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Magneto-inductive wave propagating in magnetic metamaterial structure for wireless power transfer and near-field communications

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Abstract. In this paper, we investigate the magnetic metamaterial structures capable of transmitting magneto-inductive waves in both coaxial and coplanar configurations. These metamaterial structures exhibit magneto-inductive wave propagation at a frequency band around 27 MHz, which falls within the ISM (Industrial, Scientific and Medical) frequency band. These magneto-inductive wave-propagating metamaterial structures have great potential for applications in wireless power transfer, near-field communication, and magneto-inductive wave devices.

Keywords: Metamaterials, wireless power transfer, near-field communication.

1. Introduction

Faraday's law of electromagnetic induction is a cornerstone of modern physics, with numerous technological advancements and applications [1,2]. One of the most promising and innovative applications of Faraday's law is in the realm of metamaterials. These artificially engineered materials exhibit unique properties not found in natural substances, enabling novel functionalities and applications. Specifically, the induction facilitates the transmission of energy and information through metamaterial structures via

magneto-inductive waves (MIWs). This emerging field holds significant potential for advancing communication technologies and enhancing the efficiency of energy transfer systems [3]. The exploration of MIWs in metamaterials represents a cutting-edge direction in research, promising to unlock new capabilities and applications in various scientific and engineering domains [4-8].

MIWs are a type of waveform generated within a metamaterial array. In this context, adjacent unit cells within the metamaterial structure engage in mutual coupling, facilitating the transmission of magnetic

energy from one unit cell to another via electromagnetic induction. The interactions between these unit cells can be categorized into two distinct types: positive coupling and negative coupling. Positive coupling occurs in coaxial configurations of unit cells, while negative coupling is associated with coplanar configurations [9-11].

In this work, we present a detailed theoretical analysis and simulation of two distinct configurations for transmitting MIWs. Through this comprehensive examination, we identify the optimal configuration for effective wave transmission. Our findings have significant implications for potential applications in WPT and near-field communications, highlighting the practical relevance of this research in advancing these technological domains.

2. Design of 1D array magnetic metamaterial structure

In one-dimensional (1D) magnetic metamaterial structures used to propagate MIWs, depending on the interaction between unit cells, can be divided into two types: coplanar transmission and coaxial transmission, as shown in Figure 1. The MIW transmission structures investigated in this study consist of an array with five metamaterial unit cells. When the first unit cell is excited, the MIW will spread to other unit cells throughout the waveguide structure through magnetic induction interaction in the near field with a coupling coefficient k defined as follows:

$$k = \frac{M}{L} \quad (1)$$

where M is the mutual inductance of two unit cells interacting with each other, L is the self-inductance of each unit cell. In the coplanar structure (Figure 1(a)), the unit cells are coupled to each other with a negative coupling coefficient because the magnetic flux lines change direction when passing through the surface of neighboring unit cells. In contrast, in the coaxial structure (Fig. 1 (b)), because the magnetic flux lines do not change direction when

passing through the plane of the unit cells, these unit cells interact with each other based on the positive coupling coefficient. The two MIW waveguiding configurations were simulated in detail using the CST simulation software, with open boundary conditions in all directions. Figure 2 presents the field distribution of the two MIW waveguiding configurations in coplanar and coaxial forms. We can see that the magnetic field obtained decreases along the waveguide structure as the MIW propagates in both configurations. The field intensity is strongest at the first element of the waveguide and weakest at the end of the waveguide.

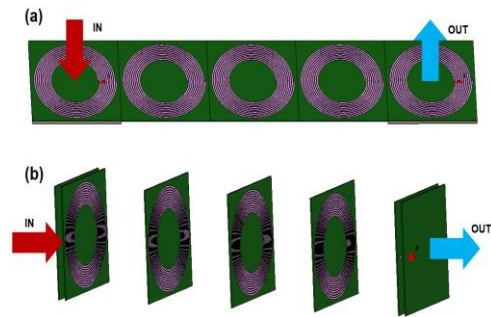


Figure 1. Design of 1D array magnetic metamaterial structure.

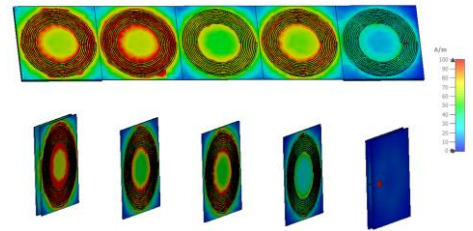


Figure 2. Field distribution in two magnetic metamaterial configurations for MIW waveguiding.

