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Visualization of Field Distributions of Waveform-Selective Metasurface

Hiroki Wakatsuchi, Member, IEEE, Daisuke Anzai, Member, IEEE, and Chris Smartt, Member, IEEE

Abstract—We demonstrate numerical simulations of recently reported waveform-selective metasurfaces by developing a new electromagnetic (EM) simulation method based on the Transmission Line Modeling (TLM) method. As opposed to a conventional method integrating an EM simulator with a circuit simulator, this simulation method allows us to fully visualize electromagnetic fields around the metasurfaces. Therefore, this demonstrates how the waveform selectivity varies the surrounding fields in response to the pulse width of the incoming wave even at the same frequency. This simulation method is expected to be useful for testing other kinds of circuit-based metasurfaces and metamaterials as well.

Index Terms—Metamaterial, metasurface, TLM, waveform selectivity.

I. INTRODUCTION

In general electromagnetic response of each material was determined by “composite molecules” and “frequency”. However, the advent of artificially engineered periodic structures, or the so-called metamaterials and metasurfaces [1], [2], [3], allowed us to control electromagnetic properties independent of composite molecules by arbitrarily designing the periodic units, which resonate in response to the incoming wave. More recently, Wakatsuchi et al. reported circuit-based metasurfaces that consisted of circuit components such as schottky diodes, capacitors, inductors, and resistors [4], [5], [6], [7]. These structures exhibited unusual electromagnetic characteristics named waveform selectivity, which enabled us to distinguish different waves even at the same frequency in accordance with their waveforms or pulse widths and thus was expected to develop new kinds of microwave techniques and applications [8]. For example, use of capacitor-based waveform-selective metasurfaces led to absorbing short pulses and transmitting long pulses at the same frequency, while inductor-based metasurfaces more effectively absorbed long pulses than short pulses. However, the simulation method used in a series of this study was based on a co-simulation method [6] that integrated a commercial electromagnetic (EM) simulator with a circuit simulator where all of the results were obtained. This indicates that while this method contributed to rapidly sweeping various parameters including input frequency, power, circuit parameters, etc, the simulation results obtained here were limited to voltages and currents at each port (i.e. effectively reflected and transmitted powers as well as voltages and currents at the circuit components used). As a consequence, this co-simulation method could not visualize how spatial field distributions varied inside the simulation space, although such information might be necessary for applying the waveform selectivity to a wider range of microwave applications (e.g. to analyze radiation patterns of antenna simulations). Besides, note that commercial EM software based on the finite element method (FEM) (e.g. HFSS version R15.0.7 [4]) cannot be straightforwardly applied for this issue since the simulation model was composed of “nonlinear” circuits and illuminated by sine wave pulses to analyze “transient” state instead of steady state. For this reason, in this study we demonstrate numerical simulations of a waveform-selective metasurface by developing a new simulation method based on the Transmission Line Modeling (TLM) method. The TLM method allows us to fully visualize how the surrounding fields vary in the simulation space with waveform-selective metasurfaces. Although four types of waveform-selective metasurfaces have been reported before [4], [5], this letter demonstrates numerical simulations of capacitor-based waveform-selective metasurfaces only. However, this simulation method can be used to model the other types of waveform-selective metasurfaces even with different geometries or dimensions. Additionally, our program code is made available online [9].

II. SIMULATION METHOD AND MODEL

First of all, the TLM method [10] is a time-domain numerical simulation method that discretizes the simulation space into TLM unit cells, which are composed of transmission lines including capacitors, inductors, etc. More details on the fundamentals of the TLM method are seen in many of past publications [10], [11], [12], [13], [14]. What we particularly need to simulate waveform-selective metasurfaces is the way to model schottky diodes and other circuit components (i.e. circuit chips). In our study these are treated as anisotropic lumped sheets or anisotropic boundary conditions between TLM unit cells. For example, the diode model is composed of an ideal diode in parallel with a junction capacitor. These components are then connected to a resistor in series as seen in Fig. 1 (a). Here the diode current \(I_D\) is determined by a well known form:

\[
I_D = I_s \left( \exp \left( \frac{V_D}{nV_t} \right) - 1 \right),
\]

where \(I_s\) is the saturation current and \(nV_t\) is the thermal voltage multiplied by the diode ideality factor. The junction
capacitor is modeled by $Z$ transform. Thus this connection process is represented as shown in Fig. 1 (b), where the diode model is connected to adjacent TLM cells through two link lines. There is also a stub line that plays the role of the junction capacitor. Therefore, the Thevenin equivalent of the entire model (including the connection process with the neighboring cells) can be represented as shown in Fig. 1 (c). Under these circumstances all the components including impedance and voltage sources may be combined as seen in Fig. 1 (d), where the source voltage $V_S$ and series resistance $R$ are respectively obtained from

$$ V_S = \frac{V_{Li} + V_{Rs} + 2V_{Cj} \ln t}{Z_0 + R_s + Z_C} $$

(2)

and

$$ R = \frac{Z_0 + R_s}{Z_C + Z_0 + R_s} $$

(3)

Since

$$ V'_D = V_S - I'_D R_s, $$

(4)

with Eq. (1) and some manipulation

$$ V_S - R_s I_S (\exp(V'_{D/n}/nV_i) - 1) - V'_D = 0. $$

(5)

This may be solved by Newton’s method giving the iterative algorithm:

$$ V'^{n+1}_D = V'^n_D - \frac{V_S - R_s I_S (\exp(V'_{D/n}/nV_i) - 1) - V'^n_D}{nV_i \ln \left( \frac{V_S - V'_D}{R_s I_S} + 1 \right) - V'_D}, $$

