Programmable Amplitude-Coding Metasurface with Multifrequency Modulations

Qiao Ru Hong, Qian Ma, Xin Xin Gao, Che Liu, Qiang Xiao, Shahid Iqbal, and Tie Jun Cui* 

Recently, programmable metasurfaces have aroused great attention for various applications such as beam manipulation, wireless communication, and holograms by modulating the spatial phase or amplitude. However, programmable amplitude-coding modulations have rarely been investigated due to the difficulty in realizing dynamic control of amplitude. Herein, a real-time programmable amplitude-coding metasurface with multifrequency modulation is proposed by integrating PIN diodes and chip attenuators to the metaelement. The element is encoded as “11,” “10,” and “00,” corresponding to the ON/OFF states of two diodes. By switching the two states of the PIN diode, the metaelement exhibits distinctly reflected amplitude responses in three frequencies (2.98, 4.11, and 5.73 GHz). For the whole metasurface, the magnitude of the reflected beam can be modulated with some specific coding patterns. To verify the performance, six coding patterns with \(10 \times 10\) metaelements are designed, and four of them are measured. Experimental results are fundamentally consistent with theoretical designs and simulations. Further, a wireless communication demonstration is designed and implemented to perform direct modulation of digital signals without using mixers required in the conventional wireless communication systems. It is envisioned that this work will find applications in new architecture encrypted communication and imaging systems.

1. Introduction

In the past decades, metamaterials have attracted considerable interest in research due to their extraordinary electromagnetic (EM) properties. Metamaterials are artificial structures with subwavelength-scale elements, which derive their EM properties from the elements and their arrangement. Based on the concept, numerous novel physical phenomena and applications have been presented, including perfect lenses, metalens, and invisibility cloaks. As the planar versions of metamaterials, metasurfaces not only inherit the aforementioned advantages, but also overcome the problems encountered in metamaterials, such as difficulties in fabrication and integration and high loss. The modulation of EM waves is an enduring topic, and various tunable metasurfaces have been designed to possess reconfigurable functionality. Reconfigurability can be applied to metasurfaces using active devices such as PIN diodes. A photoresistor was connected to control the switching state of a PIN diode to achieve beam deflections. The EM properties, such as the amplitude, phase, and polarization, are the objects of modulation. With the designing of suitable metasurface units and their proper arrangement, metasurfaces have the capacity of controlling the amplitude, phase, and polarization of incident EM waves. Recently, the design of amplitude modulation has been extensively studied, which has greatly enriched the content of metasurface modulations. A wideband-metalamplitude modulator has been presented by injecting a liquid metal eutectic gallium indium alloy into the microfluidic channels to switch the working frequency band. Some amplitude-modulation elements are applied with multiple resonant structures for multiband amplitude modulation. Also, there is an approach to embed the active device in a metamaterial element and change the resonant structure of the unit by switching the diode states, thus realizing amplitude modulation at a certain frequency point.

However, the aforementioned amplitude-modulation designs either work at a single frequency point or cannot switch the operating frequency point, which greatly limits their application prospects.
To manipulate EM waves concisely, the concept of digital coding metasurfaces was presented, which further enriches the framework of metasurface modulation. EM characteristics such as amplitude, phase, and polarization can simply be characterized by “0” and “1” binary codes, which enables the direct modulation of EM waves. Compared to passive coding metasurfaces, more active coding metasurfaces have been proposed to expand the functionalities, such as beam controlling, focusing, orbital angular momentum generating, and imaging.

Here, we propose the programmable amplitude-coding metasurface with multifrequency modulation. PIN diodes and chip attenuators are integrated into the metaelement to alter the equivalent circuit. By switching two states of the PIN diode, the metaelement shows distinctly reflected amplitude responses in three frequencies (2.98, 4.11, and 5.73 GHz). To digitize the system, corresponding to the ON/OFF states of two diodes, we encode the three units as “11,” “10,” and “00.” By applying different codes, various amplitude-modulation manipulations at different frequencies are realized, where the magnitude of the reflected beam can be modulated using specific coding patterns for the whole metasurface. Changes in the amplitude of the reflected beam can be used to transmit information. Simulation and measurement results have good agreement. Moreover, a wireless communication system is proposed, which is verified by experiments. We envision that this work will find more applications in wireless communications and imaging.

