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Review article

Functional metamaterials for wireless antenna applications – A review abetted with patent landscape analysis

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ABSTRACT

The communication network made the globe a single entity and easily acessible by everyone at any time. Growth in communication networks is unimaginable and advanced nowadays. It is growing every day by means of medium or components used in communication. There are various significant components that are generally used in the communication networks. Specifically, wireless communication (WC) is the dominant in today's communication world. It is supported by the transmitting and receiving nodes at each end of communication. The common components in communication antennas are the transmitters and receivers. It has been unalterable for many decades but their capabilities have been improved through various methods including their manufacturing by the use of alternative materials. This article focuses on metamaterial (MM) based wireless antennas. The growth of metamaterials utilization in the fabrication of microstrip antennas has been discussed comprehensively and its future scope has been envisaged through patent landscape analysis. It is done meticulously using the patent database and in addition, the growth of some of the metamaterials was also predicted using the landscape analysis. Some significant technologies related with metamaterials in WC that were patented have been discussed comprehensively along with the reference to recently published articles. This articles serves as a guide to the researchers working in the communication field to envisage the future advancements.

1. Introduction

Sensors and antennas used in wireless communication networks must be easily integrated into the users' regular lives [1]. All the body-worn technologies are to be practical, light, easy to adjust, and barely noticeable to the average person. The need for solutions like wireless body area networks (WBAN) is growing over time [2]. Wearable electronics come along with compact elements that enable a single antenna to function at multiple frequencies in addition to being placed in various parts of the body of a person and are also characterized with advantages such as being rapid sensing, smart, and reasonably a long-range covering [3]. The medical care requirements of humans can be simplified and improved with the help of such wearable devices. Flexible electronic systems must

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incorporate flexible antennas operating in specific frequency ranges to provide wireless connectivity in today's information-oriented culture [4]. The past few decades have seen numerous reports of reconfigurable antennas utilizing active switches like Positive-Intrinsic-Negative (PIN) diodes and varactors, along with Radio Frequency Micro Electric Mechanical Systems (RF-MEMS) [5–7]. Although these antennas were typically constructed on a rigid substrate, their resonance frequency [8,9], radiation distributions [10], and polarization configurations [11,12] were all subjected to change. Nevertheless, it is ideal to have only one wearable antenna that can switch between several radiation patterns, frequency ranges, polarizations, and body contours. However, there is a dearth of wearable adaptable antennas because of the complications faced during the establishment of the connections that are both electrically and mechanically robust between fixed electronic components and conductors [11]. A small number of wearable antennas that can be reconfigured have been observed in the literature [12–15]. WBAN calls for antennas that are both portable and dependable [16]. The knack of a wearable antenna to reconfigure its radiation pattern, frequency, and polarization in response to different applications is closely linked. A wearable adaptable antenna has become a workable solution in WBAN contributing to improved efficiency and reduced carbon footprint [17,18]. Because of their valuable attributes, wearable antennas that can be reconfigured are becoming increasingly popular, and significant work has been done over the past decade to incorporate them into WBAN [19–21].

Antennas are critical components in contemporary communication systems because they allow the wireless sending and receiving of electromagnetic signals. Recent wireless technologies, like 5G networks and IoT (Internet of Things) are the vehicles for the introduction of a densely connected epoch. Antennas must evolve to keep up with the rising demand for more data throughput, more robust communication links, and compact, higher-performance transceivers. In addition to an adequate radiation pattern along with gain, modern antennas need to be compact, possess a low profile, and have a wide frequency range. Additionally, massive multiple-input multiple-output (MIMO) along with beam-forming arrays present novel obstacles for antenna architecture [22,23]. Isolation from the neighbouring parts and the capacity to steer the beam are the two features that are useful and required for optimal performance. As a result, the more components an antenna assembly has, the more difficult to design it. Antennas are typically made up of several materials, including dielectrics, conductors, and other materials, all arranged in a specific geometric pattern. They are created using either analytical or empirical techniques [24]. To achieve the best possible efficiency, the structure's variables are fine-tuned with the help of full-wave simulations along with artificial intelligence [25,26]. Antenna layout is constrained by the unique features of the materials used because its primary focus is on identifying the optimal geometrical form of traditional materials. Focus has shifted toward MM due to their unique characteristics as a means of overcoming the above limitation. Although MM is made up of regular materials (conductors and dielectrics) on a microscopic level, their macroscopic properties are very distinct because of their

Fig. 1. Meta materials applications.

tailorable shapes.

