Metasurfaces

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Polarization detection in miniature

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A compact on-chip polarimeter can be created using subpixels made from metasurface photodetectors and a machine learning algorithm.

Polarization is an intrinsic degree of freedom for photons analogous to electron spin. In everyday life, applications such as three-dimensional films, sunglasses and liquid-crystal displays all use the fact that light has components with different polarizations. In research, monitoring polarization information is important in the study of biological molecules in the body and astronomical objects in deep space. And in the quantum world, photons can have entangled polarization states, which can be leveraged in quantum communication and teleportation.

The polarization state, together with light intensity, can be fully characterized by a four-component Stokes vector, and polarimeters are commercially available to measure this. These instruments are, however, based on discrete optical components (such as prisms, lenses, filters, polarizers and waveplates) and are thus bulky and complex. Writing in *Nature Electronics*, Jie Deng and colleagues now report a compact on-chip full-Stokes polarimeter that features four subpixels made from metasurface photodetectors and offers high accuracy enabled by machine learning[1].

Light–matter interactions are foundational for two reasons. First, they involve two distinct classes of elementary particles: photons (which are bosons) and electrons (which are fermions). Second, the resulting optoelectronic phenomena represent a conversion between optical and electric information. Such phenomena are sensitive to the orbital, spin and symmetry properties of electrons, and they strongly depend on the intensity, spectrum and polarization state of light. Therefore, matter can be designed and photoresponses exploited to detect the classical or quantum information of light. As the desired light information can be encoded into photoresponse data, machine learning algorithms can be used as decoders, offering efficient and accurate deep sensing solutions[2].

One approach to achieving on-chip full-Stokes polarization detection is to use low-symmetry materials that show sufficiently strong linear and circular bulk photovoltaic effects[3]. Such materials include twisted graphene moiré metamaterials[4], where the engineered interlayer couplings fall within the infrared range. Another solution is metasurface integrated photodetectors[5]. Metasurfaces are typically made up of arrays of subwavelength structures whose shape, size and ordering can be designed to interact with light in desired ways, enabling unconventional functionalities such as lensing, beam steering, wavefront shaping and cloaking[6]. In both approaches, light–matter interactions first encode the polarization information into photoresponse data. Then, empirical or machine learning models are used to extract the Stokes parameters.

Deng and colleagues — who are based at the Shanghai Institute of Technical Physics, the University of Chinese Academy of Sciences, the Southeast University in Nanjing, the National University of Singapore and the Nanyang Technological University — propose the concept of an optoelectronic polarization eigenvector that represents the linear relationship between the Stokes vector and photocurrent. They show that the photocurrent of a square-law detector can generally be expressed as the scalar product of the Stokes vector of an incident light and the optoelectronic polarization eigenvector of a designed metasurface integrated with a detection material (Fig. 1a).

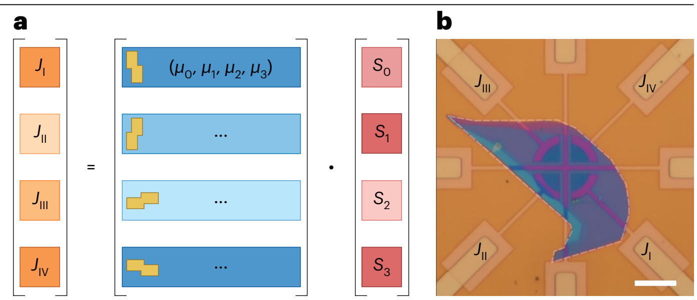

Fig. 1 | High-accuracy on-chip full-Stokes polarimetry with optimized optoelectronic polarization eigenvectors. a, Matrix representation of the optoelectronic conversion from the incident Stokes vector (**S**) to the measured photocurrents (**J**) through the designed optoelectronic polarization eigenvectors (**μ**). **b**, Optical microscopy image of the polarimeter. Four identical Z-shaped metasurfaces are ordered in different orientations and handedness in the four subpixels. All four subpixels are integrated on the same piece of detection material made from few-layer MoS_2 and are backed with Al_2O_3 spacers and Au reflectors. Scale bar, 10 μm. Figure adapted from ref. 1, Springer Nature Ltd.

Their on-chip polarimeter consists of four subpixels with different polarization dependencies. With measured photoresponse data, extracting the Stokes vector becomes an inverse problem. For the optoelectronic conversion matrix, its condition number, which measures the sensitivity of the output data to small perturbations in the input data, is an important figure of merit of the inverse problem. The smaller the condition number, the smaller the error of the extracted Stokes vector. In this case, the condition number is mainly controlled by the directions, polarization extinction ratios and uniformity of the optoelectronic polarization eigenvectors. When the directions of the optoelectronic polarization eigenvectors form a tetrahedron with a maximum volume, the minimum condition number is realized.

To gain large polarization extinction ratios of each optoelectronic polarization eigenvector, a Z-shaped metasurface is backed with an aluminium oxide (Al_2O_3) spacer and a gold (Au) reflector to form a cavity-coupled plasmonic structure. The high uniformity of the optoelectronic polarization eigenvectors is ensured by using identical Z-shaped metasurfaces but ordered in different orientations and handedness in the four subpixels, and by integrating the subpixels on the same piece of few-layer molybdenum disulfide (MoS_2) as the detection material (Fig. 1b). The researchers achieve a low condition number around 8 across the wavelength range 1,200 nm to 1,600 nm (which is a relatively narrow range).

As well as optimization of the optoelectronic polarization eigenvectors, the team use Gaussian process regression — a machine learning algorithm — to reduce the root-mean-square errors of the Stokes parameters. The model is first trained on 2,070 data points covering various polarization states and 5 incident power levels, with each data point containing an input Stokes vector and the corresponding measured photocurrent vector. The model can then accurately predict 37,265 Stokes vectors, with the root-mean-square errors being only 0.13%, 0.98%, 0.96% and 0.58% for the four Stokes parameters. These are the smallest full-Stokes reconstruction root-mean-square errors that have been reported so far for on-chip polarimeters. Remarkably, this is achieved at the same time as the coverage of polarization states far exceeds that of most previous on-chip approaches.

The work of Deng and colleagues establishes a new polarization-dependent optoelectronic conversion mechanism and helps advance the development of on-chip full-Stokes polarimetry. Their polarimeter shows an azimuth angle accuracy of 0.69° and an ellipticity angle accuracy of 0.51°, comparable to those of commercial polarimeters. In terms of device size and measurement speed, however, the new polarimeter is far better. Limited by the principle of rotating polarization elements, commercial polarimeters are typically bulky instruments on an optical table. By contrast, the new polarimeter has a chip-scale dimension of only tens of micrometres. In addition, commercial instruments require a series of waveplate rotations to extract the full-Stokes parameters, whereas the new polarimeter performs the full-Stokes polarimetry in a single shot. By leveraging more different pixels of different spectral responsivity characteristics and more advanced machine learning algorithms, future metasurface integrated photodetectors could potentially simultaneously and accurately capture complete optical information, including intensity, polarization and (broad) spectrum[3].

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Competing interests

The authors declare no competing interests.