Equivalent Circuit of Metamaterial Formed by Array of Conductive Disks

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***Abstract*—The use of metamaterials to obtain a wideband wide angle impedance matching (WAIM) for compact phased array of interconnected crossed rings is investigated. The metamaterial layer above the planar array is formed by array of conductive disks in contrast to the conventional multilayer homogeneous dielectric structure. The equivalent circuit of the metamaterial layer to enhance wideband array antenna design is derived based on a hybrid technique. The values of the components in the equivalent circuit to represent metamaterial layer is given. The response from the equivalent circuit is verified by using the full-wave numerical simulations on the metamaterial structure. The results show the effectiveness of the method in analyzing the electromagnetic characteristics of the structure and improving the performance of the whole array system.**

***Index Terms*—Metamaterial, array, equivalent circuit**

I. Introduction

Wideband antenna arrays become increasingly more important in many applications. The frequency bandwidth and range of scan angle are two key factors to measure array performance. In order to enhance phase array performance, a possible solution is to place isotropic dielectric layers over the radiating elements [1]. Usually, determining the optimal characteristic of dielectric layers (permittivity and thickness) as well as the ground plane position requires numerous simulations that are costly in time. The presence of the layers performs an impedance matching over all the scan angles but it is very difficult to obtain good results using the limited types of materials present in nature.

The introduction of tip-end capacitance in the dipole array increases the frequency bandwidth to a certain degree, but not broad enough, especially when the array is scanned to a wide angle. The conventional solution to this problem is to use wide-angle impedance matching(WAIM) structures consisting of a stack of dielectric layers [2]. However, this method potentially introduces extra loss into the system and it is not cost-effective. Much greater flexibility maybe achieved by employing anisotropic slabs with controllable spatial dispersivity. Artificially structured materials (such as metamaterials or metasurfaces) make this approach feasible by allowing the simultaneous control of dielectric and magnetic properties in different directions [3]. A metamaterial layer formed by regularly scattered conductive disks is used in this study to ensure the array can operate over the entire sub-6 GHz band for mobile communication.

Flexible metamaterial design makes it possible to achieve medium parameters with extreme values such as zero and negative, and high anisotropies and inhomogeneities, which are difficult to realize in nature [4]. Metamaterials, as a kind of artificial material, can arbitrarily control the transmission path of electromagnetic (EM) waves, have received wide attention [5]. The use of innovative metasurfaces and metamaterials as coatings in phased array can enhance wide-scan capability or manipulate polarization status [6]. To achieve a wider operating bandwidth in the tightly coupled dipole array, conductive disks are placed above the planar array periodically following the same pattern as the array elements. The layer consisting of the regularly spaced disks is named the metamaterial WAIM layer. The reason is to use low-loss conductive material rather than layers of dielectric materials in array design to maintain a low profile and maximize the radiation efficiency.

There are many different methods to analyze the WAIM layers. Such as in [7], artificial magnetic conductors (AMCs) method is used to analyze the electromagnetic characteristics of ADLs (Artificial dielectric layers). The closed-form expressions are derived based on the Floquet model expansion [5]. Moreover, as suggest in [8], dielectric layers may be superimposed above the dipole layer to further improve the array bandwidth (particularly for wide scan angles).

II. The metamaterial layer design

Conventionally, a stack of dielectric layers is employed to counter the impedance mismatch when the array is scanned to wide angles. This method restricts the application of the arrays. In addition, it often becomes a challenge to match the antenna at all angles using the limited set of dielectric materials available in nature. Material of anisotropic magnetic and dielectric properties are desired. The conductive disks arranged in particular patterns are discovered to be able to work as an anisotropic layer. The electromagnetic characteristics of the layer can be studied by placing it on the top of a phase

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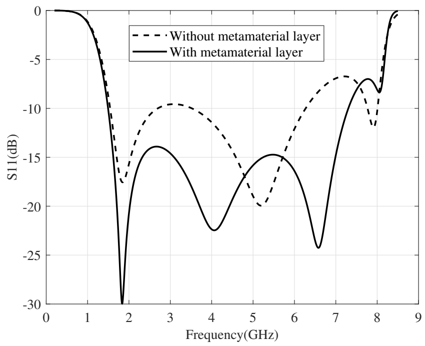

Fig 1. The metamaterial increases the bandwidth of a tightly coupled dipole array.

array. The performance of the array with and without the metamaterial layer is investigated to study the effect of the metamaterial.

