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Composite Metamaterials: Classification, Design, Laws and Future Applications

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Abstract

The development of science and applications have reached a stage where the naturally existed materials are not meeting the required properties. Metamaterials (MMs) are artificial materials that obtain their properties from their accurately engineered meta-atoms rather than the characteristics of their constituents. The size of the meta-atom is small compared to light's wavelength. A metamaterial (MM) is a term means beyond material which has been engineered in order to possess properties that does not exist in naturally-found materials. Currently, they are made of multiple elements such as plastics and metals. They are being organized in iterating patterns at a scale that is smaller than wavelengths of the phenomena it influences. The properties of the MMs are not derived from the forming materials but their delicate size, geometry, shape, orientation, and arrangement. These properties maintain MMs to manipulate the electromagnetic waves via promoting, hindering, absorbing waves to attain an interest that goes beyond the natural materials' potency. The apt design of MMs maintains them of influencing the electromagnetic radiation or sound in a distinctive technique never found in natural materials. The potential applications of MMs are wide, starting from medical, aerospace, sensors, solar-power management, crowd control, antennas, army equipment and reaching earthquakes shielding and seismic materials.

Keywords: metamaterials, permittivity, permeability, electromagnetic wave, hyperbolic, chiral, transmission matrix, reflection matrix, anisotropic

1. Introduction

Metamaterials are synthetic composite structures with peculiar material characteristics. They have protruded as a promising material for several science disciplines comprising physics, chemistry, engineering, and material science. MM has been described as structures designed according to an imposed geometry to be exploited in a definite application. The characteristics of MMs are derived from the micro-structure, inherent properties, architecture, and the features' size within it. The 3D architecture can substantially substitute some material characters such as photonic band-gaps, negative thermal expansion, negative Poisson ratio and negative refractive indices [1].

The fabrication of composite metamaterials (CMMs) enables the manipulation of the microstructure and the novel geometry resulted in new or developed

properties which were never found in bulk materials. Also, CMM expands the design space occupied by MM [1]. The industrial applications incorporated MM and CMM in lightweight materials, micro-electromechanical systems, sensors, energy storage and photovoltaic.

2. Types of metamaterials

Negative index materials (NIMs) propagate wave in a way where the wave does not parallel the Poynting vector or (energy and phase velocities are anti-parallel). The right-handed vectors of wave vector, magnetic and electric fields (k , H & E) respectively, in positive index material (PIM) transforms into left-handed triplet in negative index material, where negative refraction occurs to the propagating light beams [2]. Such a phenomenon was perceived in three systems: left-handed (or double negative) MMs [3], hyperbolic MMs [4] and in photonic crystals near band-gap edge [5].

2.1 Double negative MMs

Negative index materials (NIMs) are one of the most researched MMs. They can only be structured via meta-atoms or artificial structure that defeats the boundaries imposed on matter-light interactions due to the need for negative index of refraction which cannot be found unless both of permittivity and permeability are negative, **Figure 1** illustrates the first NIM in the world [6].

The light beam does not parallel Poynting vector because this vector is being determined via the equation:

$$S = E \times H^* \quad (1)$$

Where E is electric field and H is magnetic field H . This means that the direction of energy velocity counteracts phase velocity direction. In general, the refractive index relation is: $n = \pm\sqrt{\epsilon\mu}$ (Where ϵ is permittivity and μ is permeability), in this case the negative value must be taken because $\epsilon_r < 0$, $\epsilon_i > 0$ and $\mu_r < 0$, $\mu_i > 0$. Hence, $\epsilon_r\mu_i + \epsilon_i\mu_r$ is negative. Also, the refraction angle is negative depending on Snell's law:

$$\sin \theta_r = \sin \theta_i / n \quad (2)$$

Figure 1.
The first NIM in the world [6].

(θ is the refraction angle of the wave vector). Which means that both incident and refracted beams are on the same side of the normal. To discover or design a NIM, it is by the negative values of both permittivity and permeability. Natural materials' magnetic susceptibility is quite small compared to dielectric one, this restricts the atoms interaction to the electric constituent of the electromagnetic (EM) wave and neglects the magnetic constituent undeveloped, for that reason most of the natural materials possess a (μ) value close to 1 [6].

