Letter

ADVANCED PHOTONICS

Light-controllable time-domain digital coding metasurfaces

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Abstract. Programmable metasurfaces enable real-time control of electromagnetic waves in a digital coding manner, which are suitable for implementing time-domain metasurfaces with strong harmonic manipulation capabilities. However, the time-domain metasurfaces are usually realized by adopting the wired electrical control method, which is effective and robust, but there are still some limitations. Here, we propose a light-controllable time-domain digital coding metasurface consisting of a full-polarization dynamic metasurface and a high-speed photoelectric detection circuit, from which the microwave reflection spectra are manipulated by time-varying light signals with periodic phase modulations. As demonstrated, the light-controllable time-domain digital coding metasurface is illuminated by the light signals with two designed time-coding sequences. The measured results show that the metasurface can well generate symmetrical harmonics and white-noise-like spectra, respectively, under such cases in the reflected wave. The proposed light-controllable time-varying metasurface offers a planar interface to tailor and link microwaves with lights in the time domain, which could promote the development of photoelectric hybrid metasurfaces and related multiphysics applications.

Keywords: metasurface; light-control; time-domain; metamaterial.

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1 Introduction

Metasurfaces are artificial array structures consisting of subwavelength unit cells arranged on a specific two-dimensional surface, which have shown great capabilities to manipulate flexible electromagnetic (EM) waves.[1–3] Metasurfaces can not only tailor precisely the multiple physical characteristics of EM waves in the subwavelength scale, but also possess many advantages, such as thin thickness, conformal ease, and relatively simple fabrication for engineering applications, and thus have aroused enormous interests and extensive attention in many fields.[4–10] Recently, time-varying metasurfaces, emerging platforms with ultrafast phase or amplitude modulation, have been demonstrated to control the EM spectrum in the time domain,[11] leading to a lot of attractive functions, including Doppler cloaking,[12] frequency conversion,[13] and direct information processing.[14] A programmable metasurface that allows real-time control of EM waves in a digital coding manner is naturally suitable for constructing the time-domain metasurfaces.[15,16] More recently, time-domain digital coding metasurfaces[17–23] and space-time-coding digital metasurfaces[24] have been realized to implement different devices and systems. However, these electrically controlled time-domain metasurface schemes have difficulty performing the designs of the photoelectric hybrid metasurface, where optical signals are considered in the platform realization.

Different from the wired electrical control mechanism, the optical control approach can provide driven signals through light in a noncontact way and has unique advantages, such as simplification of bias network and reduction of signal crosstalk.[25–27] More importantly, optically controlled EM devices also show

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great potential for integration into optical systems for realizing advanced hybrid platforms. Recently, reflection-type and transmission-type light-controlled digitally programmable metasurfaces based on the joint control scheme of photocells and varactors[28–30] have been proposed and realized, which can be used to manipulate remotely EM beam shapes and EM amplitude, respectively, under visible-light illumination. Except for silicon photocells, the photoresistor has also been adopted to realize the light-controlled metasurface for controlling microwaves by light intensities.[31] In addition, two other types of optically controlled EM metasurfaces, an infrared-controlled programmable metasurface[32] and an optical-sensing smart programmable metasurface,[33] have also been verified for achieving more advanced devices. However, in these design schemes, the external optical signals are quasistatic and are only adopted to control EM waves in the spatial domain.

In this paper, we propose and realize a time-domain digital coding metasurface that can be controlled by visible light for achieving dynamic manipulations of the microwave reflection spectrum. Such a light-controllable time-domain digital coding metasurface is implemented by integrating a photoelectric detection circuit with microsecond response speed into a full-polarization programmable metasurface. By applying the light signal with a specific time-coding sequence to the time-domain metasurface platform, it can generate a group of harmonics based on rapid phase modulation under arbitrarily polarized incidences.

2 Principles and Methods

The proposed light-controllable time-domain digital coding metasurface is schematically shown in Fig. 1 for real-time harmonic manipulations. The front of the time-domain metasurface platform is a full-polarization programmable metasurface based on varactors. To control the metasurface with light, a high-speed photoelectric detection circuit is designed using a photodiode and two cascaded transimpedance amplifiers, which have an ultrafast response and a large voltage output capability. Such a photoelectric detection circuit is loaded directly on the back of the metasurface platform, and, thus, the whole platform is highly integrated. On this light-controllable time-domain metasurface platform, the microwave reflection phase can be changed by light intensity in real time. Therefore, when receiving the periodic light signal with a time-coding sequence representing rapidly changed intensities, the metasurface platform will produce harmonics based on phase modulation. In this case, by changing the time-coding sequences in light modulation signals, the time-domain metasurface platform can generate different spectrum distributions upon reflection (Fig. 1), enabling attractive applications such as direct information modulation and real-time spectral camouflage. The light-controlled time-domain digital coding metasurface provides a planar interface to link the microwaves with light signals and paves a promising way for designing multiphysics field functional devices and processing multidomain information simultaneously.

