

RESEARCH ARTICLE

Open Access



Exploiting universal nonlocal dispersion in optically active materials for spectro-polarimetric computational imaging

Xueji Wang¹, Todd Van Mechelen¹, Sathwik Bharadwaj¹, Md Roknuzzaman², Fanglin Bao¹, Rajib Rahman² and Zubin Jacob^{1*}

Abstract

Recent years have seen significant advancements in exploring novel light-matter interactions such as hyperbolic dispersion within natural crystals. However, current studies have predominantly concentrated on local optical response of materials characterized by a dielectric tensor without spatial dispersion. Here, we investigate the nonlocal response in optically-active crystals with screw symmetries, revealing their lossless, super-dispersive properties compared to traditional optical response functions. We leverage this universal nonlocal dispersion, i.e. the dispersion of optical rotatory power, to explore a novel spectral de-multiplexing scheme compared to conventional gratings, prisms and metasurfaces. We design and demonstrate an 'Nonlocal-Cam' - a camera that exploits nonlocal dispersion through sampling of polarized spectral states and the application of computational spectral reconstruction algorithms. The Nonlocal-Cam captures information in both laboratory and outdoor field experiments which is unavailable to traditional intensity cameras - the spectral texture of polarization. Merging the fields of nonlocal electrodynamics and computational imaging, our work paves the way for exploiting nonlocal optics of optically active materials in a variety of applications, from biological microscopy to physics-driven machine vision and remote sensing.

1 Introduction

Recent advancements in the study of light-matter interactions with natural crystals at the atomic scale have unveiled a variety of intriguing phenomena. These include the identification of hyperbolic polaritons in hBN [1–4], MoO₃ [5–7], α -V₂O₅ [8], WSe₂ [9], and SnO₂ [10], ghost polaritons in calcite [11], and hyperbolic shear polaritons in β -Ga₂O₃ [12] and CdWO₄ [13]. However, the majority of research has been confined to local optical responses characterized by spatially non-dispersive

dielectric tensors, limiting the exploration to phenomena exhibiting linearly polarized eigenstates. Additionally, the temporal dispersion of local responses can be captured by the Drude-Lorentz model with damped harmonic oscillators [14]. The Kramers-Kronig relations in the Drude-Lorentz model inherently suggests that the strong temporal dispersion of local dielectric functions is accompanied by large optical losses, further constraining the range of accessible phenomena.

The exploration of nonlocal responses is crucial for overcoming these limitations and unlocking new regime of light-matter interactions. Nonlocal responses extend the possible eigenstates of these interactions to include circular polarization, allowing many intriguing phenomena especially those related to Weyl and Axion physics [15–21]. A notable category of nonlocal crystals is natural optically active crystals such as α -quartz. Recent X-ray scattering experiments have demonstrated that the screw

*Correspondence:

Zubin Jacob
zjacob@purdue.edu

¹ Birck Nanotechnology Center, Elmore Family School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907, USA

² School of Physics, The University of New South Wales, Sydney, NSW 2052, Australia

symmetry in α -quartz gives rise to exotic chiral phonons [22], introducing an additional degree of freedom in condensed matter. In the realm of optics, the dispersion characteristics of nonlocal responses are intrinsically connected to photonic spin density and optical chirality density. This connection sets them apart from conventional birefringent or hyperbolic optical crystals. Crucially, the nonlocal optical response demonstrates ‘super-dispersion’, manifested by significant frequency dependence in gyration constants and optical rotatory power, surpassing the typical frequency dependence of local dielectric functions. This super-dispersion in nonlocal crystals is both universal and capable of spanning a broad spectrum while remaining lossless (Fig. 1).

In this work, we exploit this nonlocal super-dispersion, i.e. the strong dispersion of optical rotatory power, to create as well as deploy an ‘Nonlocal-Cam’ beyond the laboratory environment: an imager which allows for simultaneous capture of spectrum and polarization. We achieve spectral demultiplexing in the polarization domain as opposed to the spatial domain routinely accomplished using conventional gratings and prisms. The Nonlocal-Cam exploits techniques from computational spectral reconstruction along with natural optically active crystals to capture outdoor images. These real-world images encode a 4D data-tesseract (x , y , ω , polarization) and reveal a subtle variation of the partially polarized radiation with spectrum. This is beyond the 2D/3D data from intensity images, spectral images or polarized images captured by other cameras [23–28]. The unique capability of the Nonlocal-Cam to unravel the information hidden in frequency dependent degree of linear polarization (ω -DOLP) images in an outdoor environment opens up new avenues for physics driven machine vision [29, 30].

Furthermore, our theory and Nonlocal-Cam design are universal and applies to multitude of optically active and topological materials (Fig. 1 a-c), including Weyl semiconductor tellurium (Te) in the mid-infrared spectrum, selenium (Se), tellurium dioxide (TeO_2) in the near-infrared spectrum [31], and perovskite semiconductors [32], silver gallium sulfide (AgGaS_2) [33] in the visible, etc. By employing the appropriate materials, our design provides a practical and efficient platform for spectral separation across a broad range of wavelengths.

We note that spectral imaging techniques have evolved considerably, with approaches that can be broadly categorized into four main strategies: multi-filter [34, 35], spatial separation [36], interferometry [37–40], and computational spectroscopy [41–45]. Multi-filter methods include mechanical filter wheels and color mosaic sensors. The spectral resolution of this approach is constrained by the limited number of filters these systems

can accommodate. Mosaic sensors, although capable of snapshot spectral imaging, often require advanced micro/nanofabrication to integrate pixelated filters directly onto imaging sensors. It also significantly reduces spatial resolution of the imaging system. This limitation is particularly severe for sensors with a limited number of pixels, such as those used in mid-infrared thermal imaging. Spatial separation techniques often utilize diffractive elements like prisms, gratings to achieve high spectral resolution. However, these methods typically require line-scanning (or ‘push-broom’ scanning) to generate 2D images, which restricts their applicability especially in dynamic environments. Interferometric methods-including Michelson, Fabry-Perot, and Sagnac interferometers [37, 38] offer high spectral resolution but demand precise moving parts, strict alignment and calibration, and often involve rare materials and complex micro-electromechanical systems (MEMS) fabrication. We also note that liquid crystal technology has significantly matured and offers notable advantages in spectral separation, particularly due to its ability to achieve tunability without the need for mechanical components. Recently, liquid crystals have been combined with metasurfaces to create electrically reconfigurable photonic devices [45–49], presenting an exciting avenue for spectroscopy applications. However, it is important to note that liquid crystal devices generally require complex fabrication processes, including the integration of transparent electrodes and precise alignment of liquid crystal molecules, which can lead to higher production costs and challenges in scalability.

In contrast, our experimental demonstration exploited α -quartz single crystals, one of the most abundant and cheapest materials as the enabling element, which can dramatically reduce the cost of spectral imagers. Our approach does not require nanofabrication processes or precise mechanical/electrical control parts. The material choice and simple design also enhance the system robustness, making it well-suited for applications in off-road navigation, space exploration, and extreme environment operations (high temperature, high pressure, and intense vibration). Additionally, our design is compact, portable and scalable, as the system can be assembled in various sizes with varying spectral resolutions, admitting flexible configurations in diverse working conditions and making it easy to be integrated with drones, hand-held cameras, or even smartphones.

Additionally, computational spectral imaging has recently emerged as a powerful alternative, leveraging advanced computational techniques to extract high-dimensional information, including both spectral and polarization data [43]. Compressive sensing [50] and machine learning algorithms [43] have played a crucial