2.2 Zero-index materials

The most important property that these materials possess is a zero-phase delay. Some phenomena like infinite wavelength and quasi-infinite phase velocity can be implied from this delay. In this material, EM wave is static in the spatial field. While it allows the energy transportation due to the time domain flexibility. One of the pioneer applications of these materials is to show how it can enable the user for controlling the emission of an internal source to gather the power in a small angular field around the normal [7]. The critical angles' reflection is (0) depending on Snell's law. The external source (outside of the material) beam cannot be transmitted due to the total reflection, while the internal source results in a perpendicular beam to the surface of the beam [6].

It is being complicated to perceive a zero-index material with nullified permittivity and permeability, while many realizations of materials with one nullified parameter (permittivity or permeability) have been achieved. Zero or near zero index MMs have another fascinating property in graded-index structures known as anomalous absorption near zero index transition. In which magnetic permeability and dielectric permittivity gradually moves among negative, zero and positive values [8].

2.3 Mechanical MMs

The distinctive and tunable characteristics of MM have attracted the researchers in the mechanics discipline. Materials with negative Poisson ratio (auxetic) and near zero Poisson ratio (anepirretic) showed compression within load applying [9], such a phenomenon led to optimized shock absorbing, shear and indentation resistance. For those properties, they have been often used in medical devices (stents), protective gear and gaskets. Reports have illustrated that the geometrical design is the main reason behind auxetic property [10, 11]. The phase distribution and combination can be organized in order to produce an auxetic material, via the reaction between the host and fiber enforcement [12].

Lightweight - strength materials are another focal interest for researchers. Materials that combines both of light weight and strength are expected to be filled up in the Ashby's plot, here density reduces significantly [13]. The strength can be conserved while the weight decreased via applying 3D structuring. The mechanical properties in the micro-scale are changing according to the intrinsic and extrinsic size impact. Such properties are well known in metals, but they are also exhibited in CMM micro-lattice [14]. The researchers nowadays, are working on MMs that possess mechanical anisotropy [15, 16], programmable materials [15, 17], and nil-thermal expansion CMM [18].

2.4 Photonic MMs

MMs can dominate the path of light, and imposing a definite geometry, enables MMs to produce polarization filtering [19], negative refractive indices [20] and photonic bandgaps [21]. Negative refractive index (left-handed) materials can be applied to create a reversed Doppler effect, optical tunneling, super lenses and

electromagnetic camouflage [22]. Split ring resonators are the most used structures to discover these impacts, exposing it to exterior magnetic field makes the current in the ring evolve electromagnetic field, **Figure 2** shows the most common designs of photonic MMs [1]. Gaps possess big capacitance that impacts the frequency of the resonance. The disposition is giving the structure a great quality factor, also, cloaking often related to Split-ring resonators (SRR) due to the induction of the opposite flux to the occurring one [1].

Presenting a recurring layered structure in a 3D material can result in a photonic bandgap [23, 24]. The matching between wavelength and distance between two layers hinders the light passing and reflects it. The common name of this phenomenon is band-stops, and it attracted the researchers to be applied in optical networks approaching the semiconductors' electrical networks. The woodpile design is the most eminent structure due to its simple design [25–27]. Also, the simple fabrication of colloidal crystals via self-assembly has attracted researchers, as this method has resulted in a structure that can be used as templates because its voids can be eliminated and inverse opals can be originated. The light polarization can be controlled via chiral structure as a substitute to noble materials (gold and silver). Such a polarizer has been manufactured with template-assisted electro-deposition from pure electro-deposited gold [28], while others covered two-photon lithography pints with electroless deposited silver [29].

Also, MMs can control sound wave propagation depending on the geometrical design, the similar behavior of sound and electromagnetic waves makes the same concept applicable for photonic MMs. Conceptually, phononic and photonic crystals are the same, plenty 2D phononic crystals have been manufactured of silicone with array of holes, they are able to filter definite phonons' wavelength because of the stimulated bandgap [30, 31]. Stereo-lithography succeeded in producing 3D

Figure 2.
The most common designs for photonic MMs: (a) SRRs, (b) wood pile structures, (c) colloidal crystals, and (d) inverse opals [1].

phononic crystals out of acrylic polymer and metallic constituents, which have increased the ratio of the broad band vibration propagation. Polymer has been used in creating fano-like dampening [32]. Whilst silencers with inertial local resonant have been created for acoustic lensing [33].