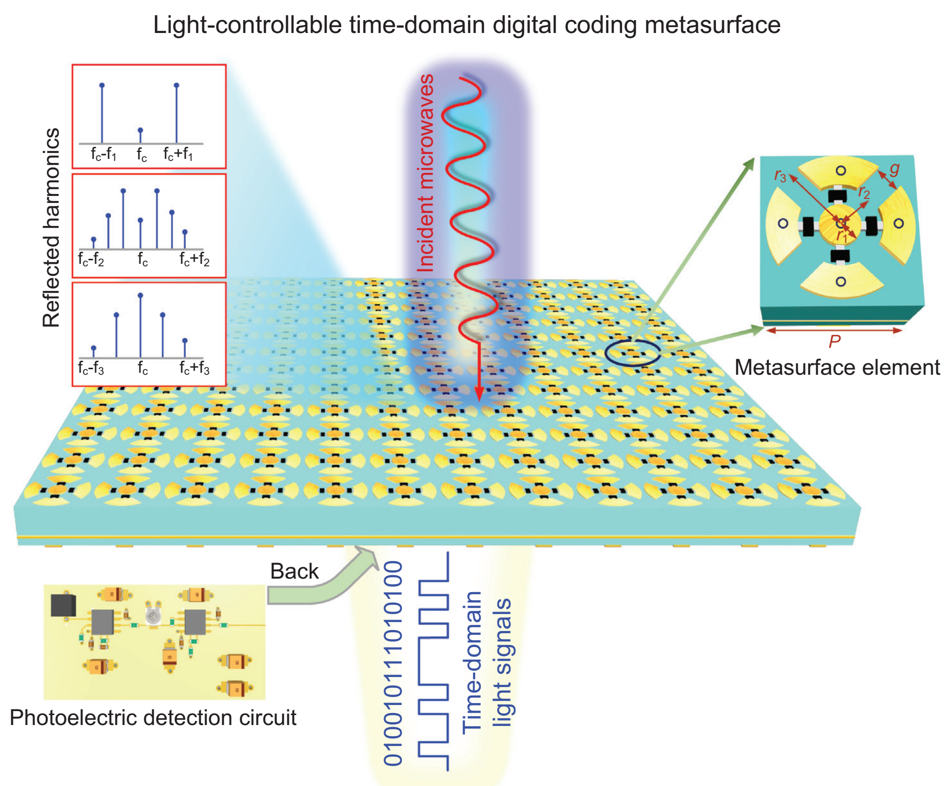

Fig. 1 Schematic of the light-controllable time-domain digital coding metasurface. Such a time-domain metasurface platform is constructed by integrating directly a high-speed photoelectric detection circuit into a full-polarization programmable metasurface. On this hybrid metasurface platform, the microwave reflection spectrum can be manipulated in real time by the light signal with different time-coding sequences.

To realize the light-controllable time-domain digital coding metasurface, we first design a dynamic metasurface element, as shown in Fig. 1. The metasurface element consists of a reflective resonator integrated with a bias network. The top layer of the resonant element is an elaborately designed metal pattern with a 90 deg rotationally symmetric feature, in which four identical "SMV2020-079LF" varactors are loaded. The middle layer is a 3-mm thick F4B dielectric substrate ($\varepsilon_r = 2.65$, $\tan\delta = 0.001$), and the bottom layer is a ground to enhance the reflection. With this configuration, the metasurface element can achieve the polarization-insensitive tunability. To tune the loaded varactors, five metallic vias with diameter of 0.5 mm are set, one of which is used to connect the central circular patch and the ground, and the other four are connected to the two vertical bias lines. The vertical bias lines are printed on the back of the thin F4B layer of the bias network. The F4B bias network layer and the resonant element are finally connected through a 0.12-mm-thick FR4 adhesive layer. The variable capacitance C_T of the SMV2020-079LF varactor can be tuned from 3.20 to 0.35 pF, showing a high capacitance ratio.[3] To achieve the required reflection performance, the main parameters of the metasurface element are optimally set as $P = 12$ mm, $r_1 = 2.0$ mm, $r_2 = 3.2$ mm, $r_3 = 5.8$ mm, and $g = 1.8$ mm.

