

APPLICATIONS OF METAMATERIAL IN ANTENNA ENGINEERING

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Abstract— In this paper, novel applications of metamaterials composite structure in antenna engineering has been considered. Compared with the conventional materials, metamaterials exhibits some specific features which are not found in conventional materials. Some unique applications of these composite structures as an antenna substrate, superstrate, feed networks, phased array antennas, ground planes, antenna radomes and struts invisibility have been discussed.

Index Terms—Left handed materials (LHM), Metamaterials (MTM), Negative refractive index (NRI), dispersion, multiple beam antenna (MBA), strut

I. INTRODUCTION

In the recent years electromagnetic metamaterials (MTMs) are widely used for antenna applications. These specifically designed composite structures have some special properties which cannot be found in natural materials. Metamaterials are also known as Double negative (DNG) materials, Left handed materials (LHM) etc.

In 1968, the concept of metamaterials was first published by the Russian physicist Victor Veselago [1]. Thirty years later, Sir John Pendry proposed conductor geometries to form a composite medium which exhibits effective values of negative permittivity and negative permeability. Based on the unique properties of Metamaterials, many novel antenna applications of these materials have been developed.

The use of metamaterials could enhance the radiated power of an antenna. Negative permittivity and permeability of these engineered structures can be utilized for making electrically small antenna, highly directive, and reconfigurable antennas. These, metamaterial based antennas have also demonstrated the improved efficiency & bandwidth performance. Metamaterials have also been utilized to increase the beam scanning range of antenna arrays. They antennas also find applications to support surveillance sensors, communication links, navigation systems, and command and control systems. [2]

In this paper we have limited our discussion to antenna applications of metamaterials.

II. ANTENNA SUBSTRATE

Metamaterials are promising candidates as antenna substrates for miniaturization, sensing, bandwidth enhancement and for controlling the direction of radiation [3]. These substrates have great potential for improving antenna or other RF device performances. Metamaterial substrate can be used for a variety of applications. It can be designed to act as a high impedance substrate that can be used to integrated low-profile antennas in various components and packages. The high impedance of designed metamaterial substrate prevents unwanted radiation from traveling across the substrate which results in a low profile antenna with high efficiency.

In general any antenna, printed on a high dielectric constant substrate has a low resonance frequency. This property contributes to miniaturization of the device. Metamaterial substrates can be designed to act as a very high dielectric constant substrate at given frequency and hence can be used to miniaturize the antenna size. [4]

Metamaterial substrates have specific abilities to control and manipulate electromagnetic fields. There is an ongoing effort to achieve field distributions suitable for growing new fields of applications such as co-ordinate transformation devices, invisibility cloaks, Luneburg lenses, and antennas. These metamaterial substrates have interesting physical properties that are well suited to realize such structures. [5]

III. ANTENNA SUPERSTRATE

Next generation telecommunication satellites are heavily demanding for multiple beam antennas. Simultaneously it is necessary to minimize the number of reflector antennas for mass as well as size reduction of antenna system. Accordingly it would be necessary to co-locate different feeds close to the focus. However this requires feeds of smaller in size and is located close to one another. Due to smaller size feeds, directivity issue arises and as a result spillover efficiency of the whole feed reflector system suffers. High directive antenna elements can be realized by introducing a set of metamaterial superstrates that can improve the radiating efficiency. [6] [7]

Metamaterials can act as resonant structures which allow the transmission and reflection of electromagnetic waves in a specific way in certain frequency bands. A dielectric superstrate

properly placed above a planar antenna has remarkable effects on its gain and radiation characteristics. Although, the presence of superstrate above an antenna may adversely affect the basic performance characteristics of any antenna, such as gain, radiation resistance, and efficiency; but It has been reported that high gain can be achieved if the superstrate layer is appropriately designed and placed above antenna. The key advantage of using metamaterial superstrate is to maintain the low-profile advantage of planar antennas. The main features of metamaterial superstrate are to increase the transmission rate and control of the direction of the transmission which enable one to design high gain directive antennas. Metamaterial superstrates can be applied to conventional antenna to increase both the impedance and directivity bandwidth of the proximity coupled microstrip patch antenna and can also be used to change the polarization state of the antenna.[8] [9] [10]

IV. ARRAY FEED NETWORK

Metamaterial phase-shifting lines can be used to develop antenna feed network which can provide broadband, compact and non-radiating, feed-networks for antenna arrays. These feed networks have less amplitude phase errors. Metamaterial based transmission line feed networks can be used to replace conventional transmission lines-based feed-networks, which can be bulky and narrowband. These feed-networks have the advantage of being compact in size, therefore eliminating the need for conventional TL meander lines [11]. In addition, these feed-networks are more broadband as compared to conventional transmission line based feed-networks, which enables antenna arrays (series-fed broadside radiating) to experience less beam squint and have the potential to significantly reduce the size of the feed networks (parallel-fed arrays). Appropriately designed metamaterial based phase-shifting lines are capable of providing arbitrary insertion phase, compact in size, and linear, flat phase response as compared to conventional transmission line delay lines. These phase shifting lines are usually operated in the NRI backward-wave region, to ensure that they do not radiate. Simultaneously It is also required that the propagation constant of the line exceeds that of free space that effectively produces a slow-wave structure with a positive insertion phase. The combination of positive and negative phase shifting lines results in a combined slow-wave metamaterial phase-shifting line of desired phase. [12] [13]