(6)

where the superscripts $n$ and $n+1$ represent time steps. This equation however gives a poorly converged algorithm. Therefore, more rapid convergence may be obtained from eq. (5), namely,

$$ nV_i \ln \left( \frac{V_S - V'_D}{R_s I_S} + 1 \right) - V'_D = 0, $$

(7)

for which Newton’s method gives the iterative algorithm as the following:

$$ V'^{n+1}_D = V'^n_D - \frac{nV_i \ln \left( \frac{V_S - V'_D}{R_s I_S} + 1 \right) - V'_D}{nV_i - R_s I_S \left( \frac{V_S - V'_D}{R_s I_S} + 1 \right) - 1}. $$

(8)

Generally this form converges very rapidly unless the the natural log function is less than or equal to zero (in this case eq. (6) is alternatively used in the following simulations). To start the iteration process in the TLM, our study determines the initial $V'_D$ based on the following condition:

$$ V_D = V_S \quad \text{(if } V_S \leq V_k \text{)} $$

$$ V_D = V_k \quad \text{(if } V_S > V_k \text{),} $$

(9)

where $V_k$ denotes a voltage at which the diode may be considered to be conducting. For example, if $I_D = 10^8 \times I_S$ then $V_k = nV_i \ln (10^8)$.

Other circuit chips such as capacitors and resistors were simply deployed between TLM cells as anisotropic, parallel components. With these circuit components a waveform-selective metasurface was deployed on the bottom of a transverse electromagnetic (TEM) waveguide as shown in Fig. 2 (a). More details of this simulation (e.g. dimensions and parameters used for modeling the metasurface) are seen in Figs. 1 and 2.

With these modeling methods a set of four diodes (i.e. red in Fig. 2 (b)) was deployed in each gap between conducting patches to play a role of a diode bridge, which converted the incoming frequency to an infinite set of frequency components. However, most of the energy was converted to zero frequency [6]. This rectified energy was then temporarily stored at capacitors (i.e. green in Fig. 2 (b)) and later dissipated by the paired parallel resistors (i.e. blue in Fig. 2 (b)). In this way the metasurface can effectively absorb a short pulse, while transmitting a long pulse or continuous wave (CW), which fully charges up the capacitors. This absorbing mechanism is more explained in our previous works [4, 5] including other...
types of waveform-selective metasurfaces that absorb different types of pulses at the same frequency.

III. RESULTS

The absorbing performance of the metasurface for CWs and 50-ns short pulses is plotted in Figs. 3 (a) and (b), respectively. As expected the metasurface more effectively absorbed short pulses around 4.4 GHz, compared to CWs. When the frequency and input power level were fixed at 4.2 GHz and 15 dBm, respectively, the metasurface decreased the absorptance from approximately 90 to 25% as the pulse width increased from 50 ns to 10 μs (Fig. 3 (c)). Note this value was in proximity to the absorptance of the CW (cf. Fig. 3 (a)). These results agreed with both our previous simulation results calculated from a co-simulation method and measurement results [4], [6], although some small differences between these two models (e.g. in geometry, diode model, cell size, etc) led to minor discrepancy.

Additionally, the new simulation method enabled us to visualize the field distributions in the simulation space. For example, Figs. 4 (a) to (c) and (d) to (f) show the electric field component along y axis ($E_y$) for 50 ns and 10 μs pulses, respectively (see Multimedia Files for these animations). As seen in these results too, the waveform-selective metasurface strongly absorbed the 50 ns pulse, while the 10 μs pulse was transmitted over the surface. Importantly, the field distributions on z-x plane (i.e. Figs. 4 (c) and (f)) are not symmetric with respect to z axis at the center, because induced electric
charges were rectified downwards in these figures and stored at capacitors. The incoming pulses were then turned off at 50 ns and 10 μs, respectively, and the field distributions were calculated again in 20 cycles as shown in Fig. 5. This figure indicates that the field distributions of the 50 ns pulse case approached zero shortly, while the 10 μs pulse left a significant amount of energy inside the capacitors used. This also demonstrates that the capacitors were fully charged up during the long pulse illumination, resulting in the reduction of the absorbing performance.

This is more clearly confirmed from Fig. 6, which plots the electric field along z axis. In this figure each panel contains three curves, in each of which the height was set to 1.5 mm (on the substrate), 3.0 mm, and 11 mm (i.e. half of the waveguide height), corresponding to black, red, and blue curves, respectively. As seen from the blue curves the field magnitude of the 50 ns pulse decreased as it propagated along z axis (see Fig. 6 (a)), while that of 10 μs remained almost the same (Fig. 6 (b)). The field magnitude more increased on the substrate, especially for the 10 μs pulse as seen from the black curves, since the capacitor chips stored the incoming energy. This field magnitude, however, approached that of the blue curves by shifting the observation position to double of the height (namely only 1.5 mm shift). In addition, at 20 cycles after the pulse illuminations, the field magnitudes in the simulation space (i.e. the red and blue curves) quickly decreased to zero as shown in Figs. 6 (c) and (d) (cf. Fig. 5). On the other hand, the black curve of the 10 μs pulse simulation still exhibited large amounts of the electric field, since the capacitors were fully charged up and required a longer time to discharge the energy to the resistors (specifically the time constant ρ).

IV. Conclusion

We have numerically demonstrated a waveform-selective metasurface by developing a new EM simulation method based on the TLM method. The use of the simulation method allowed us to fully visualize field distributions around the metasurface. Therefore, this is expected to be useful for developing a wide range of new applications using waveform-selective metasurfaces as well as other kinds of circuit-based metasurfaces. Our program code is made available online [9] including verification of the code.

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