3 Results

In our simulations, we use a resistor–inductor–capacitor series circuit with a resistance $R_S = 2.5\ \Omega$, an inductance $L_S = 0.7$ nH, and a variable capacitance C_T to mimic the SMV2020-079LF varactor. By changing the capacitance C_T, we observe the reflection features of the designed metasurface element. Figure 2(a) shows the simulated reflection amplitudes and reflection phases of the element for two different C_T under the x- and y-polarized incidences. It is obvious that for two capacitances C_T of 3.20 and 0.35 pF, in the frequency range of 6.39 to 6.79 GHz, the phase difference of the element varies around 180 deg, and the reflection amplitudes are all larger than −2.5 dB in this band. Therefore, the metasurface elements with $C_T = 3.20$ pF and $C_T = 0.35$ pF can be encoded as the "0" and "1" elements, respectively, to realize the 1-bit digital coding. We also investigated the amplitude and phase responses of the element under the left-handed circularly polarized (LCP) and right-handed circularly polarized (RCP) incidences, as shown in Fig. 2(b). From the simulated reflection curves, we see clearly that the metasurface element can also provide an approximate 180 deg phase difference in the frequency band ranging from 6.39 to 6.79 GHz. In addition, the reflection amplitudes and reflection phases are identical for two orthogonally polarized waves, which further verify the polarization-insensitive feature of the metasurface element.

As an experimental verification, we fabricate a programmable metasurface composed of 18×18 realized digital metasurface elements, as shown in Fig. 3(a). To control the metasurface with time-varying light signals, we also design and realize a photoelectric detection circuit [Fig. 3(b)] that is directly laid out on the back of the metasurface to achieve an integrated light-controllable time-domain digital coding metasurface sample. The photoelectric detection circuit mainly consists of a "BPW 34S" photodiode chip and two hierarchical transimpedance amplifiers. The photodiode is able to capture the visible-light signal and generate the weak photocurrent, which are then amplified by the transimpedance amplifiers to provide enough voltage driven signals. In such a case, the capacitance of the loaded varactor can be tuned dynamically by visible light, thus changing the reflection phase of the metasurface sample.

We first test the reflection phases of the light-controllable metasurface sample for different illumination intensities, and the measured results are plotted in Fig. 3(c). It is obvious that when the light intensities E_v are switched between 0 and 10,000 lx, a ∼180 deg phase difference can be well achieved at several tested frequencies. Therefore, we can adopt light intensities of 0 and 10,000 lx to achieve the digital 0 and 1 metasurface elements, respectively. In other words, the time-coding sequences can be offered by the light signal that is changed rapidly between these two intensities. It should be noted that here we only present the measured results for the x-polarized and LCP incidences due to the polarization-insensitive feature of the metasurface.

When the reflection phases are switched between 0 deg and 180 deg with time, the metasurface is able to generate the harmonics.[17] Therefore, the light-controllable time-domain digital coding metasurface can produce different spectrum