2. Principle and Results

Based on the frequency coding metasurface, the real-time-programmable amplitude-coding metasurface with multifrequency modulation is shown in Figure 1. For a metasurface consisting of $N \times N$ elements, under the normal incidence of plane waves, the far-field function scattered by the metasurface is expressed as

$$f(\theta, \varphi) = A(m, n, f) \sum_{m=1}^{N} \sum_{n=1}^{N} \exp\left\{ -i(\varphi(m, n) + kD \sin \theta \left( m - \frac{1}{2} \right) \cos \varphi + \left( n - \frac{1}{2} \right) \sin \varphi \right\} \right\}, \tag{1}$$

where $\theta$ and $\varphi$ are the elevation and azimuth angles of an arbitrary direction, respectively; $\varphi(m, n)$ is the phase shift of each metaelement; and $(m, n)$ is the coordinate position. As shown in Figure 1, there are three beams with different colors standing for the incident waves with different frequencies (2.98, 4.11, and 5.73 GHz), and the corresponding units are coded as “11,” “10,” and “00.” Meanwhile, the two digits “0” and “1” correspond to the OFF and ON states of the diodes in the element. According to Equation (1), for the entire metasurface, it is known that the magnitude of the reflected beam can be tuned at different frequencies by presenting different coding sequences using field programmable gate array (FPGA). Consequently, we can control EM waves in both the amplitude and frequency domains. Amplitude modulations at different frequencies enable the metasurface to represent more information.

Compared to a single-frequency amplitude modulation metasurface, the triple-frequency amplitude modulations are able to carry triple information in a one-time frame according to information theory. Meanwhile, we can use a programmable amplitude-coding metasurface with multifrequency modulation to realize a wireless communication system. As shown in

![Figure 1. The amplitude-coding metasurface with multifrequency modulations is based on a programmable metasurface, which can achieve different real-time amplitude controls at different frequencies and can also realize information transmission. Here, “11,” “10,” and “00” respectively represent the three units of different states of the PIN diode, where “1” represents the diode state is ON and “0” represents the diode state is OFF. By applying specific coding sequences, different amplitude modulations and manipulations can be realized. Such a method can be easily applied for information transmission with the programmable amplitude-coding metasurface.](image-url)
Figure 1, in wireless communications, the time-varying control voltage from FPGA can be regarded as the modulation signal and the incident wave is a high-frequency carrier. Under the effect of the metasurface, the modulation signal controls the carrier amplitude, so the amplitude of the carrier waveform changes with the modulation signal. In this way, we can easily transmit information according to the changes in amplitude. As the metasurface can realize triple-frequency amplitude modulations, we can transmit the information at three different frequencies; namely, there are three frequency channels, as shown in Figure 1, which can greatly increase its application prospects.

The key point for realizing the programmable amplitude-coding metasurface with multifrequency modulation is to choose a suitable metaelement. A metallic structure printed on a dielectric substrate is designed to realize the aforementioned amplitude–frequency properties, as shown in Figure 2a. The three metal structures are connected by two PIN diodes to tailor the reflection amplitude. The element is composed of one substrate layer and two metal layers, using FR4 as the dielectric substrate with dielectric constant $\varepsilon_r = 4.3$ and tangent loss $\tan\delta = 0.025^\circ$.

The thickness of the substrate is 1.6 mm. The dimensions of the metasurface in Figure 2a,b are optimized as $L = 30$ mm, $H = 1.6$ mm, $L_1 = 20.1$ mm, $L_2 = 18$ mm, $L_3 = 10.2$ mm.

Figure 2. The design of the metaelement and the EM responses of different codes. a) The detailed structure of the metaelement. b) The top views of the element. c) Illustration of the equivalent circuit of the diode and attenuator. d–f) The reflected magnitude responses of the metaelement in three states “11,” “10,” and “00.” g) The reflection amplitudes of three coding sequences “1110,” “1000,” and “111 000.”
L11 = 18.8 mm, L22 = 13 mm, W1 = 20 mm, W2 = 15.2 mm, W3 = 11.5 mm, sx = 4 mm, and sy = 6 mm. The element consists of two PIN diodes (MACOM 14020) and a chip attenuator. The PIN diodes are not only biased by the feeding line printed on top of the substrate but also biased by the feeding network printed at the bottom of the substrate, with through holes connected to each other, as shown in Figure 2b. The PIN diode is equivalent to a series RLC model, as shown at the top of Figure 2c, in which R = 2.2 Ω, L = 0.4 nH, and C = 0 fF when the diode is switched on, and R = 0 Ω, L = 0.4 nH, and C = 40 fF when the diode is switched off.