Negative constitutive variables are possible to attain with MM in the microwave regime, and their sub-wavelength size is another advantage. This means that incorporating MM through antennas can provide increased versatility and open up new avenues for design. Because of their potential impact on the state of the art in wireless communication, studying the advantages of antennas prompted by MM is of paramount importance. A comprehensive look at the current state of research into MM antennas is provided by various literature. Three standard antenna design techniques inspired by MM such as antenna miniaturization using Meta resonators, gain enhancement, and decoupling of nearby antennas are commonly dealt with in many of the literature works. Due to space constraints, large antennas cannot be used in mobile, airborne, wearable, or IoT-based devices; however, MM-based miniature antennas have been proposed for use in 6G networks [27]. Researchers took a close look at the pros and cons of electrically compact antennas loaded with metal resonators. Gain enhancement was required to extend the range of communication via point-to-point links, increasing the signal-to-noise ratio (SNR), and reducing interference. This motivates the introduction of metasurfaces that concentrate electromagnetic radiation and boost the gain of antennas. Moreover, antenna isolation is critical for reducing the coupling that reduces the efficiency of the multi-antenna framework, which is becoming increasingly important as the variety of antennas for each gadget for communication rises. Therefore, various methods of decoupling MM were discussed and compared in some works [28,29]. Dynamic meta surface antennas (DMA) allow beam steering with less hardware complexities than conventional phased arrays [30,31].

The "business wire" website provides an international perspective on MM by providing their utilization and forecast their application projection till the year 2030. Within the upcoming decade, innovations in MM uses like radar and LiDAR over self-driving automobiles, communications antenna, networks for 5G, protective coatings, vibration dampening, wireless charging, noise mitigation, and more will create a multi-billion-dollar market. The material characteristics (electrical, optical, magnetic, acoustic, and so on) of MM are excellent because they are tailorable structures. They consist of resonator networks capable of producing artificial electromagnetic or acoustic waves. Fig. 1 summarizes the wide variety of applications of these materials possessing tailorable dielectric characteristics and quick responses times. These materials are used to manipulate areas and waves on a sub-wavelength size [32].

Researchers have created a synthetic material identified as a MM which can sense its surroundings, form its own opinion, and take action without human intervention [33]. All the information reveals that the MM has potential growth over the next few years. However, consolidated data regarding the applications of metamaterials in the antenna and its related components applications from patent data is not available. Abetting the patent data in the literature survey not only enhances the futuristic view of the material and the process but also gives an accurate information on the recent progress in the MM research. In this article, the specific focus is given to electronic related applications of MM such as microstrip antennas. A patent landscape analysis for the utilization of metamaterials in wireless communication specifically in antennas has been made. Through patent data and inventions, the probable pathway through which the metamaterials can be progressed has been discussed elaborately. Recently published patents on metamaterials and wireless communication have been discussed elaborately in different sections to envisage their growth in the near future.

2. Metamaterials in wireless antennas

The scope of usage of the MM in WC has been adequately reported in various literature. The growth of the metamaterials in this field was also predicted by various researchers and experimenters working in this field. Its unique properties allow the researchers to envisage the scope in the future. So, further, it is assessed using the number of publications over a decade. Even though MM was found in the late 1960s, it took more than four decades to appear in articles [34]. So, the publication trend of MM usage in wireless communication during the last two decades is represented in the following Fig. 2.