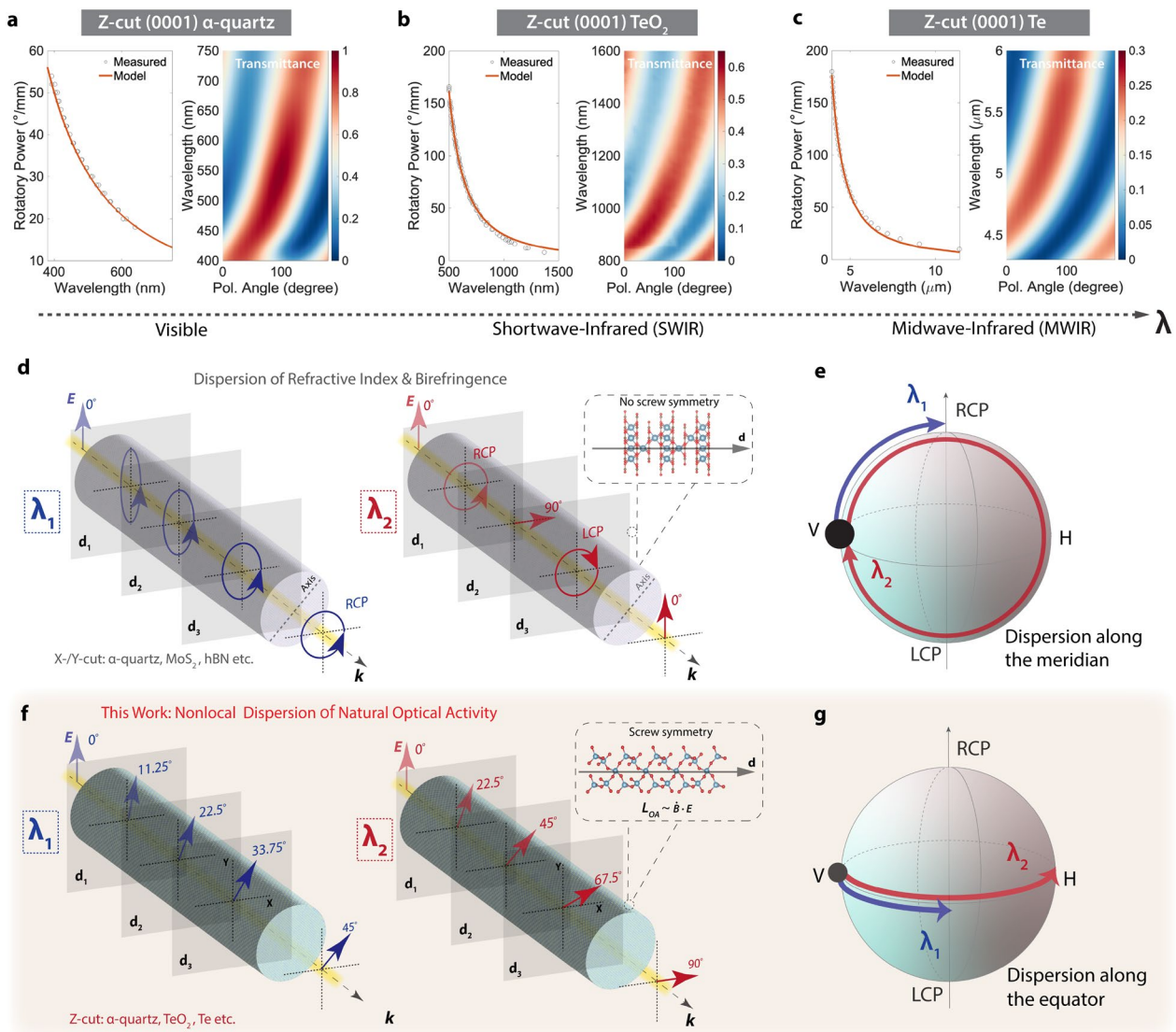


Fig. 1 Universal nonlocal dispersion in optically active materials. **a–c** Left panels: optical rotatory power of **a** α -quartz, **b** TeO_2 , and **c** Te single crystals along their optical axes (z-axis). The black dots represent the measured data, while the solid line shows the fitted results with a coupled-oscillator model. Right panels: measured tunable transmission of Z-cut **a** 3 mm α -quartz, **b** 5 mm TeO_2 , and **c** 2 mm Te single crystals under linearly polarized input light and an output polarizer rotated at different polarization angles. (d–g) Distinction of the dispersion characteristics in nonlocal optically active crystals and birefringent crystals: **d** A schematic illustrates the dispersion of refractive indices in standard birefringent crystals. When a linearly polarized light oriented at 45° to the crystal's slow-axis traverses the birefringent medium, it undergoes a transformation through linear, elliptical, and circular polarization states (and then reverses the sequence). This transformation varies in speed with different wavelengths, λ_1 and λ_2 , as depicted on the left and right, respectively. The inset highlights that birefringence microscopically originates from the anisotropic nature of the crystal lattice. **e** A schematic captures the evolution of polarization states on the Poincaré sphere. Blue and red trajectories correspond to λ_1 and λ_2 in (d), respectively. In birefringent crystals, these pathways trace the sphere's meridian. Due to dispersive effects, different wavelengths reach different states along the meridian after traversing the crystal. **f** A schematic illustrates the nonlocal dispersion in optically active crystals. As linearly polarized light traverses an optically active medium, it retains its linear polarization but experiences a rotation in orientation. For different wavelengths, λ_1 and λ_2 , the rate of polarization rotation per unit length is different. The inset shows that the polarization rotation microscopically arises from the screw symmetry of the lattice. **g** A schematic represents the evolution of polarization states on the Poincaré sphere. For nonlocal optically active crystals, evolution paths are along the equator. Dispersion causes different wavelengths to reach different states along the equator after traversing the crystal, allowing a linear polarizer to select between these wavelengths effectively.

role in these advancements. In our work, we build on these computational innovations and combine it with novel light-matter interactions in nonlocal optically active materials. Our approach not only minimizes optical complexity of current systems but also reduces the heavy computational demands and extensive data training typically required by traditional computational methods, providing a new and efficient platform for spectro-polarimetric imaging.

2 Results

2.1 Nonlocal electrodynamics of natural optical activity

To understand the fundamental physics of the nonlocal interaction in optically active crystals, we obtain optically active Lagrangian $\mathcal{L}^{OA}$,

$$\mathcal{L}^{OA} = -\frac{g_{ij}}{8\pi c}(\delta_{ij}\dot{\mathbf{B}} \cdot \mathbf{E} - 2\dot{B}_i E_j) \quad (1)$$

where δ_{ij} is the Levi-Civita symbol and g_{ij} is known as the gyration pseudotensor (see Supplementary Section I for detailed derivation). We see that the gyration tensor g_{ij} couples directly to the electromagnetic pseudotensor $C_{ij} = \delta_{ij}\dot{\mathbf{B}} \cdot \mathbf{E} - 2\dot{B}_i E_j$. As a consequence, variations in the magnetic field induce electric dipoles in the medium and vice versa. Natural optical activity, therefore, introduces a sense of chirality through nonlocality in matter.

The Nonlocal-Cam relies on dispersion to operate, therefore, we include frequency dependence of the nonlocal term in the response functions. At optical frequencies, the gyration tensor g_{ij} is highly dispersive which has important implications on dynamical variables like the energy and momentum densities. We derive the energy density u in dispersive optically active media as the summation of the electromagnetic contribution u^{EM} and the striking additional component arising from the gyration u^{OA} :

$$u = u^{EM} + u^{OA} = \frac{1}{16\pi}(\bar{\epsilon}_{ij}E_i^* E_j + |\mathbf{B}|^2) + \omega \bar{g}_{ij} q_i S_j \quad (2)$$

where $\bar{\epsilon}_{ij} = \partial_\omega(\omega \epsilon_{ij})$ and $\bar{g}_{ij} = \partial_\omega(\omega g_{ij})$. In this case, $\mathbf{q}$ is the photon momentum and $\mathbf{S} = -i\mathbf{E}^* \times \mathbf{E}/(16\pi\omega)$ is the photonic spin density, which characterizes the circular Stokes parameter along each direction. The projection of the momentum $\mathbf{q}$ and spin $\mathbf{S}$ onto the gyration tensor g_{ij} helps us build the connection to the concept of optical chirality density [51]. We define it as $\chi = \bar{g}_{ij} q_i S_j$ for the optically active medium. In Fig. 2a, we plot the chirality density of right and left circular polarization on their isofrequency surfaces. The rapid change in chirality density near the optical c -axis indicates the strong angle dependence of natural optical activity, a key factor affecting the field-of-view (FOV) of the Nonlocal-Cam. We

develop generalized Fresnel equations (see Supplementary Section III D for details) to obtain the angle-resolved parallel transmission (T_{ss}) in α -quartz and confirm the results with experimental measurements. As shown in Fig. 2b, the narrow-band transmission is observed within an approximate angular range of 20° . This angular dependence primarily originates from the birefringence ($n_o \neq n_e$) in α -quartz crystals, causing the ellipticity of the eigenmodes to rapidly drop from 1 (circularly polarized light) to near-zero values (linearly polarized light). It is worth noting that natural optical activity can also exist in isotropic (cubic) crystals with point groups 432 and 23. These crystals are expected to exhibit much weaker angular dependence, enabling the realization of significantly larger FOV imaging systems.

2.2 Nonlocal dispersion

We note that this nonlocal dispersion is different from the dispersion of waves occurring in prisms, gratings, or metasurfaces. Its spectral separation occurs in the polarization dimension, i.e. linearly polarized light of various wavelengths is rotated by different angles while propagating through a crystal (Fig. 2c), quantitatively characterized by the wavelength-dependent optical rotatory power ρ . This nonlocal dispersion has two crucial advantages compared with the conventional dispersion of permittivity. First, nonlocal dispersion can be almost lossless since the phenomenon occurs within the bandgap spectrum of α -quartz (Fig. 2d). On the contrary, strong dispersion of the real part of permittivity is often accompanied by a large imaginary part and thus with significant optical loss. This accompanying loss of rapid dispersion has been a long-standing limitation in applications, such as slow light [52, 53], fast light [54], and electromagnetically induced transparency (EIT) [55]. It can be observed in Fig. 2e that the dispersion of permittivity ϵ_o and ϵ_e in α -quartz is much weaker in the transparent spectral region of the crystal, compared with dispersion in the opaque spectral region. This is generally true for the vast majority of materials and can be justified by the Kramers-Kronig relations in the Drude-Lorentz model of the response functions. Optical transparency, i.e. a near-zero imaginary part $\Im(\epsilon) \approx 0$, only occurs at frequencies far away from the resonant frequency (bandgap energy). In such an off-resonant region, the derivatives of the real part $\partial_\omega \Re(\epsilon)$ are also close to zero leading to weak dispersion.