The energy of incident waves can be divided into three parts, namely, the transmitted energy T(ω), the reflected energy R(αω), and the absorbed energy A(αω), which can be expressed as the following formula

\[ R(αω) = 1 - T(αω) - A(αω) \]  

As the bottom of the proposed metasurface is completely covered with a metal sheet, the EM wave cannot pass through. Therefore, the reflected energy R(αω) is nearly zero and only the absorbed energy A(αω) needs to be considered. The more is the energy absorbed, the less is the energy reflected, and the more pronounced the amplitude modulation will be. Thus, we use an attenuator chip for amplitude modulation. The 10 dB chip attenuator is integrated into the metaelement to dissipate the incident energy. The equivalent circuit of the attenuator is shown at the bottom of Figure 2c. It contains four resistors, two of which are 75 ohms for R1 and two of which are 25 ohms for R2. It possesses four pins, where we take ports 1 and 2 as the grounding port. A π network is formed when connecting ports 1 and 2 to the ground. Port 3 of the attenuator is connected to the bottom of the microstrip line, where R1 is parallel to the y-axis and R2 is parallel to the x-axis. Energy passing through the microstrip line is guided into the attenuator through port 3. Part of the introduced EM energy is first dissipated through the resistance and then reflected through the ground port. Some of the reflected energy is again dissipated through the resistance, eventually resulting in the majority of the incident energy being absorbed. Therefore, multifrequency amplitude modulation can be achieved by integrating an attenuator in the metaelement.

Figure 2d–f provides the simulated EM responses in three states for the metaelement. The simulations are performed using the commercial software Computer Simulation Technology (CST) Microwave Studio. As shown in Figure 2d–f, the ON–OFF states of the diode are encoded as “1” and “0,” respectively. In this way, we encode the metaelement as “11,” “10,” and “00” according to the switching state of the diode, which corresponds to three different operating frequencies 2.98, 4.11, and 5.73 GHz. We can obtain various amplitude modulation manipulations by applying different unit codes. Due to the existence of the attenuator, the reflected amplitudes at the three coding frequencies are very small. As shown in Figure 2d, when both PIN diodes are switched on, we encode the element as “11,” where the reflection magnitude is -28.2 dB at 2.98 GHz. The reflection amplitudes of the other two states are ≈0 dB, namely, the total-reflection states. Similarly, the other two unit states are coded as “10” and “00,” depending on the corresponding diode states, corresponding to reflection coefficients of -25.6 dB at 4.11 GHz and -19 dB at 5.73 GHz. In this way, the metasurface can realize more flexible controls on the amplitudes of the EM waves at three different frequencies. We can encode the information in a different frequency for better interference resistance and stability.

Next, we consider more situations when the array is composed of 1 × 2 and 1 × 3 elements, in which the coding patterns are “1110,” “1000,” and “111000,” respectively. In these cases, the simulation results of the reflection amplitudes are shown in Figure 2g. We note that when the state is “1110,” the reflection amplitudes of the array at 2.8, 2.98, and 4.12 GHz are less than -10 dB. The three frequency points are close to the operating frequency points of the metaelement in the working states “11” and “10.” Similarly, when the state is “1000,” the reflection coefficients of the array at 3.9, 4.12, and 5.82 GHz are close to -11.3 dB; when the state is “111000,” we observe that the reflection amplitudes of the array at 2.97, 3.88, 4.13, and 5.8 GHz are -7.7, -6.8, and -5.7 dB, respectively. That is to say, applying different coding sequences, the magnitude of the reflected beam can be modulated at different frequencies.

To validate the performance of the amplitude–frequency modulations, we propose six typical pattern states as examples, and the results and pattern diagrams are shown in Figure 3, in which the results are numerical simulations using CST. By applying different coding sequences to the metasurface array, we can modulate the magnitudes of far-field powers at different frequencies. As the amounts of metaelements in states “11,” “10,” and “00” in the coding sequences have changed, the magnitudes of the reflected beam vary accordingly.

