shorted near the adjacent edges of a square patch antenna to its ground, as represented in Figure 17a, to minimize the MC. In another case, a folded shorting strip (Singh et al., 2013) has been attached to each of the two-port antennae to enhance the port-to-port isolation. A simple metallic strip and shorting vias (Sipal et al., 2019), as represented in Figure 17b, have been used to counter MC. Similarly, two stubs as shunt inductor (Abdalla & Ibrahim, 2017), H-shaped conducting wall shorted by vias (Park & Son, 2016), a shorting strip and isolation stub (Ling & Li, 2011), a pair of novel shorted inverted L-shaped strips (Zaker, 2018) and two shorted strip between two gap-coupled loop antennas (Wong et al., 2017) have been used to provide an additional path to the coupled fields and hence reduces the MC.

It can be observed from Table 6 that the shorting vias and pins work mainly in narrow-band MIMO antenna for achieving high isolation. It means, if high isolation in a narrow-band compact MIMO antenna is targeted, then shorting vias and pins is one of the best techniques.

Table 6
Comparison of MIMO Antenna Based on Shorting Vias and Pins

Ref.	Substrate area (l × b) mm^2, $\lambda_0 \times \lambda_0 = \lambda_0^2$	Min. Isolation (dB)	Max. ECC value and computation approach	Type	No. of elements	Narrowband/ Wideband/ Multi-band/UWB
(Abdullah et al., 2019)	30 × 55, 0.35 × 0.64 = 0.22	20	0.01, Far-field	Pair of shorted six metallic pins	2	Narrowband
(Singh et al., 2013)	110 × 60, 0.88 × 0.48 = 0.42	26	0.01, Far-field	Folded shorting strip	2	Narrowband (Dual-band)
(Sipal et al., 2019)	42 × 38, 0.32 × 0.25 = 0.08	20	0.05, Far-field	Metallic strip along with shorting vias	2	Narrowband (Dual-band)
(Abdalla & Ibrahim, 2017)	26 × 30, 0.50 × 0.58 = 0.29	45	0.0002, S-parameters	Two stubs as shunt inductor	2	Narrowband
(Park & Son, 2016)	30 × 50, 0.52 × 0.87 = 0.45	51	–	H-shaped conducting wall shorted by vias	2	Narrowband
(Ling & Li, 2011)	50 × 15, 0.40 × 0.12 = 0.05	20	0.01, S-parameters	Shorting strip and isolation stub	2	Narrowband (Dual-band)
(Zaker, 2018)	–	58	0.1, Far-field	A pair of novel shorted inverted L-shaped strips	2	Narrowband
(Wong et al., 2017)	150 × 75, 1.7 × 0.85 = 1.46	–	0.1	Two shorted strip between two gap-coupled loop antennas	8	Narrowband

Abbreviation: MIMO, multiple-input-multiple-output.

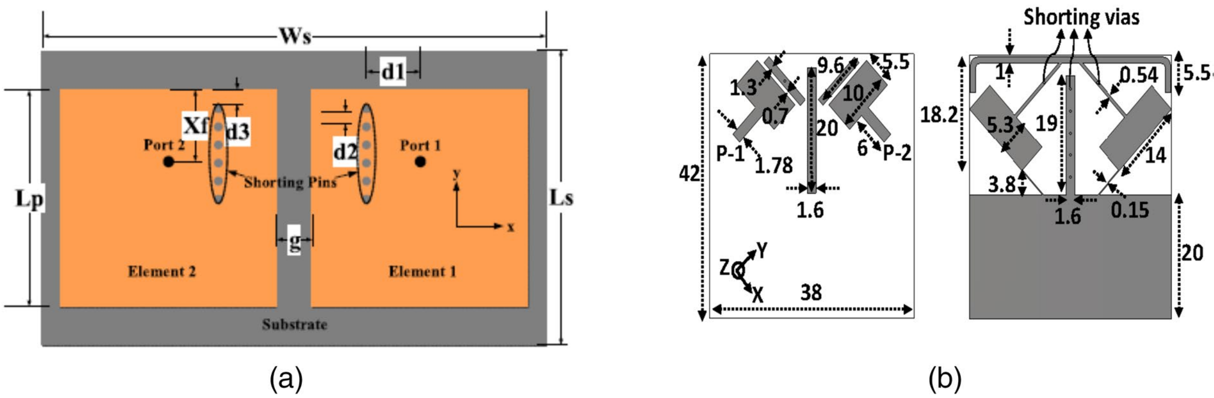

Figure 17. (a) Six pairs of shorting vias (Abdullah et al., 2019) (b) metallic strip along with shorting vias (Sipal et al., 2019).