3. Transmission properties of magneto-inductive waveguide

First, we present the magnetic energy transmission capabilities of the two transmission configurations described in the previous section. As shown in Figure 3, we can observe the transmission performance of the metamaterial structure with these two different configurations. For

the coplanar configuration, the transmission spectrum is represented by the red line, reaching a transmittance of -17.5 dB at a frequency of 27 MHz. This planar configuration exhibits a transmission band from 26.8 to 27.6 MHz.

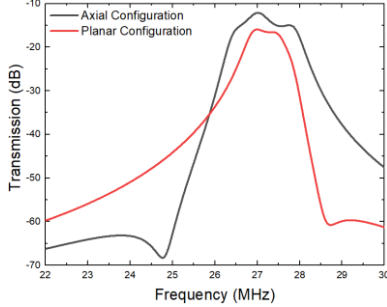


Figure 3. Transmission coefficient of two waveguide configurations.

In contrast, for the coaxial configuration, the transmittance is greater, reaching -12.8 dB at 27 MHz, as indicated by the black line. Furthermore, the transmission band in the coaxial configuration is also broader than that in the coplanar configuration, spanning from 26.3 to 28.2 MHz. This can be explained by the fact that in the coaxial configuration, the unit cells interact with each other with a higher coupling coefficient compared to the planar configuration. We extracted the coupling coefficient values for these two configurations and obtained the results: $k = 0.0206$ for the coaxial configuration and $k = -0.0108$ for the planar configuration.

After presenting the transmission of the two configurations, we conducted an investigation of the attenuation of each configuration to explain the difference in transmission coefficient as well as transmission bandwidth. When the excitation source is applied to the first unit cell of the metamaterial array with a current I_1 , this current will cause induced currents on the remaining unit cells on the array. From there, the current in the unit cells can be calculated by using the following formula [12]:

$$I_n = I_1^{-\gamma na} \quad (2)$$

Where $\gamma = \beta - j\alpha$ is the wavenumber, β is the propagation constant and α is the

attenuation coefficient per length. The propagation coefficient β can be calculated based on the angular frequency as follows:

$$\beta = \frac{1}{a} \arccos \left(\frac{\omega_0^2 / \omega^2 - 1}{k} \right) \quad (3)$$

Where ω_0 is the angular resonance frequency of the metamaterial unit cell. The dependence of the attenuation coefficient on the quality factor (Q -factor), coupling coefficient (k), and lattice constant (a) can be expressed as follows:

$$\alpha a = 1 / kQ \sin(\beta a) \quad (4)$$

The attenuation coefficients for the two configurations have been calculated and shown in Fig. 4. In both configurations, the lowest attenuation coefficient is obtained at center transmission band. Because the absolute value of the coupling coefficient (k) in the axial configuration (0.0206) is larger than in the planar configuration (-0.0108), the attenuation coefficient (α) of the axial configuration (2/m) is smaller than that of the planar configuration (4/m). Furthermore, the width of the transmission band in the axial configuration (26.3 - 28.2 MHz) is also larger than that in the planar configuration (26.8 - 27.6 MHz).

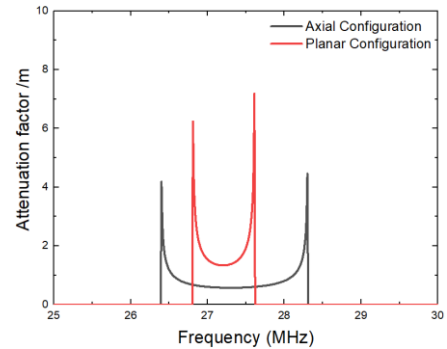


Figure 4. The attenuation coefficient of two waveguide configurations.

4. Conclusions

This paper presents detailed analyses of two magnetic metamaterial configurations for MIW propagation. The coaxial configuration has a positive coupling coefficient, while the coplanar

configuration has a negative coupling coefficient. This leads to differences in the dispersion curves of the two configurations. The absolute value of the coupling coefficient is higher in the coaxial configuration, resulting in a lower attenuation. Consequently, the coaxial configuration exhibits a higher transmission coefficient compared to the coplanar configuration. The metamaterial configurations investigated in this work can be utilized for simultaneous energy and information transmission, with potential applications in next-generation electronic devices.

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