Investigation of Deep Neural Networks for Rapid Characterization of Nonreciprocal, Time-Modulated Waveguide on Metamaterial

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요 약

Beyond the first three generations of metamaterials, space-time metamaterials provide the important capability for dynamically manipulating the electromagnetic wave. By controlling the structure parameters, the metamaterial could exhibit the nonreciprocal characteristic implying that wave propagates in different ways when interchanging source and observation points. Due to depending on multiple parameters, this characteristic is difficult to investigate. In this paper, we propose a time-varying metamaterial-based waveguide that breaks the reciprocity nature. After that, we apply Deep Neural Network (DNN) algorithm to determine which parameter sets show this property. The results show that DNN successfully predicts the forward and backward transmission difference with high accuracy: 99.2% and 98.8% of 1,472 cases for each have mean square error (MSE) of less than 2.5×10^{-3}. In addition, comparing to ADS simulation, the computation time can be decreased 1,500 times.

I. Introduction

The capability of wave propagation control has made a significant contribution to many physical areas. Metamaterials have been studied for nearly two decades as a promising method to govern electromagnetic waves, such as guiding or confinement of these waves, especially at the deep subwavelength scale [1]. Regarding the fourth-generation metamaterials, space-time metamaterial whose properties can be indirectly controlled through their physical parameters allows manipulation of electromagnetic waves beyond the previous generation of static metamaterials [2].

In many modern communication and power applications, to separate signals from a power supply or simultaneously use a single antenna in different roles, the systems require one-way wave propagation based on the nonreciprocity nature. This concept implies that when interchanging source and observation point, the traveling wave does not remain similarly [3]. The most popular nonreciprocal components are isolator and circulator. While an isolator is a 2-port network used in high-power microwave transmitters, circulators whose applications are found in multi-function communication receivers and radars contain three ports connected to receiver, transmitter and antenna [3]. However, it is difficult to determine which specifications of a system exhibit nonreciprocity property.

In recent years, machine learning technology has been of interest to several science branches. With the advantages of high accuracy and calculating rate beyond human ability, DNN has been employed to solve numerous problems in materials science. The previous approach shows that the DNN can forecast the scattering coefficients with miniature error [4].

In this work, we propose a time-variant metamaterial-inspired waveguide which powerfully confines wave to travel in one direction while allows propagation in the reverse direction. Besides, we examine that the difference between forward and backward transmission (S_{21} and S_{12}) in this waveguide can be successfully predicted by DNN.

II. Design

The schematic of the waveguide is demonstrated in Fig 1(a); it contains nine unit cells are divided into two alternate layers. Each space-time variant unit cell is constructed by a static 4T-SR cell and an external circuit whose modulation source is turned to break its reciprocal characteristic (Fig 1(b)). In our structure, its characteristic is determined by five parameters: power put on waveguide input P_{in}; coupling coefficient between two nearest cells in the same layer k_c; voltage V_m and frequency f_m of modulated signal; total capacitance of unit cell C_S.

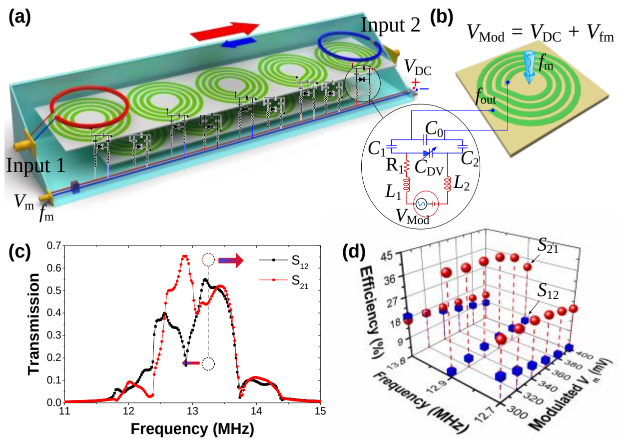

Fig 1. (a) Schematic of the RF Isolator device using time modulated metamaterial. (b) The modulated circuit model on a 4T-SR unit cell. (c) The transmission of the device with modulated frequency f_m = 554 kHz and amplitude V_m = 400 mV. (d) The transmission efficiency of the S_{21} and S_{12} of the device as a function of the modulated amplitude V_m.

Fig 1(c) shows the broken reciprocal transmission with the time modulation's amplitude V_m and frequency f_m equals 400 mV and 554 kHz, respectively. The maximum difference between forward and backward transportation is observed at the cell's resonant frequency (f_0 = 12.9 MHz). The dependence of transmission efficiency on modulated amplitude function V_m is illustrated in Fig 1(d). In all cases, the system exhibits the strongest nonreciprocity at the resonant frequency.

By varying the five parameters mentioned above, we consider about 1.52×10^{12} possible design combinations. Among them, 18,232 cases are randomly selected to be synthesized in a fully connected network (FCN) called Input to S-Parameters. There are 1,024 nodes in each of its nine layers. The diagram of the overall network is presented in Fig 2.