By implementing independent controls on each element through FPGA, we can realize different states of the array at three frequencies. Here we use the array for simulations and experiments, in which the period pattern is 30 mm and the element number is 10 × 10. We present six sets of schemes, as shown in Figure 3a–j, to illustrate different functions achieved by the programmable amplitude-coding metasurface with multifrequency modulation in different coding modes. The simulated far-field results are displayed in Figure 3a–j, where the red part represents the far-field results of the perfect electric conductor (PEC) and the blue part represents the far-field results of the metasurface. The square in the upper left corner of Figure 3a–j represents the corresponding coding patterns of the simulated results. The square represents a 10 × 10 array in which the parts with different colors denote the units in different encoding states. Three colors are used to clearly distinguish the three coding states. We encode the elements with numbers “11,” “10,” and “00” to represent the three operating frequencies (3.01, 4.12, and 5.76 GHz). A small blue square denotes a unit that is in state “11.” In Figure 3a, because all elements of the array are in state “11,” the square in the upper left corner of Figure 3a is composed of only small blue squares. Similarly, in Figure 3b,c, all elements of the array are in states “10” and “11”; the square in the upper left corner of Figure 3b,c is composed of only small green and yellow units. From the radar-cross-section (RCS) results of the three schemes, it can be seen that RCSs in three cases are significantly reduced compared with the reflected beam of a perfectly conducting plate, which has the same dimension as the metasurface. When all elements are in state “11,” the RCS reduction is ~34.9 dB at 3.01 GHz. In state “10,” the RCS reduction is ~21.2 dB at 3.01 GHz.
4.12 GHz, while in state “00,” the RCS reduction is −19 dB at 5.76 GHz. These results demonstrate that we can realize the reduction of RCS at three frequencies, applying the same frequency codes (“11,” “10,” and “00”) on each metaelement.

To further validate the amplitude–frequency modulation characteristics, three periodic coding sequences “1110,” “1000,” and “111000” are introduced. Figure 3d–j shows the detailed simulation results for the aforementioned coding sequences, where...
2D far-field patterns are provided at the corresponding frequencies in each subgraph. When the coding sequence is “1110,” it means that all ten units in the first row are in state “11,” and all 10 units in the second row are in state “10.” The array elements are totally in the same state in the x-direction, and the “11” and “10” alternative states in the y-direction, as shown in the upper left corner of Figure 3d,e. The coding arrangement is the same for coding sequences “1000” and “111000.” The coding sequence “1000” represents that the “10” and “00” states alternate in the y-direction, and “111000” means that the “11,” “10,” and “00” states alternate in the y-direction, which can be seen from the diagram in the upper left corner of Figure 3f–j. When the code is “1110,” we can clearly observe that the RCS of the metasurface is reduced by 9.2 and 7.2 dB at 3 and 4.05 GHz, as shown in Figure 3d,e. Figure 3f,g shows that the RCS decreases by 8.8 dB at 4.07 GHz and 3.9 dB at 5.8 GHz in frequency coding patterns “1000.” In Figure 3h–j, when the state is “111000,” the RCS of the metasurface relative to the PEC drops 5.5, 2.9, and 2.6 dB, respectively. Therefore, for the whole metasurface, the magnitude of the reflected beam can be modulated by specific coding patterns.

To verify the metasurface performance experimentally, we used the printed circuit board (PCB) technique to fabricate a metasurface sample (see Figure 4a). The experimental environment for the S-parameter measurement is shown in Figure 4b. A lens antenna is applied to measure the reflection coefficient. The metasurface sample is composed of 10 × 10 elements, with 200 PIN diodes and 100 chip attenuators integrated, as shown in Figure 4a. The control voltages of PIN diodes corresponding to digits “1” and “0” are 1.6 and 0 V, respectively. Every row of the array shares two control voltages. The voltage-controlled bias network is integrated on the right side of the metasurface.

![Figure 4](https://www.advancedsciencenews.com)
The amplitude-coding modulation here is applied to one dimension rather than two dimensions for several reasons. First, we focus on the beam-amplitude manipulation using the entire metasurface, and hence 1D bias control is sufficient for the amplitude regulations we need in this demonstration. Second, the 1D feed is convenient to implement and cost-saving, whereas the control circuit of a 2D feed is very complicated and expensive.