Second, the optical rotatory power along the c -axis of α -quartz crystals demonstrates a ‘super-dispersion’ behavior in the visible transparency window (Fig. 2e). This super-dispersion can be explained through a coupled-oscillator model [56, 57] (see Supplementary Section IV for details). According to the model, the dispersion relation for the optical rotatory power ρ

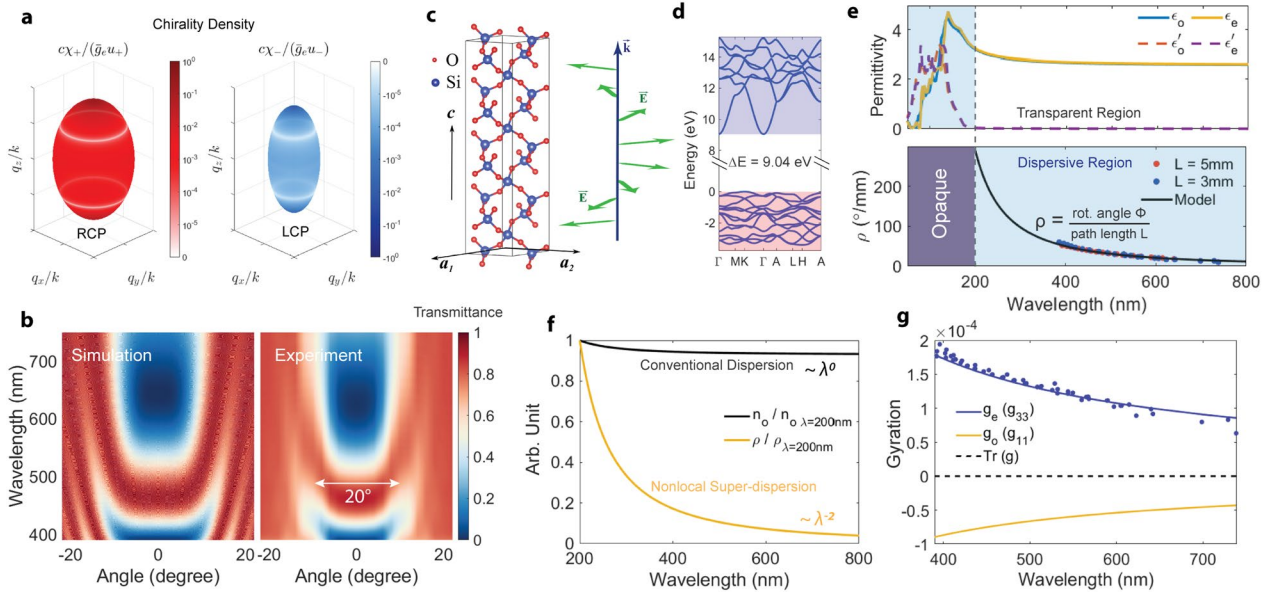


Fig. 2 Unraveling super-dispersion and non-locality of α -quartz crystals. **a** The chirality density projected onto the isofrequency surface (not to scale) of RCP (+) and LCP (-), respectively. The concentration near the optical c -axis and the difference between RCP and LCP illustrates the fundamental nonlocal mechanism of the natural optical activity. **b** Simulated (left) and measured (right) angular dependence of the transmission for a 5 mm Z-cut α -quartz crystal between two linear polarizers with parallel polarization orientations (T_{ss}). The angular range with narrow-band transmission (approximately 20°) determines the field of view of a spectral imaging system. **c** Left: crystal structure of α -quartz exhibits a screw structure along the c -axis. Right: illustration of the polarization rotation as light travels through the crystal along the c -axis. We exploit the spectral dependence of this polarization rotation to design the Nonlocal-Cam. **d** The electronic bandstructure of α -quartz obtained from DFT calculations. We function in the bandgap region to exploit super-dispersion in a broadband lossless way. **e** Comparison between the dispersion of conventional permittivity and optical rotatory power. Top panel displays the calculated real (solid lines) and imaginary (dashed lines) components of the permittivity along both the ordinary axis (ϵ_o and ϵ'_o) and the extraordinary axis (ϵ_e and ϵ'_e). The regions of high dispersion in the real part of the permittivity (highlighted by the blue-shaded areas) are accompanied by significant values in the imaginary part, indicating substantial optical loss. Bottom panel illustrates the optical rotatory power within the same spectral region. The measured optical rotatory power of a 5 mm α -quartz crystal (red dots) and a 3 mm α -quartz crystal (blue dots) aligns well with the theoretical predictions derived from a coupled-oscillator model (solid black line). Notably, the blue-shaded areas also mark the regions of high dispersion in the optical rotatory power, which occur in the transparent region of the crystal. **f** The super-dispersive behavior of the optical rotatory power ρ (along the c -axis) in α -quartz is compared with the slow dispersion of the ordinary refractive index in the transparent spectral region. ρ and n_o are normalized with their corresponding values at 200 nm. **g** Spectra of the non-zero components of the gyration tensor (g_{33} and g_{11}) in α -quartz (solid lines: calculated result, dots: experimental data). The gyration tensor displays the broadband traceless relation, $\text{Tr}(g_{ij}) = 0$

along the c -axis is given by $\rho = A_{||} \frac{\lambda^2}{(\lambda^2 - \lambda_0^2)^2}$. Conversely, the ordinary refractive index is given by $n_o^2 - 1 = B_0 \frac{\lambda^2}{(\lambda^2 - \lambda_0^2)}$, where λ is the wavelength, $A_{||}$, B_0 and λ_0 are parameters determined by the atomic structure. As shown in Fig. 2e, the model of ρ fits the measured dispersion of optical rotation power in α -quartz well and accurately describes the ‘super-dispersive’ characteristics. To clarify this advantage, in Fig. 2f, we directly compare ρ and n_o as a function of wavelength normalized with their corresponding values at 200 nm. As predicted by the model, the optical rotatory power decays as $\rho \sim 1/\lambda^2$, whereas the refractive index approaches a constant value ($n_o \sim 1$) at large wavelengths $\lambda \gg \lambda_0$. This super-dispersion of the gyration tensor (Fig. 2g) and optical rotatory power, combined

with the polarization-based spectral separation, offers a unique advantage for spectral imaging applications.

We emphasize that our deep understanding of non-local interactions in optically active crystals forms the foundation of our Nonlocal-Cam design. This knowledge also provides critical insights into key imaging characteristics, such as transmission efficiency, spectral separation capability, and field-of-view. More importantly, our integrated theoretical and experimental framework offers valuable guidance for discovering and designing new non-local optical materials and metamaterials tailored for spectroscopy applications. It is worth mentioning that natural optical activity can exist in 15 classes among the total 32 crystal classes, in which four of them are non-chiral (m, mm2, $\bar{4}$ and $\bar{4}2$ m) [33]. While α -quartz in the visible spectrum serves as a proof-of-concept demonstration for a specific spectral range, this comprehensive