2.5 Chiral MMs

Chiral means lacking of mirror symmetry, chiral medium is subcategory of bianisotropic, where magnetic and electrical fields are conjugated together. The optical response of the general chiral media has been described by these two fundamental equations:

$$\overline{D} = \epsilon_0 \overline{\epsilon} \overline{E} + \frac{i}{c_0} \overline{\chi} \overline{H} \quad (3)$$

$$\overline{B} = -\frac{i}{c_0} \overline{\chi} \overline{E} + \mu_0 \overline{\mu} \overline{H} \quad (4)$$

Where $\overline{\epsilon}$, $\overline{\mu}$ and $\overline{\chi}$ are permittivity, permeability, and chirality tensors, respectively [34]. A zero in the subscript position (X_0) for any of the variables illustrates the vacuum. $\overline{H}$ magnetic field, $\overline{B}$ magnetic induction, $\overline{E}$ electric field and $\overline{D}$ is the electric displacement. If the chiral material is isotropic, ϵ , μ , and χ scalars are used to simplify and facilitate the fundamental parameters. The left and right handed circular polarization (LCP & RCP) of the refractive indices are given via a different equation:

$$n_{\pm} = \sqrt{\epsilon\mu} \pm \chi \quad (5)$$

Dissimilar phase accumulation will result via the waves according to the handedness, while both are having corresponding impedance:

$$Z = Z_0 \sqrt{\epsilon/\mu} \pm \chi \quad (6)$$

LCP and RCP overlapping with identical amplitude will illustrate a linearly polarized wave. The refractive index difference between two circularly polarized waves gives a rotation in the value of an angle

$$\Theta = (n_+ - n_-) \frac{\pi d}{\lambda_0} \quad (7)$$

or

$$\Theta = [\arg(T_+) - \arg(T_-)]/2 \quad (8)$$

Where d is the thickness of the medium, λ_0 is the wavelength in the vacuum, T is the transmission coefficient in different spin conditions. This is the optical rotation's mechanisms and physical consequences [34].

It can be inferred that if chirality χ is strong enough, the occurring refraction may be negative in the case of one circularly polarized light albeit both ϵ and μ are positive [35].

The retrieval method can be applied to acquire effective parameters from scattering ones [36] to address the characters of the MM. The optical response forms an apt way to describe the properties of the MM. John matrices can be used in defining optical response of planar MM, which relate the scattered fields and the complex amplitudes of the incident [37].

$$\begin{pmatrix} E_r^x \\ E_r^y \end{pmatrix} = \begin{pmatrix} r_{xx} & r_{xy} \\ r_{yx} & r_{yy} \end{pmatrix} \begin{pmatrix} E_i^x \\ E_i^y \end{pmatrix} = R \begin{pmatrix} E_i^x \\ E_i^y \end{pmatrix} \quad (9)$$

$$\begin{pmatrix} E_t^x \\ E_t^y \end{pmatrix} = \begin{pmatrix} t_{xx} & t_{xy} \\ t_{yx} & t_{yy} \end{pmatrix} \begin{pmatrix} E_i^x \\ E_i^y \end{pmatrix} = T \begin{pmatrix} E_i^x \\ E_i^y \end{pmatrix} \quad (10)$$

T & R, are the transmission and reflection matrices for linear polarization. E_r^x , E_i^x , & E_t^x are the reflected, incident, and the transmitted electric fields polarized along the x axis, respectively. Y direction has similar notations with an apt superscript (Y). Applying the Cartesian base to a circular base result in Jones' matrices for the two conditions of circular polarization.

$$\begin{aligned} R_{\text{circ}} &= \begin{pmatrix} r_{++} & r_{+-} \\ r_{-+} & r_{--} \end{pmatrix} = \Lambda^{-1} R \Lambda \\ &= \frac{1}{2} X \begin{pmatrix} r_{xx} + r_{yy} + i(r_{xy} - r_{yx}) & r_{xx} - r_{yy} - i(r_{xy} - r_{yx}) \\ r_{xx} + r_{yy} + i(r_{xy} + r_{yx}) & r_{xx} + r_{yy} - i(r_{xy} - r_{yx}) \end{pmatrix} \end{aligned} \quad (11)$$

$$T_{\text{circ}} = \begin{pmatrix} t_{++} & t_{+-} \\ t_{-+} & t_{--} \end{pmatrix} = \Lambda^{-1} T \Lambda = \frac{1}{2} X \begin{pmatrix} t_{xx} + t_{yy} + i(t_{xy} - t_{yx}) & t_{xx} - t_{yy} - i(t_{xy} - t_{yx}) \\ t_{xx} + t_{yy} + i(t_{xy} + t_{yx}) & t_{xx} + t_{yy} - i(t_{xy} - t_{yx}) \end{pmatrix} \quad (12)$$

Where $\Lambda = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ i & -i \end{pmatrix}$ is the variation of the fundamental matrix, subscript +/− indicates the circularly polarized waves along +z direction whether it is clockwise or counterclockwise.

Symmetrical distribution has been an effective method to anticipate to which extent the symmetrical structure influences the properties of the structure and Jones matrices' characters. If the MM represent a certain symmetry group, the original and the Jones matrices must be identical. In Jones matrices of the linear polarizations, the mirror symmetry results in an absent to all the off-diagonal elements ($r_{xy} = r_{yx} = t_{xy} = t_{yx} = 0$) with respect to the incident plane. Hence, the Jones matrices for circular polarizations become symmetric ($r_{--} = r_{++}, r_{-+} = r_{+-}, t_{+-} = t_{-+}, t_{--} = t_{++}$) [37].

Furthermore, chirality nullifies polarization rotation as the optical activity has been always described by $\theta = [\arg(t_{++}) - \arg(t_{--})]/2$. The correspondence of the two circularly polarized waves results in similar efficiency for the polarization conversion due to the correspondence of the off-diagonal elements. Inevitably, mirror symmetric structures have neither CD nor optical activity, and this result explains why chirality exist in the structures that suffers mirrors symmetries deficiency -from Jones matrix perspective-. **Figure 3** shows various types of 3D chiral mechanical metamaterials [38].

Other rotational symmetries (threefold & fourfold) with respect to symmetry guides to $r_{xx} = r_{yy}$, and $r_{xy} = -r_{yx}$ [37]. For circular polarization, $r_{+-} = r_{-+} = 0$ and the transmission matrix possess the same reasoning so that $t_{+-} = t_{-+} = 0$. The reciprocity of De Hoop declares that the matrix of reflection follows the general identity $R = R^T$, where t performs the transpose operation in the specific case of normal incidence [39]. Combining the aforementioned restrictions will guide to a linear polarization conversions where ($r_{xy} = r_{yx} = 0$). Thus, Jones' matrices can be formed as

$$R_{\text{circ}} = \begin{pmatrix} r_{xx} & 0 \\ 0 & r_{xx} \end{pmatrix} = r_{xx} I \quad (I, \text{ is the identity matrix}) \quad (13)$$

$$T_{\text{circ}} = \begin{pmatrix} t_{xx} + it_{xy} & 0 \\ 0 & t_{xx} + it_{xy} \end{pmatrix} \quad (14)$$

Figure 3. Various types of 3D chiral mechanical metamaterials: (a) 3D anti-tetrachiral mechanical metamaterials; (b) 3D chiral metastructures; (c) computational optimized auxetic lattice with 3D anti-tetrachiral configuration; (d) 3D chiral-antichiral-antichiral mechanical metamaterials; (e) alternative anti-tetrachiral lattices; (f) 3D chiral lattice with negative Poisson ratio; (g) 3D chiral-antichiral-antichiral mechanical metamaterials; (h) 3D cellular metamaterials with planar anti-tetrachiral topology; (i), compression-twist chiral mechanical metamaterials; (j) 3D chiral-chiral-chiral mechanical metamaterials; (k) 3D cellular metamaterials with planar tetrachiral topology; (l) alternative 3D chiral unit cell; (m) 3D chiral pyramid lattice; (n) 3D chiral dodecahedron lattice; (o) 3D chiral regular icosahedrons lattice prepared by the author [38].