A planar antenna with a differential structure was proposed to analysis the effect of matemetarial layer. The antenna design mainly with two C-shape dipole which has wider bandwidth than linear dipole. The conductive disks with the same radius as dipole as metamaterial layer was placed on the top of the antenna. Capacitors were introduced between elements to cancel the ground plane inductance. As indicated in Fig. 1, in the presence of the metamaterial layer, a significant increase in the operational frequency bandwidth of the antenna array is observed, using -10dB of reflection coefficient as the criteria, the bandwidth is increased from 4.73GHz to 5.81GHz.

III. The Analysis Method

It is observed that the metamaterial layer formed by array of conductive disks improved the impedance matching performance of the interconnected wideband array. However, the principle behind it is not clear. Equivalent circuit is an effective method to explain the working mechanism of the metamaterial layer. The equivalent circuit for the metamaterial layer is investigated by using a hybrid technique. First the scattering parameters of the layer is obtained by using the full-wave simulator, it is noticed that the response of the layer is analogy to a low pass band filter, then equivalent circuit model is derived based the this hypothesis.

A. Equivalent Circuit Model of tightly coupled dipole array above ground plane

The input impedance Z_{in} of the element in a tightly coupled dipole array can be calculated by using the Munk's model [8]. However this only applies when the element used is a typical dipole. A new planar array design formed by interconnected disks was proposed. Equivalent circuit model proposed for ultra-wideband tightly coupled array in [9] is suitable for the new design but with some modifications. The equivalent circuit model for the new design of interconnected disk dipole array is shown in Fig. 2. Two components (inductance L_p and capacitance C_p) are added to the conventional equivalent

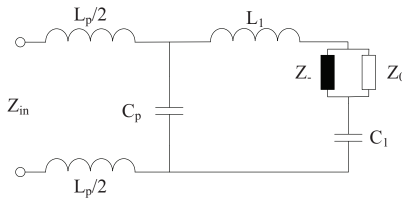

Fig 2. Equivalent circuit model of a tightly coupled dipole array above a ground plane

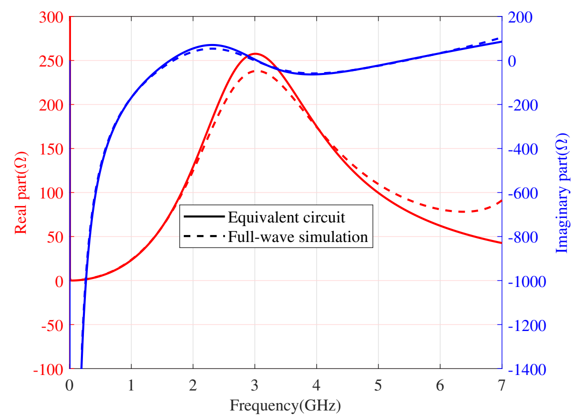

Fig 3. Input impedance of the element in a tightly coupled dipole array backed up by a ground plane, the results are compared by using the equivalent circuit model and a full-wave simulation

circuit model. For freespace, the characteristic impedance $Z_- = Z_0$, and in practice, a ground plane may be added to direct radiation to one side of the array. ${Z_1}^-$, the input impedance of a short-circuited TL with the electrical length of h_{ground}, represents the characteristic of ground plane. ${Z_1}^-$ can be expressed by

$$Z_- = jZ_0 \tan\left(\frac{2\pi}{\lambda} h_{ground}\right) \quad (1)$$

where λ is the wavelength in vacuum, h_{ground} is the distance between the plane of antenna array and the ground plane. We found that the optimal values are: $L_p = 5nH$, $C_p = 0.18pF$, $L_1 = 4nH$ and $C_1 = 0.4pF$.

The input impedance based on the full-wave simulation and calculation by using the equivalent circuit model are given in Fig. 3. The revised equivalent circuit model with extra components produced a similar result to the full-wave simulation. This reflected the effectiveness of the ECM to characterize the metamaterial layer.