2.7. Inherent or No Isolation Techniques

Sometimes the designed MIMO antenna has inherent characteristics to counter the MC induced from one antenna to another, like in few cases of the quasi self-complementary antenna (QSCA). While in some cases, the pattern diversity due to the unique design style gives us the privilege of no requirement of additional decoupling mechanisms to enhance the isolation. However, the significant disadvantages of such kind of structure are the increased space requirement between the elements of the MIMO antenna. Two coupled feed MIMO antennas have broad impedance matching bands, separated by a small gap that has a built-in isolation mechanism, due to the opposite currents generated at the edges of the circular pads and the feeds (S. M. Wang et al., 2015) as represented in Figure 18a-18b. A semi-ring slot Yagi-like MIMO antenna (Jehangir & Sharawi, 2017) with a compact complementary slot reflector element has been proposed without having a specific decoupling structure for MC reduction. Similarly, many designs have been reported in the literature (Abed, 2018; Duan et al., 2019; Ekrami & Jam, 2018; Jin et al., 2019; Malik et al., 2015; Sipal et al., 2018), which does not require any additional decoupling mechanism/structure to achieve the necessary isolation. Self-decoupled X-shaped arms etched on the square-shaped substrate (H. Wang et al., 2015) as represented in Figure 19a will show ultra-high isolation having orthogonal modes while in another case, two MTM-inspired monopole antennas (Jiang. Zhu & Eleftheriades, 2010) have reduced MC because of self-cancellation of the induced common ground and near field currents without requiring any additional decoupling mechanism as represented in Figure 19b.

QSCA designs are favorable to the UWB-MIMO antenna proposal because of their wide impedance matching capability and no requirement of an additional decoupling mechanism for having sufficient isolation (L. Liu et al., 2014; X. L. Liu et al., 2014). Two such QSCA designs have been shown in Figures 20a and 20b.

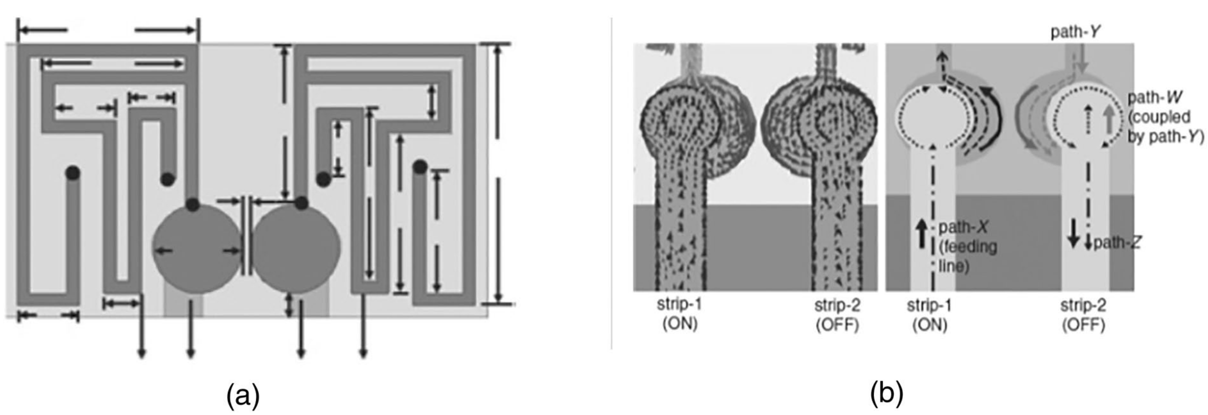

Figure 18. (a) Couple feed MIMO antenna (b) current distribution along the circular edge and feeds (S. M. Wang et al., 2015). MIMO, multiple-input-multiple-output.