V. PHASED ARRAY ANTENNA

A phased array antenna is consists of an array of antennas that enables long-distance signal propagation by directional radiation. It requires phase shifters to scan the beam in various directions[14]. Design of phased antenna array with integrated phase shifters and wider scan-angle range continues to be a big

challenge for antenna designers. Metamaterials can be used to improve the impedance matching of planar phased array antennas over a broad range of scan angles [15] In recent years metamaterial phase shifters are adopted to fine tune the phase difference between adjacent elements. These metamaterial phase shifters can be easily integrated onto the CPW feeding line also. Measured unidirectional scan-angle range of 66 degree is also reported in the-plane which is wider than conventional various tunable NRI phase shifters (using switch and varactor elements in addition to the L/C circuits) have also been incorporated in phase shifter designs. The complex bias circuits and beam scan angle range designs are still challenges to antenna communities and will require additional research.[16] [17] [18]

VI. ANTENNA RADOME

Radome technology was spin off in second World War. The maximum speed of fighter plane and aircraft are limited to the speed at which external antennas on these aircrafts are able to survive. A plastic cover over a B18 bombers radar antenna was the first known application of Radome which was used in Second World War.

Radome is a covering to protect an antenna from rain, wind perturbations, aerodynamic drag, and other disturbances. Radomes and other structures that enclose radiating systems are designed for their mechanical integrity, and they are typically made from ceramics or composites having inherently high dielectric constant values. Radomes are generally used for various antennas such as SATCOM antennas, Air traffic control, parabolic reflector antennas, ocean liners, small aircraft antennas, missile, vehicular antennas, cell phone antenna towers, and other microwave communication applications to conceal antennas.[19]

Ideally, Radome should be made from a perfectly RF transparent and non-refractive material in order to not disrupt radiated fields from and to the enclosed antenna. However they are typically made from dielectric materials. In order to exhibit these characteristics, the Radome material would require being impedance and index-matched to free space for all angles of plane wave incidence. Due to differences in curvature between the inner and outer surfaces of Radome structure, refraction in dielectric materials introduces deflections to exiting local planewaves. The quantitative measure of such deflections is known as Boresight error. However there are various other bottlenecks of Radomes, such as:

Bandwidth: The system bandwidth is limited by Radome bandwidth.

Noise floor: the noise floor (system noise temperature) cannot be less than Radome noise temperature (~10K for every 0.1 dB loss)

Dynamic range: The Radome depolarization limits the dynamic range in a frequency reuse application.

There are various parameters which may affect the broadband performance of Radome such as:

Wall thickness (thin wall is generally better)

Wall design i.e. number of layers, thickness

Permittivity of each layer (multi-layer design is better) selection of low loss materials (small loss tangent is required).

Any radome is said to be non-refractive when its index of refraction is matched to air ($n_{\text{radome}}=n_{\text{air}}$) and is fully transparent when its impedance-matched to the impedance of air medium ($Z_{\text{radome}}=Z_{\text{air}}$).

For matching, wave impedance of a radome material

$$Z=120\pi \sqrt{(\mu_r/\epsilon_r)} \quad (1)$$

If relative permittivity ϵ_r and relative permeability $[\mu]_r$ of materials are same then radome has no reflection loss. Since materials with $\mu_r > 1$ doesn't exist in nature at frequencies above 1 GHz, Ideal way to satisfy the above criteria is to use air as a dielectric material for Radome, but such a solution precludes the presence of an actual Radome. The possible approach is to make use of metamaterial radome, with both relative permittivity and permeability close to 1, which is one of the main areas of current research. [20] [21]

Metamaterial can be suitably designed to use as Radome. By embedding metamaterial structures inside a host dielectric medium, the desired material parameters of the composite material can be adjusted to desired values of interest. Although commercial metamaterial Radomes are not yet state of the art but antenna researchers are looking for following features in metamaterial radomes:

The structure should be non-reciprocal for incoming and outgoing waves.

Metamaterial radomes should enhance out of band signal rejection.

Metamaterial radomes are useful for multiband radomes also.

Metamaterial UWB radomes can also be developed.

VII. ANTENNA GROUND PLANE

Metamaterial ground planes also known as artificial magnetic conducting ground planes are widely used as the planar antenna

ground planes in order to enhance the input impedance bandwidth. [22]

Metamaterials ground planes find important applications in low profile cavity backing and isolation improvement in cavity backed antennas and microwave components respectively. When employed in the ground planes it improves isolation between radio frequency or microwave channels of (multiple-input multiple-output) (MIMO) antenna arrays systems. Metamaterial ground planes provides high impedance surface that can be used to improve the axial ratio and radiation efficiency of low profile antennas located close to the ground plane surface. High impedance surface as the antenna ground plane can improve the input impedance matching High impedance surfaces not only can match the planar antennas impedances but they also can increase the gain of antenna as well. [23]

VIII. STRUTS IN REFLECTOR ANTENNAS

Struts in reflector antenna systems are generally mechanical structures, supporting the feed in a single reflector system or the sub-reflector in a double reflector system. These struts usually block the aperture and consequently affect the antenna performance, such as a reduction of the antenna gain and an increase of the side lobe levels. [24]

Conventionally the adverse effect of strut is usually minimized by shaping the struts, but with the advent of metamaterials a new method has also been introduced to minimize these effects. This new approach is based on guiding and launching the electromagnetic radiation in preferred directions and reducing the effect to nearly zero in the operational directions.[25]

IX CONCLUSION

The research work presented in this paper summarizes the recent developments and applications of metamaterials in antenna engineering. This paper has also highlighted potential future research directions in this field. However it will take collaborative efforts from researchers in antennas, physics, optics, material science electromagnetics, to ultimately exploit the potential of metamaterial technology through practical implementation.

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