Waveform Selective Surfaces

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The role of frequency is very important in electromagnetics since it may significantly change how a material interacts with an incident wave if the frequency spectrum varies. Here, a new kind of microwave window is demonstrated that has the unique property of controlling transmission and reflection based on not only the frequency of an incoming wave but also the waveform or pulse width. This is achieved by designing a planar periodic surface with circuit elements including diodes, which convert most of the incoming signal to zero frequency. This surface can preferentially pass or reject different kinds of signals, such as short pulses or continuous waves, even if they occur at the same frequency. Such a structure can be used, for example, to allow long communication signals to pass through, while rejecting short radar pulses in the same frequency band. It is related to the classic frequency selective surface, but adds the new dimension of waveform selectivity, which is possible only by introducing nonlinear electronics into the surface. Thus, the study is expected to provide new solutions to both fundamental and applied electromagnetic issues ranging from traditional antenna design and wireless communications to emerging areas such as cloaking, perfect lenses, and wavefront shaping.

1. Introduction

The response of a material to an incident wave changes as the frequency component of the wave changes. Conversely, materials are generally incapable of distinguishing between different waves at the same frequency unless these materials exhibit, for example, nonlinearity,[1] anisotropy,[2–4] or other dependencies on thermal heating[5,6] or light intensity.[7] In this study, we show that pulse width can be used as an additional degree of freedom—specifically, we use metasurfaces[8] composed of several circuit elements to control the scattering of an incident wave at the same frequency depending on the waveform (Figure 1a). In addition, we demonstrate that these waveform-selective metasurfaces are readily tuned externally or internally to realize more complex scattering responses. Moreover, our structures have the potential to exploit a conventional design drawback or physical limitation of an application as design flexibility. Note that our study shows a simple design methodology to control not only absorption[9,10] but also a wide range of scattering parameters through the use of periodic conductor effects. In addition, circuit-level effects enhance the design flexibility in waveform-selective responses. Our structures are related to the classic frequency selective surface (FSS),[11] but add the new dimension of waveform selectivity.

2. Results and Discussion

2.1. Theory

Such unusual electromagnetic responses are obtained using conventional periodic structures with several circuit elements, including sets of four diodes that play the role of diode bridges.[9] Thus, the energy of an incoming wave is converted into an infinite set of frequency spectra, although most of the energy is at zero frequency (see Table S1 in the Supporting Information). Within each diode bridge, we paired a resistor with either a capacitor or an inductor (Figure 1b,c). This allowed the control of rectified electric charges through the time-domain response of these paired circuit elements, as a capacitor gradually increases its electric potential and thereby reduces the number of incoming electric charges, while an inductor lowers its electromotive force, allowing more electric charges to enter.[10] In essence, these metasurfaces respond to how long an incident wave continues but not to the difference in the frequency spectrum, which appears due to the discontinuity of the waveform at the beginning and end (see Figure S1 in the Supporting Information for more details). Note that since practically diodes have both a turn-on voltage and breakdown voltage, the input power level needs to be in a proper range.
2.2. Fundamental Waveform-Selective Scattering Controls

These circuit characteristics were first integrated with two types of periodic structures, specifically, cut-wire and slit structures, which exhibit resonant mechanisms at a particular frequency (Figure 1d,g and Figure S3a,b, Supporting Information). When designed complementarily using Babinet’s principle,[12] these structures enhance either reflection (in the case of cut-wire structures) or transmission (in the case of slit structures) at the same frequency. In our study, however, they are not designed to be complementary to each other to improve waveform-selective responses but are instead used as specific examples that control the level of these fundamental scattering parameters. These structures contain either of the abovementioned circuit elements, i.e., Figure 1b or Figure 1c, between conductor edges where the electric field intensifies due to each resonant phenomenon (see the circled numbers in Figure 1d,g and the insets of Figure 1e,h). For this reason, the resonant mechanism is associated with the rectification process in response to the incoming wave pulse width.

These structures were numerically tested by using an electromagnetic/circuit cosimulation solver (see Section 4). We found that, for a cut-wire structure composed of a capacitor-based circuit (i.e., Figure 1b), the reflecting performance is limited for a 50 ns short pulse at 4.0 GHz (Figure 1e) because induced electric charges are effectively rectified and the intrinsic resonance of the cut-wire structure is disrupted. However, this rectification process is mitigated for a continuous wave (CW) signal so that the resonance emerges again at 4.0 GHz. Similarly, a strong level of transmission is observed in Figure 1h for a CW at 4.2 GHz, while this performance is suppressed in the case of a short pulse at the same frequency.

These waveform-selective resonant mechanisms were also designed using an inductor-based circuit (i.e., Figure 1c) for a different type of waveform. In this case, a short pulse is not effectively rectified due to the electromotive force of the inductor. Thus, a cut-wire structure strongly reflects the incoming wave as a conventional structure in Figure 1f. However, a sufficiently long pulse or a CW reduces the electromotive force and is thus effectively rectified by the diodes. This eventually leads to a suppression of the intrinsic resonant mechanism of the cut-wire structure.

A third method for controlling fundamental electromagnetic scattering is shown in Figure 1i,j, where an incident wave is reflected back with a different polarization by deploying a symmetric L-shaped conductor as a periodic unit together with a ground plane (GND) (see the inset of Figure 1j and Figure S3c in the Supporting Information for its small signal response).[13] This structure contains capacitor-based circuits and thus exhibits a reduced polarization change for a short pulse at 3.5 GHz compared to a CW at the same frequency.

2.3. Tuned Waveform Selectivities

Importantly, the waveform-selective response can be tuned by replacing some of the circuit elements. For instance, the periodic unit cell depicted in Figure 2a has a conducting square...
patch and a ground plane above and underneath a substrate, respectively, and thus exhibits waveform-selective absorption, if a capacitor-based circuit is introduced (Figure S6a, Supporting Information). In the diode bridge circuit, the role of the resistor is to determine the magnitude of the reflected power at the steady state (Figure S6b, Supporting Information), since it varies the amount of electric charges to be released for energy dissipation at the steady state. To realize further waveform-selective responses through the use of a single circuit element, the resistor can be replaced with a jFET, which varies its effective resistance between the drain and source in relation to the gate voltage. c) Measurement setup. d,e) Experimentally measured reflected power for a short pulse and a CW signal with various gate voltages (see also Figure S11 in the Supporting Information for more details). Without a gate bias, the difference between the pulse and CW cases is small; however, applying a gate voltage of $-1.4 \text{ V}$ leads to more than 60% difference (or 15 dB on the decibel scale) in absorption (Figure S12, Supporting Information). Consequently, waveform selectivity can be modulated between on and off depending on the electric stimulation.

Figure 2. Waveform selectivity tuned by an external bias source. a) Periodic unit cell. b) The circuit configuration deployed between patches ($C = 1 \text{ nF}$). This resembles the capacitor-based circuit (i.e., Figure 1b), but the resistor is replaced with a jFET, which varies its effective resistance between the drain and source in relation to the gate voltage. c) Measurement setup. d,e) Experimentally measured reflected power for a short pulse and a CW signal with various gate voltages (see also Figure S11 in the Supporting Information for more details). Without a gate bias, the difference between the pulse and CW cases is small; however, applying a gate voltage of $-1.4 \text{ V}$ leads to more than 60% difference (or 15 dB on the decibel scale) in absorption (Figure S12, Supporting Information). Consequently, waveform selectivity can be modulated between on and off depending on the electric stimulation.
achieve our nonreciprocal waveform-selective response, as the transmittance peak seen in the inset of Figure 3b remains at a low frequency. For this reason, the nonreciprocity and waveform selectivity disappear if the varactor diodes are replaced with fixed capacitors (3 pF) (Figure S17, Supporting Information).

2.4. Application

In addition to these fundamental scattering controls, waveform-selective metasurfaces potentially provide additional design flexibility in applied electromagnetic problems. Figure 4a,b describes a well-known resonant problem often seen in a conducting enclosure or cavity. Specifically, a strong external field can be excluded by entirely covering an object with conducting walls—for instance, to protect sensitive electronic devices. However, small openings or apertures often exist from the viewpoint of a realistic design (such as for ventilation). This leads to more strongly sensing external fields if the conductive enclosure resonates at specific frequencies $f_{m,n,p}$

$$f_{m,n,p} = \frac{c_0}{2} \left( \frac{m}{a_x} \right)^2 + \frac{n}{a_y} \right)^2 + \frac{p}{a_z} \right)^2$$

where $c_0$ is the speed of light and $a_x$, $a_y$, and $a_z$ are the internal dimensions of the enclosure—set to 54, 54, and 36 mm here, respectively (Figure 4a). $m$, $n$, and $p$ are integers, no more than one of which can be zero. This equation clearly shows that resonance is correlated with the dimensions of the enclosure and is thus a physically inevitable issue.

One of the classical solutions to this issue is to design a part of the conducting walls with an absorbing material to dissipate the resonant energy,[11,19] although this simultaneously prevents waves from transmitting through the apertures. As an alternative solution, this study replaces the front conducting wall (i.e., the one containing slits in Figure 4a) with a waveform-selective transmitting slit structure composed of inductor-based circuits (Figure 4c). Under these circumstances, a short pulse is not rectified by the diode bridges due to the electromotive force of the inductors. Hence, as usual, the slits resonate to permit the transmission of the incoming wave, resulting in poor shielding effectiveness ($S_E$) close to or lower than 0 dB near 3.2 GHz (Figure 4d). In the same frequency region, however, CWs are largely shielded, as electric charges induced by this waveform can enter the diode bridges, which prevents the resonance of the slits. As a result of these features, this waveform-selective conducting enclosure enables control over the shielding effectiveness by varying the level of transmission through the apertures. Note that compared to the analytically

![Figure 4. Waveform selectivity applied for electromagnetic issues to enhance device design flexibility. a) External fields can be separated with a conducting enclosure. b) The fields, however, appear more strongly at intrinsic resonant frequencies of the enclosure. c,d) Experimental setup and result using the conducting enclosure including a waveform-selective transmitting metasurface (see Figure S18 in the Supporting Information for the corresponding simulation). The use of waveform selectivity provides different levels of shielding effectiveness depending on the waveform so that, for instance, a short pulse can still be transmitted through the front apertures for wireless communications, while a CW at the same frequency would be blocked, and any sensitive electronics are therefore protected.](image-url)
derived resonant frequency of the enclosure (i.e., 3.9 GHz), the minimum shielding effectiveness for the pulse measurement appeared near 3.2 GHz in Figure 4d due to the presence of a monopole antenna that coupled to the resonance of the enclosure, although this antenna was still necessary for sensing the internal field.

2.5. Discussion

The concept of waveform selectivities is not limited to the examples demonstrated above but could be extended to the design of other types of scattering parameters and even electromagnetic properties (e.g., permittivity and permeability) if the circuit components are properly deployed between conductor edges where a strong electric field is obtained, as seen in the insets of Figure 1e,h,j. Consequently, the operation of the rectification process depends on the waveform of the incident wave. In this case, our idea is potentially applicable to recently studied fields, for instance, to perfect lenses \[20,21\] cloaking \[22,23\] and wavefront shaping \[24,25\]. However, this requires further improvements in waveform-selective performances with respect to the dynamic range and difference between pulse and CW responses. Especially, the latter point depends on several factors including parasitic circuit parameters, dielectric loss, and conduction loss. Furthermore, waveform-selective metasurfaces can be designed to respond to not only simple short and long pulses but also intermediate pulses \[10,26\]. The capability of waveform-selective metasurface can be more enhanced by introducing additional conducting layers, each of which has a different functionality or mutual coupling with other layers, as reported in other metasurface studies \[27,28\]. Note that on the one hand circuit values are involved with determining the time constant of waveform selectivity (i.e., transient response) but on the other hand these values need to be individually considered to achieve large difference between pulse and CW performances (see Figure S4, Supporting Information).

Importantly, our structures are planar periodic surfaces, similarly with FSSs \[11\] which are an old class of metamaterial \[29,30\] and metasurface \[8\]. However, compared to conventional FSSs, which respond only to waveforms of different frequencies, our structures additionally sense the difference in the waveform of an incoming wave even at the same frequency, which gives us a higher degree of control over transmission and reflection (compare Figure S5 in the Supporting Information to Figure 1e). A frequency selective surface has, for instance, different transmission coefficients for short or long pulses because the short pulse contains a wider range of frequency components, some of which may fall outside the pass band. While this is correct, the difference with our proposed structure is the scale of difference in pulse widths over which this can occur. With our surface, even if the bandwidth of the pass band is broad enough to contain the full frequency spectrum of both short and long pulses, we can still manipulate the difference in transmission characteristics because the pulse width dependence is controlled by the time constant of the circuit elements (i.e., \(R_C\) or \(R_L\)) within the diode bridge, which do not have any role in its low-power transmission spectrum. In fact, we can control this pulse response completely independently of the low-power transmission spectrum (compare Figure S3a in the Supporting Information to Figure 1e,h)]. Furthermore, the same surface can be made more transmissive to either long or short pulses. This is not possible with a simple bandpass surface using the method mentioned above, which always has lower transmission for shorter pulses.

Another important point here is that since the structure is electrically thin, the concept of group velocity is not the best way to explain its behavior. This is a nonlinear effect, where the change in transmission characteristics occurs on a much longer timescale than the period of the RF (radio frequency) wave, but on the order of the pulse width. For the slit structure that contains inductor-based circuits and preferentially transmits short pulses, those short pulses see the surface as static, and thus are transmitted without significant distortion. However, long pulses see the surface properties change over the duration of the pulse, as the surface transforms from transmissive to reflective (or in part absorptive). Therefore, the initial portion of a long pulse may be transmitted. On the other hand, the slit structure that contains capacitor-based circuits and transmits long pulses (i.e., Figure 1h) can be expected to block all short pulses. However, the initial portion of a long pulse may be reflected as the surface takes some time to transform from reflective (or absorptive) to transmissive states. These effects are most significant for pulse widths that are on the order of the time constant determined by \(R_C\) and \(R_L\) circuits, and are negligible for much shorter or much longer pulses.

3. Conclusion

In conclusion, we have investigated the theoretical basis and demonstrated the experimental feasibility of circuit-based metasurfaces to control various types of fundamental electromagnetic scattering parameters in response to the waveform of the incoming wave. These unique properties were achieved by designing planar periodic surfaces with circuit components including diodes, which converted most of an incoming signal to zero frequency so that they behaved differently in the time domain even at the same frequency. Waveform-selective metasurfaces were shown to be externally or internally tunable, which allowed the design of more complex scattering responses. In addition, the concept of waveform selectivity potentially provides additional design flexibility in applied electromagnetic issues ranging from traditional antenna designs \[31\] to wireless communications \[30\] and even emerging areas such as perfect lenses \[20,21\] cloaking \[22,23\] and wavefront shaping \[24,25\].

4. Experimental Section

Simulations: Numerical simulations were performed using a cosimulation method that integrated an electromagnetic solver (Ansys HFSS) with a circuit simulator (Ansys Desigher). In this method, the circuit components necessary for the design of waveform-selective metasurfaces were replaced with lumped ports in electromagnetic simulations. The actual components were then connected to the metasurfaces through the lumped ports in circuit simulations. This cosimulation method significantly reduced the time to sweep input power, frequency, and other design parameters, reducing the total
simulation time and facilitating optimization of the waveform-selective performance. Reflectance $R$, transmittance $T$, and absorptance $A$ for pulsed signals were calculated by entirely integrating reflected and transmitted waveforms in the time domain (specifically, from 0 to 100 ns for 50 ns pulses), which were then compared to the energy of the incident wave $E_i$, namely, $R = E_r/E_i$, $T = E_t/E_i$, and $A = 1 - R - T$, where $E_r$ and $E_t$ respectively, represent the energies of the reflected and transmitted waves. For CW simulations, incident waves continued until the time-domain response reached a steady state (mostly in 10 µs for this study).

Subsequently, the incident, reflected, and transmitted energies were calculated by integrating their waveforms only for 10 ns, which was sufficiently long to ignore discretization errors in the time domain.

**Measurement Samples:** The measured waveform-selective metasurface samples used in Figure 2, Figure 3, and Figure 4 were prepared by using Rogers3003 as their substrates. They had periodic conducting patterns made of copper. Additionally, a thin coating layer was added to the surface of the conductors both to prevent oxidation and to facilitate soldering of the circuit components necessary for waveform selectivity. The dimensions of these samples are listed in Table S4, Table S6, and Table S8 in the Supporting Information. In these samples, commercial Schottky diodes, jFETs, and varactor diodes provided by Broadcom (H8SM-2860/28612864), Toshiba (2SK209 BL), and Skywork (SMV2019-079LF), respectively, were used. The conducting enclosure used in Figure 4 was assembled using the abovementioned samples as well as copper plates coated for antioxidation.

**Measurement Methods:** For the measurements in Figure 2 and Figure 3, a signal generator (Anritsu MG3692C) was used as a signal source (see Figure 2c). This was connected to a standard rectangular waveguide (WR284) where a measurement sample was deployed. In the case of Figure 2, a circulator (Pasternack PE8401) was connected between the signal generator and waveguide so that the incident wave entered the waveguide, while the reflected wave was propagated to an oscilloscope (Keysight Technologies DSOX 6002A). This circulator was removed for the measurement shown in Figure 3, and the oscilloscope was connected to another side of the waveguide to measure the transmittance. A DC source (Keysight Technologies E3631A) was additionally introduced for the measurement shown in Figure 2 to bias jFETs via cables. In both measurements, the reflectance $R$, transmittance $T$, and absorptance $A$ were obtained similarly to simulations (see the Simulations subsection in Section 4).

The measurement in Figure 4 used a vector network analyzer (VNA; Keysight Technologies N5249A) instead of the pair of the signal analyzer and oscilloscope (see Figure 4c). Note that pulse measurements were conducted using the pulse measurement mode of the VNA to measure performance for pulsed waves but not for CWs. The incident waves were radiated from a standard horn antenna (WR284) to a conducting enclosure ($54 \times 54 \times 36$ mm$^3$) including a waveform-selective metasurface. An 18-mm-tall monopole antenna was connected to the bottom of the enclosure to receive transmitted waves, which were eventually measured at the second port of the VNA via a coaxial cable. This transmittance $T_w$ was compared to that without the shielding walls (see Figure S19, Supporting Information), $T_{wo}$, to obtain the shielding effectiveness as follows: $S.E. = 10 \log_{10}(T_{wo}/T_w)$ dB. In this measurement setup, an amplifier, couplers, and attenuators were also deployed to increase the input power level, maintain the calibration of the VNA, and protect instruments from a large input power, respectively.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

A patent application that covers the technology described in this paper has been filed (PCT/JP2015/070276).

**Keywords**

metamaterials, metasurfaces, nonlinear circuits, waveform

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