As examples, we choose four frequency coding sequences to validate the concepts: “11,” “10,” “00,” and “111 000.” The results of the measured reflection coefficients for different coding states are given in Figure 4a–d. We note that there are some excrescent resonance points in the measurements compared to the simulation data, and a frequency deviation exists between the measured and simulated frequency points. These disagreements are mainly caused by the error in components, fabrication, and measurements.

The measured reflection coefficients when applying the same states (“11,” “10,” and “00”) on each element are shown in Figure 4c–e, represented by straight lines. Also, the corresponding unit simulation results are displayed in Figure 4c–e by dotted lines. The blue, red, and purple curves represent the reflection coefficients when the codes are “11,” “10,” and “00,” respectively. We note that the metasurface element exhibits distinctly reflected amplitude responses when switching the two diode states. As shown in Figure 4c, when the frequencies are 2.9 and 3.05 GHz, the measured array reflection amplitudes of the “10” and “00” states are close to 0 dB, whereas on switching to the “11” state, the reflection amplitude reduces to –12.5 dB, and the simulated reflection coefficient of the unit is –28.2 dB at 2.98 GHz. It can be seen that the frequency point of the unit simulation and the frequency point of the measured array are very close in state “11.” In the highlighted regions of Figure 4d, when the state is “10,” the measured array reflection amplitude is –14 dB at 4.22 GHz, where the other two states are close to the total reflection. Corresponding to this frequency point, the simulated frequency is 4.17 GHz, as shown by the dotted lines, which has a deviation of 0.05 GHz from the measured frequency point. As shown in Figure 4e, at 5.17 GHz, the reflection amplitude of state “00” is –15 dB. However, the reflection amplitudes of the other two coding states are between –5 and –10 dB. We believe that this is because the design frequency of the attenuator is 3 GHz, and its equivalent circuit may change to some extent at 5 GHz. The attenuator chip has a parasitic effect, which may lead S11 to alter in states “11” and “10.” Meanwhile, the frequency deviation of both measured and simulated is less than ±0.5 GHz. Figure 4f shows the reflection coefficient diagram when the coding sequence is “111 000,” and the corresponding array coding diagram is given in Figure 4g. In the highlighted regions of Figure 4f, the measured frequency points correspond to 2.92, 3.96, and 5.17 GHz, and their amplitude values are –6, –7.5, and –18 dB, respectively. On the other hand, the frequency points of the simulation results are located at 2.84, 3.86, and 5.71 GHz. In this case, the frequency deviations become larger because some excrescent resonance points occur in the measurement results. The error between the simulation and measurement results is mainly due to the following reasons: 1) the error of the simplified RLC equivalent circuit between the simulation model and fabricated sample; 2) the error in the fabrication process; and 3) the manual experiment and operation errors.

Using the programmable amplitude-coding metasurface, we propose to design a wireless communication demonstration as a proof of concept. The carrier modulation process of the traditional wireless communication system requires mixing the baseband signal with the modulation signal by a device such as a mixer. Usually, the baseband signal is applied with information to modulate the physical properties, such as the amplitude and phase, of the high-frequency carrier. In this system, the coding metasurface can be designed to receive signal modulation and transmission without using the original complicated analog devices. As shown in Figure 5a, the digital drive voltage signal from the FPGA can be regarded as the baseband signal in wireless communications, where the amplitude contains the binary information we want to transmit. In the same way, the high-frequency incident signal generated by the signal generator can be taken as a high-frequency carrier. Under the influence of the metasurface, the modulation signal controls the carrier amplitude so that the amplitude of the carrier waveform can be viewed by an oscilloscope. In this way, we can easily encode the 1 bit digital information in one frequency channel. As the metasurface can achieve amplitude modulation in three frequencies, three frequency channels can take advantage to transmit information, which will broaden its application prospects. The modulation speed can be achieved to 10 kHz in this demonstration based on the current FPGA. The time-switching frequency of the FPGA used for the test is 10 kHz, so the time occupied by 1 bit of information on the x-axis in Figure 5d is 0.1 ms, as marked in the figure. Also, the magnitude values are added on the y-axis, which is normalized to 1. According to the principle of amplitude keying modulation, as shown in Figure 5d, the baseband signal waveform contains the information to be transmitted. Under the modulation of the high-frequency carrier, the modulated signal is generated, and the amplitude of the modulated signal varies with the baseband signal, so the modulated signal also contains the information we need.

