Numerical and experimental demonstration of nonlinear metamaterial surfaces designed for high power surface current absorption

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Abstract

In this paper we demonstrate both numerically and experimentally absorbing performance of nonlinear metamaterial surfaces (MSs) for high power surface currents. They are composed of metallic patterned surfaces and several circuit components, i.e. capacitors, resistors, and diodes. The use of the diodes allows rectification of incident waves to DC, which results in absorption for high power incident waves but with low loss for low power incidences. The MSs studied here can potentially be used as a new type of intelligent artificial surface for applications such as nonlinear artificial surfaces on which antennas can communicate with weak signals, while protecting themselves from high power interference.

1. Introduction

The use of high impedance surfaces (HISs) [1], or metamaterial surfaces (MSs), makes it possible to block surface currents propagating on metal surfaces, which is useful for protecting, for example, vulnerable communication or electronic systems from unexpected strong surface currents. A remaining issue here is that the reflected surface currents may keep propagating on the surfaces and potentially cause interference at different locations. Additionally, this limits communications of antennas surrounded by the MSs. These issues were addressed in our past study by incorporating diodes into a MS design together with resistors and capacitors, resulting in suppression of high power surface currents [2]. In this paper we analyze the absorbing mechanism of nonlinear MSs numerically and then experimentally demonstrate their feasibility.

2. Simulations

A periodic unit of the numerical simulation model is illustrated in Fig. 1 (a). Each dimension is given in the figure caption. Rogers standard microwave substrate RO3003 was used for the substrate, and the relative permittivity and loss tangent were respectively set to 3.0 and 0.0013. Each periodic unit had two resistors (51.1 Ω), two capacitors (47 pF), and one diode as found from Fig. 1 (a). In our previous study [2] a simulation model of a MS was decomposed into sub–unit models, i.e. the interface, via, and gap models, and the scattering parameters of each sub–unit model were calculated with HFSS ver. 14.0. The sub–unit models were then repeatedly cascaded as scattering matrices in Ansoft Designer ver. 6.1. This simulation method allowed us to simulate the entire MS with diodes. In this study the same manner was adopted to simulate nine periodic units of nonlinear MSs inside a TEM waveguide (34 mm height, i.e. the same height as a WR284 waveguide used for measurements later).

The scattering parameters and absorptance of the simulation model are shown in Fig. 2 (a). The calculation results showed a pass band up to 3 GHz, which means that the structure did not respond to low power incident signals at this frequency range. Next, the magnitude of the incident wave was varied at

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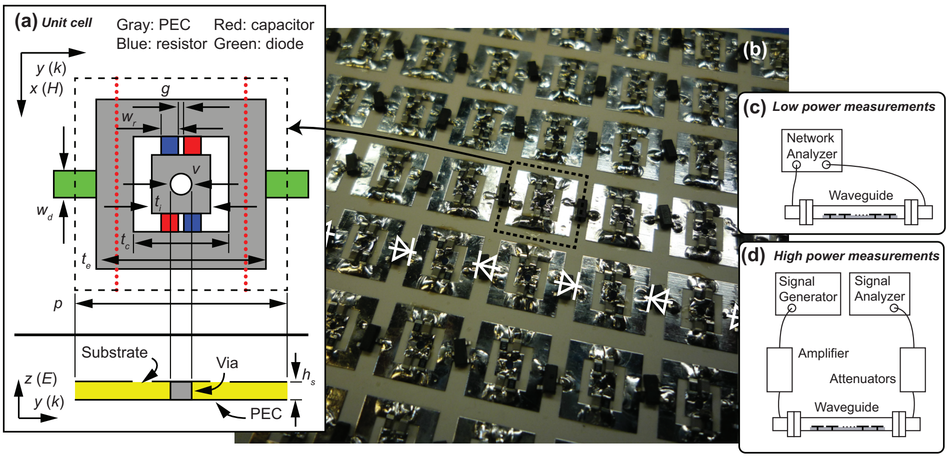

Fig. 1: (a) Unit cell of nonlinear MS. Each dimension used in the figure is as the followings: $p = 10$, $t_e = 8$, $t_c = 5.2$, $t_i \approx 2.8$, $w_d \approx 1.3$, $w_r = 0.8$, $g = 0.3$, and $h_s \approx 1.5$ (all in mm). (b) Measurement sample. As illustrated by the white lines, the directions of diodes were alternately changed. (c) Low power measurement setup. (d) High power measurement setup.

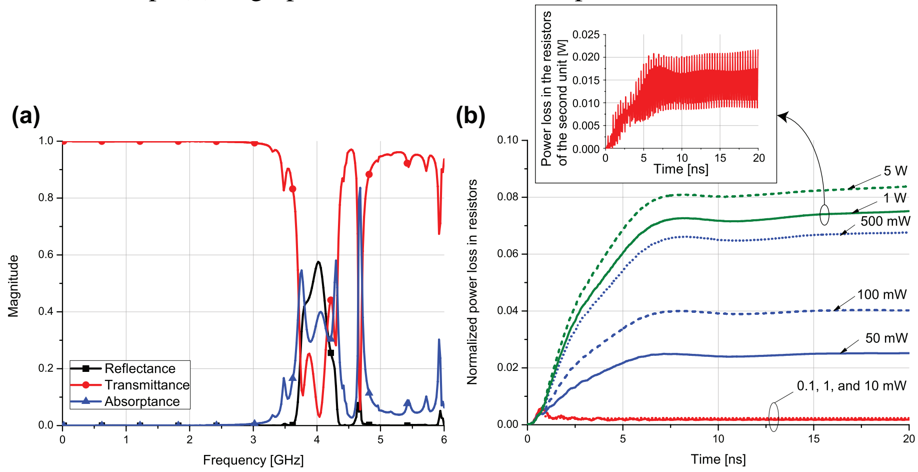

Fig. 2: Simulation results. Scattering parameters (left) and normalized power loss due to resistors at 3 GHz (right). The inset of the right figure shows the power loss in the resistors of the second periodic unit.