Since MM is used in wireless communication its growth is found to be progressive and there is no downtrend. For the year 2023, it is

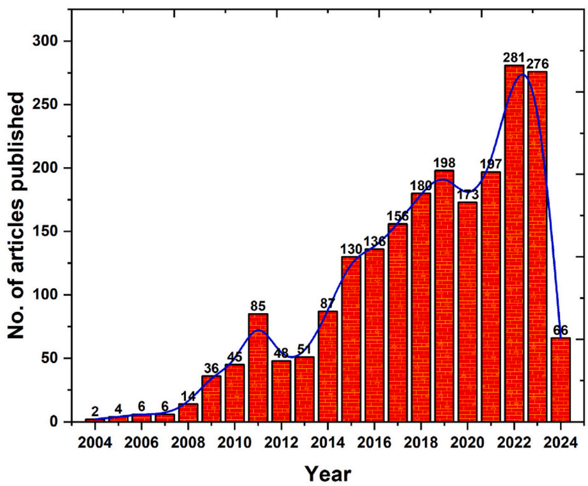

Fig. 2. Number of publications in MM and wireless communication from 2004 to 2024 (Source: Scopus database).

Table 1
Usage of MM in various WC applications.

S. No.	Components	Communication	Ref.
1	Antennas	Narrow range	[35]
2	Antenna	Very low range	[36]
3	Split-Ring Resonator (SRR) and Compact SRR	Multi-band (MB) and Quad-band	[37,38]
4	Traveling wave Antenna	Multiple	[39]
5	Patch Antenna	MB	[40,41,42,43,44,45,46,47]
	MS Patch Antenna	5G, performance enhancement communication, superstrate technique in communication UWB Wearable communication	
6	Microstrip (MS) Antenna	Sub-6 GHz waveguide	[48]
7	Tuneable and compact Antenna	Multi-band	[49]
8	Sensor networks	Body textile within 10 cm	[50]
9	MS patch Antenna	5G	[41]
10	Time-based directional modulation schemes	Layer security	[51]
11	Triple band MS Antenna	High gain	[38]
12	Inverse “L” slotted Antenna	Improved and width	[52]
13	Multi-layer Antenna	Satellite	[53]
14	As absorber of MM	Broadband	[54]
15	Transmission line Antenna	Next-gen communication (comm.)	[55]
16	Triple band Antenna	Microwave	[56]
17	Antenna	MB	[57]
18	2D directional array transmitter	Layer security	[58]
19	Split rings	Microwave	[59]
20	Antenna	Multiple comm. applications	[60]
21	As filter	Optical	[61]
22	Reconfigurable surface	Novel comm.	[62]
23	As textile	Implant to implant comm.	[63]
24	MS	5G	[64]
25	Resonator Antenna	5G	[65]
26	As absorber	Comm.	[66,67]
27	MIMO Antenna	High gain and isolation	[68]
28	Planar MS Antenna as resonators	MB omni-directional	[69]
29	Modulator	Ultrafast comm.	[70]
30	MIMO Antenna	High speed	[71]
31	Reconfigurable Antenna	Dual band	[72]
32	MS radiating surface	MB high gain	[73]
33	Traveling Wave Antenna	Transmission Lines in comm.	[74]
34	Bandpass filters	THz waves in comm.	[75]
35	MS fractal Antenna	Comm.	[76]
36	Electronically reconfigurable	Stop band filter	[77]
37	Surface Antenna	Bandwidth boosted comm.	[78]
38	As absorber	Worldwide Interoperability for Microwave	[79]
39	Novel 3D SRR	High negative refractive index	[80]
40	THz frequency	Short range	[81]
41	Antenna	Long-term evolution handset	[82]
42	Modulator	Wireless multi-level	[83]
43	MS band pass filter	5G	[84]
44	Monopole Antenna	Integral component comm.	[85]
45	Ultra-wideband (UWB) MIMO	High bandwidth comm.	[86]
46	Inspired reconfigurable	Dual-band	[87]
47	Hepta-band Antenna	WC	[88]
49	Printed Antenna	Wearable comm.	[89]
50	Quad Antenna	Wireless comm.	[90]
51	Antenna	UWB transceivers	[91]
52	Tri-band Antenna	Precise comm.	[92]
53	Graphene rotator	THz comm.	[93]
54	Spherical array	Magnetism-based induction comm.	[94]
55	Implantable circularly polarized Antenna	High gain comm. for biomedical application	[95]
56	Slot Antenna	Wireless comm.	[96]
57	Mini Antenna	Quad-band improved gain	[97]
58	Unit cell Antenna	Mobile comm.	[98]
59	Reconfigurable Antenna	WC	[99]
60	Elliptical curved Antenna	An improved gain in communication	[100]
61	Array Antenna	Bandwidth and gain improved	[101]
62	Multiband Antenna	Versatile application including GPS	[102]

