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Full controls of OAM vortex beam and realization of retro and negative reflections at oblique incidence using dual-band 2-bit coding metasurface

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Abstract

This paper addresses a reflection-type dual-band 2-bit coding metasurface (CM) design to achieve the dual-band functionalities in two different operating bands, independently. We are particularly interested to control linearly polarized incident waves by encoding the propagation or dynamic phase in order to realize and fully control the orbital angular momentum (OAM) vortex beam (VB) for dual bands. In this regard, we perform digital addition operations to combine the coding sequences of traditional OAM (OAM that propagates in the normal direction) and phase-gradient to construct the proposed CM, which generates and steers OAM-VBs with different topological charges ($\pm l$) in both lower ($l_f$) and higher ($h_f$) bands. The proposed concept is further extended to realize multiple OAM-VB with various beam shaping by combining the coding sequence that generates OAM in the normal direction and the coding sequence of beam shaping, and we discuss three different scenarios. Firstly, split OAM-VB is generated in both lower and higher bands. Secondly, quad OAM-VB is realized to verify the proposed concept. Finally, yet importantly, we show that the reflected beam directions can be further independently controlled to achieve anomalous, negative and retro reflections at the two bands. Two CM samples are fabricated to experimentally validate the proposed OAM-VB generation with steering features and retro or negative reflections at oblique incidences, which are in good agreement with the simulation results. The proposed concept will open up possibilities of multifunctional meta-devices and will be useful in many applications such as optical spanners, quantum optics, spatial mode multiplexing for telecommunications, and astronomy etc.

1. Introduction

Orbital Angular Momentum (OAM) carried by vortex beam (VB) is increasingly recognized as an important dimension in the field of communication optics. The phase profile of OAM is described by the $\exp(i\theta)$, in which the topological charge $l$ can be any integer value [1–4]. This unlimited freedom of $l$ provokes the larger information capacity. Thus, OAM-VB has various potential applications in antennas and radio communication to increase communication capacity without broadening the bandwidth [5, 6]. The generation of OAM-VB has been investigated in the microwave bands [7–10] and optical domain [11–13]. In addition, several good approaches exist for OAM-VB generation including circular phased array antenna [14–17], spiral parabolic antenna [18–20], and spiral phase plate (SPP) [21, 22]. Recently, metasurfaces (MS) provided a novel route to
successfully generate the OAM beams [23–36] having more advantages compare to conventional methods such as: easy-to-fabricate, light weight, and ultrathin profile [37, 38] etc.

In general, MS acts as a lens or a reflector in OAM-VB generation. In which the transmission and (or) reflection phase of the incident wave can be easily tailored to satisfy the phase-condition of OAM-VB by properly adjusting the rotation angle/size of the MS’s elements. Curiously, traditional MS does not resolve the basic problem to generate flexible and multiple OAM-VB with different angles. To overcome this, the coding metasurface (CM) [39] concept was proposed that creates link between digital codes and MS particles to realize the powerful manipulation of electromagnetic (EM) waves using simple coding sequences. Since then, various functionalities [39–48] have been obtained by simply implementing the corresponding coding sequences, i.e., beam focusing [43, 44], beam steering [42–44], random EM-wave scattering [47], beam shaping [39, 48] and OAM-VB generation [49–51] etc. Further ahead, passive MSs [43, 44, 48, 52, 53] were investigated to fulfill the demand of multifunctional devices. On the other hand, these passive MS designs are hard to be electronically controlled. In order to resolve these flaws of passive MS, active MS [54–56] approach is employed involving multi-band and multifunctional applications. Similarly, more endeavors have been made to improve the bi-functional MS opportunities for EM waves controlling in full-space [57].