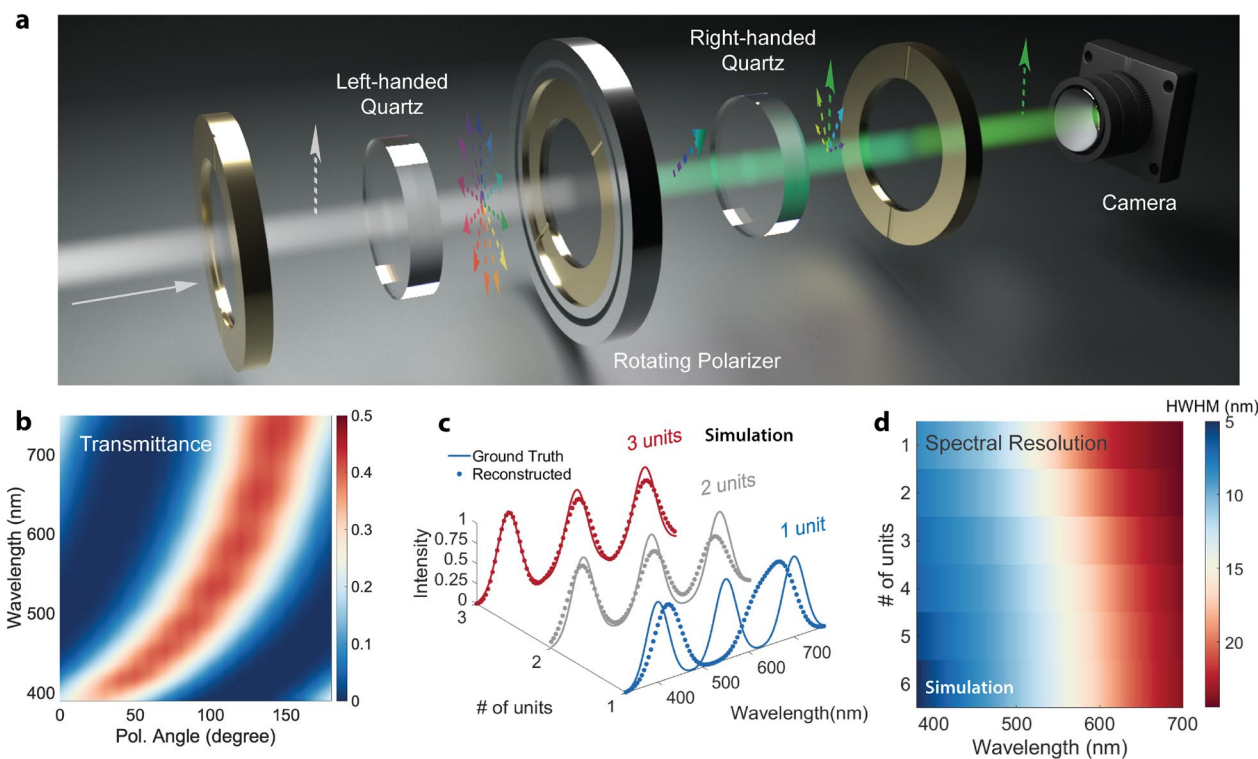


Fig. 3 Design of the Nonlocal-Cam. **a** Schematic of the prototype Nonlocal-Cam based on α -quartz crystals. **b** Observed transmission spectra at different polarization angles. **c** Simulated spectral reconstruction results with a different number of spectral filtering units. The ground truth spectra are Gaussian peaks with 25 nm HWHM at different wavelengths (400 nm, 550 nm, and 700 nm). The accuracy of spectral reconstruction increases as the number of units is increased. **d** The calculated spectral resolution of the Nonlocal-Cam with a different number of units (1–6 units). The spectral resolution is defined as the HWHM of the Gaussian peak that can be reconstructed with MSE less than a defined threshold. By merging the fields of nonlocal electrodynamics and computational imaging, Nonlocal-Cam design provides a platform for low size, weight, and power (SWaP) spectro-polarimetric imaging system

framework paves the way for extending beyond α -quartz, enabling the development of spectral filtering platforms across a broad electromagnetic spectrum.

2.3 Design of nonlocal-cam

Next, we describe our design and the performance of the α -quartz-based ‘Nonlocal-Cam’. We exploit the broadband chirality of the optically active crystal and establish a unique system architecture as shown in Fig. 3a. Here, two z -cut α -quartz crystals with the same thickness (3 mm) but distinct chirality (left-handed and right-handed) are used. Two fixed linear polarizers are placed at the input end and the output end with the same orientation. A rotating linear polarizer is placed between the two chiral crystals for spectral tuning. As shown in the figure, the spectrum of the input light is initially filtered by the first three components consisting the input polarizer, the left-handed crystal, and the rotating polarizer. It is filtered a second time in the same manner by the right-handed crystal and the output polarizer. The advantage of this architecture is that we achieve two-stage filtering

with just a single rotating part. We note that this two-stage filtering provides narrower spectral bands and reduces correlations between the transmission spectra at different rotation angles - achievements not possible with single-stage filtering, even when using a thicker crystal (see Supplementary Section V for details). The polarization-controlled transmission spectra of the system is shown in Fig. 3b, where a tunable transmission band can be observed. We emphasize that this design also makes the system easily scalable, as both the first element and the last element of the spectral filtering unit are fixed linear polarizers. One can repeat the unit multiple times to achieve narrower spectral bands and higher spectral resolution according to the requirements of desired applications.

We emphasize a critical distinction between our demonstration and traditional Lyot or Solc filters, as well as emerging methods using spinning metasurfaces [58]. These analogous designs utilize anisotropic crystals placed between polarizers, relying on the difference in local dielectric functions of two linearly polarized

eigenstates, and are unrelated to the phenomena of super-dispersion and non-locality. As illustrated in Fig. 1e, the wavelength-dependent polarization states produced by the anisotropic crystals align along the meridian of the Poincaré sphere. Consequently, tuning the filter through a single rotating polarizer is not feasible. Traditional designs often depend on alternative tuning methods, such as the incorporation of broadband waveplates or liquid crystals with electrically controlled birefringence. In contrast, our design leverages the super-dispersion of optical rotatory power to enable direct spectral tuning through the selection of linear polarization, providing a compact and robust spectro-polarimetric imaging system.

Subsequently, to obtain the spectra from the measured signals of the Nonlocal-Cam, we adopt a ‘learning - sampling - reconstruction’ scheme [58–64]. The measured signal I can be expressed as a function of the polarization angle p of the rotating polarizer, as $I(p) = \int_{\lambda_{\min}}^{\lambda_{\max}} R(p, \lambda) S(\lambda) d\lambda$, where $S(\lambda)$ is the ground truth spectrum we want to obtain, and $R(p, \lambda)$ is the spectral response function. After discretizing the spectral range of interest, we employ compressive sensing and dictionary learning techniques [65–68] to reconstruct spectrum from sampled signal $I(p)$ and pre-calibrated response function $R(p, \lambda)$. This increases the reconstruction accuracy of the Nonlocal-Cam, making it more robust and less sensitive to noise (Methods).

To quantitatively show the increased spectral resolution as the system scales up, we simulate the spectral reconstruction result. Figure 3c is a direct illustration of the reconstructed spectra, where Gaussian peaks of 24 nm half-width at half minimum (HWHM) are the ground truth. We demonstrate that the accuracy of the reconstruction increases as the number of spectral filtering units increases from 1 to 3. Similarly, we run Gaussian-peak-based reconstruction trials with different HWHM at different wavelengths (380–700 nm) and with a different number of units (1–6 units). We define the minimum HWHM of the Gaussian peak that can be reconstructed with mean square error (MSE) $< 10^{-3}$ as the spectral resolution. The result displayed in Fig. 3d demonstrates the spectral resolution as a function of wavelength and the number of units. The resolution show significant improvement from 1 to 4 units and it eventually converges to a constant level because of the decreased SNR. The minimum achievable spectral resolution itself is wavelength-dependent and arises from the nature of the optical activity in α -quartz, i.e. the optical rotatory power is stronger toward shorter wavelengths and results in higher spectral resolution.

2.4 Spectro-polarimetric imaging

To demonstrate the potential of our prototype Nonlocal-Cam, we test the spectral imaging performance with an ‘AXION’ imaging target. As shown in the RGB image of Fig. 4a, each letter in the target is assigned a different color, producing distinct reflection spectra. As a result, the reconstructed spectral frames at different wavelengths exhibit varying spatial patterns (Fig. 4b–f). In Fig. 4g, we present the reconstructed spectra (orange solid line) at four representative pixels, which match well with the ground truth spectra (blue dashed line).

As the spectrum is intimately tied to polarization in nonlocal dispersion, a unique feature of Nonlocal-Cam is its ability to simultaneously capture both the spectral and polarimetric information. To show this, a pair of plastic goggles with linear polarized background illumination was chosen as the imaging target. Figure 4h depicts the image of Stokes parameter S_0 , which represents the total light intensity at each pixel. Since the polarimetric information is unavoidably lost in S_0 , the image is of low contrast. Figure 4i shows the image of degree of linear polarization (DoLP), where spatial dependence of the DoLP can be observed. The spatial feature originates from the stress-induced birefringence in plastics: the stress distribution on a curved plastic surface converts linear polarized light into different amounts of circularly polarized light. Such information is completely lost in conventional intensity images. At the same time, Nonlocal-Cam generates the spectral dependence of the DoLP as shown in the inset of Fig. 4i. The DoLP spectrum reveals the wavelength-dependence of the stress-induced birefringence in the goggles. Such a four-dimensional spatial-spectro-polarimetric data-tesseract provides significantly more insight associated with an imaging target, proving Nonlocal-Cam can be employed as a powerful tool in a wide range of imaging applications.