(*continued on next page*)

Table 1 (*continued*)

S. No.	Components	Communication	Ref.
63	Slab - zero refractive character	Effective power transfer	[103]
64	Enhanced medium ratio	WC	[104]
65	MIMO Antenna	5G	[105]
66	Loop dual function Antenna	Power transfer (wireless)	[106]
67	Dynamical manipulation in network (Graphene)	THz comm.	[107]
68	Antenna (hexagonal shape MM)	WC	[108]

taken only up to July, even though the count is 1880. All these analyses made the researchers envisage the potential of MM in wireless communication and more specifically the MM as an antenna. MM is potentially used as an antenna than other components in wireless communication, so it is further assessed. Table 1 depicts the application of metamaterials in various WC applications according to the published literature. Table 1 depicts that the MM is most preferably used as an antenna in WC. It additionally reveals that the MM is used in a versatile manner including enhancing the gain in communication, extending the bandwidth size, used in wireless power transfer, next-generation communication including current 5G, applied for terahertz communication, and specifically in terms of wireless communication in the medical field including the wearable electronics.

3. Patent landscape analysis

The patent landscape is performed to understand the potential growth of MM in wireless communication. The core reason behind this particular patent database is the rate at which it gets updated. It is quite dominant in faster updates over any other database in the globe. The following Table 2 reveals the usage of MM in wireless communication. Search carried out in English all categories with specific keywords "wireless communication" and "Metamaterial". “Stemming” is an option that allows the users to search by converging the allied keywords into the stem or root, it means the cluster is created for that domain (for example wireless communication can be expressed as a wireless network, non-contact communication, and other most common are brought together). In addition, the “single family member” option is also used because the same patent can be filed in multiple countries and the database shows higher patent counts so this option makes the user consider it as one patent. The total number of patents filed is 2180 for the above set conditions.

Table 2 infers that the USA is quite dominant in this field of using MM in wireless communication. Further, the dominant applicant is “Samsung Electronics Co. Ltd.” filed 677 patents. Growth based on the year-wise filing since 2014 its progress is quite non-linear and shows potential growth in the last three years. Researchers while focusing on the combination of IPC with keywords the dominant is H04W which consolidates only on wireless communication. In addition, the dominative wireless communication is achieved using the microwave and therein it is addressed by the IPC H01Q. Its extension is carried out based on transmission which is addressed by the H04B.

Search carried out in English all categories with specific keywords "Metamaterial antenna". “Stemming” is an option that allows the users to search by converging the allied keywords into the stem or root, it means a cluster is created for that domain (for example wireless communication can be expressed as a wireless network, non-contact communication, and other most common are brought together). In addition, the “single family member” option is also used because the same patent can be filed in multiple countries and the database shows higher patent counts so this option makes the user consider it as one patent. The total number of patents filed is 511 for the above set conditions.

Table 3 infers that the USA is quite dominant in the field of MM antenna. Further, the dominative applicant is “Kymeta Co.” filed 88 patents. Growth based on the year-wise filing since 2014 progress has ups and downs and shows potential growth in the year 2021. Researchers while focusing on the combination of IPC with keyword the dominative wireless communication is achieved using the microwave and therein it is addressed by the IPC H01Q. Its extension is carried out based on transmission which is addressed by the H04B. In addition, the dominant IPC is H04W which consolidates only the wireless communication. This is an observation for the

Table 2
MM in wireless communication [109].

S. No	Countries	Count	IPC[a]	Count	Year	Count
1	Patent Cooperation Treaty	1065	H04W	710	2014	68
2	United States of America	939	H01Q	658	2015	78
3	India	81	H04B	392	2016	80
4	European Patent Office	42	H04L	379	2017	108
5	China	38	G02B	145	2018	134
6	Australia	4	H02J	133	2019	144
7	Canada	3	G01S	101	2020	120
8	Sweden	3	A61B	98	2021	202
9	United Kingdom	2	H01P	96	2022	468
10	Republic of Korea	2	G06F	69	2023	453

[a] - International patent classification.

Table 3
Patent landscape for "Metamaterial antenna" [110].