However, previous works done dealt with the bi-functional realizations for steering and shaping EM beams. Alongside this, L. Zhang et al. proposed a single-band Pancharatnam-Berry (PB)/geometric-phase CM to steer and shape the OAM-VB by controlling the circularly polarized EM waves [51]. It is clear that linear polarization is an important factor to use OAM-VB in many applications for example: optical spanners [58], quantum optics [59], spatial mode multiplexing for telecommunications [60], and astronomy [61–65] etc. Therefore, multifunctional dual-band CM for linear polarization still needs to be explored for the generation of flexible, and multiple OAM-VB with different topological charges, independently.

So, the work in this paper focuses on the realization of flexible (steerable) and multiple OAM-VB with different modes at two different frequency bands. Compare to the PB-CM design [51], here, two different kinds of phase modulation apertures are closely integrated into one meta-atom, and then use the entire CM aperture to realize the OAM beam independently at dual-band for linear polarization. We combine the normal OAM coding sequence and phase gradient coding sequence to design a new coding sequence of the proposed CM that can operate at two different operating bands independently, i.e., lower \( f_l \) and higher \( f_h \) bands. By independently designing dynamic propagation phase distributions, the proposed CM is expected to achieve OAM-VB with different topological charges \( l \) and deflect to opposite half planes. This phenomenon of OAM-VB deflection can be seen in figure 1(a). We further extended this work to generate OAM-VB shaping and discuss two different scenarios. In the first case, OAM-VB splitting is performed to achieve different topological charges \( l \) in both lower and higher bands, independently. Similarly, quad-beam shaping is realized to verify the proposed concept of this paper. Overall, this OAM-VB shaping task is accomplished by the addition of OAM-phase and splitting phase [39, 48] unit-cells. Finally, yet importantly, figure 1(b) illustrates that the reflected beam directions can be further independently controlled to achieve anomalous and retro reflection at two different operating bands. The proposed concept will be crucial in the design of multifunctional meta-devices with multispectral features in terahertz and optical regimes.

The rest of the manuscript is organized as follows: section 2 presents relevant aspects of the unit-cell design that is important in metasurface formation. The detailed discussion of proposed designs and its various

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**Figure 1.** Schematic illustration of the dual-band 2-bit CM to generate and fully control both the: OAM vortex beam, and anomalous and retro reflection, with linear polarization and oblique incidences, respectively. (a) Independent manipulations of incident waves to generate and deflect OAM-VB to opposite half-plane in both lower \( f_l \) and higher \( f_h \) bands. (b) Independent manipulations of planar waves to achieve anomalous reflection (in lower band) and retro reflection (in higher band) under the oblique incidence.
applications are examined in section 3. Section 4 demonstrates the fabrication and measurements of the proposed designs. Section 5 concludes the manuscript.

2. Materials and methods

2.1. Unit-cell design

To start with, we required sixteen quantized reflection phases to achieve the dual-band 2-bit functionality of the proposed CM that obey the binary rule of $2^{m,n}$. Where, ‘$m$’ and ‘$n$’ represent the number of operating bands and the number of quantized phases, respectively. In the meanwhile, the quantized phases for each operating band can be found with the help of the following matrix, given in equation (1).

$$M^{2-bit} = \begin{array}{cccc}
00/00 & 00/01 & 00/10 & 00/11 \\
01/00 & 01/01 & 01/10 & 01/11 \\
10/00 & 10/01 & 10/10 & 10/11 \\
11/00 & 11/01 & 11/10 & 11/11
\end{array}$$

(1)

In equation (1), each binary number before slash (in each row) represents the phase state for lower band ($l_2$). On the other hand, the binary numbers after slash show the phase state in the higher band ($l_1$). The unit-cell of the proposed CM is composed of two square and (or) rectangular metallic patch resonators with a ground metallic layer for complete reflection, can be seen in figure 2(a). Therefore, two dielectric spacers F4B (with $\varepsilon = 2.65$ and tangent loss $\delta = 0.001$) are used to separate the ground metallic layer and two patches. To make the design procedure easy to understand, the geometrical parametric values of coding particles are given as following: lattice constant $p = 7 \text{ mm}$, thickness of each dielectric substrate $h = 1 \text{ mm}$, thickness of the ground
layer and each copper metallic patch \( t = 0.018 \text{ mm} \). In addition, \( w_1 \) and \( w_2 \) describe the side lengths of both inner and top metallic patches along the \( x \)-axis, respectively. Similarly, \( l_1 \) and \( l_2 \) represent the side lengths of both inner and top metallic patches along the \( y \)-axis, respectively. The specific aim of this paper is still questioned to provide a dual-band 2-bit CM in favor of controlling OAM-VB for linear polarization. In this context, we choose the off-diagonal phase states of matrix \( M^{2-\text{bit}} \), i.e., \( M_i = [00/11, 01/10, 10/01, 11/00] \). Interestingly, it can be noticed that the direction of phase gradient is opposite in the two operating bands. For example, the phase gradients for lower-band \([00, 01, 10, 11]\) are in ascending order, while for the higher band, the phase gradients \([11, 10, 01, 00]\) are in descending order. Therefore, such a difference in phase gradients provoke steering in the opposite half-space by sharing the same aperture and this phenomenal beauty is the key point to accomplish the proposed concept of this paper.

Here, we claim that the proposed dual-band 2-bit CM determines the properties of the OAM-VB generation and steering in opposite half-plane with equal and opposite topological charges, in the presence of linear-polarized incidence wave. In this scenario, all sixteen coding-particles are obtained from \( M_i \) by optimizing the dimensions \((l_1, w_1, l_2, w_2)\) of two patches as shown in figure 2(a). Moreover, commercially available software CST, MWS is used to verify the validation of the proposed unit-cell under normal incidence of \( x \)-polarized plane waves with unit cell boundary conditions. Optimized geometrical parameters for all coding particles of figure 2(a) are achieved by employing parametric sweeps for the values of the side-lengths of both patches in the unit cell. The desired reflection- phases for the acquired coding particles are achieved in both the lower-band (9.2–10 \( \text{GHz} \)) and higher-band (14.4–15.1 \( \text{GHz} \)) under the normally incident \( x \)-polarized wave, can be seen in the supplementary material as figure S1(b) and S1(c) is available online at stacks.iop.org/MRX/6/125804/mmedia, respectively.

It can also be noticed that for each four identical reflection phases in lower-band, there exist four reflection phases in higher-band. Therefore, two consecutive phases are \( 90^\circ \pm 10^\circ \) out of phases from each other to mimic dual-band 2-bit coding particle. Therefore, figure S1b illustrates the phase response of the first four meta-atoms in which the pink color shaded region represents the lower-band and blue-color is for higher-band. Similarly, phase responses of all coding particles in lower band can be seen in figure S1c. Moreover, phase responses of all coding particles in higher band are given in figure S1d. Most importantly, phase responses of both the diagonal and off-diagonal phases of matrix \( M^{2-\text{bit}} \) for both operating bands are presented in figures 2(b) and (c), respectively. The amplitude responses of all coding particles in both operating bands are given in figure S1e.

### 3. Results and discussions

Firstly, the concept of super unit-cell is used for various coding sequences to avoid unwanted coupling between different coding particles that are placed adjacently and have different patch sizes. Secondly, the super unit-cell has freedom for the coding sequence to achieve the desired functionalities in different operating bands, independently. As an example, we focus on the generation of OAM-VB in different direction, and to achieve negative, anomalous and retro-reflection, independently. In the following, full-wave simulations are carried out by employing CST, MWS with open add space boundary conditions under both normal and obliquely incident \( x \)-polarized plane waves.

#### 3.1. OAM-VB steering

Although, a series of research has been done for beam steering using MS [39, 41–43, 66–68] and such previous designed meta-devices are applicable to single-band. Meanwhile, OAM-VB steering has also been investigated in [51] having lack of multi-band and linear-polarization features. Here, we demonstrate the generation of OAM-VB steering to opposite half planes in the two operating bands independently. This task is achieved by the proper selection and careful distribution of the coding particles among the available designed sixteen meta-atoms. For this purpose, we selected the off-diagonal particles of \( M^{2-\text{bit}} \) represented by \( M_i \) and distributed them carefully. In this perspective, the convolution theorem [69] helps to link the coding patterns of different functionalities that enable us to construct the coding pattern of new design of CM. In simple words, the new coding sequence of the proposed CM is the combination of both the normal OAM coding sequence and phase gradient coding sequence. For the current design, the coding sequence has the binary pattern of \( M_i = M_t + M_g \), where the addition is the binary addition, and \( M_g \) is the phase gradient coding sequence, i.e., \( M_g = 00, 01, 10, 11 \). To verify the OAM-VB steering feature, the proposed concept of unit-cell (section 2.1) is adopted. Overall, the full structure is composed of 32 \( \times \) 32 coding particles, where the period of gradient coding sequence is 16 unit-cells under \( x \)-polarization incidence for both operating bands. Moreover, the deflection angle for the proposed design in two operating bands can be calculated from equation (2).
\[ \theta_d = \sin^{-1} \left( \frac{\lambda}{\Gamma} \right) \]  

where, ‘\( \lambda \)’ is the wavelength of the incident wave and ‘\( \Gamma \)’ is the period of the coding sequence.

For easy to understand, figure 3 depicts the coding patterns of proposed design to generate OAM-VB and beam steering for linearly x-polarized incidence. Figure 3 contains three different coding patterns (figures 3(a)–(c)) and their corresponding 3D and 2D scattering patterns (simulated results) for both lower-band (figures 3(d)–(e)) and higher-band (figures 3(f)–(g)). The coding pattern in figure 3(a) consists of four segments and the successive phase step from one segment to another is ±90°. This kind of rotated phase distribution has a tendency to generate OAM-VB of mode \( l = 1 \). In the next step, we add the coding pattern ‘\( M'_1 \)’ of figure 3(a) with the phase gradient coding sequence ‘\( M'_2 \)’ varying along the x-direction (figure 3(b)). The resultant coding pattern ‘\( M'_3 \)’ can be seen in figure 3(c) that generates the OAM-VB with deflection angle \( \theta_d \). For lower-band, the generated OAM-VB from figure 3(c) deflects to the left-side that can be seen in figures 3(d)–(e). Similarly, for higher-band, figures 3(f)–(g) represent the generation and deflection of OAM-VB towards the right side. It can be noticed that the topological charge of the realized OAM have opposite values in each operating bands, such as ‘\( l = +1 \)’ in lower-band and ‘\( l = -1 \)’ in higher-band.

Figure 3. Coding patterns and the simulated 3D and 2D far-field scattering patterns to show the performance of dual-band OAM-VB steering for linear polarization incident with topological charge \( l = 1 \). (a)–(c) Coding pattern of the normal OAM-VB generation, beam steering and OAM-VB deflection respectively. (d), (e) 3D and polar form scattering pattern of OAM-VB steering in the lower band for x-polarized incident at frequency of 10 GHz. In which the normal incident wave creates the reflected OAM-VB that steers to left direction. (f), (g) 3D and polar form scattering pattern of OAM-VB steering in the higher-band for x-polarized incident at frequency of 15 GHz. In which the normal incidence causes OAM-VB generation that steers to right direction.
3.2. OAM-VB shaping

From the aforesaid discussion, the deflection of OAM-VB to any direction is achieved by the addition of two different coding patterns, i.e., the addition of coding pattern which generates OAM in the normal direction and gradient coding pattern which is responsible for beam steering. Similarly, beam shaping [39, 48] of OAM-VB can be obtained by adding the beam shaping coding sequence with the coding sequence of normal OAM-VB. In this section, we will again use the convolution operation to realize flexible and multiple OAM-VB for linear-polarization. For this purpose, we add the OAM-VB coding pattern (figures 3(a)/4(a)) to the coding pattern of the normal OAM-VB and beam-splitting respectively (c) The mixed coding pattern formed by adding the coding patterns in (a) and (b). (d)–(f) Coding pattern for normal OAM-VB, quad beam generation and quad OAM-VB generation respectively. (g), (h) 3D scattering pattern of OAM-VB splitting in the lower and higher band respectively. (i), (j) 3D Scattering pattern of quad OAM-VB in the lower and higher band respectively. (k), (l) Scattering pattern in polar form of split OAM-VB in the lower and higher band, respectively. (m), (n) Scattering pattern in polar form of OAM-VB in the lower and higher band respectively. (o)–(p) Scattering patterns in polar form of quad OAM-VB in lower and higher bands.

Figure 4. Coding patterns and the simulated 3D and 2D far-field scattering patterns to show the performance of dual-band OAM-VB splitting and OAM-VB quad-beam splitting for linear polarization incident with topological charge \( \ell = 1 \). (a), (b) Coding pattern of the normal OAM-VB and beam-splitting respectively (c) The mixed coding pattern formed by adding the coding patterns in (a) and (b). (d)–(f) Coding pattern for normal OAM-VB, quad beam generation and quad OAM-VB generation respectively. (g), (h) 3D scattering pattern of OAM-VB splitting in the lower and higher band respectively. (i), (j) 3D Scattering pattern of quad OAM-VB in the lower and higher band respectively. (k), (l) Scattering pattern in polar form of split OAM-VB in the lower and higher band, respectively. (m), (n) Scattering pattern in polar form of OAM-VB in the lower and higher band respectively. (o)–(p) Scattering patterns in polar form of quad OAM-VB in lower and higher bands.
higher-band with x-polarized incidence, respectively. Moreover, the coding Pattern of OAM-VB (figure 4(d)) is added to the coding pattern of chess board like configuration (quad-beam generator) as shown in figure 4(e). Whereas, the chess board like configuration shape the reflected field into quad-beam. Consequently, the new coding pattern (figure 4(f)) is the addition of quad-beam generator and the OAM-VB that has the ability to generate quad-OAM-VB. The simulated results for this case are displayed in figures 4(i)(j) and figures 4(m)–(p). Figure 4(i) shows the 3D scattering pattern of quad OAM-VB in the lower-band, in which four OAM-VB can be observed. Further, scattering patterns in polar co-ordinates of quad OAM-VB in lower-band are given when the cut angle \( \theta = -45^\circ \) (figure 4(m)) and \( \theta = 45^\circ \) (figure 4(n)). Similarly, figure 4(j) represents the 3D scattering pattern of quad OAM-VB in the higher band for x-polarized incidence. In addition, scattering patterns in polar co-ordinates for this case are given when the cut angle \( \theta = -45^\circ \) (figure 4(o)) and \( \theta = 45^\circ \) (figure 4(p)). In all the cases, the simulation results have an excellent agreement with the theoretically predicted results.

3.3. Negative and retro reflection

All the positive results for the above-described proposed CM in section 3.1–3.2 point out the full-control of OAM-VB in different bands, simultaneously. In some scenarios, we need to control the reflected beams to achieve anomalous, negative and retro reflection etc. For this sake, CM provides more flexibility to deflect the reflection or transmission beam in the user defined direction [41–43] for both normal and oblique incidences. In addition, the retro reflection phenomenon has also been investigated using planar MS [70] in which the angle of reflection is the same as the angle of incidence. However, these designs are applicable to predefined functionality and still suffer multifunctional and multispectral properties. Similarly, a need still exists to achieve anomalous and negative reflection with oblique incidence of linear polarization. In general, retro reflection phenomenon can be realized using a bi-layer planar MS; luckily our design is also a bi-layer structure that can be used to realize this important functionality. It is worthy to mention that the direction of scattered field from the proposed bilayer structure has a strong dependence on incidence angle of the incoming waves, and by this virtue retro and/or negative reflection in one band and anomalous reflection in other band can be realized for a series of incidence angles. Here, we are supposed to investigate a CM to achieve anomalous and retro reflection with oblique incidence in the two operating bands independently, while the aperture remains unchanged. In this regard, a CM is designed encoded with the off-diagonal elements of the matrix \( M^{2- \text{bi}} \) with a period of eight coding particles having the coding sequence, 00/11, 00/11, 01/10, 01/10, 10/10, 11/00, 11/00, 00/11, 00/11 ..... with an overall size of the design is 32 × 32 particles and an area of 224 × 224 mm². Figure 5 demonstrates the simulation results for 3D and 2D far-field patterns of the proposed CM to realize anomalous, negative and retro reflection for x-polarized oblique incidence. The anomalous reflection in lower-band for a series of incidence angles ranging from 9° to 11° along with the retro reflection in higher-band is achieved. For brevity, here, we show only the results at an incidence angle of \( \theta = 10^\circ \) only, whose 3D scattering patterns in the two operating bands can be seen in figures 5(a) and (c), respectively. The corresponding 2D equivalents can be seen in figures 5(b) and (d), where a retro reflection in the higher band can be seen at 10° (figure 5(d)). Furthermore, the reflected beam direction can be controlled by tuning the incident angle of the x-polarized wave, and in this way a negative reflection for a series of oblique incidence angles can be achieved. Here, we show the anomalous reflection realized for incidence angle 7° in lower-band along with the negative reflection in higher-band. The simulated results for this case can be seen in figures 5(e) and (g), respectively. Moreover, figures 5(f) and (h) show the 2D radiation patterns in lower-band [for anomalous reflection] and higher-band [for negative reflection], respectively.

4. Fabrication and measurement

To experimentally validate the proposed concepts, two CM samples are fabricated utilizing the standard PCB technology with dielectric F4B and copper annealed metal to further verify the operations of OAM-VB steering, retro reflection and negative reflection for different operating bands with oblique incidences. The coding particles embedded in CM sample for OAM-VB steering are derived from equation (1). The overall size of the fabricated sample for OAM-VB steering is 240 × 240 mm² having 32 × 32 coding particles (figure 6(a)) under x-polarization incidence for both operating bands. For near field measurements of the proposed sample for OAM-VB steering, a near-field microwave anechoic chamber is used. The complete experimental setup for measuring near field can be seen in figure 6(a), containing a microwave probe as a receiver and horn antenna as a feeding source. It can be noticed that in the reflection-type CM both the feeding source (horn antenna) and receiver (probe) are at the same side of CM. To avoid overlapping between the incidence and scattered fields, the microwave probe and horn antenna are carefully adjusted where the probe is placed at 200 mm away from the CM sample on the reflection side in order to collect the co-polarized scattered field. In this scenario, the receiver was able to scan an area of 200 × 200 mm².
For lower band, the measured near-field results for the OAM-VB steering are given in figures 6(b) and (c) that clearly describe the near field intensity and the phase pattern, respectively with $l = 1$. Similarly, the similar procedure is applied to measure the near-field patterns of OAM-VB steering at higher-band. The corresponding results for this higher-band are given in figures 6(d) and (e), where the phase pattern shows $l = -1$. It can also be observed that the measured near-field pattern of fabricated sample has realized and controlled the OAM-VBs with good efficiency that can reach 80%. Moreover, the measured results can be easily compared with the simulated results in figure 3.

It is important to mention that in the experiments of measuring OAM-VB we adjusted the feeding source (horn antenna) and receiver (microwave probe) in such a way to avoid the overlapping of incoming and scattered fields. After these adjustments we were not able to collect all the scattered fields, as the microwave probe was able to scan a limited area only, and thus the scattered field we collected is not complete and a part is missing due to which we can only show part of the scattered field in our measured results, which are obvious especially in figures 6(c) and (d). Moreover, the simulated results are lossless. On the other hand, the losses cannot be ignored in the measured results. Albeit, the existence of these limitations in the experimental setup the measured results plotted in figures 6(b)–(e) still have enough information to show the OAM-VB deflected to the opposite half planes and have opposite topological charges.

Furthermore, another CM sample is fabricated to achieve the anomalous reflection, retro- and negative reflection that can be seen in figure 7. In this regard, far-field measurements are performed in a different anechoic chamber that can be seen in figure 7(a). The fabricated sample’s size of this design is $240 \times 240$ mm$^2$ with $32 \times 32$ coding particles. Whereas, the coding sequences is same as mentioned in section 3.3. Moreover, two separate horn antennas are used to feed the CM sample and to receive the reflected fields. The feeding source labeled as horn antenna is adjusted at a distance in such manner that the CM sample can obtain the two separate horn antennas are used to feed the CM sample and to receive the reflected fields, as the microwave plane waves. The receiving horn antenna is adjusted to receive the co-polarized reflected field. The corresponding far-field patterns are plotted for oblique incidence of $\theta = 10^\circ$ in figures 7(b)–(c), where the clear influence of the lower and higher bands can be verified. For lower-band, the proposed CM behaves for anomalous reflection (figure 7(b)) and gives impression of retro reflection (figure 7(c)) at higher-band, as maximum energy is reflected to an angle of $(\theta_i = \theta_1 = 10^\circ)$. Furthermore, the same CM sample is used for another oblique incidence of $\theta = 7^\circ$ to verify the negative reflection property of the proposed CM that can be seen in figures 7(d)–(e). In this case, anomalous reflection (figure 7(d)) is achieved at lower-band and negative
reflection is obtained (figure 7(e)) at higher-band, where a peak of the reflected field (maximum energy) can be observed at $\theta = 15^\circ$.

5. Conclusion

In summary, a reflection-type dual-band 2-bit CM is presented. We combined the coding sequences of traditional orbital angular momentum (OAM) vortex beams (VB) and phase-gradient to construct the proposed CM. The proposed CM can generate and steer the OAM-VB with different topological charges ($\pm l$) in both lower ($f_l$) and higher ($f_h$) bands, independently. Multiple OAM-VBs have also been realized by applying the addition operation on the coding sequences of beam-splitting (and quad-beam shaping) and normal OAM-VB.
Moreover, reflected beam directions are independently controlled to achieve anomalous, negative and retro reflection at two different operating bands. Two different CM samples are fabricated to experimentally verify the OAM-VB steering, and to achieve anomalous, negative and retro reflection at two different operating bands, respectively. The obtained results of the fabricated CM are highly consistent with the simulation results. The proposed concept will open possibilities of multifunctional meta-devices with multispectral properties for reflection type optical devices.

Figure 7. Far-field experimental setup and measured results for retro reflection and negative reflection in lower and higher bands with different oblique incidences. Far-field experimental setup with the fabricated CM. (b), (c) Measured results of far field intensity when the oblique incidence is at $\theta_i = 10^\circ$. (b) Anomalous reflection in lower band. (c) Retro reflection in higher band. (d), (e) Measured results of far-field intensity when the oblique incidence is at $\theta_i = 7^\circ$. (d) Anomalous reflection in lower band. (e) Negative reflection in higher band.
Authors Contribution

S Iqbal and H A Madni designed the devices and carried out the simulations. S Liu, L Zhang, and T J Cui analysed the data and interpreted the results. H A Madni, S Iqbal and L Zhang drafted the manuscript with the input from the others. T. J. Cui supervised the project.

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Conflicts of Interest

The authors declare no conflict of interest.

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