Metamaterial based Antennas for wireless and space communications, GPS, satellites, airplanes and missile seekers

Researchers are always looking for new materials with novel properties. A metamaterial is a kind of artificial synthetic composite material with a specific structure, which exhibits properties not found in natural materials. Metamaterials have received increasing attention due to their unique electromagnetic properties.

One of the most important applications of metamaterials is antenna design. Due to the unusual properties of metamaterials, we can achieve antennas with novel characteristics which cannot be realized with traditional materials.

Various types of metamaterial have been proposed with different characteristics, e.g. e.g. negative permittivity or permeability, zero refractive index, and huge chirality, etc. These unusual properties play an important role in modern antenna design, which can provide better performance, more functions, and more flexibility.

These novel antennas aid applications such as portable interaction with satellites, wide angle beam steering, emergency communications devices, micro-sensors and portable ground-penetrating radars to search for geophysical features.

Some applications for metamaterial antennas are wireless communication, space communications, GPS, satellites, space vehicle navigation and airplanes.

Metamaterials are a basis for further miniaturization of microwave antennas, with efficient power and acceptable bandwidth. Antennas employing metamaterials offer the possibility of overcoming restrictive efficiency-bandwidth limitations for conventionally constructed, miniature antennas.

Conventional antennas that are very small compared to the wavelength reflect most of the signal back to the source. A metamaterial antenna behaves as if it were much larger than its actual size, because its novel structure stores and re-radiates energy. Established lithography techniques can be used to print metamaterial elements on a PC board.

Metamaterials permit smaller antenna elements that cover a wider frequency range, thus making better use of available space for space-constrained cases. In these instances, miniature antennas with high gain are significantly relevant because the radiating elements are combined into large antenna arrays. Furthermore, metamaterials’ negative refractive index focuses electromagnetic radiation by a flat lens versus being dispersed

For broadband satellite communications applications where the platform is mobile, where the satellite is non geostationary, or both, a scanning antenna is required. Metamaterials surface antenna technology (M-SAT) is an invention that uses metamaterials to direct and maintain a consistent broadband radio frequency beam locked on to a satellite whether the platform is in motion or stationary. Gimbals and motors are replaced by arrays of metamaterials in a planar configuration.

Some of the advantages of Metamaterial Antennas are:

- High gain, electrically configurable beam forming maximizes channel efficiency

- Ultra-fast reconfiguration allows SDAs to realign on a frame-by-frame basis
- Self-alignment eliminates the need for expensive technician installations or mechanical steering gimbals, as well as self-recovery from displacement
- Active dynamic null generation allows mitigation of interfering signals when used in cluttered spectrum
- Lightweight, compact and capable of being ruggedized for size-sensitive applications in harsh environments
- Conformal form factor enables geometry-flexible antennas to be placed where conventional antennas could not be located
- Support for a wide spectrum of frequencies across the RF, microwave, and millimeter wave spectrums

Researchers have proposed two classification of metamaterial based antennas . The first category is the concept of a transmission line composed of a periodic repetition of a unit cell comprising a series capacitance and a shunt inductance. This category is a direct application of the leaky-wave metamaterial antennas, which consists of a cascaded series of unit cells lying on a matched microstrip line. This type is preferred for beam scanning applications.

In the second category are the resonant antennas, which, in opposition to the first category, are obtained by terminating the structure to the free space by a short or open circuit. The metamaterial based resonant types of antenna structures allow dual-band, multiband behaviours and can be miniaturized but do not increase the bandwidth of the antenna.

A Broadband Left-Handed Metamaterial

Microstrip Antenna with Double-Fractal Layers

Antennas are essential for wireless communication systems. The size of a conventional antenna is dictated mainly by its operating frequency. With the advent of ultra-wideband systems (UWB), the size of antennas has become a critical issue in the design of portable wireless devices. Consequently, research and development of suitably small and highly compact antennas are challenging and have become an area of great interest among researchers and radio frequency (RF) design engineers

In commercial wireless communication systems, the antenna remains a key element of the communication chain. The efficiency of a radio broadcasting system is directly related to the characteristics of its antennas. In addition, future communication systems using cognitive radio or flexible radio will need smaller wideband antennas.

