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A Review on Metamaterial Used in Antennas Design: Advantages and Challenges

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ABSTRACT

Metamaterial (MTM) is an artificial structure with electromagnetic specifications that are not available in materials naturally, as it acquires its distinctive characteristics from its shape. For this reason, this material has garnered great interest from researchers in the field of microwave components. In order to get around the restrictions and enhance the performance of antennas, MTM is also used in antennas. The 5G applications aspire to high gain and to provide acceptable performance, which gets attention to the necessity protection the human body from radiation. Metamaterial (MTM) provides surface waves suppression, in-phase reflection, and high impedance. This review paper addressed MTM in terms of its electrical analysis, simulation analysis, and internal structure of the unit cell to demonstrate its impact on the performance of the antenna. In addition to that, an overview of the strengths and weaknesses points of MTM characteristics have involved. Furthermore, the details about many applications like; Specific Absorption Rate (SAR) reduction, isolation, enhancing gain, miniaturization, reflector, and Artificial Magnetic Conductors AMC have been demonstrated to guide antenna designers to have an obvious picture of this material.

Keywords:

5G communication; antenna; gain; isolation; metamaterial MTM.

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1. INTRODUCTION

The rapid development in wireless communications, in terms of speed, bit rate, directivity and gain has motivated to improve the performance of the mobile devices[1]. Many studies on antennas have gone ahead with the progress and the increasing demand of consumers[2][3]. This is provided by the metamaterial MTM embedded to the antennas.

As it is known, 5G application shows the clear necessity of providing efficient isolation in multi band/wide band antenna systems that have arbitrary topologies [4], where the importance of using metamaterial will be considered here. The 5G phones and future generations are the focus of studies around the world. This is because of their provision of high data speed on both transmission and reception sides, and their use for Internet of Things IoT applications, etc. There are many antenna designs in different mobile devices [5]. However, it has been noted that the values of specific absorption rate SAR are high, so these designs require reducing SAR values to protect human health.

Antennas are usually designed in portable devices or those in contact with the human body to match the development in current communication systems. At the same time, it should provide the customer with outstanding performance according to the required application. Recent studies have focused on developing antenna systems in various applications. One of the most important of these improvements is the inclusion of unnaturally MTM's in antennas due to their important properties that distinguish them from other materials in the nature. Therefore, it was necessary to put this material under the microscope in our study. Furthermore, this study is analysing its performance from several aspects, with a detailed study of the strengths and weaknesses when used in various communication applications.

Metamaterial absorber has been used to provide unnatural properties with negative permittivity or negative permeability, as well as negative refractive index. Beside that this artificial metamaterial has absorbed the incident electromagnetic waves as shown in [6] and [7].

The head and hand of human body, are susceptible to electromagnetic waves emitted by portable devices, which contribute to tissue damage when these devices are used for a long time. Thus, SAR will be of concern when using 5G mobile devices[8]. Including the metamaterial in the antenna reduces SAR values, as indicated by previous scientific works that can be evaluated by relevant computer programs[9]. In order to achieve miniaturization, the antenna is supported by a ground plane construction with slots. This antenna utilizes MTM properties to attain SAR reduction, gain enhancement, and compact size[10]. MTM is used to produce powerful isolation between a pair of patch antennas in a two-element multi-input multi-output (MIMO) operating at 5.5 GHz for WiMAX application[11]. The negative refractive index of MTM is useful in antenna design for enhance the gain. The multi layers of this MTM attached to conventional patch achieve high gain and wide bandwidth operating at X band as in[12]. On the other hand, a wide angle incidence is achieved because of MTM symmetry, and the polarization angle is insensitive[13]. Using a composite right/left-handed transmission line (CRLH - TL) approach, a small dual-band antenna supported with metamaterial is described in [14].

This review paper has addressed the MTM by electrical analysis, simulation analysis, beside the structure and dimensional variation analysis of the MTM unit cell. MTM effective influence on the performance of the antenna has demonstrated in this paper. As a result, this paper reviews the researches in recent years that dealt in their study with the inclusion of metamaterial in antennas and shows its characteristics and challenges for its importance in future generations.

