## Title

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**Journal**
Electronics Letters, 49(24)

**ISSN**
0013-5194

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**Publication Date**
2013-11-01

**DOI**
10.1049/el.2013.3010

Peer reviewed

# Experimental demonstration of nonlinear waveform–dependent metasurface absorber with pulsed signals

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We demonstrate the absorbing performance of a nonlinear waveform–dependent metasurface with pulsed signals. The metasurface a periodic structure containing diodes, capacitors and resistors. These enable us to first rectify a high–power incoming signal to a static field, then store the energy during the illumination and dissipate it before the next pulse comes in. The incident pulses contain a finite width of spectrum around 4.2 GHz. Using our nonlinear metasurface, we measure absorption that depends on both the power and duty cycle of the incoming signals. These measurements demonstrate the first waveform–dependent absorbing metasurface.

*Introduction:* A surface current propagates on a conducting surface and, with sufficiently high power, can disrupt electronic devices deployed there, leading to microwave interference issues. A difficulty lies in handling different levels of signals simultaneously. This is because widely used linear materials, such as lossy materials [1], Salisbury screens [2] or high impedance metasurfaces [3, 4], either simply absorb or reflect any incoming signals, including low power signals used for wireless communications. Therefore, it is important to decouple the high power surface impedance from its low power response by introducing nonlinearity. Such an idea was proposed by Wakatsuchi et al. in [5, 6], where circuit–based nonlinear metasurfaces absorbed high power pulsed sine waves, while allowing transmission of low power continuous waves. Interestingly, these structures exhibited *waveform dependence*, which distinguishes even the same frequency in accordance with the waveform, i.e. pulsed or continuous signals [6]. Moreover, the absorbing performance was demonstrated with a Gaussian pulse including a finite width of frequency spectrum. Such a pulse is assumed to be a more realistic threat to modern electronics. However, this demonstration was limited to only numerical simulations. Therefore, in this letter we experimentally investigate the absorbing performance of the nonlinear metasurface with short pulses containing a finite width of frequency spectrum.

*Metasurface and Method:* The geometry of the nonlinear metasurface is illustrated in Fig. 1 (a). This structure was composed of a conducting ground plane and periodic patches (17 mm × 17 mm with a 18 mm periodicity), both of which were separated by dielectric substrate Rogers3003 (1.5 mm thick). Between the patches we deployed circuit components, i.e. diodes (Avago HSMS–2863; HSMS–2864), capacitors (1 nF) and resistors (10 kΩ), which form a full wave rectification circuit [6]. Under these circumstances, the incoming high power pulse is mostly rectified to a static field, whose energy is stored in the capacitors during the high power illumination. The stored energy is later dissipated in the resistors before a next pulse comes in. In this way, high power pulses are effectively absorbed by the nonlinear metasurface, while low power signals are transmitted since the magnitude is not large enough to turn on the diodes. For realistic realisation the metasurface in Fig. 1 (a) was slightly modified as Fig. 1 (b) but still the fundamental mechanism remained the same. More details on the measurement sample are described in [6], where the same measurement sample was used for different types of measurements.

The measurement system used is shown in Fig. 2. In this measurement, the incoming signal was generated from a pulse pattern generator (Advantest D3185A), which was triggered by a 494 MHz sine wave from a signal generator (Agilent Technologies N5181A). The pulse pattern generator was then coupled to filters (Mini–Circuits VHF–4400; VLP–41; VLP–41) to generate frequency spectrum around 4.2 GHz, where our metasurface is capable of maximising the absorbing performance [6]. The magnitude of the incoming signal was controlled by using an amplifier (Ophir RF 5193) after the filters. The amplified signal was then sent into a transverse electric (TE) waveguide (WR187), where the nonlinear metasurface was deployed on the bottom surface. The transmitted signals were measured by connecting another port of the waveguide to either an oscilloscope (HP 83480A; 83483A) or spectrum analyzer (Agilent Technologies N9010A). In order to avoid strong reflection from the

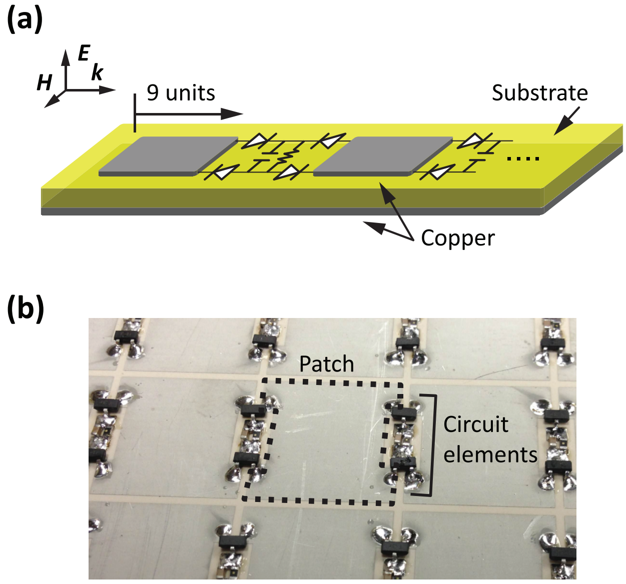


**Fig. 1** *(a) The circuit–based nonlinear metasurface absorber. The structure was composed of diodes, capacitors and resistors. This circuit geometry formed a full wave rectification circuit. As a result, the incoming high–power signal was rectified to a static field and stored in the capacitors during the pulse. The stored energy was then dissipated in the resistors before the next pulse came in. (b) The physically realised metasurface based on printed circuits.*

waveguide, we also used an isolator (Electronics Inc JIC2000T8000S1) between the waveguide and amplifier. The duty cycle of the incident pulse was controlled by varying the bit length of the pulse pattern generator.