Hence, all the polarizations' reflection coefficients are identical. Scalar χ expresses the chirality parameter that nullifies the polarization conversions which leads to symmetric structure of threefold/fourfold [40]. The identical illumination reflection may occur in the LCP or RCP material due to being isotropic material, in other words, it can only be determined by the ratio between permeability and permittivity of the material and never related to the parameters of the chirality [41]. Moreover, if there are no losses at all the energy conversion, also, reciprocity controls the coefficients of the transmission and leads to identical spin states [39]. Conversion between two spin states of the polarization would occur to chiral MMs such as in twofold (C2) MMs becoming anisotropic [34]. It is notable that the 2D planar structures' disability results in a structural chirality in 3D space, caused by the off-diagonal elements equality in Jones matrices due to the in-plane mirror symmetry output ($t_{++} = t_{--}$). Still, the dichroism phenomenon being supported in the transmission of two spin states via a devised structure supported with unequal sufficiency in polarization conversions ($t_{+-} \neq t_{-+}$) [42] and this phenomenon is known as asymmetric transmission in reciprocal materials [43].

Metasurfaces, is an innovative method for circularly polarized light manipulation [44]. The circularly polarized light optical response spatially adjusting the achiral elements phase response than designing chiral metamolecules are manipulated via metasurfaces being diverse from the common MMs. The aforementioned approach, justifies several optical phenomena like high efficiency holograms [45], optical vortex generation [46], all-dielectric focusing [47], optical angular momentum achromatic generation [48] and dispersionless irregular refraction and reflection [49].

2.5.1 Optical chiral MMs fabrication

The optical chiral MMs depends on structures consisted of nanoscaled blocks. The two main fabricating techniques (top-down & bottom-up) can be used to fabricate optical chiral materials. The conventional example of chiral MMs is the 3D helix structure. It is being fabricated by direct laser writing completed with electrochemical precipitation of gold. The array of helical pores is being fabricated via positive-tone photo-resist, accompanied with spinning onto a glass substrate. This method is not applicable for bichiral-structures where the left- and right-handed spirals arranged in three orthogonal spatial axes [50]. Whilst using electroless silver plating with direct laser writing results in bichiral plasmonic crystals [51]. Also, 3D chiral plasmonic nano-structure can be fabricated via glancing angle deposition [52]. Moreover, the On-edge lithography is a pioneer method to manufacture a 3D chiral material [53].

Top-down manufacturing technologies are expensive, requiring a lot of time, non-scalable but capable of manufacturing structures below 100 nm. Unlike, self-assembled technology (bottom-up approach) it is tunable, cost effective and a fast process. It exploits the basic forces of nature in converting the blocks of the building into multi-atom systems. The equilibrium state of the structure depends on the accurate balance among the distinct forces [54]. One can take advantage of the delicate positioning and manipulate the metal's nano-particles with chemical compositions, sizes and geometries.

2.5.2 Chiral MMs applications

In the second harmonic generation, chiroptical influences are naturally bigger than their linear equivalents [55]. In this process, two photons are being converted into a single photon in a double frequency [56]. The response can be described via

nonlinear polarization, as same as the electric dipole approximation, it can be presented via this equation:

$$P_i^{NL}(2\omega) = \chi_{ijk}^{(2)} E_j(\omega) E_k(\omega) \tag{15}$$

Where ω is the angular frequency, $\chi_{ijk}^{(2)}$ is the second order susceptibility tensor, E is the electric field and the Cartesian indices are i, j & k .

The weak chiroptical in nature are languid, the unique mechanism that overcome this obstacle is the superchiral fields. The chiroptical signals are being enhanced by several nano-structures such as dielectric nanoparticles [56], plasmonic structure [57], and negative index MMs [58]. It has been suggested that the chiral Purcell factor can help in characterizing the optical resonator capability and enhance the chiroptical signals [59]. Future optical systems like polarization sensitive interactive and imaging display, can be developed by achieving an active manipulation over the MMs' chirality. The full control includes the reconfiguration of the molecule from right- handed enantiomer to left- handed counterpart, vice versa. **Figure 4** illustrates a design and fabricated chiral-airfoil with water-jet cutting technique [60].

Figure 4.
Chiral airfoil and aerodynamic performance simulation [60].

2.6 Hyperbolic MMs (HMMs)

This term has been inspired from the topology of the isofrequency surface. They are an extreme anisotropy, as they act like metal for polarization or direct light propagation while they act like dielectric for others due to positive and negative permittivity tensor constituents. Its extreme anisotropy results in propagation of light on the surface and within the material [61]. Thus, its applications are promising in the field of controlling optical signals, sensors, imaging, and enhanced plasmons resonance effect [62]. For instance, this equation:

$k_x^2 + k_y^2 + k_z^2 = \omega^2/c^2$, expresses the spherical isofrequency surface that implicated by the linear dispersion and isotropic behavior of waves propagating in vacuum, where $\vec{k}$ is the propagating wave vector, ω is the radiation frequency and c is the light velocity in space.

For an extraordinary wave in a uniaxial medium, the relation becomes:

$$\frac{k_x^2 + k_y^2}{\epsilon_{zz}} + \frac{k_z^2}{\epsilon_{xx}} = \frac{\omega^2}{c^2} \quad (16)$$

If the case is about anisotropic the spherical isofrequency surface transforms into elliptical one in the vacuum. While in extreme anisotropic like $\epsilon_{\parallel}\epsilon_{\perp} < 0$, the isofrequency surface become an open hyperboloid. Here, the scrutinized material has two different behaviors, metal and dielectric (insulator), according to the direction.

The fundamental property of such material is the large magnitude, while the properties of large wave vector waves like evanescence and exponential decay are the most important ones in vacuum. However, waves propagation with infinite wave vectors in the typical limit are permitted via the isofrequency surface open form in hyperbolic media [63]. Thus, the vanishing waves don't occur in such medium which is a promising property for plethora of devices using hyperbolic media [64].

In order to classify the hyperbolic media, it will be enough to know the components' signal. In other words, the first type (I HMMs) has one negative component of the dielectric tensor ($\epsilon_{zz} < 0$; $\epsilon_{xx}, \epsilon_{yy} > 0$) while the other type (II HMM) have two negative components ($\epsilon_{xx}, \epsilon_{yy} < 0$; $\epsilon_{zz} > 0$). Whilst, if the three components are negative, it means that a metal has been acquired. If all of them are positive, then, it means that the medium is dielectric **Figure 5** [66].

2.6.1 HMMs designing

HMMs requires metal and dielectric to be used in the structure to act like metal and insulator at once. The exalted- k propagating wave, derived from the metallic content of the structure to develop the dispersion behavior of the material. The light-matter coupling is necessary because of the metallic polaritonic properties as it creates a hurdle to induce high- k waves. Absolutely, HMMs structure should have optically active phonons known as phonon-polaritonic or free electron metal known as Plasmon- polaritonic. The high- k modes caused via the surface Plasmon polariton as near-field coupling at both of the interfaces metal and dielectric. While the dielectric-metal lattices provides the bloch modes which in turn creates a fertile base for the high- k modes [34].

The dielectric and metal layers forms superlattice (multilayer) resulting in the excessive anisotropy [67]. The thickness of the layer must be shorter than the operating wavelength in order to be valid. The most important factors that

Figure 5.
 (a) Metal/dielectric multilayered structures, (b) cylindrical metal/dielectric multilayered structures, (c) metal wires array in a dielectric matrix, and (d) fishnet structure [65].

influence the absorption and the impedance matching of the MMs are the metal plasma frequency and the loss [68]. The behavior of the hyperbolic refers to the dielectric's high index and the plasmonic metals' wide spectra. For instance, silver, gold, and alumina forms a fertile base for MMs at the frequencies of the ultraviolet. Adding high index dielectrics like SiN or titania to expand the design ratio to comprise visible wavelengths [69].

Concerning the near IR wavelengths, substituting plasmonic metals such as silver and gold for their reflective behavior requires materials provided with low plasma frequency. These materials are consisted of transparent conducting oxides or transition metal nitrides and applicable for HMMs [68]. The hyperbolic behavior can be achieved via a dielectric host with metallic nanowires. It possesses great advantages like high transmission, low loss and wide broadband. **Figure 6** is showing a good illustration of the two types [34].

2.6.2 HMMs fabrication

The multilayer design depends on precipitating smooth ultrathin layers of dielectric and metal, but surface roughness causes light scattering and material loss. But the minor aberration of the layer thickness does not effectively influence the medium response [70]. This strict stoichiometry is achievable by using pulsed laser deposition or reactive sputtering [68].

Figure 6. (a) Illustrates multilayer structure consisting of alternating metallic and dielectric layers forming a metal-dielectric superlattice, and (b) shows nano-wire structure consisting of metallic nanorods embedded in a dielectric host [34].

Fabricating HMMs has been successfully achieved by using anodizing aluminum [71], another method depends on anodic alumina membranes [72]. The dielectric medium structure shall be a periodic nano-porous in order to host the electrodeposited silver (or gold) nanowires [73]. It is worthwhile to be mentioned that the behavior of the material can be controlled by the porosity due to the fill fraction of the metal.

2.7 Semiconductor MMs

Usually, a special surface exists at the interface between a dielectric and a noble metal, is known as surface plasmonic polariton (SPP) [74]. This surface has opened new applications such as high order harmonic generation [75], MM design [76], sensors [73], microelectronics [77], lasers [78], photovoltaics [79] and photonics [80]. Moreover, research has shown that the dispersion of SPP can be manipulated or excited in a prescribed manner via nano structuring the metal surface [81–83].

HMMs' ability to prop large wave vectors has enabled the researchers to use it in several intriguing applications, such as, hyper-lens [84] and sub-wavelength imaging [85], which were impracticable with natural materials. Between two anisotropic MMs a type of surface wave has been scrutinized other than SPPs and Dyakonov waves [34]. These waves promoted via the nanostructured MM, cross the light track and fundamental share that has low frequencies stabilize above the light line in free space, which divide radiative and nonradiative areas.

The semiconductor's effective permittivity can be calculated via:

$$\epsilon_{1,3}(\omega) = \epsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\delta\omega}, \quad (17)$$

where ω_p is the frequency of the plasma and ϵ_{∞} is the background permittivity. The effective medium approach, helps in describing the optical response, it describes the size of the wavelength of the radiation to be compared to the thickness of the studied layer [86]. At the interface, the tangential constituents' matching of the magnetic and electrical fields, implicates the relation of the dispersion for the surface states located at the boundaries splitting two anisotropic media [87]. For example, doping silicon heavily, resulted in a metal-like properties at terahertz frequencies, where it is promising to be used in applications instead of metals [88]. The frequency range of the surface can be manipulated via adjusting layers'

thickness and permittivity [89]. The resonant behavior of $\epsilon_{\perp}$ can be achieved by manipulating the doping ratio, this manipulation results in tuning of resonant frequencies over the thresholds of the frequency ranges. Also, fill fractions of the semiconductor sheet and dielectric, will influence the resonant behavior of $\epsilon_{\perp}$.

2.8 Quantum and atomistic MMs

The domains of quantum MMs studies in near IR or optical region are still shallow but promising as the quantum degrees of freedom are incorporated [90]. In the photonic structure, the quantum wells have been used to describe the permittivity influence over the structure behavior electromagnetically. Studying layered MMs supplied with two quantum wells of GaAs, showed an effective permittivity tensor resulting in a negative refraction [91]. Many proposals have been done to extend the quantum magnetism of the MMs via organic synthesis or molecular engineering. Theory showed that Cu-CoPc₂ (copper phthalocyanine and cobalt phthalocyanine chains) provided a relatively robust ferromagnetism [92].

A chain of studies has been implemented that can be described as a development of work. It has been discovered that a full quantum process happens between two level atoms and a quantized electromagnetic field [93]. Then Cavity Array MMs (CAM), where 2D network of coupled atom-optical cavities were scrutinized to analyze the model via 2D photonic crystal membrane [34]. For a reasonable hypothesis, Jaynes-Cummings-Hubbard Hamiltonian method can be used to depict a system that exhibits a quantum phase transition [94]. So, it is possible to work as a quantum simulator [95]. Also, negative refraction and cloaking phenomena were elucidated. Moreover, the polaritons hybrids that formed of atomic and photonic states are an exciting system.

The dielectric function ϵ_{QD} expresses the quantum dots [96]:

$$\epsilon_{\text{QD}}(\omega) = \epsilon_b + (f_c(E_h) - f_v(E_h)) \frac{a}{\omega^2 - \omega_0^2 + 2i\omega\gamma} \quad (18)$$

Figure 7.
 A cavity array metamaterials [34].

Where, $(f_c(E_h) - f_v(E_h))$, is the difference between population levels.

Figure 7, is showing cavity array metamaterials [34].

3. MMs applications

Besides all the aforementioned applications, MMs are promising candidates for micro-robotics and micro-electromechanical systems (MEMS). Nowadays, the CMMs researchers focus is on the microscale, where applying them in micro-robotics and MEMS is spatially constrained. Moreover, literature reports endorsed those substantial applications of non-mechanical MM depend on the architecture microstructure.

Furthermore, MMs have been used in sensors and in micro-robotics as Negative permeability and permittivity of SRR arrays introduced them as promising sensors for molecule detection, deposit sensing, mechanical strain, temperature, gas detection and concentration [97].

The change in resonance frequency stimulates the detection, SRR is similar to IC-oscillator and the frequency is being calculated by:

$$f = x = \frac{1}{2\pi\sqrt{LC}} \quad (19)$$

Where L is inductance, C is capacitance of the narrow gap section.

Mechanical contortion changes the capacitance because of the geometrical change of the gap region. SRR was built with conductive polymer to sense the gas via the changes of the dielectric of the adsorption of the gas in the polymer [98]. (Publications of sensing SRR).

Also, CMMs are considered fundamental candidate for micro-robotics application due to the existence of anisotropy in the design which can be defined through the shape and the change in the material. A plenty of magnetic micro-robotics and chemical propulsion have been scrutinized [99–101]. These micro-robotics, have been applied in environmental cleaning devices [99, 100], drug delivery system and cargo transport [102, 103].

4. Composite metamaterials (CMMs) synthesis

4.1 Additives manufacturing

Plethora of MM applications require microscale structure which complicates the manufacturing process. Additive manufacturing offers many benefits, such as decreasing the resource effort which develop sustainability, expedites design, prowess step from macroscale into nanoscale, and manufacturing on demand. This method is the most apt method in manufacturing CMMs, taking in consideration its simple batch manufacturing, modeling, research and development [104]. Thus, it is already applied in medical products, electronics, machining, aerospace and automobile who are possible users for the CMMs [105].

4.2 Methods and size

Additive and subtractive methods have been used in MM & CMMs production. Selective laser melting and sintering (SLM & SLS) are additive manufacturing methods that can be used in micromachining and established mesoscale. In

microscale, subtractive methods with the necessary resolution have been scarce, besides the available methods like focused ion beam milling, has limited degree of freedom. Anyway, this method is critical to evolve a metamaterial with the desired characters. Whilst, negative Poisson ratio, mechanical linearity, zero thermal expansion and programmable mechanical MMs are size independent, while the other MM applications are size-dependent. Applications that depend on effect, such as artificial bandgap in acoustic and optics, SRR's resonance frequency require manufacturing in the appropriate size range. Moreover, microscale manufacturing is required in micro robotics and MEMS devices.

5. Conclusion

The development of MMs and Metasurfaces is clarifying their exotic behavior. Detail work is still required to understand, analyze, fabricate and finding the effect of the design on these materials engineering. Although the recent studies have shown changes in the common principles and laws of EM waves, photonics and optics for the future. NIMs and Zero-index materials need to be studied and their law must be exposed because manipulating such materials may help in conquering new fields of applications were been impossible to be anticipated.

Acknowledgements

The authors would like to thank Dr. WAEL FAWZI for his ineffable contribution in completing this work.

Conflict of interest

The authors declare no conflict of interest.

Nomenclature

MM	Metamaterial
HMM	Hyperbolic metamaterials
CMM	Composite metamaterial
SPP	Surface plasmonic polariton
PIM	Positive index material
CAM	Cavity Array metamaterial
EM	Electromagnetic
MEMS	Micro-electromechanical systems
SRR	Split-ring resonators
SLM	Selective laser melting
LCP	Left handed circular polarization
SLS	Selective laser sintering
RCP	Right handed circular polarization

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