More importantly, the simplicity and robustness of our design provides the opportunity for building a portable spectro-polarimetric imaging system without strict alignment and environment requirements. To demonstrate this, we carried out spectro-polarimetric imaging experiments in outdoor fields using the Nonlocal-Cam. The scenes are displayed in the visible RGB images of Fig. 5a–c. Some objects in the scene show strong contrast in the spectral frames at certain wavelengths (point A versus point B in Fig. 5d, as well as point C versus point D in Fig. 5e). The contrast is due to the objects’ distinct spectra at these wavelengths, which is quantified in Fig. 5g–h. We note that the black regions observed in Fig. 5d and e primarily result from artificial errors in data collection during outdoor experiments. These errors are likely due to two main factors: movement in the scene, such as swaying grass or shifting

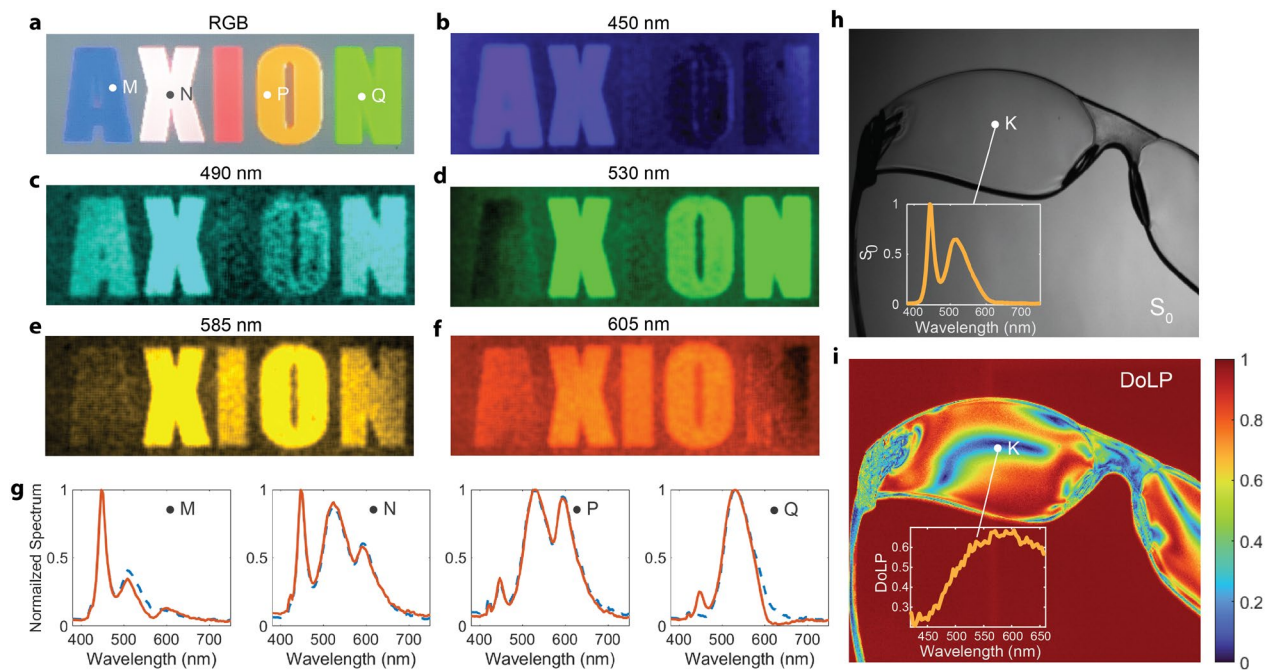


Fig. 4 Demonstrations of spectro-polarimetric imaging using the Nonlocal-Cam. **a** RGB image of the 'AXION' imaging target. **b–f** False color representations of reconstructed spectral frames at 450 nm, 490 nm, 530 nm, 585 nm and 605 nm, respectively. The reconstruction is based on 100 raw imaging frames acquired over a 10-second duration. **g** Normalized reconstructed spectra (solid) and the corresponding ground-truth spectra (dashed) of four representative pixels (M, N, P, Q) as marked in **a**. **h** S_0 (intensity) image of a pair of plastic goggles. Inset: normalized S_0 spectrum at pixel K. **i** Degree of linear polarization (DoLP) image of the plastic goggle at 450 nm. Inset: DoLP spectrum at pixel K. The DoLP spectrum reveals the wavelength-dependence of the stress-induced birefringence in the goggles unavailable to conventional spectral imagers

shadows during the 10-second detection period, and the limited dynamic range of the camera, which causes pixel saturation in bright areas with strong sunlight. Due to the correlation between transmission spectra at different polarization states, measurement errors in outdoor settings can cause breakdowns in spectral reconstruction, resulting in unphysical negative values that appear as black areas in the image. These challenges can be addressed by enhancing the robustness of spectral reconstruction algorithms or by increasing the number of spectral filtering units to reduce spectral correlation.

In addition to spectral details, we note that polarimetric imaging can also reveal substantial information associated with the objects' material or surface properties. As shown in Fig. 5f, artificial objects like cars often express higher contrast DoLP features than natural objects like trees and grass. Remarkably, we can also capture the subtle wavelength dependence of the DoLP (ω -DOLP) as shown in Fig. 5i. We emphasize that these results indicate the Nonlocal-Cam can provide a new platform for improving the performance of object detection, recognition and ranging. We anticipate this high-dimensional spatial, spectral and polarimetric information will enable automatic annotation of image data and accelerate the

development of physics-aware deep neural networks. [30].

3 Discussion and conclusions

We have shown that optically active materials encode features of nonlocal electrodynamics, and their corresponding nonlocal dispersion couples the spectrum and polarization in a super-dispersive manner. The nonlocal term in the Lagrangian of the optically active crystals leads to an additional contribution to energy density and Poynting vector arising from the photonic spin density, which does not exist in a conventional birefringent media. It is well-established that magnetic and magneto-electric (chiral) effects can be viewed as forms of spatial dispersion of permittivity [69]. Our study aims to provide a more nuanced understanding by distinguishing between chirality, magnetic responses, and natural optical activity. Unlike traditional chirality, which involves magnetic responses and unpaired spins, our focus is on optical active materials where no magnetic response is required. Additionally, our derivation highlights the 'super-dispersive' nature of gyration components, advancing the understanding of nonlocal electrodynamics in optically active materials. Moreover, our theory provides a general framework for exploring

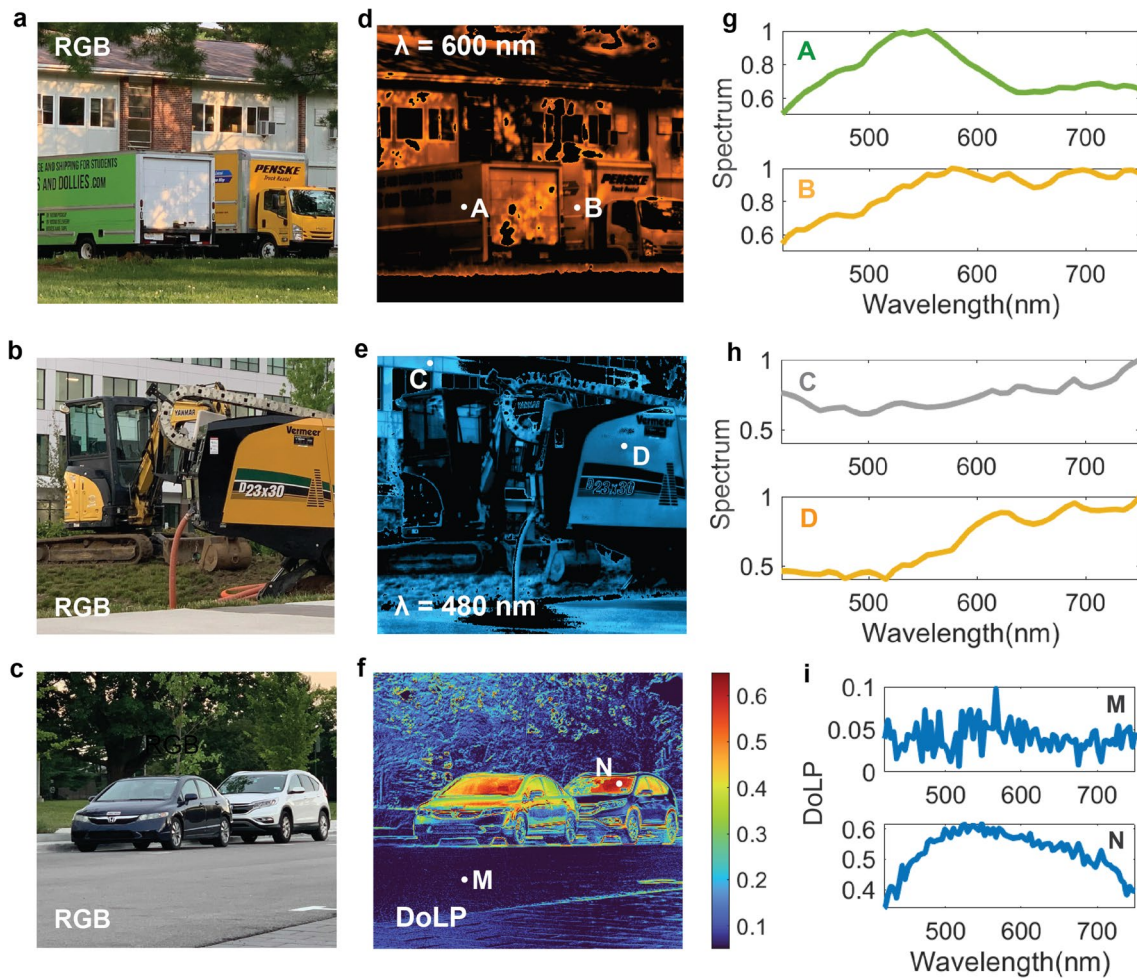


Fig. 5 Outdoor spectro-polarimetric imaging using the Nonlocal-Cam. **a, b, c** RGB images of outdoor scenes. **d, e** False color representations of reconstructed spectral frames at 600 nm and 450 nm, respectively. The reconstruction is based on 100 raw imaging frames acquired over a 10-second duration. **f** Degree of linear polarization (DoLP) image of the scene in **c** (at 540nm). **g, h** Normalized reconstructed spectra (solid) of four representative pixels (A, B, C, D) as marked in the spectral images. **i** DoLP spectrum of two representative pixels (M and N in **f**). These real-world images encode a 4D data-tesseract (x, y, ω , polarization) and reveal a subtle variation of the partially polarized light with spectrum

new materials and metamaterials with tailored nonlocal properties, expanding the potential of nonlocal optics for future photonic applications.