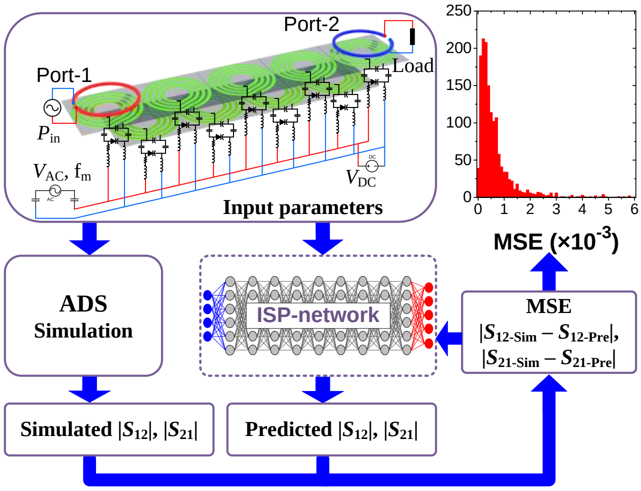

Fig 2. Process of the ISP-network to predict the transmission coefficients ($|S_{21}|$ and $|S_{12}|$)

Fig 3 shows some $|S_{12}|$ examples of 1,472 test sets after 2500 epochs. MSE of each is put together with the according sub-figure. We also calculate the MSE of all other cases; 99.2% of them have MSE smaller than 0.25 $\times10^{-3}$.

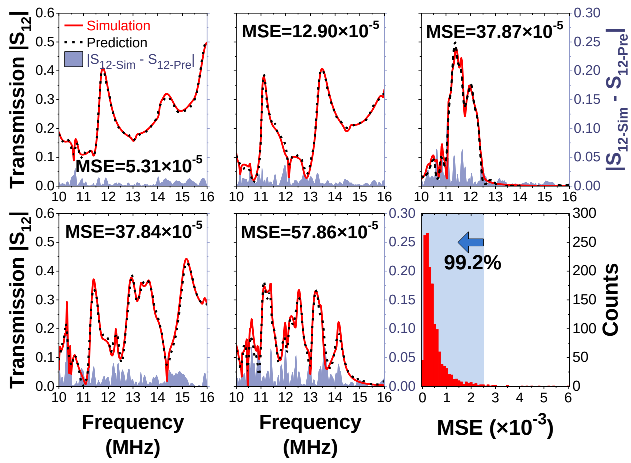

Fig 3. Examples of $|S_{12}|$ obtained by ISP-network. The MSE of all test sets is shown in the last histogram.

$|S_{21}|$ values of corresponding examples are shown in Fig 4. Similar to $|S_{12}|$, all cases' MSE is also calculated to point out that 98.8% of them have MSE smaller than 0.25×10^{-3}.

These two figures prove that DNN can accurately predict the nonreciprocal characteristic of the time-modulated 4T-SR waveguide.

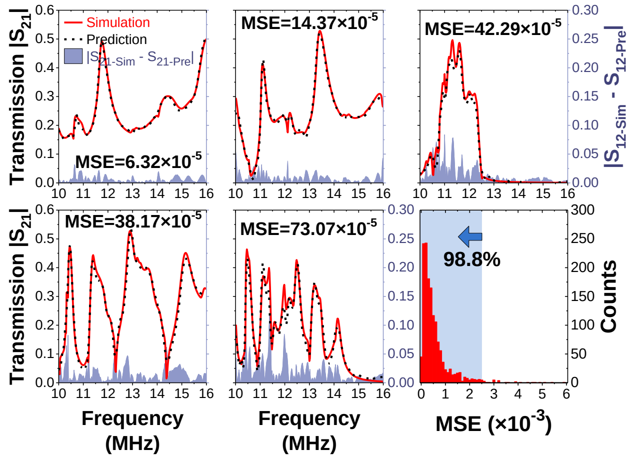

Fig 4. Examples of $|S_{21}|$ obtained by ISP-network. The MSE of all test sets is shown in the last histogram.

We use Agilent Advanced Design System for EM solver and Tensor-flow for DNN. For comparing the working time, we run both ADS and DNN on the HP Z6 workstation, which has processor, GPU and memory capacity is Intel Xeon Gold 6128, Nvidia Quadro RTX 4000 and 128 GB, respectively. With 1,000 samples are analyzed, while ADS needs 2,777 seconds (46.28 minutes) to simulate and give the outputs, it only takes the DNN about 1.85 seconds to get all the transmission values. This dramatic decline in calculating time is another confirmation of DNN power.

Ⅲ. Conclusion

In this work, we successfully investigated that the DNN algorithm can predict the bidirectional transmission of the time-modulated waveguide with around 1,500 times time reduction compared to ADS simulation. It also can determine the nonreciprocity nature that our proposed system exhibited before.

ACKNOWLEDGMENT

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (No. 2021R1A2B5B01001475).

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