B. Equivalent Circuit Model of Metamaterial layer

The equivalent circuit of planar disk dipole array was depicted in Fig. 4. A ground plane is present under the planar array, and the distance from the antenna array plane is defined as h_{ground}. The metamaterial layer is put above the planar array. The finite array with metamaterial layer, unit cell of the

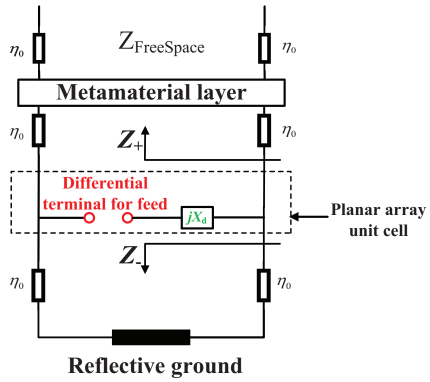

Fig 4. Illustration of equivalent circuit for tightly coupled dipole array between ground plane and metamaterial

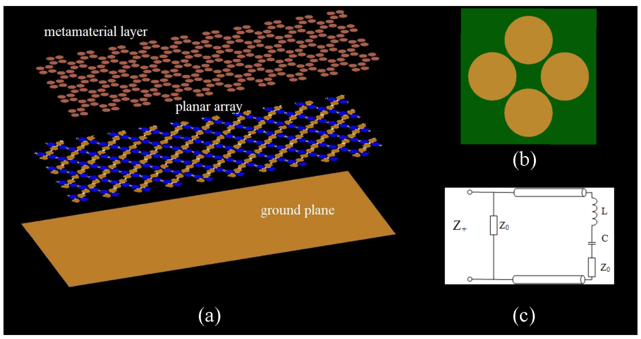

Fig 5. The metamateiral layer and the equivalent circuit model, (a) the metamaterial layer, (b) unit cell for the metamaterial layer, (c) equivalent circuit of the metamaterial layer ($L = 3nH$,$C = 0.1pF$, the TL is loaded by free-space impedance Z_0 with the electrical length of $7mm$)

metamateiral and the equivalent circuit model are illustrated in Fig. 5. The planar elements for the array and the corresponding disks for the metamaterial layer maintain an identical period. The period of the cells for the metamaterial layer is 26mm. The equivalent circuit model of the metamaterial layer and freespace surrounding it can be represented by a simple RLC circuit. The input impedance of of the elements in the planar array with metamaterial layer is compared between full-wave simulation and the equivalent circuit model. They are given in Fig. 6. The agreement is good up to 7GHz.

IV. Results and Discussions

The metamaterial layer is studied by using both full-wave simulator and the equivalent circuit model. The input impedance characteristic of the array elements is employed as an indicator to examine the effectiveness of the equivalent circuit model. The comparison on input impedance of the element in the array between the simulation on the metamaterial structure and the equivalent circuit model is illustrated in Fig. 6. The agreement is good from few hundred of megahertz to 7GHz. ECM is proven to be an effective tool to interpret the effect of metamaterial layer on antenna array performance.

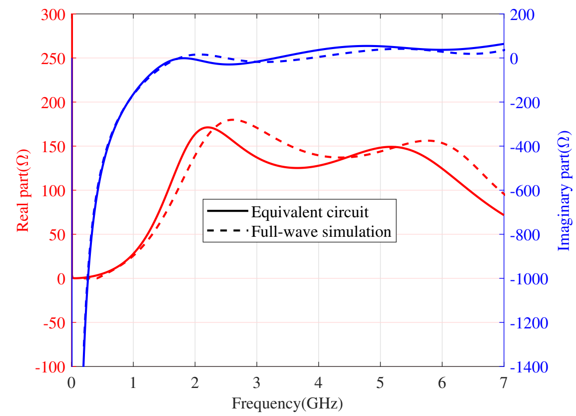

Fig 6. Input impedance Z_{in} of an infinite coupled dipole array with ground plane and metamaterial layer calculated using equivalent circuit and full-wave simulation

V. Conclusion

A metamaterial layer formed by an array of conductive disks can be used to enhance wide angle scan capability of phase arrays. The principle behind this is investigated by equivalent circuit modeling. The electromagnetic performance of the metamaterial layer is intuitively observed by using it in an ultra wideband array based on full-wave simulation. The equivalent circuit models for the arrays with and without metamaterial layer are derived. For the normal incidence of plane waves, the equivalent circuit model shows a good agreement with the simulation model for a full-wave simulator. It can be used to improve the performance of the metamaterial design.

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