S. No	Countries	Count	IPC	Count	Year	Count
1	United States of America	207	H01Q	380	2014	36
2	Patent Cooperation Treaty	170	H04B	71	2015	36
3	China	97	H04W	57	2016	19
4	India	12	G01S	49	2017	52
5	Republic of Korea	11	H04L	27	2018	35
6	Japan	6	H01P	20	2019	46
7	European Patent Office	3	H02J	15	2020	41
8	Canada	2	H01L	11	2021	67
9	Australia	1	H04 M	11	2022	36
10	Romania	1	G06K	10	2023	17

researchers that even though the search is carried out for the MM antennas, the IPCs are referring to the communication more than the material, so the inventors can focus on which way the material works. It means the application based on the material is more dominant than the material itself. In addition, in the case of materials are concern every material never has a separate IPC. It is classified based on the application. So, the direction of the researcher is to focus on the application-based search. This search is quite tricky and needs a lot of practice to get the right keyword with an IPC combination. Further, let us predict some of the potential inventions which have grown.

4. Envisaging the MM in WC based on the patent landscape

Future technology is predicted based on the potential technology, IPC keyword combination, technique derived, year of publication, and based on the applicant or assignee to a small extent. Some of the following highlighted techniques have potential growth assessed based on the above-mentioned combination.

4.1. Metamaterial lens for signal receiving

In the context of a WC system, metamaterials are more often used to transceive the signals. In a WC framework, the base station contains a transceiver and a processor in which the antenna and the MM unit make up the transceiver [111,112]. The processor is programmed to produce an initial beam using a beam obtained from the antenna unit which is sent to the MM lens system resulting in another beam. This beam is produced and controlled by the control unit of the MM lens manager. The beam that comes out of the MM unit is considered to be the second beam which sends a downlink connection to the terminal [113].

4.2. Reconfigurable antennas made of metamaterials

Miniaturized versions of a multi-beam array antennae and a mixed-mode directional illustration adaptable antennae were fabricated using metamaterials. The array of the multi-beam antenna is formed by several reduced blended MM directional illustration

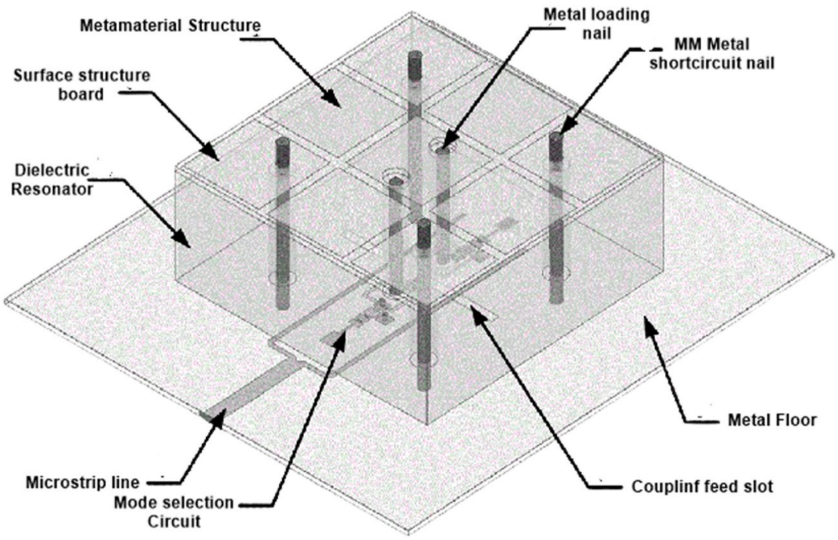

Fig. 3. MM as reconfigurable antenna arrangement [116].

adaptable antennas, which are arranged on a metal guided plate. A metal base, a coupled feed structure, and an integrated electromagnetic MM structural stability body are the constituent parts of the reduced combination mixed mode directional illustration adaptable antenna [114,115]. The design allows for antenna diminution and array cost-effectiveness, and a wide employed frequency range, as well as wide-angle beam scanning capacity, satisfying the stringent requirements for high-quality communication posed by a 5G broadband multi-beam foundation station as well as Sub 6 GHz WC, is represented in Fig. 3 [116].