2. OVERVIEW ON METAMATERIAL

Metamaterial MTM is an artificial material used to achieve unique permittivity and permeability features that are not really found in nature. This MTM, which is composed of dielectric and/or conductive materials, is installed near or on the radiating element, etched on the ground plane, or embedded as substrate sandwich in the antenna. MTM as substrate has been useful to enhancing gain, directivity, miniaturization and bandwidth. Although the patch antenna has the ease of design and integration, the low profile, and its lightness in weight, gives a narrow bandwidth and has limitations in gain, directivity, even size and low power control [15]. As a result, MTM has incentive to get beyond these restrictions because of its features.

Since the MTM acquires its properties from its intelligent shape consisting of a microscopic conductors and dielectrics, it works to suppress surface waves beside it in phase reflects them, which qualifies it to be an efficient reflector that has integrated with modern antennas [16][17]. MTM types are [4][18]: single-negative SNG, double-negative DNG, zero-index materials ZIM which have $\epsilon = 0$ or $\mu = 0$ or both equal zero.

An electric band gab EBG and artificial magnetic conductors AMC with zero magnetic field act as metamaterial. There are many other types such as omega cells, S shaped cells, and electric-LC element (ELC).

Usually the DNG or called left handed metamaterial has a good performance with backward propagation, in which the phase and group velocity have propagated oppositely (vgvp <0)[19]. Actually, left handed MTM is hardly available in natural materials, but many studies have shown that split ring resonators SRR act as left handed MTM. SRRs provide negative ϵ & μ, and manipulating with number of rings and split between them have garnered a significant performance [3].

2.1. Electrical analysis of MTM

A Split Ring Resonator SRR metamaterial is shown in Fig. 1. It can be analyzed by an equivalent LC circuit. The induced current in the rings (circular, square, triangular, or others) will represent the inductance L (where the current is formed as a result of the external magnetic field perpendicular to the surface of the SRR, which induces a current in the rings), while the capacitive C is formed as a result of the accumulation of charges in the spaces between the outer and inner squares. The resonant frequency is adjusted by the values of capacitance and inductance as in the following equations [20]:
The resonant frequency f_r will be:

$$\lambda_{f_r} = \frac{c}{f_r\sqrt{\epsilon_{eff}}} \qquad (1)$$

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (2)$$

$$L = \mu_0 h \qquad (3)$$

$$C = \frac{w\epsilon_0(1+\epsilon_r)}{\pi}\cosh^{-1}\frac{a}{g} \qquad (4)$$

The geometric dimensions of unit cell are *a*, *g*, *s*, *and w* as shown in Fig. 1.

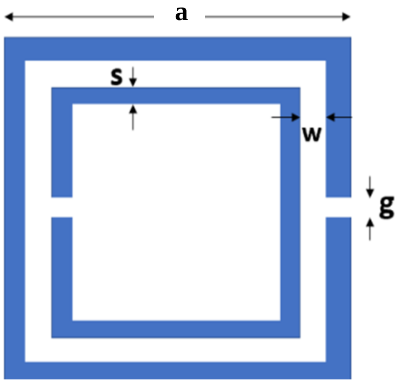


Fig. 1 SRR unit cell

Where L and C are the inductance and capacitance respectively. μ_0 is the free space permeability, *w* is the separation between adjacent unit cells, s is the width of unit cell strip, and ϵ_0 is the permittivity of vacuum. The split 'g' in the MTM unit cell creates the capacitance, while the metal strips represent the inductance of the structure. The interaction between capacitance and inductance generates the resonant frequency. Fig. 2 represents SRR with thin wire positioned in front of it. This structure provides DNG media as they push the resonance frequency below plasma frequency, that means *fr* will enter the negative area.