On one of the common antenna designs is microstrip patch antenna. This design has many advantages; it can be easily fabricated using a lithographic technique, it has a low profile, it has a low production cost, and its structure is fairly simple. However, these advantages are offset by the narrow bandwidth of the antenna. To date, several approaches have been proposed to address this deficiency. In most cases, the proposed solution was to increase the thickness and decrease the dielectric constant of the substrate at the same time. However, these attempts did not produce significant bandwidth enhancements in redesigned antennas.

With the development of new materials called left-handed materials (LHM), or left-handed metamaterials, it is possible to achieve a significantly wider frequency range. As a result, many antennas with LHMstructures with better performance than conventional microstrip patch antennas were proposed.

Planar left-handed metamaterial structures were proposed a few years ago. The discussed structures consist of 2D periodic arrays of unit cells. This concept was applied to LHMantennas, resulting in broadband and high gain designs. The periodic patterns which showed left-handed characteristics were applied to rectangular conventional microstrip patch antennas. These configurations allowed obtaining a frequency range several times wider than the same patch antenna without the metamaterial pattern.

Researchers Roman Kubacki and others from Military University of Technology,Warsaw, Poland have proposed a microstrip patch antenna based on the left-handed metamaterial concept, using planar periodic geometry, which results in improved characteristics. This periodic geometry is derived from fractal shapes, which have been widely used in antenna engineering. The metamaterial property was obtained as a result of the double-fractal structure on both the upper and the bottom sides of the antenna. The upper side of the antenna follows the shape of crossbar fractals, with Minkowski fractals on the lower layer. The proposed self similarity and ease of repetitiveness of the geometry make these designs attractive for creating a periodic structure.

The final structure has been optimized to enhance bandwidth, gain, and radiation characteristics of the microstrip antenna.

This combination significantly improved antenna performance; our design could support an ultrawide bandwidth ranging from 4.1 to 19.4GHz, demonstrating higher gain with an average value of 6 dBi over the frequency range and a peak of 10.9 dBi and a radiation capability directed in the horizontal plane of the antenna.

Fractal Firm Confirms Breakthrough

Metamaterial Antenna Technology

Fractal Antenna Systems has confirmed that it has developed a new proprietary antenna technology with broad applications, particularly in point to point access with directional antennas. The new technology is enabled by the firm’s fractal metamaterial discoveries and inventions. Fractal metamaterial devices are populated by closely packed ‘self similar’ shaped electromagnetic structures. Developed by the firm, the use of fractal metamaterials has already resulted in a broad range of critical attributes. Now magnification ability publicly joins the list of essential practical advantages.

The new antenna technology, referred to as “FM/R”, has the advantages of smaller size, wider bandwidths, and high efficiency, at high magnification, or “gain”. In addition, it has a unique characteristic of being nearly agnostic to its form factor shape. This means that most conventional, prescribed ‘fishbone’, ‘arrowhead’, and ‘bubble’ shapes for directional antennas are obsolete, or severely limited in comparisons of their footprint, supporting electronics, and cost. In addition, the FM/R antennas may replace several directional antennas at once, diminishing coveted tower and building real estate needs for antennas.

Notes CEO and inventor Nathan Cohen: “Others have oversold the case of metamaterials for lens-like applications, and ended up with ‘me-too’ technology of limited practical value. We’ve delivered on the promise.” Cohen attributes previous impediments to a failure to recognize the potential afforded by: “Greater sampling of the nearfield, through fractals. The physics was sound, but the assumptions about how to apply it were stuck in an age-old rut.”

Metamaterials surface antenna technology

For broadband satellite communications applications where the platform is mobile, where the satellite is non geostationary, or both, a scanning antenna is required. The satellite communications industry, however, is dominated by dish antennas mounted on motorized gimbals for these applications. These solutions are too large, heavy, and power-consuming to offer solutions for consumer mobile applications such as the connected car or a personal satellite terminal. Another alternative is phased array technology, but this technology is typically available only to government and military customers because of its expense and power consumption.

Kymeta has addressed these obstacles by developing an electronically-scanned antenna technology, based on a diffractive metamaterials concept, called Metamaterial Surface Antenna Technology (MSAT). Electronic scanning is achieved through the use of high-birefringence liquid crystals. The use of liquid crystals (LC) as a tunable dielectric at microwave frequencies permits large-angle (> 60°) beam scanning with power consumption of < 10 Watts and antenna thickness ~ 5.0 cm, with no moving parts. Kymeta's engineering approach, through the use of LC and optimization of the materials and design for compatibility with liquid crystal display (LCD) manufacturing processes, positions the technology for mass production by leveraging the capital infrastructure of the LCD industry.