To verify the feasibility of the aforementioned wireless communication, we decided to transmit the word “META” at a frequency of 2.98 GHz. The binary ASCII codes corresponding to the letters M, E, T, and A are shown in Figure 5b. The codes of M, E, T, and A are “01001101,” “01000110,” “01010100,” and “01000001,” respectively. Figure 5c shows the amplitude response of the metasurface. At 2.98 GHz, when the ON–OFF state of the PIN diodes is altered, different amplitude responses are produced. We can acquire the transmitted information based on the received reflected signal. Encoding a reflection signal with a very low amplitude of –28.2 dB as “0” and a reflection signal of 0 dB as “1,” by this means, the FPGA can be applied to output a specific series of voltage signals whose amplitudes correspond to the binary ASCII codes of these letters. The waveform received by the oscilloscope, namely, the test result of the modulated signal waveform, is shown in Figure 5e. We find that the amplitude of the waveform varies regularly with the modulated signal and is in good consistency with the modulated signal waveform in the schematic diagram. The circled part in Figure 5e, representing the code “1,” is the waveform in which the high level of the baseband signal is modulated by the high-frequency carrier and the actual waveform is shown on the left.
Because the programmable amplitude-coding metasurface can realize amplitude modulation in three frequencies, the communication system is capable of multifrequency transmission of information. Suppose that we want to transmit information at 4.11 GHz. As shown in Figure 2e, the reflection amplitude of the unit is $25.6$ dB at 4.11 GHz in the “10” states, and $S_{11}$ in the other two states at that frequency is nearly 0 dB, which is close to the fully reflected state. Similarly, as shown in Figure 2f, the reflection amplitude of the unit at 5.73 GHz is $19$ dB in the state “00.” The reflection amplitudes of the other two states are $\approx 0$ dB, namely, the total-reflection states. Therefore, it can transmit the information at the three frequency points. However, the three frequency points are not completely independent in regulation because we only have two PIN diodes to generate four states. Although we only test one of the frequency points, this design can transmit information at three frequency points based on the same principle.

3. Conclusion

We proposed a programmable amplitude-coding metasurface with multifrequency modulation based on the programmable metasurface to realize amplitude modulation at three frequencies. We designed the coding element integrated with PIN diodes and a chip attenuator to obtain the multifrequency amplitude modulation properties. A metasurface array with $10 \times 10$ elements was fabricated. Six coding sequences are presented and
simulated, and four of them are measured. The experimental results have good agreement with the numerical simulations, further verifying the programmable amplitude-coding metasurface with multifrequency modulation and the design method. By applying different sequences of coding, the synthetic amplitude responses of reflected waves at different frequencies can be controlled, making the functionality more flexible. Meanwhile, a wireless communication system was designed where the programmable amplitude-coding metasurface with multifrequency modulation is used to modulate the signal without the conventional complex analog devices. Transmitting the letter “META” by applying the system, the experimental results show good agreement with the expected assumptions. We conceive that this work will provide more application potential in the field of frequency-hopping systems, communications, imaging in multifrequency.

Acknowledgements

Q.R.H. and Q.M. contribute equally in this work. This work was supported by the National Key Research and Development Program of China (2017YFA0700201, 2017YFA0700202, and 2017YFA0700201), the National Natural Science Foundation of China (61631007, 61571117, 61522106, 61731010, 61722106, 61701107, and 61701108), the 111 Project (111-2-05), and the Fund for International Cooperation and Exchange of National Natural Science Foundation of China (61761136007).

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

amplitude coding, multifrequency modulations, programmable metasurfaces

[1] J. B. Pendry, D. Schurig, D. R. Smith, Science 2006, 312, 5781.
[2] R. A. Shelby, D. R. Smith, S. Schultz, Science 2001, 292, 5514.
[3] J. B. Pendry, Phys. Rev. Lett. 2000, 85, 18.
[4] T. Ergin, N. Stenger, P. Brenner, J. B. Pendry, M. Wegener, Science 2010, 328, 5976.
[5] F. M. Hui, T. J. Cui, Nat. Commun. 2010, 1, 3.
[6] Q. Ma, Z. L. Mei, S. K. Zhu, T. Y. Jin, T. J. Cui, Phys. Rev. Lett. 2013, 111, 173901.
[7] T. J. Cui, S. Liu, L. L. Li, Light: Sci. Appl. 2016, 5, 16172.
[8] C. M. Soukoulis, M. J. N. P. Wegener, Nat. Photonics 2011, 5, 9.
[9] N. F. Yu, P. Genevet, M. A. Kats, F. Aieta, J. P. Tetienne, F. Capasso, Z. Gaburro, Science 2011, 334, 6054.
[10] L. Chen, Q. F. Nie, H. Y. Cui, J. Appl. Phys. 2020, 128, 7.
[11] L. Chen, Q. F. Nie, Y. Ruan, S. S. Luo, F. J. Ye, H. Y. Cui, Opt. Express 2020, 28, 13.
[12] Q. Ma, Q. R. Hong, X. X. Gao, H. B. Jing, C. Liu, G. D. Bai, Q. Cheng, T. J. Cui, Nanophotonics 2020, 9, 3271.
[13] X. Ding, Z. Wang, G. Hu, J. Liu, K. Zhang, H. Li, B. Ratni, S. N. Burokur, Q. Wu, J. Tan, C. W. Qiu, PhotonX 2020, 1, 16.
[14] H. K. Kim, S. Lim, IEEE Antennas Propag. Soc. Int. Symp. 2016, 495–496, 7695956.
[15] L. Huang, H. Chen, Prog. Electromagn. Res. 2011, 113, 103.
[16] Z. Mao, S. Liu, B. Bian, B. Wang, B. Ma, L. Chen, J. Xu, J. Appl. Phys. 2014, 115, 20.
[17] Q. W. Ye, Y. Liu, H. Lin, M. H. Li, H. L. Yang, Appl. Phys. A: Mater. Sci. Process. 2012, 107, 1.
[18] M. Bakir, M. Karaaslan, F. Dincer, K. Deliahicaglu, C. Sabah, J. Mater. Sci.: Mater. Electron. 2016, 27, 11.
[19] H. Jeong, S. Lim, Sci. Rep. 2018, 8, 9226.
[20] L. Chen, Q. Ma, H. B. Jing, H. Y. Cui, Y. Liu, T. J. Cui, Phys. Rev. Appl. 2019, 11, 054051.
[21] Q. Ma, L. Chen, H. B. Jing, Q. R. Hong, H. Y. Cui, Y. Liu, L. L. Li, T. J. Cui, Adv. Opt. Mater. 2019, 7, 1901285.
[22] J. Luo, Q. Ma, H. B. Jing, G. D. Bai, T. J. Cui, J. Appl. Phys. 2019, 126, 113102.
[23] Q. Ma, G. D. Bai, H. B. Jing, C. Yang, L. Li, T. J. Cui, Light: Sci. Appl. 2019, 8, 1.
[24] Q. Ma, Q. R. Hong, G. D. Bai, H. B. Jing, T. J. Cui, Phys. Rev. Appl. 2020, 13, 021003.
[25] T. J. Cui, S. Liu, L. Zhang, J. Mater. Chem. C 2017, 5, 15.
[26] T. J. Cui, M. Q. Qi, X. Wan, J. Zhao, Q. Cheng, Light: Sci. Appl. 2014, 3, 218.
[27] Q. Ma, T. J. Cui, PhotonX 2020, 1, 1.
[28] Q. Ma, C. B. Shi, G. D. Bai, T. Y. Chen, A. Noor, T. J. Cui, Adv. Opt. Mater. 2017, 5, 1700548.
[29] L. Li, T. J. Cui, W. Ji, S. Liu, J. Din, X. Wan, Y. B. Li, M. Jiang, C. W. Qiu, S. Zhang, Nat. Commun. 2017, 8, 197.
[30] L. Li, H. Ruan, C. Liu, Y. Li, Y. Shuang, A. Alù, C. W. Qiu, T. J. Cui, Nat. Commun. 2019, 10, 1082.
[31] D. Wang, C. Liu, C. Shen, Y. Xing, Q. H. Wang, PhotonX 2020, 1, 6.
[32] H. T. Wu, S. Liu, X. Wan, L. Zhang, D. Wang, L. Li, T. J. Cui, Adv. Sci. 2017, 4, 1700098.
[33] C. E. Shannon, Bell Syst. Tech. J. 1948, 27, 379.
[34] T. J. Cui, S. Liu, G. D. Bai, Q. Ma, Research 2019, 2019, 2584509.
[35] T. Zhan, J. Xiong, J. Zou, S. T. Wu, PhotonX 2020, 1, 12.