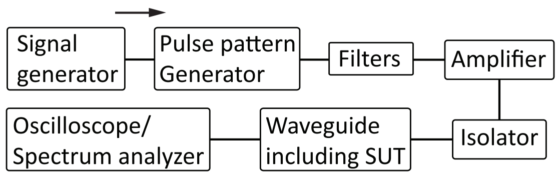


**Fig. 2** *The measurement system used. The pulse pattern generator was triggered by a 494 MHz sine wave generated from a signal generator. The signal from the pulse pattern generator was then sent into filters, amplifier and waveguide (WR187), where the metasurface was deployed. The output signal was measured with either an oscilloscope or spectrum analyzer.*

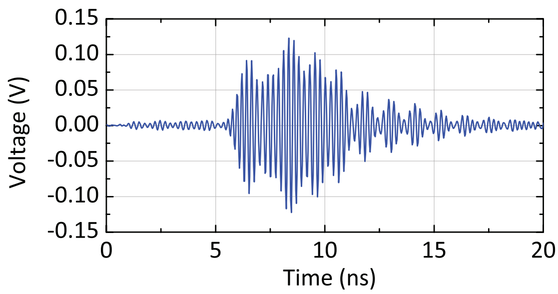


**Fig. 3** *The time domain response of the incident wave without the metasurface. The incident wave oscillated for about 10 ns as a modulated Gaussian pulse.*

*Results and Discussion:* First, without the metasurface, the incident wave was measured in both time domain and frequency domain as Figs. 3 and 4 (a), respectively. It turned out from Fig. 3 that the incoming signal oscillated for ∼10 ns as a modulated Gaussian pulse (e.g. one modulated by a cosine function [6]). This contributed to generating frequency components mostly around 4.2 GHz in Fig. 4 (a). Next, the metasurface was deployed in the waveguide, resulting in a minor reduction as seen in Fig. 4 (b). However, when the input power was increased by 30 dB (i.e. by a factor of 1,000), the transmitted signal was further reduced as in Fig. 4 (c), which is expected to be due to the nonlinear absorption of the

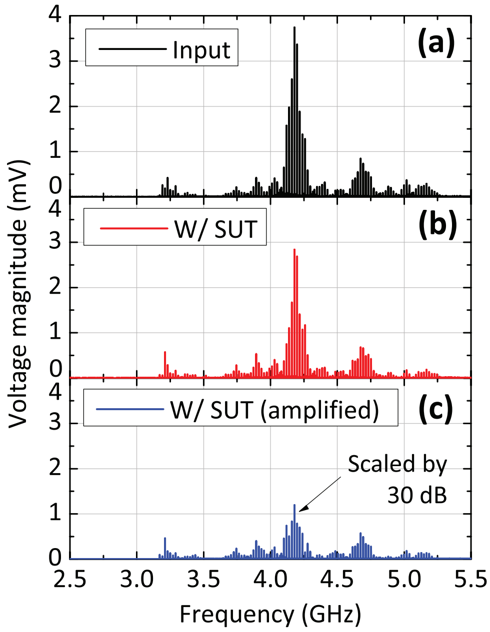


**Fig. 4** *The frequency spectra of (a) the incoming signal without the surface under test (SUT), (b) the output with SUT and (c) the output amplified by 30 dB with SUT. The input signal was found to have a peak at 4.2 GHz, where our metasurface maximises the absorbing performance [6]. The use of the metasurface led to minor reduction in (b). However, as the input magnitude increased, the absorbing performance was further enhanced (c).*

metasurface. More interestingly, this absorbing performance was reduced and approached the low power case by increasing the duty cycle from approximately 10 to 50 %. This is summarised in Table 1. This reduction can be accounted by the saturation of the capacitors, which prevented the rectification process of the diodes [6].

**Table 1:** Energy reduction rate of transmitted signals. The duty cycle was calculated by assuming that the incident signals had a 10 ns pulse width.

| Duty cycle [%] | High power | Low power |
|---|---|---|
| 10 | 88.1 (Fig. 4 (c)) | 63.3 (Fig. 4 (b)) |
| 50 | 71.6 | 58.6 |

*Conclusion:* We have experimentally demonstrated absorbing performance of a nonlinear metasurface with pulsed signals containing a finite width of frequency spectrum. Measurement results showed a clear reduction of a transmitted signal, when the input power was amplified by 30 dB. More interestingly, this absorbing performance was reduced by increasing the duty cycle, which can be explained by the saturation of the capacitors used. We believe that such a dependence on duty cycle or waveform allows us to create new kinds of microwave technologies and applications by distinguishing even the same frequency in accordance with the power and waveform.

*Acknowledgment:* This work was supported by the Office Naval Research under Grant N00014–11–1–0460. The authors also thank Stojan Radic, Nikola Alic and Andreas O. J. Wiberg for support in constructing the measurement system used.

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