Metamaterials Electronically Scanned Array (MESA)

A low-cost, high-performance RF beam steering module that can be adapted for a broad range of applications, including: collision avoidance system for self-driving cars or drones, broadband satellite internet/radio, hypothermia treatment, wireless communications, etc. The key performance feature of PARC’s MESA is its capability to maintain a high signal-to-noise ratio and high-resolution, simultaneously.

Metamaterial-Based Radar Lets Drones Fly beyond Visual Line Of Sight

Echodyne Corporation, a developer of metamaterials-based radar systems, says it has completed testing on its airborne Metamaterial Electronically Scanning Array (MESA)-Detect and Avoid (DAA) radar on a small Unmanned Aerial Vehicle (sUAV).

“Echodyne’s airborne detect-and-avoid radar is made especially for small to medium UAS and enables safe beyond visual-line-of-site operations – in all environments and conditions,” said Jerry Hendrix, Executive Director for the LSUASC. “Before the MESA-DAA became commercially available, there were no options for long-range radar on small to medium commercial drones.”

“Radar is an ideal sensor technology for all sorts of scanning and imaging applications, especially when environmental conditions are less than ideal,” explained Thomas Driscoll, Chief Technology Officer for Echodyne. “Our radar thrives over other sensors in unpredictable weather conditions, can rapidly scan a broad field of view, can track Cessna-sized targets at distances greater than two kilometers, and dramatically increases situational awareness for UAS operators.”

Echodyne’s radar array is made of multiple layers of carefully patterned copper wiring, and beam control results from heating specific areas of the wiring, according to IEEE Spectrum. The smaller design is less powerful and has shorter range, but it also is more affordable to build, and is no less than effective for most commercial applications.

METamaterials for Active ELEctronically Scanned Arrays (METALESA)

An AESA, as core component of modern military radar systems, is a type of phased array, whose transmitter and receiver functions are composed of numerous small transmit/receive modules.

The objective of the METALESA project was to employ MetaMaterials in order to increase the efficiency and reliability of operating radar systems Electromagnetic MTMs are artificial materials with unusual macroscopic propagation properties of electromagnetic waves, which are normally generated by microscopic periodic metallo-dielectric structures.

Four main topics were identified as critical in the AESA design process, where MTM concepts could be applied, and have been analysed, prototyped and tested methodically in the project:

- Expensive RF feeding networks, with considerable space requirements.
- The coupling between radiating elements of the antenna array is the principal source of the scanning angle limitations, causing the undesired angular blind spots.
- The parasitic back-lobe and side-lobe radiation caused by the antenna´s finite dimensions can cause unwanted disturbances of other systems or in the system itself.
- A MTM based radome is proposed to reject the out of band interference and simultaneously, the in band back-lobe and side-lobe radiation

Smart Metamaterial Antennas

Highly reconfigurable metamaterial antennas are a natural evolution of the MESA architecture. They are tailored for 4G LTE/5G bay stations and for satellite communications.

RF Energy Harvesting Platform

RF Energy Harvesting PlatformAn RF energy harvesting platform that converts Wi-Fi and other RF bands to electricity, to power IoT sensors. It consists of a metamaterial-inspired antenna and a custom rectifying circuit. There are two classes of prototypes that we have demonstrated: hybrid (printed antenna with integrated silicon chips) and all-printed devices. The performance and bandwidth of the RF energy harvesters exceed by at least an order of magnitude that of the state of the ar

US DOD’s Requirement of Antenna Electronic Beam Steering for Missile Seekers

US DOD has issued SBIR to investigate low-cost alternatives to steerable antennas for the munitions application. The performance enhancements afforded by electronically steerable antennas is of high interest to the radar seeker community. Traditionally phase array antennas require beam forming networks with distributed phase shifters or time delay mechanisms and additional control circuits, to perform beam steering that lead to expensive and complicated circuitry not economically feasible for use in small missile radar seekers.