The reflection coefficient Γ can be calculated as:

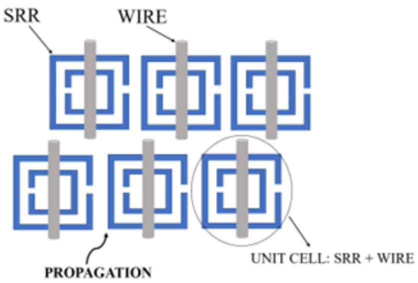


Fig. 2 MTM unit cells with wires (ENG) in front of SRR (MNG)

$$\Gamma = \frac{Z_0 - 1}{Z_0 + 1} \quad (5)$$

where $\mathbf{Z}_o$ represents the characteristics impedance which determined as [21]:

$$Z_o = \sqrt{\frac{\mu_r}{\epsilon_r}} \quad (6)$$

The reflection coefficient (S_{11}) and the transmission coefficient (S_{21}) of the SRR unit cell can be calculated as:

$$S_{11} = \frac{(1-\Gamma^2)Z}{1-\Gamma^2 Z^2} \quad (7)$$

$$S_{21} = \frac{(1-Z^2)\Gamma}{1-\Gamma^2 Z^2} \quad (8)$$

Fig. 3 illustrates the composite right left hand transmission line TL consisting of RH (series inductor + shunt capacitor) and LH (series capacitor + shunt inductor). This figure represents the transmission line theory as MTM medium because the use of SRR gives a narrow band of frequencies with high losses and is not suitable for microwave services, so the transmission line is the alternative.

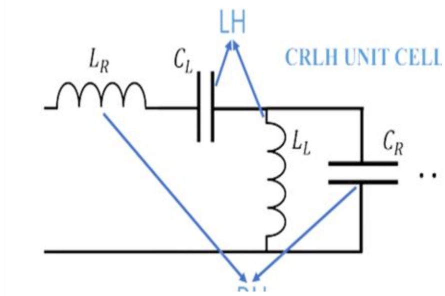


Fig. 3 CRLH_TL consisting of RH and LH

The classic RH_TL unit cell comprises of *L_series* and *C_shunt*. By alternating the dispersion properties, an additional *L_shunt* and *C_series*, will achieve CRLH_TL as shown in Fig.3. The TL propagation constant is $\gamma = \alpha + j\beta = (Z_{cell}Y_{cell})^{0.5}$, where Z_{cell} is the equivalent impedance, and Y_{cell} is the equivalent admittance which given by:

$$Z_{cell}(\omega) = j\left(\omega L_R - \frac{1}{\omega C_L}\right) \quad (9)$$

$$Y_{cell}(\omega) = j\left(\omega C_R - \frac{1}{\omega L_L}\right) \quad (10)$$

More specifically, the term "Composite Right/Left-Handed" came from the fact that it is impossible to obtain pure left-handed specifications, because there are always right-handed specifications (L_R & C_R) in TL. For this reason, the term CRLH TL is the most appropriate description of this line. The effective permittivity ϵ_{eff} and permeability μ_{eff} of CRLH_TL are:

$$\epsilon_{eff}(\omega) = L_R - \frac{1}{\omega^2 C_L} \quad (11)$$

$$\mu_{eff}(\omega) = C_R - \frac{1}{\omega^2 L_L} \quad (12)$$

Both of ϵ_{eff} and μ_{eff} are negative in LH media (DNG), only one of them is negative in (SNG), and both of them are positive in RH media [22]. Hence, Fig.3 has produced Negative Refractive Index NRI or MTM as DNG even if it comprises RH TL properties. In other words, we can say that:

- Thin wire gives negative permittivity
- SRR give negative permeability
- TL give negative permittivity & permeability DNG =CRLH [4]

It is known the importance of the MTM under the antenna, but it is necessary to choose a correct distance between them to avoid interference between the reflected waves with the radiated waves in front of the antenna. The distance is designed equal to or more than λ/4 according to the relation $\boldsymbol{\varphi - 2\beta H = 2m\,\pi}$**;** where m=(…-1, 0, 1…), H is the distance between the MTM and antenna, φ is the reflection phase by MTM, and β is the free space propagation constant [16].

