

Polarimetric-hyperspectral microscopy for resolving chemical and structural signatures

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Abstract: We present polarimetric-hyperspectral microscopy for resolving chemical composition and structural anisotropy in materials. By integrating complementary signatures, the approach mitigates morphology-induced spectral ambiguity, enabling physically grounded material characterization beyond conventional hyperspectral imaging. © 2026 The Author(s)

1. Introduction

Accurate material characterization requires resolving both chemical composition and structural organization. Hyperspectral imaging provides rich molecular fingerprints through wavelength-resolved measurements, enabling identification of material constituents across diverse applications [1, 2]. However, hyperspectral signatures are inherently insensitive to spatial anisotropy and morphology, and are often distorted by orientation-dependent scattering, internal stress, or surface roughness, leading to spectral ambiguity in heterogeneous materials. Polarimetric imaging, in contrast, is highly sensitive to birefringence, orientation, and microstructural organization, yet lacks chemical specificity [3, 4]. As a result, each modality alone offers only a partial view of material signatures: hyperspectral imaging primarily encodes compositional information, whereas polarization reveals structural contrast. This separation limits physically grounded interpretation when either technique is used independently, particularly at the microscale where materials rarely behave as optically isotropic media.

Here, we present polarimetric-hyperspectral microscopy for resolving complementary chemical and structural signatures in materials. By co-registering polarization-resolved measurements with hyperspectral data, our approach disentangles composition-driven and morphology-driven optical responses. This joint framework mitigates structure-induced spectral ambiguity and enables chemically specific yet structurally sensitive characterization. Rather than pursuing accuracy-driven multimodal fusion, we establish a physics-informed imaging paradigm that enables interpretable material analysis across complex anisotropic systems.

2. Methods

The polarimetric-hyperspectral microscopy system integrates a broadband optical microscope with a non-polarizing beam splitter to enable co-registered acquisition of polarization-resolved and hyperspectral data from the same field of view (Fig. 1(a)). A polarization camera captures linear Stokes parameters capturing four orientations (0° , 45° , 90° , 135°) simultaneously, from which intensity, degree of linear polarization (DoLP), and angle of polarization (AoP) are derived to characterize structural anisotropy. In parallel, a hyperspectral imaging arm records wavelength-resolved image stacks, providing detailed spectral signatures related to material composition.

Spatial alignment between modalities is achieved using calibration-based registration. Hyperspectral measurements are corrected using dark and white references to reduce illumination variability, while polarimetric features such as DoLP and AoP provide sensitivity to orientation and microstructural organization. Regions of interest corresponding to individual material domains are segmented from the co-registered data. Spectral and polarimetric descriptors are then extracted to represent chemical and structural signatures, respectively. By jointly analyzing these complementary features, the framework disentangles composition-driven and morphology-driven responses, enabling chemically specific yet structurally sensitive characterization for physically grounded material analysis.

3. Results and discussion

Representative polymer samples, including Polyethylene terephthalate (PET) and Polymethyl methacrylate (PMMA) films and nanoplastic fragments, were first examined to evaluate modality-specific contrast. As shown in Fig. 1(b-c), hyperspectral imaging captured characteristic absorption profiles across 400–1000 nm, yet exhibited noticeable intra-class variability due to morphology-dependent scattering and orientation effects. For instance, mechanically deformed regions produced spectral distortions despite unchanged chemical composition, leading to

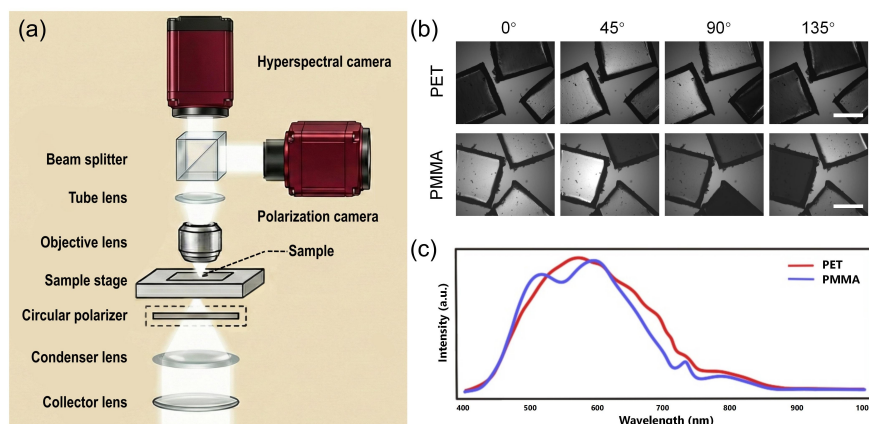


Fig. 1. (a) Schematic of the polarimetric-hyperspectral microscopy system. (b) Polarization-resolved images of PET and PMMA films acquired at analyzer angles of 0°, 45°, 90°, and 135°. Scale bar: 1 mm. (c) Corresponding hyperspectral responses across 400–1000 nm.

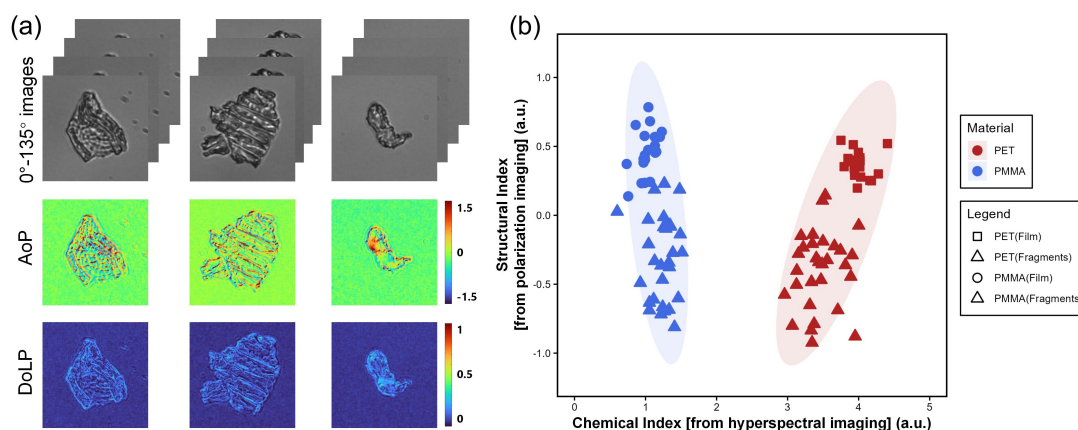


Fig. 2. (a) Polarization images of nanoplastic fragments with derived AoP and DoLP maps. (b) Joint polarimetric-hyperspectral characterization enabling clearer separation between PET and PMMA.

partial overlap between materials. In contrast, polarization imaging revealed distinct structural variations across orientations (Fig. 1(b)), highlighting anisotropic domains invisible to spectral contrast alone.

Further analysis of nanoplastic fragments demonstrated that polarimetric features such as AoP and DoLP captured microstructural organization and orientation-dependent anisotropy (Fig. 2(a)). While hyperspectral signatures alone were insufficient to distinguish fragmented morphologies, the incorporation of polarization-derived structural descriptors enabled clearer separation in the joint characterization space (Fig. 2(b)). This integration reduces morphology-induced spectral ambiguity and improves material discrimination.

Together, these results indicate that hyperspectral and polarimetric modalities provide complementary signatures of chemical composition and structural organization. Their joint analysis enables chemically specific yet structurally sensitive characterization, offering a physically interpretable framework for microscale material identification beyond conventional spectral imaging.

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