Recent breakthroughs in engineered electronic and electromagnetic materials and continuous transverse stub arrays have made agile, reconfigurable apertures possible where the beam-forming function is integrated in to the aperture. These technologies are opening avenues to provide new levels of real-time control of the aperture and performance as well as affordability, says SBIR.

There is a need to investigate innovative beam steering schemes that eliminate traditional beam forming networks and lead to digitally controllable RF apertures for radar seeker. Minimal figures of merit and functionality are frequency control and agility (17 GHz +/- 10 percent or 35GHz +/- 10 percent), wide bandwidth (600 MHz to 1.2GHz) and instantaneous pattern control. Instantaneous Field of View (IFOV) of approximately 7 degrees, Field of Regard (FOR) of approximately +/- 35 degrees in azimuth and elevation with a gain greater than 21dBi and nominal aperture of six inches.
An antenna that can possibly meet these requirements and is able to work at 17 GHz in addition to 34 GHz is also of interest but not required. The techniques should be implementable in a small, lightweight package and, at minimum, allow for classical sum and difference mono-pulse beam forming. The technique should be evaluated against factors such as beam forming capability, gain, Size, Weight, Power and Cost (SWAP-C) and radiation characteristics such as FOR, IFOV, beam width, etc.

Metamaterials in Antenna Design

One of the most important applications of metamaterials is antenna design. Due to the unusual properties of metamaterials, we can achieve antennas with novel characteristics which cannot be realized with traditional materials.

1. Electrically small antennas based on zeroth resonant mode

In mobile communication systems, electrically small antennas (ESA) are desired. Modern integrated circuit technology has the ability to miniature circuits to a very small size. However, in a traditional design, the performance of the antenna is related with its size. The antenna usually has dimensions in the order of the operating wavelength. This sets boundaries for the size of the whole system.

A ZIM medium, whose refractive index is near zero, shows an operating wavelength that is infinite at an arbitrary designed frequency. This phenomenon is named zeroth resonant mode. Since the wave number in this antenna is zero, in theory, the physical size of the antenna can be made independent of its working frequency. Because the operating wavelength is infinite, the field distribution and the radiation pattern are different from the normal ones.

2. Dual-band and multi-band antennas

Normal dual-band antennas are realized with different resonant structures, or different resonant modes in one structure. The main disadvantage of this technique is that the field distributions in these structures can hardly be the same in both bands. This means that the radiation patterns in the operating bands are different. Since metamaterials can support a negative refractive index, the resonant modes can be selected as a symmetric pair, i.e. so-called negative and positive modes. The field distributions of these two modes can be very similar, and thus also the radiation patterns.

Negative and positive modes can be designed together with a zeroth-order mode. This yields a multi-band antenna with a specific pattern for each mode. An extra advantage of a metamaterial-loaded multi-band antenna is the fact that its size is usually smaller than in a traditional design, where the size is decided by the lowest operating frequency.

3. Low Profile planar reflectors

In an electric dipole antenna positioned parallel on top of a PEC plane, the distance between the dipole antenna and the reflector should be approximately a quarter wavelength. Indeed, since the reflective phase at the PEC plane is 180°, the radiation of the image of the electric dipole will start to cancel the radiation of the dipole itself if it is located closer to the reflector.

However, if the reflector is a PMC plane, the reflective phase is zero, and the image of the electric dipole will enhance the radiation when the dipole is located near the PMC plane. This technique allows designing low profile reflectors for electric dipole antennas.

Conversely, magnetic dipoles, in practice realized by slots or apertures in a ground plate, are also not suitable for placement near any PEC plane because of the generation of parallel plate modes between the two metal planes, which considerably distorts the characteristics. An AMC plane can help to suppress any parallel plate modes. Also in this case, low profile structures become feasible.

4. Antenna lenses and polarizers

Dielectric lenses can be used to improve the directivity and gain of an antenna. However, the cost to fabricate a 3D lens is large. Further, the location of the lens should be carefully chosen in relation with the phase centre of the antenna. A metamaterial lens can be formed by a flat 2D structure. Their manufacturing cost is much lower. They can even be integrated with the planar antenna structure to reduce the profile and size of the antenna system.

A polarizer can be based on a chiral medium which has the capability to transform a linearly polarized wave into a circularly polarized wave. This opens a way to design circularly polarized antennas based on existing linearly polarized antennas.

References and Resources also include: