Chiral Kirigami for Bend-Tolerant Real-Time Reconfigurable Holograms

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Abstract

Despite the commonality of static holograms, the holography with multiple information layers and reconfigurable grey-scale images at communication frequencies remain a confluence of scientific challenges\textsuperscript{1-4}. One well-known difficulty is the simultaneous modulation of phase and amplitude of electromagnetic wavefronts with a high modulation depth\textsuperscript{5,6}. A less appreciated challenge is scrambling of the information and images with hologram bending\textsuperscript{7,8}. Here, we show that chirality-guided pixelation of plasmonic kirigami sheets enables tunable multiplexed holography at terahertz frequencies needed for 6G communications. The convex and concave structures with slanted Au strips exhibit gradual variations in local chirality facilitating modulation of light ellipticity reaching 40 deg. Real-time switching between three-dimensional images of the letter “\textit{M}” and the \textit{Mona Lisa} demonstrate the possibility of complex grey-scale information content. Unexpectedly, the microscale chirality of each pixel experiences little change with bending while retaining controllable reconfigurability upon stretching. The remarkable resilience of chiral holograms to bending and the simplicity of their design with local chirality measures open the door to information technologies with fault-tolerant THz encryption and wearable holographic devices.

Main Text

Specular diffracting patterns engineered to modulate either the phase or amplitude of electromagnetic waves\textsuperscript{9-11} enable reliable generation of holographic images and sensing of a wide range of analytes\textsuperscript{12-14}. However, the current holograms are typically static and have small field of view\textsuperscript{15-17}. Data storage\textsuperscript{18}, beam shaping\textsuperscript{16}, and encrypted communication\textsuperscript{11} require real-time and gradual modulation of phase, amplitude, and directionality of the wavefronts which remains challenging with traditional holography technologies. Two-dimensional sub-wavelength nanostructures, also known as metasurfaces, open new pathways for wavefront engineering\textsuperscript{5,6} because they increase the spatial resolution and enable electric field modulation of diffracting elements\textsuperscript{19-21}. Particular attention was given to chiral metasurfaces because they are able to switch holographic images by using light beams from left- to right-handed polarization\textsuperscript{22-25}. However, the modulation depth and dynamic range remain small. Even in the best-case scenario of graphene, the dynamic range is limited because it relies on a single narrow resonance mode\textsuperscript{20,26}. Both field- and geometry–driven modulations of metasurfaces display distinct advantages for depth and spectral range capabilities\textsuperscript{17,24,27,28}. For emerging 6G information technologies these holograms will need to be realized on flexible substrates\textsuperscript{4}. Such optical devices, however, have no fault tolerance to bending, which destroys the images and scrambles the encoded information\textsuperscript{29-31}.

Here we show that chiral ‘kirigami’ metamaterials (CKMs) (\textbf{Figure 1}) enable dynamically tunable holograms in the terahertz (THz) frequency range. The kirigami sheets with simple rectangular slit patterns (\textbf{Fig. 1a, b}) display reversible deformations\textsuperscript{32,33} converting transverse strain into rotational motion\textsuperscript{32,34}. Consequently, a flat achiral surface becomes an array of chiral scattering elements.
Importantly, the mechanical deformations can be accurately predicted even for an array of geometrically dissimilar reconfigurable pixels (Supplementary Materials).

To fabricate CKMs, we used Parylene C™ polymer as a substrate for cut and ± 45° slanted Au strips with varying width, \( d \), for optically active elements. The plastic sheet is transparent in the THz range\(^{35}\) and only serves as a substrate enabling modulation of the curvatures of microscale Au strips. Handedness of left and right kirigami is determined by the angle of the slanted strip and sign of curvatures. Gaussian and mean curvatures, denoted as \( K \) and \( H \), respectively, distinguish different optically active domains in the stretched kirigami sheets with concave \( (K > 0, H > 0) \) and convex \( (K > 0, H < 0) \) geometries\(^{36}\). A repeating unit cell for the entire kirigami consists of four such domains – two convex and two concave – alternating in both the horizontal and vertical directions. Note that the planar stacking of such four-domain cells results in achiral optical media with time-reversal symmetry. It is the slanted strip that becomes the asymmetric element and breaks the symmetry.

THz time-domain spectroscopy with three polarizers were used to characterize the CKMs with different widths from 5 µm to 100 µm (Fig. 2). Ellipticity (\( \eta \)) and polarization rotation angle (\( \theta \)), defined as parameters in the Stokes equations, were measured under the mechanical strain (\( \varepsilon \)) range from 0 % to 22.5 % (Fig. 2b-g). As the symmetry of the original sheets becomes broken under strain, the radii of curvature of Au strips decrease, and the magnitude of \( \eta \) and \( \theta \) increase. Terahertz circular dichroism (TCD) spectra of left and right kirigami are almost exactly the same but with opposite polarities (signs). Also, the relation between \( \eta \) and \( \theta \) satisfies the Kramers-Kronig relation nearly perfectly (Fig. 2b, c), indicating predictability of the TCD spectra despite its complexity. The positions of the first peak of \( \eta \) are red shifted from 0.9 THz to 0.68 THz as the shape of Au strips evolved from rods \( (d = 5 \, \mu m) \) to ribbons \( (d = 20 \, \mu m) \) and eventually to parallelograms \( (d = 100 \, \mu m) \) (Fig. 2d-f). Not only the spectral shifts, but also the magnitudes of the peaks increase as Au strips become wider (Fig. 2g). The maximum of \( \eta \) reached as high as 40 degrees, which represents the highest value among all known tunable metasurfaces\(^{37}\).

The nanoscale (~50 nm) Au layer with slanted edges can effectively modulate the polarization of lights on curved surfaces. Electromagnetic simulation visualizes how polarized THz beam interacts with CKMs of different geometries. The simulations give virtually identical matches for the experimental spectra (fig. S8a, b) as exemplified by the \( \eta \) spectra and the predicted shift from 1 THz to 0.85 THz (fig. S8c). What is important for holograms, CKM interactions with linearly-polarized THz photons is also frequency- and chirality-dependent. For example, right-handed CKM (\( R \)-CKM) converts a linearly-polarized THz beam into right (RCP) and left (LCP) circularly polarized light at 0.77 and 0.92 THz, respectively (fig. S8d, e). The spectra in fig. S8f clearly show the gradual progression of polarization modulation from linear to elliptical and to circular enabled by the gradually changing chirality of CKMs.

Unstrained CKMs display almost no asymmetry for transmittance of left- and right-handed CPL (Fig. 3a, b), while CKMs emerging after strain show distinct difference in resonance frequency of transmittance. Both experimental and simulation results show that transmittances of stretched \( R \)-CKMs with RCP show
their local minimum frequencies below those of LCP. This is also consistent with the positive to negative transition of bisignate \( \eta \)-spectra.

To better understand how CKMs interact with THz CPL, we calculated the current norm distributions on the surface of Au layers of \( R \)-CKM for the irradiance of left- and right-handed CPL (Fig. 3c-j). Two examples of \( R \)-CKMs (\( w = 20 \) and 100 \( \mu \text{m} \)) visualize the direction and magnitude of induced currents (shown in red arrows). At the resonance frequency of \( R \)-CKMs illuminated with RCP (0.94 THz for \( w = 20 \) \( \mu \text{m} \) and 0.83 THz for \( w = 100 \) \( \mu \text{m} \)), the CKMs exhibit counterclockwise currents that align with the forward rotational direction of RCP (Fig. 3c, e, g, i). These collective rotational currents are generated along the curved surfaces within each unit cell. Side views of \( R \)-CKMs suggest that induced currents are wound up similar to the phenomena found in helical structures\(^{32,38-41}\). On the other hand, at the resonance frequency with LCP, complex flow (not simply following the rotation of CPL) of currents are induced by the LCP, which total power of currents exceeds that of RCP.

Considering the need for real-time gradual modulation of phase and amplitude of generated beams, the structural tunability of CKMs can cover a wide range of chirality of the scattering elements\(^{42}\), which differentiates CKMs from microscale spiral patterns\(^{38,39}\) and double layer of gammadions\(^{43,44}\). Here, we used Osipov-Pickup-Dunmur (OPD) chirality measure to establish quantitative relationships between chirality and optical activity (Fig. 4)\(^{45,46}\). Among many chirality measures, OPD was chosen because it describes left and right handedness with opposite sign. Importantly, the problem of ‘chiral zeros’ for pseudoscalar chirality measures can be avoided by defining the reconfiguration path of the chiral structures as going strictly through the achiral intermediate state. This is possible for CKMs but impossible for chemical structures represented by chiral molecules with a wide range of geometries.

Specifically, the pristine 2D CKM has OPD of zero regardless of the width of Au strips. In addition, the magnitude of OPD increases as CKM is being stretched in all cases (Fig. 4a). The contribution of each node on the kirigami surface to OPD was also calculated to assess the impact on chirality (Fig. 4b, c). Quite strikingly, the nodes with higher contributions to OPD overlap almost exactly with the points displaying higher magnitudes of induced currents (Fig. 3e, i, and Fig. 4b, c), suggesting that chiroptical responses of CKMs are indeed proportional to structural chirality. Most interestingly, the OPD calculation also shows that CKMs based on geometrical chirality could exhibit high tolerance to bending. When the kirigami sheet is stretched to \( \varepsilon = 20\% \) it undergoes bending, and the change in OPD at the highest point is minimal, maintaining the overall distribution and magnitude of OPD for each node (Fig. 4d).

Guided by chirality measures, we decided to test whether a hologram can combine mechanical tunability and fault-tolerance upon mechanical deformation – properties that seem contrarian to each other. We designed pixel arrays to display one picture to one handedness of the beam and the other to the opposite handedness. Two holographic images designed to appear were “Mona Lisa” and the letter “M” (Fig. 5a). As different widths of Au strips show different peak positions in ellipticity we can leverage this spectral characteristic for displaying contrast of image. We patterned each pixel using seven different widths of Au strips (\( w = 0, 5, 20, 40, 60, 80, 100 \) \( \mu \text{m} \)) and this pixelation was done by image processing, which
converts an original image (Fig. 5b) into a grayscale seven-level image (Fig. 5c). The greyscale in the image of Mona Lisa enabled by the high value and continuity of the chirality of the scattering elements makes these complex images possible.

Each pixel of CKM for a chiral hologram consists of four kirigami domains and left- and right-handed pixels are arranged alternatively to each other (Fig. 5d). The size of each pixel and arrangement were rationally selected based on the size of the beam (diameter of the beam = ~500 µm at 1THz) at the focal point. Figure 5e shows the results of raster scanning of ellipticity at 0.62 THz for different CKM strains in transmission mode. Before stretching, as expected, the chirality of CKM is zero and both encrypted images are latent. As strain increases, the ellipticity of light increases and hidden images (Mona Lisa - RCP, M - LCP) appear (Fig. 5e). Also, CKMs demonstrate high fault tolerance (Fig. 5e, bottom). The encoded image persists even when CKMs are bent and crumpled, which is unexpected but in complete agreement with OPD calculations for deformed CKMs. It is evident that the structural chirality of CKMs persists even under mechanical bending. Consequently, the diffracted beam retains a substantial level of polarization rotation, resulting in minimal disruption to the images.

In conclusion, CKMs can serve as reconfigurable and programmable modulators at communication THz frequencies with high depth. Besides lengthy electromagnetic calculations as it is the case for large grey-scale encodings, the design of CKMs can be guided by the local bi-signate chirality measures, avoiding the problem of ‘chiral zeros’ due to predefined reconfiguration pathway definitively passing through the ‘flat’ achiral state. The fault-tolerance of the designed holograms, biocompatibility of the THz light, and their high communication bandwidth, makes CKM suitable for 6G telecommunications1–4, wearable optical biosensors12–14, haptic interfaces7,8, and other encryption and optical machine learning technologies47.

Declarations

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References and Notes


**Figures**
**Figure 1**

**Schematics and optical microscope images of chiral kirigami metamaterials.**

**a,** A sinusoidal model can be used to express the deformation of a kirigami substrate. By ensuring continuity of positions at both ends and their first derivatives, the kirigami structure can be reconstructed for both mechanical and electromagnetic modeling.  

**b,** Tilting occurs simultaneously when the kirigami is stretched. Tilting angle can also be predicted and well fitted with the experimental results.  

**c,** Optical microscope images before and after stretching of kirigami ($d = 20 \, \mu m$). These images provide a visual representation of the deformation and tilting that occurs when the kirigami is stretched.  

**d,** Mathematical model allows for exact tracking of any point on the kirigami surface, regardless of the degree of strain.
Figure 2

Experimental results of ellipticity and polarization rotation angle of CKM for different strain (0 – 22.5%).

**a,** Optical microscope images of CKM with different widths of Au strip.  
**b, c,** Ellipticity and polarization rotation angle spectra of CKM under application of mechanical force, respectively.  
**d, e,** Full results of ellipticity and polarization angle spectra of CKM at $\varepsilon = 22.5\%$ with respect to the width of Au strip.  
**f, g,** Relation between peak position/magnitude of ellipticity and the width of Au strip.
Figure 3

Circularly polarized light - R-kirigami interaction. a, b, Transmission differences with respect to the handedness of circularly polarized THz beam of experimental (a) and simulation (b) results. c-j, Time-averaged current norm distribution along the surface of CKMs (w = 20, 100 µm) for the RCP and LCP. c, d, g, h show the interaction between LCP and R-kirigami while e, f, i, j are with RCP and R-kirigami.
Figure 4

a, OPD chirality measure of CKM for different strain (0 – 22.5%). b, c, Analysis of contribution of OPD at each node for two CKMs with different widths of Au strip ($w = 5, 100 \mu m$). d, Effect of bending on magnitude and distribution of OPD.
Figure 5

Time-variable multiplexed hologram with chiral kirigami. **a,** Image processing from original images to 7-level images using gray scaling and grouping. **b, c,** Before and after image processing using the code we developed. **d,** Image of CAD file for seven-level kirigami pixelation. **e,** Photographs of fabricated kirigami and their holographic images for LCP and RCP.

Supplementary Files

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