Our current Nonlocal-Cam design has certain limitations that warrant further improvement. Firstly, the use of a mechanical rotating polarizer imposes constraints on the compactness and robustness of the system. This issue could potentially be addressed by incorporating electrically tunable optically active materials [70] or metamaterials [71] (electro-gyration), which would eliminate the need for mechanical components and enhance the device's overall durability and miniaturization. Secondly, the system is not yet capable of real-time imaging, as the current data collection process requires approximately 10 s (involving 100 raw frames). This limitation could

be mitigated by improving synchronization between the rotating mounts and the camera, as well as by optimizing the reconstruction algorithms to reduce the number of raw frames needed. Thirdly, there is a trade-off between spectral resolution and signal-to-noise ratio; increasing the number of spectral filtering units enhances spectral resolution but reduces the signal. This challenge could also be overcome by advancing spectral reconstruction algorithms, enabling effective spectrum reconstruction with fewer spectral filtering units. These improvements would make the Nonlocal-Cam more practical and efficient for a wide range of applications.

In conclusion, we design a spectro-polarimetric imaging system based on the nonlocal super-dispersion in optically active materials, and experimentally

demonstrate the performance of Nonlocal-Cam to capture a 4D data-tesseract beyond a lab environment. We believe that the Nonlocal-Cam merges two distinct fields of nonlocal electrodynamics and computational imaging, and can be a powerful tool in physics-driven machine vision.

4 Methods

4.1 Material characterizations

All α -quartz single crystals used in this work were purchased from Crystran Ltd. and Knight Optical Ltd. The crystals were cut along the (0001) plane (z-cut) to make the optical axis perpendicular to the crystal surface. The spectra of optical rotatory power ρ along the c -axis were characterized by measuring the polarized transmission spectra using a standard dual-beam spectrophotometer (PerkinElmer Lambda 950). The crystals were placed between two broadband linear polarizers, where the orientation of the input polarizer was fixed at 0° , and the orientation of the output polarizer ϕ was rotated from 0° to 180° . The local maxima and local minima in the transmission spectra are corresponding to polarization rotation angles Φ of $\phi + n\pi$ and $\phi + (n+1)\pi/2$ ($n=0, 1, 2, 3, \dots$), respectively. The optical rotatory power was calculated by normalizing the polarization rotation angles Φ with the crystal thickness L , i.e. $\rho = \Phi/L$, and g_{33} of the gyration tensor was obtained through $\rho = \frac{\pi}{\lambda n_o} g_{33}$. For the angle-resolved transmission spectra T_{ss} , a custom-built rotation stage was used. A 5 mm crystal was placed between two fixed broadband linear polarizers with the same polarization orientation of 0° (vertical), where the surface normal of the crystal was rotated horizontally from -20° to 20° .

4.2 Nonlocal-cam and spectro-polarimetric imaging

The spectro-polarimetric module of the prototype Nonlocal-Cam consists of three broadband linear polarizers (400–750 nm) and two 3 mm α -quartz single crystals with distinct chirality. We note that a 3 mm crystal thickness was used in our demonstration to generate a single-band transmission spectrum within the working spectral range of 400–750 nm. The clear aperture of crystals is 1 inch (25.4 mm). A 2.8-megapixel monochromatic visible camera (Blackfly S-PGE-27S5M-C) with a 16 mm lens and 74.29 dB dynamic range was placed closely behind the spectro-polarimetric module to collect image data. We note that our computational algorithm processes the image uniformly on a pixel-by-pixel basis and is entirely linear, thus it does not affect the spatial resolution or the overall dynamic range of the imaging system. The central rotating linear polarizer was synchronized with the camera to generate 100 raw imaging frames for spectral reconstruction, resulting in a total collection time of

around 10 s. For polarimetric imaging, the entire module in front of the camera was collectively rotated, selecting four different input polarizations, while maintaining the same spectral transmission band. The polarimetric information associated with each pixel was quantitatively characterized through the Stokes parameters: $S_0 = I_0 + I_{90}$, $S_1 = I_0 - I_{90}$, $S_2 = I_{45} - I_{-45}$ and $\text{DoLP} = \sqrt{S_1^2 + S_2^2}/S_0$. In this case, I_0 , I_{90} , I_{45} and I_{-45} are the light intensity at polarization angles of 0° , 90° , 45° and -45° , respectively. We note that our Nonlocal-Cam is designed to collect information related to linear polarization and does not capture the Stokes parameter S_3 , which quantifies circular polarization. However, most real-world images exhibit vanishing S_3 characteristics in a broad spectrum (visible to infrared regime). Hence, the ability to capture S_0 , S_1 , and S_2 parameters are sufficient to completely capture the polarimetric data for most imaging applications.

4.3 Spectrum reconstruction

For the spectral reconstruction, we discretized the polarization angle p and defined each angle corresponding to a ‘polarized spectral state’ of the system. By further discretizing the spectral range of interest, the signal equation $I(p) = \int_{\lambda_{\min}}^{\lambda_{\max}} R(p, \lambda) S(\lambda) d\lambda$ can be rewritten in a tensor form as $I_p = R_{p\lambda} S_\lambda$. To obtain S_λ , we first calibrated the camera’s spectral response function $R_{p\lambda}$ using uniform imaging targets with known ground truth spectra in the ‘learning’ phase. Then, after collecting the raw data I_p in the ‘sampling’ phase, the spectrum was obtained in the ‘reconstruction’ phase based on the learned $R_{p\lambda}$ and the measured I_p .

Specifically, in the learning process, we had

$$I_{mp} = S_{m\lambda} R_{\lambda p} \quad (3)$$

We first used several different calibration targets (m is the index of the calibration targets) and obtained the ground truth spectra $S_{m\lambda}$ with a spectrometer. Then we measured each of the targets by rotating the linear polarizer, generating raw signals I_{mp} . The spectral response function $R_{\lambda p}$ was thus obtained by solving the systems of linear equations Eq. (3) at each of the fixed polarized spectral states p .

Note that the FOV of images in the current experiments were small (around 10 degrees). For computational simplicity, we ignored the angular dependence of the spectral response function in calibration and treated all pixels from the center to the edges of the sensor equally, i.e. $R_{p\lambda}$ are the same for all the pixels. For large FOV systems, the same process can be implemented separately for each pixel, generating spatially dependent spectral response functions $R_{p\lambda}(x, y)$.

Afterwards, we collected the raw data I_p at each pixel of an unknown scene in the sampling phase. We had

$$I_p = R_{p\lambda} S_\lambda \quad (4)$$

In our system, the performance of spectral reconstruction is limited by two main factors. Firstly, when the number of discretized spectral bands is large, the problem becomes under-determined due to correlations between the response functions (transmission spectra) of different polarized spectral states p . Secondly, the noise in both I_p and $R_{p\lambda}$ leads to unstable reconstruction results. To address these challenges, we utilized compressive sensing and dictionary learning algorithms, which proved to be effective in solving these under-determined linear equations. Specifically, in the reconstruction phase, we found sparse representations θ_k of the spectra S_λ by first obtaining a basis matrix $D_{\lambda k}$ using dictionary learning [67, 68]. Spectra extracted from a real-world hyperspectral images database [72] were used to generate the basis matrix $D_{\lambda k}$ for outdoor imaging. We had,

$$S_\lambda = D_{\lambda k} \theta_k \quad (5)$$

Then, the reconstruction problem can be converted to,

$$\begin{aligned} \theta_{\text{recon}} &= \arg \min_{\theta} \|\theta\|_1 \\ \text{s.t. } \|I_p - R_{p\lambda} S_\lambda\|_2 &= \|I_p - A_{pk} \theta_k\|_2 < \epsilon \end{aligned} \quad (6)$$

where $A_{pk} = R_{p\lambda} D_{\lambda k}$ and ϵ is the residual error. Then, θ_{recon} was obtained by solving Eq. (6) using CVX [73]. We note that the size of the discretized wavelength λ , polarized spectral state p , and sparse representation basis D are crucial in this reconstruction scheme, and they can be optimized to achieve the best reconstruction performance. Finally, the spectra at each pixel of a scene can be reconstructed by

$$S_{\text{recon}_\lambda} = D_{\lambda k} \theta_{\text{sparse}_k} \quad (7)$$

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s43593-024-00078-2>.

Below is the link to the electronic supplementary material. Supplementary file 1 (pdf 10064 KB)

Supplementary file 2 (mov 174 KB)

Supplementary file 3 (mov 309 KB)

Supplementary file 4 (mov 17309 KB)

Acknowledgements

This work was supported by the Office of Naval Research (ONR) under the award number N00014231270, the U.S. Department of Energy (DOE) under award number DE-SC0017717, and the Defense Advanced Research Projects Agency (DARPA) under the Nascent Light-Matter Interactions (NLM) program.

Author contributions

X. W. built the imaging system and performed the experimental characterizations as well as the imaging data collection. T. V. M., S. B., X. W. and Z. J. developed the electrodynamic theory of this work. X. W. and F. B. developed the spectral reconstruction algorithms. M. R. and R. R. performed the density functional theory calculations. X. W., T. V. M., S. B. and Z. J. wrote the manuscript. Z. J. supervised the research.

Data availability

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no Conflict of interest.

Received: 8 July 2024 Revised: 2 October 2024 Accepted: 12 October 2024

Published online: 06 December 2024

References

1. S. Dai, Z. Fei, Q. Ma, A. Rodin, M. Wagner, A. McLeod, M. Liu, W. Gannett, W. Regan, K. Watanabe, Tunable phonon polaritons in atomically thin van der Waals crystals of boron nitride. *Science* **343**, 1125–1129 (2014)
2. P. Li, I. Dolado, F.J. Alfaro-Mozaz, F. Casanova, L.E. Hueso, S. Liu, J.H. Edgar, A.Y. Nikitin, S. Vélaz, R. Hillenbrand, Infrared hyperbolic metasurface based on nanostructured van der Waals materials. *Science* **359**, 892–896 (2018)
3. A.J. Giles, S. Dai, I. Vurgaftman, T. Hoffman, S. Liu, L. Lindsay, C.T. Ellis, N. Assefa, I. Chatzakis, T.L. Reinecke, Ultralow-loss polaritons in isotopically pure boron nitride. *Nat. Mater.* **17**, 134–139 (2018)
4. K.-J. Tielrooij, N.C. Hesp, A. Principi, M.B. Lundeborg, E.A. Pogna, L. Banszerus, Z. Mics, M. Massicotte, P. Schmidt, D. Davydovskaya, Out-of-plane heat transfer in van der Waals stacks through electron-hyperbolic phonon coupling. *Nat. Nanotechnol.* **13**, 41–46 (2018)
5. W. Ma, P. Alonso-González, S. Li, A.Y. Nikitin, J. Yuan, J. Martín-Sánchez, J. Taboada-Gutiérrez, I. Amenabar, P. Li, S. Vélaz, In-plane anisotropic and ultra-low-loss polaritons in a natural van der Waals crystal. *Nature* **562**, 557–562 (2018)
6. Z. Zheng, N. Xu, S.L. Oscurato, M. Tamagnone, F. Sun, Y. Jiang, Y. Ke, J. Chen, W. Huang, W.L. Wilson, A mid-infrared biaxial hyperbolic van der Waals crystal. *Sci. Adv.* **5**, eaav8690 (2019)
7. G. Hu, Q. Ou, G. Si, Y. Wu, J. Wu, Z. Dai, A. Krasnok, Y. Mazar, Q. Zhang, Q. Bao, Topological polaritons and photonic magic angles in twisted α -MoO₃ bilayers. *Nature* **582**, 209–213 (2020)
8. J. Taboada-Gutiérrez, G. Álvarez-Pérez, J. Duan, W. Ma, K. Crowley, I. Prieto, A. Bylinkin, M. Autore, H. Volkova, K. Kimura, Broad spectral tuning of ultra-low-loss polaritons in a van der Waals crystal by intercalation. *Nat. Mater.* **19**, 964–968 (2020)
9. A. Sternbach, S. Chae, S. Latini, A. Rikhter, Y. Shao, B. Li, D. Rhodes, B. Kim, P.J. Schuck, X. Xu, Programmable hyperbolic polaritons in van der Waals semiconductors. *Science* **371**, 617–620 (2021)
10. F.H. Feres, R.A. Mayer, L. Wehmeier, F.C. Maia, E. Viana, A. Malachias, H.A. Bechtel, J.M. Klopff, L.M. Eng, S.C. Kehr, Sub-diffractive cavity modes of terahertz hyperbolic phonon polaritons in tin oxide. *Nat. Commun.* **2021**, 12 (1995)
11. W. Ma, G. Hu, D. Hu, R. Chen, T. Sun, X. Zhang, Q. Dai, Y. Zeng, A. Alù, C.-W. Qiu, Ghost hyperbolic surface polaritons in bulk anisotropic crystals. *Nature* **596**, 362–366 (2021)
12. N.C. Passler, X. Ni, G. Hu, J.R. Matson, G. Carini, M. Wolf, M. Schubert, A. Alù, J.D. Caldwell, T.G. Folland, Hyperbolic shear polaritons in low-symmetry crystals. *Nature* **602**, 595–600 (2022)
13. G. Hu, W. Ma, D. Hu, J. Wu, C. Zheng, K. Liu, X. Zhang, X. Ni, J. Chen, X. Zhang, Real-space nanoimaging of hyperbolic shear polaritons in a monoclinic crystal. *Nat. Nanotechnol.* **18**, 64–70 (2023)

14. Ashcroft, N. W.; Mermin, N. D. Solid state physics; Cengage Learning, (2022)
15. D.M. Nenno, C.A. Garcia, J. Gooth, C. Felser, P. Narang, Axion physics in condensed-matter systems. *Nat. Rev. Phys.* **2**, 682–696 (2020)
16. A.M. Essin, J.E. Moore, D. Vanderbilt, Magnetolectric polarizability and axion electrodynamics in crystalline insulators. *Phys. Rev. Lett.* **102**, 146805 (2009)
17. A. Gao, Y.-F. Liu, C. Hu, J.-X. Qiu, C. Tzschaschel, B. Ghosh, S.-C. Ho, D. Bérubé, R. Chen, H. Sun, Layer Hall effect in a 2D topological axion antiferromagnet. *Nature* **595**, 521–525 (2021)
18. L. Wu, M. Salehi, N. Koira, J. Moon, S. Oh, N. Armitage, Quantized Faraday and Kerr rotation and axion electrodynamics of a 3D topological insulator. *Science* **354**, 1124–1127 (2016)
19. N. Armitage, E. Mele, A. Vishwanath, Weyl and Dirac semimetals in three-dimensional solids. *Rev. Mod. Phys.* **90**, 015001 (2018)
20. B. Zhao, C. Guo, C.A. Garcia, P. Narang, S. Fan, Axion-field-enabled nonreciprocal thermal radiation in Weyl semimetals. *Nano Lett.* **20**, 1923–1927 (2020)
21. S. Zhong, J. Orenstein, J.E. Moore, Optical gyrotropy from axion electrodynamics in momentum space. *Phys. Rev. Lett.* **115**, 117403 (2015)
22. Ueda, H.; García-Fernández, M.; Agrestini, S.; Romao, C. P.; van den Brink, J.; Spaldin, N. A.; Zhou, K.-J.; Staub, U. Chiral phonons in quartz probed by X-rays. *Nature* **2023**, 1–5
23. F. Yesilkoy, E.R. Arvelo, Y. Jahani, M. Liu, A. Tittl, V. Cevher, Y. Kivshar, H. Altug, Ultrasensitive hyperspectral imaging and biodetection enabled by dielectric metasurfaces. *Nat. Photonics* **13**, 390–396 (2019)
24. Z. Wang, S. Yi, A. Chen, M. Zhou, T.S. Luk, A. James, J. Nogan, W. Ross, G. Joe, A. Shahsafi, Single-shot on-chip spectral sensors based on photonic crystal slabs. *Nat. Commun.* **10**, 1–6 (2019)
25. A. McClung, S. Samudrala, M. Torfeh, M. Mansouree, A. Arbabi, Snapshot spectral imaging with parallel metasystems. *Sci. Adv.* **6**, eabc7646 (2020)
26. N. A. Rubin, G. D'Aversa, P. Chevalier, Z. Shi, W.T. Chen, F. Capasso. Matrix Fourier optics enables a compact full-Stokes polarization camera. *Science* **2019**, 365
27. T. Xu, Y.-K. Wu, X. Luo, L.J. Guo, Plasmonic nanoresonators for high-resolution colour filtering and spectral imaging. *Nat. Commun.* **1**, 1–5 (2010)
28. K. Monakhova, K. Yanny, N. Aggarwal, L. Waller, Spectral DiffuserCam: lensless snapshot hyperspectral imaging with a spectral filter array. *Optica* **7**, 1298–1307 (2020)
29. F. Bao, X. Wang, S.H. Sureshbabu, G. Sreekumar, L. Yang, V. Aggarwal, V.N. Boddeti, Z. Jacob, Heat-assisted detection and ranging. *Nature* **619**, 743–748 (2023)
30. G.E. Karniadakis, I.G. Kevrekidis, L. Lu, P. Perdikaris, S. Wang, L. Yang, Physics-informed machine learning. *Nat. Rev. Phys.* **3**, 422–440 (2021)
31. A. Yariv, P. Yeh, *Optical waves in crystal propagation and control of laser radiation* (John Wiley and Sons Inc, 1983)
32. X.-B. Han, C.-Y. Chai, M.-L. Jin, C.-C. Fan, W. Zhang, Quartz-like structure, optical activity, and high stability in the first chiral cation-coordinated perovskite semiconductor. *Adv. Opt. Mater.* **11**, 2300580 (2023)
33. M. Hobden, Optical activity in a non-enantiomorphous crystal silver gallium sulphide. *Nature* **216**, 678–678 (1967)
34. G. Cai, Y. Li, Y. Zhang, X. Jiang, Y. Chen, G. Qu, X. Zhang, S. Xiao, J. Han, S. Yu, others Compact angle-resolved metasurface spectrometer. *Nat. Mater.* **23**, 71–78 (2024)
35. S. Wen, X. Xue, S. Wang, Y. Ni, L. Sun, Y. Yang, Metasurface array for single-shot spectroscopic ellipsometry. *Light* **13**, 88 (2024)
36. L. Yuan, J. Xie, Z. He, Y. Wang, J. Wang, Optical design and evaluation of airborne prism-grating imaging spectrometer. *Opt. Express* **27**, 17686–17700 (2019)
37. P.G. Lucey, M. Wood, S.T. Crites, J. Akagi, A LWIR hyperspectral imager using a Sagnac interferometer and cooled HgCdTe detector array. Algorithms and technologies for multispectral, hyperspectral, and ultraspectral imagery XVIII. 2012; pp 218–225
38. M.W. Kudenov, M.E. Jungwirth, E.L. Dereniak, G.R. Gerhart, White-light Sagnac interferometer for snapshot multispectral imaging. *Appl. Opt.* **49**, 4067–4076 (2010)
39. A. Hegyi, J. Martini, Hyperspectral imaging with a liquid crystal polarization interferometer. *Opt. Express* **23**, 28742–28754 (2015)
40. D.M. Kita, B. Miranda, D. Favella, D. Bono, J. Michon, H. Lin, T. Gu, J. Hu, High-performance and scalable on-chip digital Fourier transform spectroscopy. *Nat. Commun.* **9**, 4405 (2018)
41. Q. Zhang, P. Lin, C. Wang, Y. Zhang, Z. Yu, X. Liu, Y. Lu, T. Xu, Z. Zheng, Neural-optic co-designed polarization-multiplexed metalens for compact computational spectral imaging. *Laser & Photon. Rev.* **2024**, 2400187
42. W. Han, Q. Wang, W. Cai, Computed tomography imaging spectrometry based on superiorization and guided image filtering. *Opt. Lett.* **46**, 2208–2211 (2021)
43. Y. Fan, W. Huang, F. Zhu, X. Liu, C. Jin, C. Guo, Y. An, Y. Kivshar, C.-W. Qiu, W. Li, Dispersion-assisted high-dimensional photodetector. *Nature* **2024**, 1–7
44. A. Fan, T. Xu, G. Teng, X. Wang, C. Xu, Y. Zhang, X. Xu, J. Li, Deep learning reconstruction enables full-Stokes single compression in polarized hyperspectral imaging. *Chin. Opt. Lett.* **21**, 051101 (2023)
45. Y. Ni, C. Chen, S. Wen, X. Xue, L. Sun, Y. Yang, Computational spectropolarimetry with a tunable liquid crystal metasurface. *eLight* **2**, 23 (2022)
46. T. Badloe, J. Kim, I. Kim, W.-S. Kim, W.S. Kim, Y.-K. Kim, J. Rho, Liquid crystal-powered Mie resonators for electrically tunable photorealistic color gradients and dark blacks. *Light* **11**, 118 (2022)
47. M. Bosch, M.R. Shcherbakov, K. Won, H.-S. Lee, Y. Kim, G. Shvets, Electrically actuated varifocal lens based on liquid-crystal-embedded dielectric metasurfaces. *Nano Lett.* **21**, 3849–3856 (2021)
48. J. Kobashi, H. Yoshida, M. Ozaki, Planar optics with patterned chiral liquid crystals. *Nat. Photonics* **10**, 389–392 (2016)
49. O. Buchnev, N. Podoliak, M. Kaczmarek, N.I. Zheludev, V.A. Fedotov, Electrically controlled nanostructured metasurface loaded with liquid crystal: toward multifunctional photonic switch. *Adv. Opt. Mater.* **3**, 674–679 (2015)
50. A. Wagadarikar, R. John, R. Willett, D. Brady, Single disperser design for coded aperture snapshot spectral imaging. *Appl. Opt.* **47**, B44–B51 (2008)
51. Y. Tang, A.E. Cohen, Optical chirality and its interaction with matter. *Phys. Rev. Lett.* **104**, 163901 (2010)
52. T. Baba, Slow light in photonic crystals. *Nat. Photonics* **2**, 465–473 (2008)
53. J.B. Khurgin, R.S. Tucker, *Slow light: science and applications* (CRC Press, 2018)
54. M.D. Stenner, D.J. Gauthier, M.A. Neifeld, The speed of information in a 'fast-light' optical medium. *Nature* **425**, 695–698 (2003)
55. M. Fleischhauer, A. Imamoglu, J.P. Marangos, Electromagnetically induced transparency: Optics in coherent media. *Rev. Mod. Phys.* **77**, 633 (2005)
56. S. Chandrasekhar, Theoretical interpretation of the optical activity of quartz. *Proc. Indian Acad. Sci.* **37**, 468–484 (1953)
57. O. Arteaga, A. Canillas, G.E. Jellison Jr., Determination of the components of the gyration tensor of quartz by oblique incidence transmission two-modulator generalized ellipsometry. *Appl. Opt.* **48**, 5307–5317 (2009)
58. X. Wang, Z. Yang, F. Bao, T. Sentz, Z. Jacob, Spinning metasurface stack for spectro-polarimetric thermal imaging. *Optica* **11**, 73–80 (2024)
59. S. Yuan, D. Naveh, K. Watanabe, T. Taniguchi, F. Xia, A wavelength-scale black phosphorus spectrometer. *Nat. Photonics* **2021**, 1–7
60. Z. Yang, T. Albrow-Owen, W. Cai, T. Hasan, Miniaturization of optical spectrometers. *Science* **371**, eabe0722 (2021)
61. Z. Yang, T. Albrow-Owen, H. Cui, J. Alexander-Webber, F. Gu, X. Wang, T.-C. Wu, M. Zhuge, C. Williams, P. Wang, Single-nanowire spectrometers. *Science* **365**, 1017–1020 (2019)
62. H.H. Yoon, H.A. Fernandez, F. Nigmatulin, W. Cai, Z. Yang, H. Cui, F. Ahmed, X. Cui, M.G. Uddin, E.D. Minot, Miniaturized spectrometers with a tunable van der Waals junction. *Science* **378**, 296–299 (2022)
63. J. Bao, M.G. Bawendi, A colloidal quantum dot spectrometer. *Nature* **523**, 67–70 (2015)
64. Y. Xiao, C. Wan, J. Salman, I.J. Maywar, J. King, A. Shahsafi, M.A. Kats, Planck spectroscopy. *Laser Photonics Rev.* **15**, 2100121 (2021)
65. Z. Wang, Z. Yu, Spectral analysis based on compressive sensing in nanophotonic structures. *Opt. Express* **22**, 25608–25614 (2014)
66. S. Zhang, Y. Dong, H. Fu, S.-L. Huang, L. Zhang, A spectral reconstruction algorithm of miniature spectrometer based on sparse optimization and dictionary learning. *Sensors* **18**, 644 (2018)
67. K. Kreutz-Delgado, J.F. Murray, B.D. Rao, K. Engan, T.-W. Lee, T.J. Sejnowski, Dictionary learning algorithms for sparse representation. *Neural Comput.* **15**, 349–396 (2003)
68. K. Skretting, K. Engan, Recursive least squares dictionary learning algorithm. *IEEE Trans. Signal Process.* **58**, 2121–2130 (2010)
69. K. Shastri, F. Monticone, Nonlocal flat optics. *Nat. Photonics* **17**, 36–47 (2023)

70. O. Vlokh, Electrogyration properties of crystals. *Ferroelectrics* **75**, 119–137 (1987)
71. Q. Zhang, E. Plum, J.-Y. Ou, H. Pi, J. Li, K.F. MacDonald, N.I. Zheludev, Electrogyration in metamaterials: chirality and polarization rotatory power that depend on applied electric field. *Adv. Opt. Mater.* **9**, 2001826 (2021)
72. A. Chakrabarti, T. Zickler, Statistics of real-world hyperspectral images. *CVPR* **2011**, 193–200 (2011)
73. M. Grant, S. Boyd, CVX: Matlab Software for Disciplined Convex Programming, version 2.1. <http://cvxr.com/cvx>, (2014)

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.