2.2 Simulation analysis of MTM

To extract the characteristics of the MTM using simulation programs, the most important of which is Studio CST Software, measurements of S parameters (S_{11} and S_{21}) are used,

$$V_1 = S_{21} + S_{11} \quad (13)$$

$$V_2 = S_{21} - S_{11} \quad (14)$$

$$S_{11} = re(S_{11}) + j(im(S_{11})) \quad (15)$$

$$S_{21} = re(S_{21}) + j(im(S_{21})) \quad (16)$$

The negative ϵ & μ of (SRR) can be obtained from the Nicolson-Ross-Weir (NRW) method [23] [24][25]:

$$\mu_r = \frac{2}{jK_0 h} * \frac{1-V_2}{1+V_2} = \frac{c}{j\pi f h} * \frac{1-V1}{1+V1} \quad (17)$$

$$\epsilon_r = \frac{2}{jK_0 h} * \frac{1-V_1}{1+V_1} = \frac{c}{j\pi f h} * \frac{1-V2}{1+V2} \quad (18)$$

where K_0 represents wave number and h is the substrate thickness. The refractive index (n) can be calculated using the permittivity (ε_r), the permeability (μ_r) ,S_{11}, and S_{21} as:

$$n = \sqrt{\epsilon_r \mu_r} = \frac{c}{j\pi f h} * \sqrt{\frac{(S_{21}-1)^2 - {S_{11}}^2}{(S_{21}+1)^2 - {S_{11}}^2}} \quad (19)$$

$$Z = \sqrt{\frac{(1+S_{11})^2 - {S_{21}}^2}{(1-S_{11})^2 - {S_{21}}^2}} \quad (20)$$

Using the software analysis like python or MATLAB, The negative permittivity ϵ_r and permeability μ_r can be simulated from the refractive index (n) and impedance z in order to check if the designed SRR characterizes a double negative MTM [26]. The negative permittivity ϵ_r, permeability μ_r, and refractive index n of the antenna proposed in [25] are shown in Fig. 4.

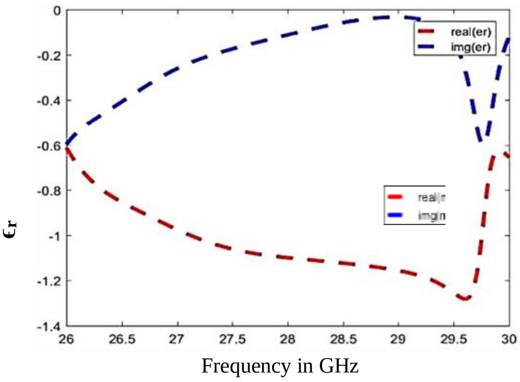
$$\epsilon_r = \frac{n}{Z} \quad (21)$$

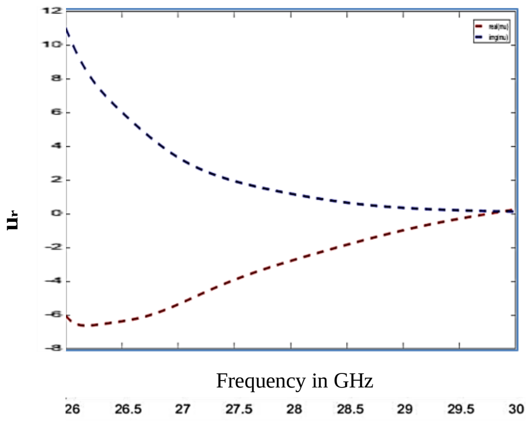
$$\mu_r = nZ \quad (22)$$

2.3. Structure Analysis of MTM

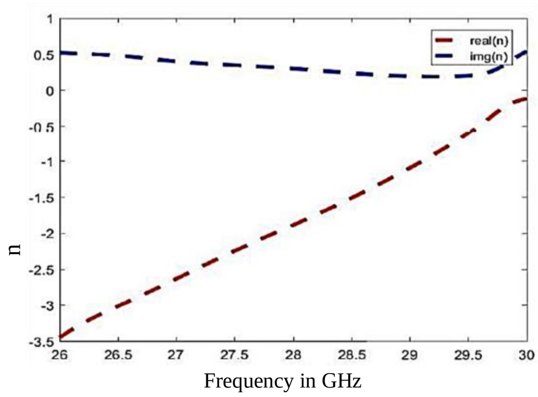
The metal strips in the unit cell are considered as inductance, while the space cut out in the ring represents the capacitance, which in turn will lead to mutual coupling with the surface electric field. Hence, we will get the electrical resonance. Similarly, the magnetic resonance will occur as a result of magnetic loops of rings and magnetic fields. Finally, the total inductance and capacitance will determine the resonant frequency of MTM unit cell [27].

effect on the MTM performance as shown in Fig. 6.