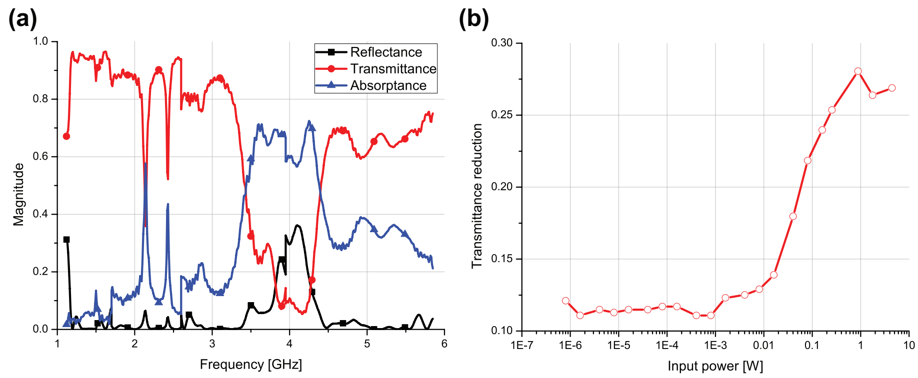

Fig. 3: Measurement results. Scattering parameters (left) and dependence of transmission reduction compared to the measurement without sample present on various input powers at 3 GHz (right).

3 GHz in Fig. 2 (b), where the power loss in the resistors was averaged per cycle and normalized by the input power magnitude. This figure indicates that the power loss in all the resistors increased as the input power increased from 0.1 mW to 5 W, i.e. nonlinear absorption. The inset of the figure shows the power loss in the resistors of the second periodic unit and demonstrates the rectification of the incident

wave (i.e. 3 GHz) to the DC component (i.e. an offset to about 0.015 W), which was obtained by using the nonlinear property of the diodes. Note that in this simulation the height of the MS was only 1.5 mm, which was much smaller than that of the waveguide (34 mm). In addition, the length of the whole structure was 90 mm and shorter than the wavelength of the incident wave (100 mm). For example, even reducing the waveguide height to 5 mm led to increasing the normalized power loss of 1 W input to 0.4 (not shown here).

2. Measurements

To demonstrate the feasibility of the nonlinear absorbing performance of the MSs, measurement samples were fabricated as Fig. 1 (b) and measured inside waveguides. Similarly with the simulation model, the measurement samples had nine periodic units along the propagation direction of the incident wave. The number of the units in the transverse direction was varied depending on the sizes of the waveguides used, i.e. 16, 11, 7, and 5 units, respectively, for WR650 (for 1.12 to 1.70 GHz), WR430 (1.70 to 2.60 GHz), WR284 (2.60 to 3.95 GHz), and WR187 (3.95 to 5.85 GHz). For WR430 and WR187 the edges of the measurement samples were slightly cut off so that they fit inside the waveguides.

For low power measurements (see Fig. 1 (c)) a network analyzer (Agilent Technologies; ENA Series Network Analyzer E5071C) was used to measure scattering parameters, while for high power measurements (Fig. 1 (d)) a signal analyzer (Agilent Technologies; EXA Signal Analyzer N9010A) was used to observe incident waves sent from a signal generator (Agilent Technologies; MXG Analog Signal Generator N5181A) and amplified by an amplifier (OPHIR RF; 5193 RF Power Amplifier). To protect the signal analyzer from high power inputs, two attenuators (-3 dB and -20 dB) were used between the signal analyzer and each waveguide.

The scattering parameters measured with the network analyzer are illustrated in Fig. 3 (a), where similarly with the simulation results a pass band was confirmed at a low frequency range. Since in these measurements four types of waveguides were used and each of them had a different waveguide height, the scattering parameters were not continuous at the edges of each measurement frequency range (i.e. at 1.70, 2.60, and 3.95 GHz). Next, nonlinear absorbing performance was evaluated at 3 GHz by calculating the differences between the transmittances with and without the measurement sample. As shown in Fig. 3 (b), the transmittance reduction was found to increase as the input power increased from 0.1 mW to 5 W, which generally agreed with the simulation results in Fig. 2 (b) and was assumed to be due to the rectification by the diodes as found in the inset of Fig. 2 (b).

4. Conclusion

We have demonstrated both numerically and experimentally nonlinear absorbing performance of MSs for high power surface currents. Numerical simulation results showed that the surface passes a low power incident wave at 3 GHz with negligible attenuation, while a high power wave is rectified to DC and absorbed. Additionally, the nonlinear absorption was validated by experimental results, demonstrating the feasibility of the proposed nonlinear MSs. The MSs studied here can potentially contribute to developing a new type of intelligent artificial surface applications, e.g. a surface that can be used to build antennas in which the nonlinear surface has no effect on performance for weak signals, while protecting themselves from high power hazard.

Acknowledgment

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References

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