4.3. Antennas for millimeter wave communication

The utilization of the MM antennas used for millimeter wave communication has been demonstrated by a few of the research works to accomplish small size, miniaturization, and larger bandwidths [117,118]. The MM antenna used for millimeter wave communication is made up of an initial dielectric layer, an MS feeder line situated on the bottom portion of the initial dielectric layer, as well as a reflecting plate situated in the initial dielectric layer and offered with a through hole, all of which lie in the same plane. The initial dielectric layer as well as the reflecting plate are the substrates for the second dielectric layer. On the subsequent dielectric is where will find the initial annular MM structure. The radiation patch is situated on the top surface of the 3rd dielectric layer, the subsequent annular MM framework is situated on the outer edge of the radiation patch, as well as the initial annular MM structure, as well as the subsequent annular MM structure, is positioned in an anti-parallel fashion as shown Fig. 4 [119].

4.4. MM in microwave sensor (MS)

Various research works demonstrated the equivalent of a high dielectric constant in an innovative miniaturized MM/Microwave Sensor (MS) line [120]. To create the super-structure MS line, a mushroom-type super-structure substance is embedded into the dielectric substrate of a standard MS line. Every unit of the mushroom-shaped MM consists of a metal patch and a hole, along with the metal patches linked to the metal ground plane via holes. The mushroom-shaped MM is situated beneath the MS line signal layer. The invention also reveals a two-part MM/MS line implementation using the mushroom-type MM. The findings demonstrate that the novel super-structure MS line supplied by design possesses a less extensive guided wave wavelength contrasting to a conventional MS line due to its greater effective dielectric constant. The MS line supplied by the design is a simple superstructure, making it easily implementable. The MM MS line allows for the fabrication of a wide variety of reduced microwave transmitters that are well-suited to meet the needs of modern WC applications as shown in Fig. 5 [121].

4.5. Metamaterials for phase regulation functions

Few research works dealt with the active metamaterials to tackle the phase transition, strain mismatch, and stimuli-responsiveness of the structural components. A few patents relate to the technology of antennas for WC terminals and consist of a dielectric kind phase regulation MM structure with a device and a substrate layer. The device layer contains several silicon devices organized in a radial pattern, and the dimensions of the silicon devices decrease progressively as they move away from the center of the structure [122,123]. By controlling the temporal heterogeneity of the MM framework, it is possible to focus incident waves, carry out efficient wave-front shaping on incoming waves, gain distinct phase gradients using silicon components of different sizes, achieve an ongoing phase shift from 0 to 2 pi, as well as spatially modulate the amplitude and phase of carried waves or waves that are reflected. Scattering throughout the propagation process of incoming waves no longer poses an issue [124]. Fig. 6 shows the MM with phase regulation.

4.6. Malleable magnetic MM

Fig. 7 describes near-field body-area networks that can make use of functionalized fabrics on demand. At least one embodiment of a body area network includes an initial array in magnetically coupled resonators established for propagating magneto-inductive (MI) wave surfaces. The initial array in magnetically coupled resonators consists of several MI components, and the initial array of magnetically coupled resonators establishes an adaptable magnetic MM path over WC employing the MI surface wave propagation

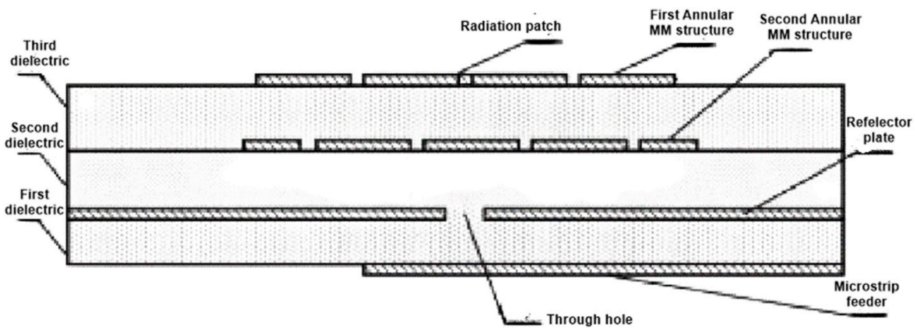

Fig. 4. MM as reconfigurable antenna arrangement [119].

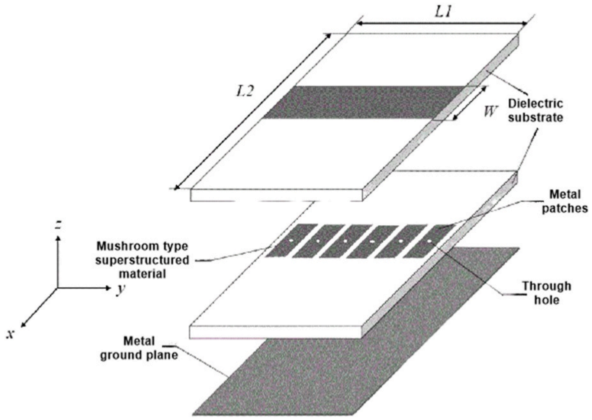

Fig. 5. Microwave sensor using Metamaterials [121].

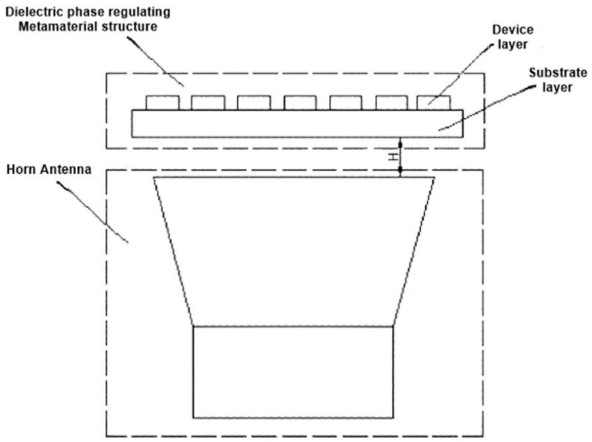

Fig. 6. Metamaterials used for phase regulation [124].

[125].

4.7. MM-based dielectric medium with a metallic pattern

Many research works dealt with the dielectric metamaterials consisting of anisotropic crystals to showcase a large refractive index and hence larger antenna gain in the WC devices [126,127]. An issue of low antenna gain in the prior art is addressed by an MM structure unit consisting of an antenna housing and antenna system. The metallic pattern layers in the MM framework unit undergo etching on both the front and back faces of the dielectric base. The triangle-shaped open-loop structures in the metallic pattern sections

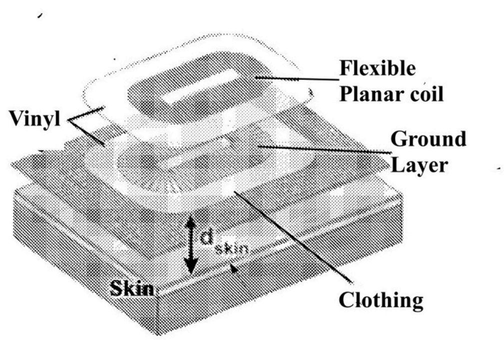

Fig. 7. Malleable magnetic MM for WC [125].

are responsible for adjusting their magnetic frequency of resonance while electromagnetic waves penetrate the structural unit through the front face. The electric resonance frequency can be changed by modifying the cross-shaped framework on the metallic pattern layer. An antenna's gain is capable of being increased by employing wavefront shaping on emitted electromagnetic waves and compressing the antenna's directional illustration via the structural unit, provided the antenna's framework remains unaltered as shown in Fig. 8 [128].

4.8. Metamaterials in slow wave path

Metamaterials are considered to be the apt materials for slowing the wave path to increase the wave matter interactions. Metamaterials can replace the wavelength-scaled composite structures for deep sub-wavelength scales of resonant metamaterials [129, 130]. A millimeter-wave WC source of power employing an MM all-metal gradual wave framework as shown in Fig. 9. Each of the divided ring structures in this design consists of two sets of semi-circular rings embedded and aligned between the initial split ring and the subsequent split ring. The initial split ring is firmly interconnected in the subsequent split ring, with an opening orientation in the reverse radial direction and the subsequent split ring is firmly interconnected in the initial split ring. The MM all-metal gradual wave framework possesses the benefits of an easy design, all metal, reduction in size, a natural electron beam way, ease of processing, as well as a high coupling impedance; the central using a hole of each split ring framework types an annular electron beam channel [131].