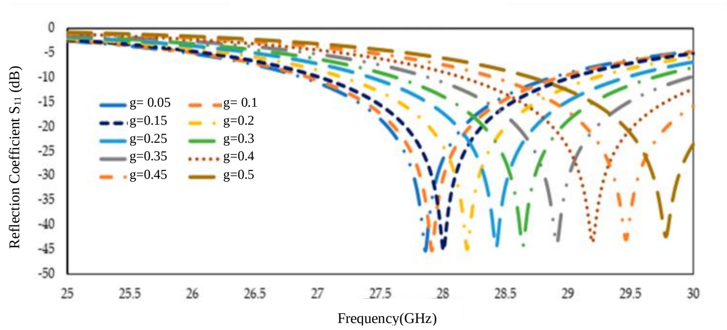
(a) **(b)**



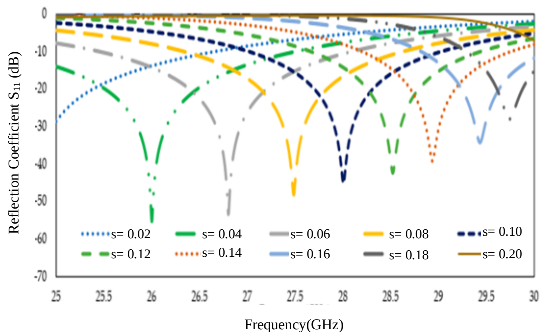
(c)

Fig. 4 MTM characteristics (a) Negative permittivity, (b) Negative permeability, (c) Refractive index

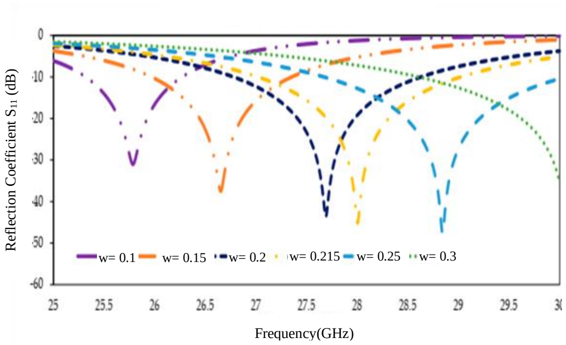
The most important factors affecting the resonance frequency are the ring width, the spacing between the rings, and the slit distance. Increasing the split gap increases the frequency, increasing the separation distance increases the frequency, and increasing the width of the loop increases the frequency as shown in Fig. 5. The position of split in the ring can be a significant



(a) S_{11} with different split distance 'g'



(b) S_{11} with different width of ring 's'



(c) S_{11} with different separation between rings 'w'

Fig. 5 Effect of split distance, ring width, and separation between rings on the resonant frequency

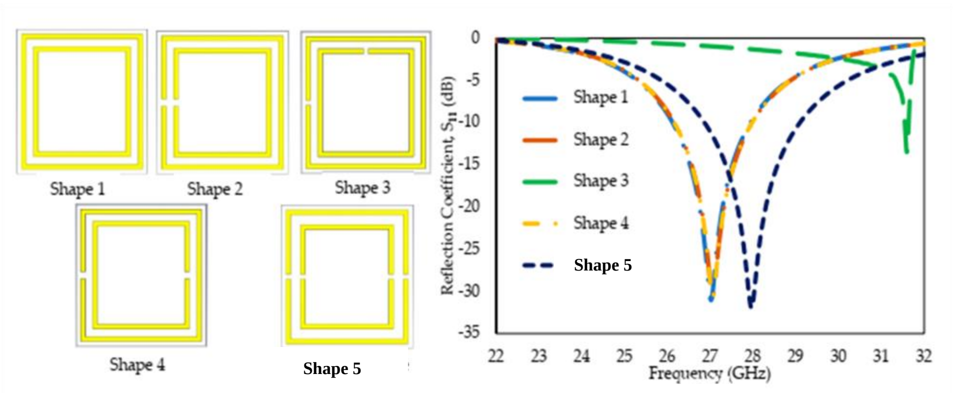


Fig. 6 Reflection coefficient S_{11} response at different slit(gap) positions

3. Metamaterial Applications

As mentioned earlier, the ground plane does not provide sufficient damping for surface waves, which will reduce the antenna gain. Therefore, the use of metamaterial is the alternative. The 5G applications aspire to high gain and to provide acceptable performance in comparison with the increased demand in wireless communications networks, which draws attention to the necessity protection the human body from radiation, and again metamaterial appears for its role in this point [16]. In addition, the use of the MTM sheet will suppress the back-ward waves and save the human tissues[28]. The block diagram in Fig. 7 summarizes the most applications of MTM used in antennas design.

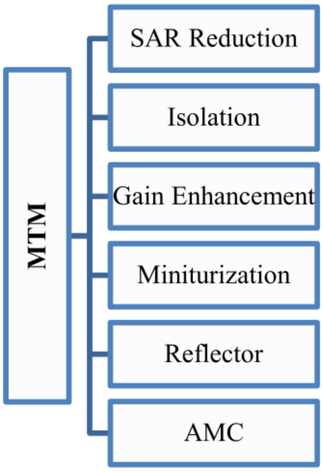


Fig. 7 Block diagram of MTM applications

3.1. SAR Reduction

Electromagnetic radiation is considered the most complex and important by users of wireless communications. Where studies focus on techniques to reduce radiation towards the human body, metamorphosis has been and still is the focus of researchers' attention because of its aforementioned distinct properties. To measure the absorption rate of body tissues for the energy emitted by the devices, the term Specific Absorption Rate (SAR) has used as watt per kilogram (W/kg). According to the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the IEEE C95.1-2019 standards, the SAR value should not exceed to 2 W/kg averaged over 10 g of tissue volumes [29] [30]. The Studies show that reducing the SAR at resonant frequencies is the main challenging problem facing designers. MTM, an extraordinary and superior material is one of the most important ways to reduce SAR[31].

In addition to all of what was mentioned above, MTM is not only used to reduce SAR, but it is used in microwave, satellite, sensors and other applications [32] [33][34]. Latest researches have shown that the use of distinct types of MTM will give them extraordinary outcomes. In the reference [3], MTM was used to reduce SAR for multi-frequency bands and multi-layers in addition to the compressed size of the antenna attached into the mobile phone. Usually, the numerical analysis for many MTM properties with conducting SAR values have performed using the most powerful software, Computer Simulation Technology (CST) Microwave Studio software.

3.2. Isolation

5G applications have using MIMO (Multiple Input Multiple Output), which mean using more than one antenna within the device, which may cause interference in its electromagnetic field. Therefore, it is necessary to provide efficient isolation between the radioactive elements, which is the space domain technology[35]. Previously, an external structure was used for isolation, but this would cost in terms of size, cost, and complexity. There are techniques for carrying out isolation, including[36][37]:

- Reducing the field between antenna elements
- Using a decoupling network and ground.
- Inclusion of parasitic agents to achieve reverse coupling.
- diversity of polarization.
- increasing the separation between transceiver elements, or placement a sheet between them [38] [39].

These techniques are used in microwave frequencies. For millimetre frequencies, It will need direct scaling, and the problem of decoupling losses will appear [25]. In order to overcome this problem, modern research is resorting to the use of MTM, where it has been proven that the overlap is not obtained in multi-antenna systems with various topologies [35]. Fig. 8 shows the use of MTM as isolation between antenna elements in MIMO, the substrate made of FR4 and dielectric resonators made of RO5880, while the MTM inscribed above is to improve the isolation[25]. In 5G communication, complementary SRR with slots was used which will act as a band stop filter and thus reduce coupling by 27dB [40].