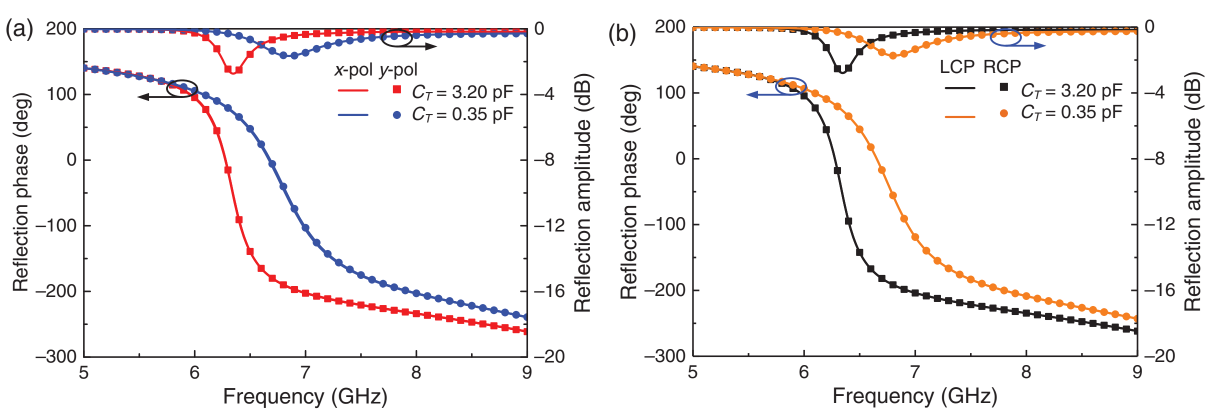

Fig. 2 Reflection performance of the digital metasurface element. (a) Simulated reflection phase and amplitude curves of the element for two different capacitances C_T under x- and y-polarized incidences. (b) Simulated reflection phase and amplitude curves of the element for two different capacitances C_T under LCP and RCP incidences.

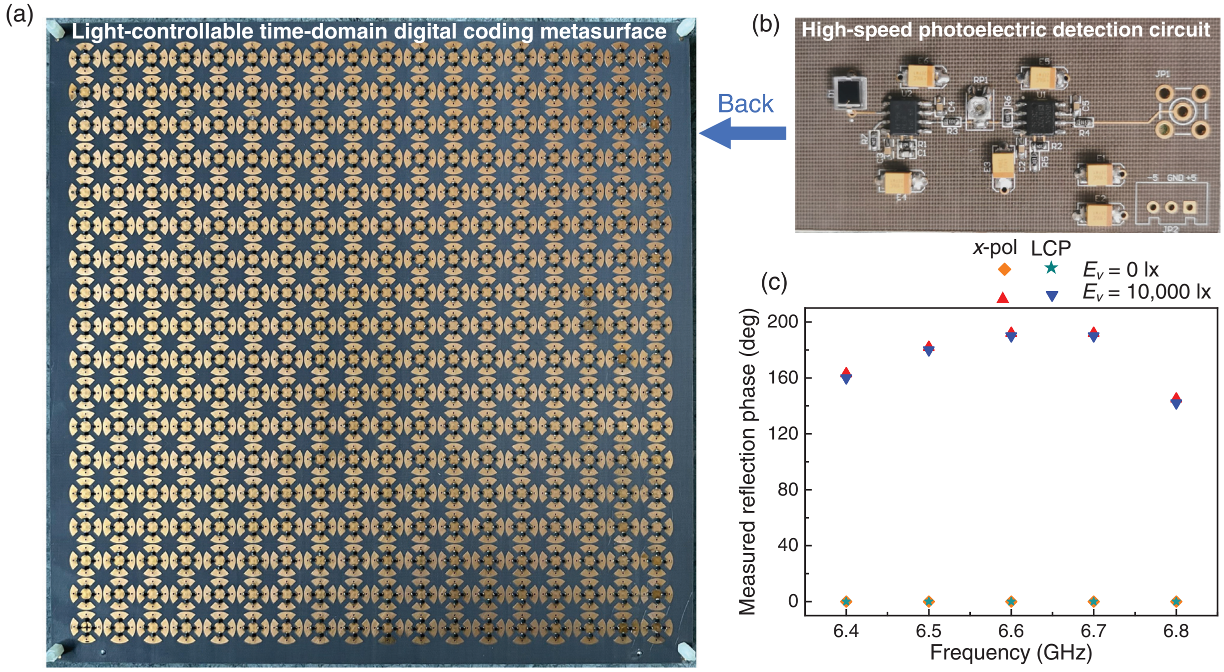

Fig. 3 The fabricated light-controllable time-domain digital coding metasurface and its performance. (a) Photograph of the programmable metasurface sample consisting of 18 × 18 digital metasurface elements. (b) Photograph of the high-speed photoelectric detection circuit integrated directly into the back of the metasurface sample. (c) Measured reflection phases of the light-controllable metasurface sample at several different frequencies for two different illumination intensities E_v under x-polarized and LCP incidences.

distributions when it is modulated by the time-coding sequences in light signals. Next, we will investigate the spectrum manipulation capability of the light-controllable time-domain digital coding metasurface. To provide time-varying light signals with different coding sequences, we design and realize a programmable light transmitting module that consists of a field-programmable gate array (FPGA) and a high-precision light-emitting diode (LED) light source. The FPGA is used to output digital codes to control and drive the LED light source. To avoid interferences, our experiments are carried out in a microwave chamber, and the experiment setup is shown in Fig. 4(a). In the experiments, the focused light source was fixed 1 m away from the back of the metasurface sample, which is used to provide time-varying light signals for illuminating the metasurface. In such a case, to generate enough illumination intensity, the maximum power of the LED light source is about 3 W. The transmitting antenna and the receiving antenna were connected to a vector network analyzer and a spectrum analyzer for emitting monochromatic waves and receiving reflected waves from the metasurface, respectively. It should be noted that here the metasurface sample is fully controlled by the programmable light source. In fact, except for the visible-light source, a laser light source can also be used to drive the metasurface sample, because the BPW 34S photodiode can work under the wavelength ranging from 400 to 1100 nm.

In measurements, we first test the reflection spectra of the metasurface sample for the periodic time-coding sequences of "0101010101…" with different modulation frequencies f_0 under x-polarized incidence. The measured spectrum distributions of the metasurface sample at $f_c = 6.5$ GHz for $f_0 = 100$ kHz and $f_0 = 200$ kHz are shown in Figs. 4(b) and 4(d), respectively. It is obvious that under this digital 0 and digital 1 alternately changed time-domain coding the spectrum of the metasurface is distributed symmetrically, and the main frequency components of the reflected waves are at $f_c \pm f_0$. By modulating the metasurface with the periodic pseudorandom sequence of "0010110111…" with different modulation frequencies f_0, the incident monochromatic signals are well spread into the white-noise-like spectra, as shown in Figs. 4(c) and 4(e). We also measure the reflection spectrum distributions of the light-controllable metasurface sample at 6.5 GHz for the two different kinds of time-coding sequences under the LCP incidence, as shown in Figs. 4(f)–4(i). From the tested spectrum distributions, we observe that the time-domain metasurface is able to generate the symmetrical spectrum and white-noise-like spectrum upon reflection under corresponding time-coding sequences. All the measured results indicate that the reflected harmonics of the metasurface can be well controlled by wireless light signals.

4 Discussion and Conclusion

For the 1-bit time-domain metasurface, the time-modulated reflection coefficient of the metasurface element is a periodic function of time, which can be decomposed into a Fourier series. Therefore, the modulated waves contain many harmonics, and the time-varying modulated waveform and the phase difference between two discrete states will affect both the amplitude and phase of the reflected harmonics.[34] By changing the 1-bit time-coding sequences, the metasurface element is able to produce an

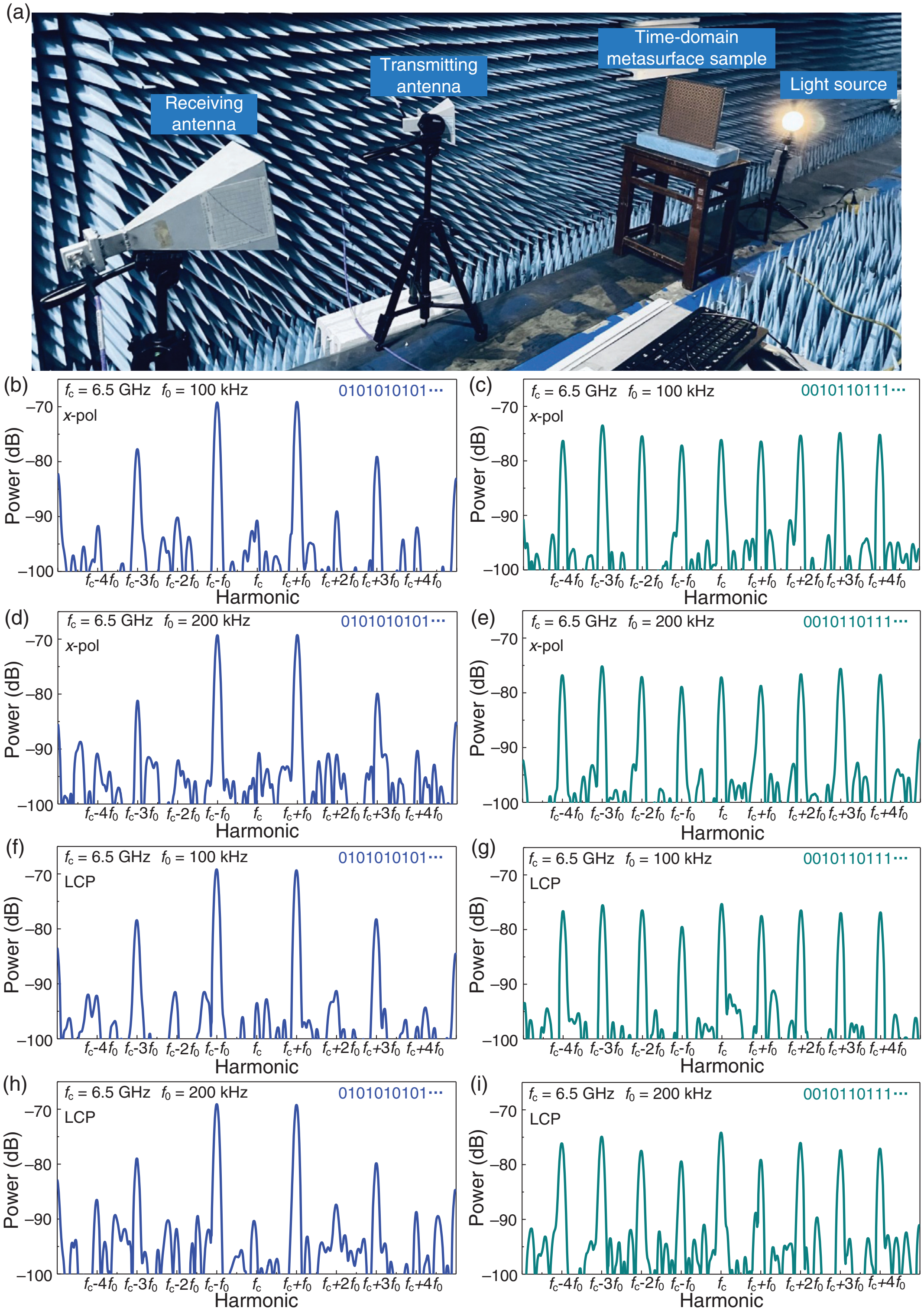

Fig. 4 Experiment setup and tested results. (a) Photograph of the experiment setup for spectrum tests. (b)–(e) Under x-polarized incidences, the measured reflected harmonics of the light-controllable time-domain metasurface at 6.5 GHz for two time-coding sequences of 0101010101… and 0010110111… with different modulation frequencies [(b), (c)] $f_0 = 100$ kHz and [(d), (e)] $f_0 = 200$ kHz. (f)–(i) Measured reflected harmonics for corresponding cases under LCP incidences.

equivalent phase, and the generated equivalent phase can be tuned from 0 deg to 360 deg. However, the 360 deg equivalent phase coverage can only be achieved at harmonic frequencies.[24] In addition, for the 1-bit temporal modulation, the modulated waves always contain a series of harmonics, and it is hard to realize a 100% frequency conversion, producing a pure frequency component. That is to say, the amplitude of the generated harmonics cannot reach 1.[12]

In our design, we use the photoelectric detection circuit to receive light signals to drive the varactor-based metasurface. Therefore, the switching speed of the time-domain metasurface mainly depends on the response time of the used varactor and the photoelectric detection circuit. In addition, because all varactors in the metasurface are connected in parallel, resulting in a large capacitance, the number of varactors will also affect the switching speed. On the designed light-controllable time-domain digital coding metasurface, the reflected spectra of the metasurface can be controlled by time-varying light signals in real time, which provides an effective way to process optical and microwave signals simultaneously. For example, digital information can be modulated on the waveforms of the light signal and then mapped directly onto the spectral characteristics of the reflected microwaves, achieving the light-to-microwave signal conversion. Therefore, such a light-controllable time-domain metasurface can be used to construct the direct light-to-microwave signal conversion platform, which is of great value for developing hybrid wireless communication systems using both light and microwaves as carriers.

In summary, we demonstrated a light-controllable time-domain digital coding metasurface for manipulating the dynamic microwave reflection spectrum in an optical programming way. The key to realizing the metasurface platform is integrating a high-speed and high-sensitivity photoelectric detection circuit into a programmable digital metasurface. Experimental results verified that the reflection phase of the metasurface can be controlled and modulated by visible light, thus generating the symmetrical spectrum distribution and white-noise-like spectrum upon reflection under the time-varying light illuminations with the designed 1-bit time-coding sequences. Moreover, the nonlinear harmonic manipulation capability can be achieved for arbitrarily polarized incoming microwaves, improving robustness and practicability of the metasurface. Our approach provides an actual route to control microwaves with visible light in the time domain on one single platform, which may helpful for developing advanced programmable multiphysics field devices and systems.

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Code, Data, and Materials Availability

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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