4.9. Metamaterial in antenna reflector

To reduce the size of the reflector and to enhance the operating bandwidth, metamaterials were chosen in many of the earlier research works [132,133]. Inventions focusing on antenna reflectors using metamaterials were discussed through patent publications. Fig. 10 shows an MM-based antenna reflector with one or more feeds connected to a spherical reflector with a WC antenna. The interior part of the sphere is constructed from a material that scatters radiofrequency (RF) beams, as well as the outer portion, located on the edge of the interior section, and is constructed from MM that is capable of producing reflective or transparent depending on the RF wavelength being used. The multiple feeds can be used to direct multiple reflected RF beams from the sphere. Antennas with multiple processors can split incoming radio frequency (RF) signals into multiple beams and direct the outer portion of a spherical reflector to either reflect or attenuate the RF beams depending on the antenna's processing of the RF signals [134].

5. Conclusions

This article summarizes that MM-based wireless communication is envisaged using the existing publication and patent landscape. It reveals as per the publication MM is mostly used as an antenna in wireless communication. The number of articles published has exponentially grown since 2003 to date with the highest number of 3330 in the year 2022, also showing great progress in 2023. The patent landscape also ensures that growth is exponential which is considered to be the potential research area to work. In addition, the patent landscape reveals that MM has been used for multiple purposes in wireless communication in recent years not only as antennas. The potential technology identified as MM as a lens, MM as the reconfigurable antenna, MM antenna for millimeter wave communication, MM as MS line, MM for phase regulation, malleable magnetic MM, MM as dielectric medium with a metallic pattern, MM as slow wave path, and MM as a reflector. This article provides a guideline to carry out the research in the identified potential technology using patent landscape analysis for young researchers in this domain.

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CRediT authorship contribution statement

G. Vetrichelvi: Data curation, Conceptualization. **P. Gowtham:** Methodology, Formal analysis. **D. Balaji:** Writing – original draft, Visualization, Data curation, Conceptualization. **L. Rajeshkumar:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Rajeshkumar L. is currently an AE in Materials Science section in Heliyon journal If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

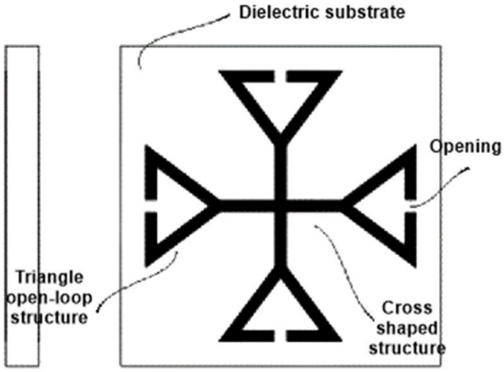

Fig. 8. Dielectric medium with metallic pattern [128].

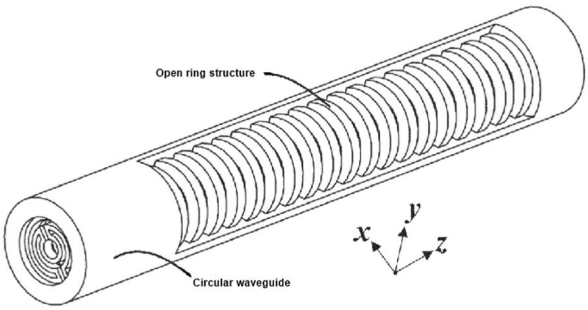

Fig. 9. Dielectric medium with metallic pattern [131].

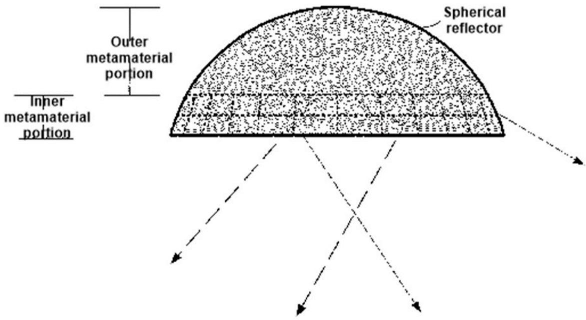

Fig. 10. Antenna reflectors [134].

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