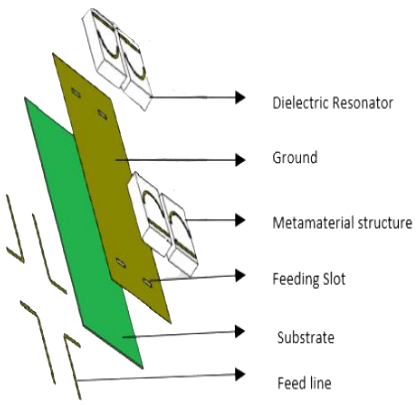


Fig. 8 MTM as isolator in MIMO antenna

3.3. Gain enhancement

The gain is important in point-to-point communications because it will increase the communication range at a certain transmitter power and is anti-interference. In order to obtain high directivity that is proportional to the antenna aperture, large antennas or array radiators have used. The main techniques based on MTM to enhance gain are [4]:

- Place a superstrate of ZIM (zero-index material) or NZRI (near-zero refractive index).
- Deploy an AMC surfaces adjacent to the patch.
- Place a GRIN (Gradient Refractive Index) MTM facing the antenna.

Using MTM with ϵ or µ equal to zero will give n= 0 and thus will increase the radiation perpendicular to the surface of the material regardless of the angle of incidence as in Fig. 9.

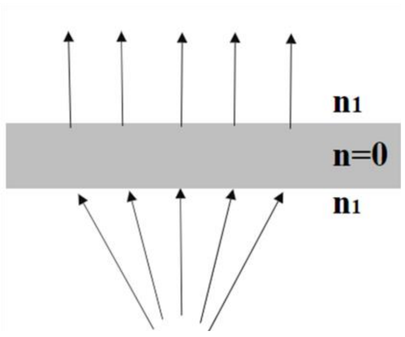


Fig. 9 Transmission through MTM as NZRI

Thus, we will take advantage of this property (converting propagating spherical waves into flat waves and in a specific direction using a substrate with n = 0 or nearly zero) to increase the gain and increase the antenna equivalent aperture [16].

3.4. Miniaturization

Electrically Small Antenna ESA is considered small if $\boldsymbol{k\alpha} < \mathbf{1}$, where the radius of the sphere around antenna is α, and the wave vector at the designed antenna frequency is k. This has achieved when designing antenna without ground plane. The Q value represents the appropriate description of the antenna bandwidth, based on its calculations on the antenna size. It is defined as the ratio between the stored power in the antenna to the radiated power and losses. The minimum value of Q for omni-directional antenna expressed by the Chu limit equations, where the linearly and circularly polarized small antennas as (eq 23) and (eq24) respectively[41]:

$$Q_{min} = \frac{1}{(k\alpha)^3 + k\alpha} \quad (23)$$

$$Q_{min} = \frac{1}{2}\left(\frac{1}{(k\alpha)^3} + \frac{2}{k\alpha}\right) \quad (24)$$

When the size of the antenna decreases, the B.W decreases, and $BW \approx 1/Q$. So, any small antennas will show narrowband performance. The antenna geometry must be carefully designed to give a current distribution that provides high bandwidth, this is what MTM offers in small antennas. The other approved method for miniaturization is TL-MTM, where the resonant frequency depends on the L and C, not the antenna dimensions. This means that if we reduce the size, it does not affect the resonant frequency[42]. Another miniaturization method is SRR placed with monopole which has $\lambda/10$-$\lambda/14$ length as shown in Fig. 10.

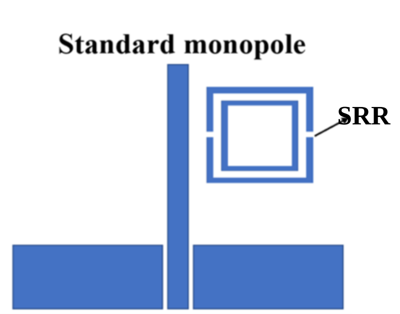
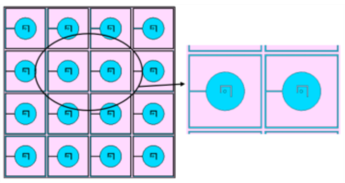


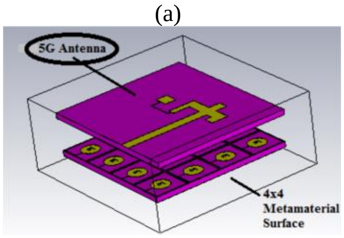
Fig. 10 MTM as miniaturization based on monopole antenna

3.5. Reflector

The use of a metal sheet or a ground plane within the antenna will reflect the waves towards the desired direction, which increases the radiation efficiency and gain. Usually the distance between the antenna and the reflector is taken as a λ/4, or else, the reflected waves will interfere affectively with the directed waves and thus weakened the efficiency[4]. As for the conductive ground plane, the waves are neither damped nor reflected, which leads to the presence of side & back lobes, and as a result the gain decreases[16]. MTM works to suppress surface waves, and their reflection will be in the same phase. Beside that MTM has high impedance, i.e. MTM as a reflector, improves the antenna's performance in terms of directivity, gain, and radiation efficiency. Fig. 11 shows the using of MTM as a wave reflector.



(a)



(b)

Fig. 11 MTM as reflector: a. 4×4 MTM surface. b. Antenna incorporated with MTM surface

3.6. AMC

Artificial Magnetic Conductors (AMC) with zero magnetic field is considered as MTM [43]. In fact, AMC reflects the incident waves with phase=0, ($R_{AMC} \approx 1 + 0j$). It is considered complementary PEC ($R_{PEC} = -1$). As the M-field of AMC is less than E-field, it has high impedance which donated high impedance surface (HIS), so no distortion on radiation pattern. Another important issue is the fact that within AMC band interval (phase of -90 to +90) the currents will be in-phase rather than out-of-phase. The presence of AMC can be in vicinity of antenna (i.e. $d << \lambda/4$), unlike reflector sheet, with powerful directivity. The metallic shapes of AMC are arranged and repeated embossed on the substrate surface as in the Fig. 12.

Fig. 12 MTM as AMC unit cells

4. CONCLUSION

This article summarizes the references that include MTM-principles in their study and sheds light on the strengths and weaknesses points. The MTM-theoretical analysis was arranged to show the characteristics and capabilities. This review has explained the details of the applications of MTM in SAR reducing, miniaturization, isolation, enhancing gain, reflector, and AMC & EBG to be a promising opportunity in future communications. The use of an SSR design with a thin wire will enhance the directivity, reduce the size and give a negative refractive index. The review concluded that the MTM is the best in miniaturization of the ESA antenna, but so far, the correlation between the MTM with the patch or the monopole has not been taken, and this is very important in determining the rest of the antenna characteristics. Finally, we suppose that this review will be as an inspiration for researchers in the MTM development of antennas for modern telecommunications consumers and their wide-ranging applications.

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مراجعة لمواد ميتامتريال المستخدمة في تصميم الهوائيات: المزايا والتحديات

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الملخص

الميتامتريال MTM هي بنية اصطناعية ذات مواصفات كهرومغناطيسية غير متوفرة في المواد الموجودة في الطبيعة، حيث تكتسب خصائصها المميزة من شكلها. لهذا السبب، حظيت هذه المادة باهتمام كبير من الباحثين في مجال الموجات الميكروية. من أجل التغلب على القيود وتحسين أداء الهوائيات، يتم استخدام MTM ايضاً في الهوائيات. تطمح تطبيقات الجيل الخامس إلى تحقيق مكاسب عالية وتقديم أداء مقبول ، مما يلفت الانتباه إلى ضرورة حماية جسم الإنسان من الإشعاع. توفر المادة (MTM) كبتاً للموجات السطحية وانعكاسًا في الطور ومقاومة عالية. في هذا المقال، تم مراجعة هذه MTM من حيث التحليل الكهربائي وتحليل المحاكاة والهيكل الداخلي لخلية الوحدة لتوضيح تأثيرها على أداء الهوائي. بالإضافة إلى ذلك ، تم تقديم نظرة عامة على نقاط القوة والضعف في خصائص MTM. علاوة على ذلك، تفاصيل حول العديد من التطبيقات مثل ؛ تقليل معدل الامتصاص النوعي ، والعزل ، وتعزيز الكسب ، وتصغير الحجم ، والعاكس ، وفي الموصلات المغناطيسية الاصطناعية AMC لتوجيه مصممي الهوائيات للحصول على صورة واضحة لهذه المادة.

الكلمات الداله :
اتصالات الجيل الخامس 5G، الهوائي، الكسب، العزل، مادة الميتامتريال MTM.