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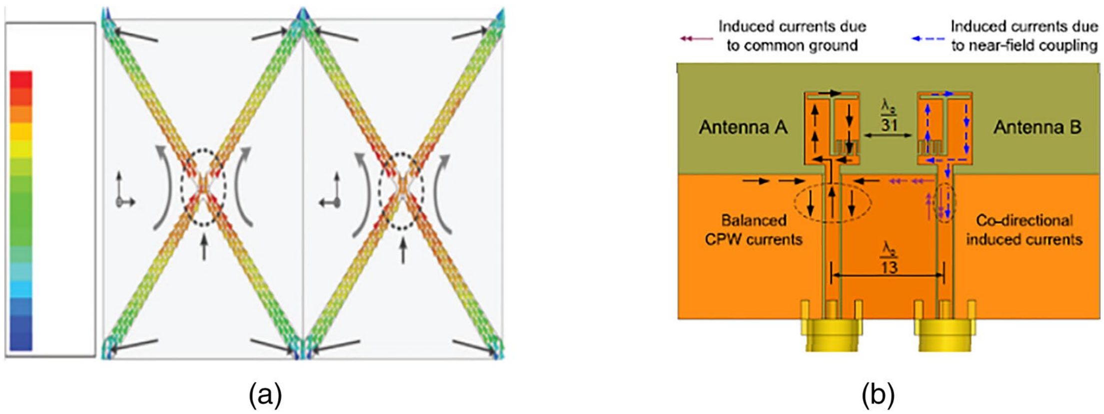

Figure 19. (a) X-shaped etched arms (H. Wang et al., 2015) (b) MTM-inspired MIMO antenna (Jiang. Zhu & Eleftheriades, 2010). MIMO, multiple-input-multiple-output; MTM, Metamaterials.

Therefore, we have discussed various existing literature methods for minimizing the MC among the MIMO antenna elements.

3. Conclusions and Future Scope

In all the above cases, it has been found that the isolation or suppressing of MC is a significant problem in the lower frequency range as the λ increases with the decrease of the frequency. It has been observed throughout that the ECC calculated from far-field radiation patterns will have higher values than the one calculated from S-parameters. Protruding Ground Stubs, DGSs, Slots/Slits-etching, and Parasitic Elements/Structures are widely suitable for reducing MC in wideband and UWB-MIMO antennas as discussed in part one of this two-part article. Whereas MTMs, EBG, and Shorting Pins/Vias are more useful in lowering MC among elements of narrow-band MIMO antenna.

There is plenty of room in the future to extend the research. Some possible solutions are mentioned below:

a) the use of other expensive lossless substrates as compared to the lossy inexpensive FR-4 one for better efficiency and gain
b) till now, the study focused mainly on 2×2 or 4×4 MIMO antenna design. Massive MIMO can be designed for future wireless communications which will have at least eight antenna elements which will further increase the data throughput without sacrificing additional spectrum
c) fractal geometry-based MIMO antenna isolated with the help of EBG or Metamaterials can be proposed and designed

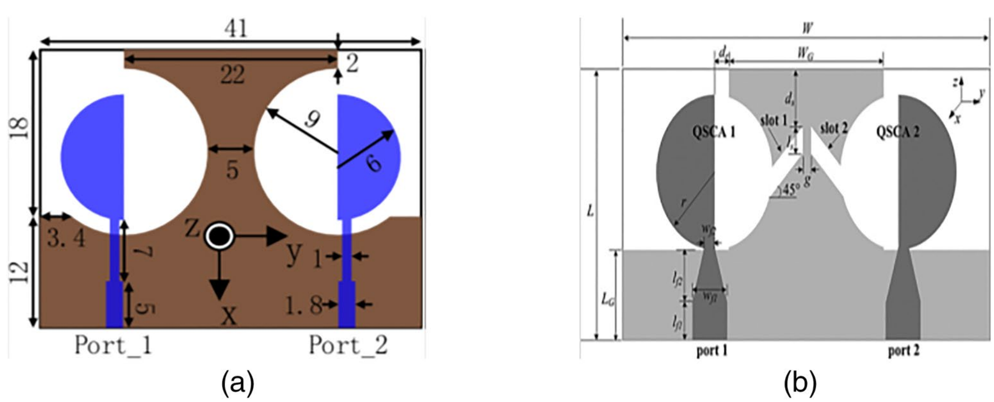

Figure 20. (a) QSCA (L. Liu et al., 2014) (b) QSCA with a minor defect in the ground (L. Liu et al., 2014). QSCA, quasi self-complementary antenna.

d) tunable MIMO antenna with reduced MC will give an immense scope of research
e) tunable isolation structure as per the required operating frequency range, like overlapping of SRRs of different dimensions and their switching with the help of varactor diodes, will be of great help
f) designing of MIMO antenna having zeroth-order resonance with high isolation

Data Availability Statement

It is a review article. All the particulars like content, Figures, taken from other articles are specifically cited on all occasions. Rest everything are contributed by the authors only.

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