nature portfolio

Peer Review File

Metasurface-enabled Broadband Multidimensional Photodetectors

Open Access This file is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. In the cases where the authors are anonymous, such as is the case for the reports of anonymous peer reviewers, author attribution should be to 'Anonymous Referee' followed by a clear attribution to the source work. The images or other third party material in this file are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

Editorial Note: Parts of this Peer Review File have been redacted as indicated to remove third-party material where no permission to publish could be obtained.

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

A broadband multidimensional photodetector simultaneously detects polarization-sensitive spectral information on a single integrated chip, which may inspire many researchers in broad fields across academia and industry. This article presents a novel metasurface-enabled graphene photodetector capable of various polarization states and wavelengths of broadband light from 1 to 8 micrometers. They suggest precise spin-wavelength differentiation by utilizing dual-arm plasmonic nanostructures and machine-learning techniques. The device exhibits vectorial photocurrents with varying polarities and amplitudes based on light's wavelength and polarization, allowing for efficient encoding and decoding of optical information. The authors claim significant advancements in optical sensing, communication, and computing, offering a compact and reliable solution for high-dimensional spectral-polarization co-detection. Their efforts should be deserved, but their demonstrations are pretty predictable, considering the graphene photodetector coupled with plasmonic nanoantennas, and the new findings are not very recognizable. This work with comprehensive experimental datasets has scientific value for photonic and optoelectronic scientists in the relevant community. However, considering the novelty and advancement, I cannot recommend that Nature Communications accept this paper for publication. At least, I would like to check the author's answers to the following questions and suggestions.

1. The authors mentioned "the wavelength resolution of 0.5um," but I think they must change it to "the wavelength prediction accuracy of 500nm" based on Supplementary Note 6. Note that the spectral wavelength) resolution indicates the ability to distinguish two narrow spectral peaks separated by fine wavelength intervals. Since their wavelength prediction relies on the confusion matrix of machine learning and they did not extract the resolution from two narrow spectral peaks from the measured or reconstructed spectra, the authors cannot mention the "wavelength or spectral resolution" in this work.

2. Can the current design effectively differentiate between closely spaced wavelengths within the 1-8 micrometer range? Since we cannot confirm the "spectral resolution" in this work, how does it handle potential signal overlap or interference?

3. According to the state-of-the-art works recently reported on miniaturized computational spectrometers, their "spectral resolution" has already achieved a few nanometers to at least tens of nanometers. Regarding the "high peak wavelength accuracy," some works have achieved nanometers below the decimal point (like 0.Xnm or 0.0Xnm, depending on their designs). In comparison, the authors could not demonstrate "wavelength or spectral resolution" but "the wavelength prediction accuracy of 500nm." How can we recognize this work's advancement?

4. I agree that traditional methods require multiple discrete optical components to extract such multidimensional information, but the proposed device integrates this functionality on a single

chip. However, I guess the current design must have limitations regarding the "spatial resolution" of detected signals. In other words, even if their proof-of-concept claims the broadband photodetection of high-dimensional optical information with a single integrated on-chip detector, the trade-off between the footprint and spatial resolution might hinder performance and increase process cost when expanding them to a single integrated chip. Furthermore, how do they compare to existing state-of-the-art technologies?

5. The authors claim their design simplifies the detection process by eliminating the need for additional degrees of freedom like twists or gate control. Instead, their design relies on a plasmonic metasurface combined with the graphene film, and the metasurface area containing the nanoantenna array must be at least several tens of micrometers, which is a disadvantage in the device footprint. In particular, their three-port (or ports of any odd number) graphene photodetector design coupled with plasmonic nanoantennas further increases the device footprint when integrated on a chip for the exact spatial resolution. It seems they tried the two-port design presented in Supplementary Information. How about a four-port design to increase integration density, and why do they only highlight the three-port design? Can authors defend their design or suggest a better one?

6. What are the additional potential trade-offs between achieving high-dimensional detection and maintaining spatial resolution or footprint?

7. How does the proposed metasurface-enabled graphene photodetector ensure the stability and reliability of information detection without additional degrees of freedom? In terms of stability and noise, unlike what was shown in Supplementary Fig. 17, the photovoltage level in the switch signal in Supplementary Fig. 18 is weak, and the value appears to be unstable over time. Also, was the fitting done correctly when obtaining the Rising and Decaying times on the right side of Supplementary Fig. 18? Please express the general exp fitting.

8. How does the device perform under different environmental conditions, such as varying temperatures and humidity levels, which could affect the graphene and metasurface materials? The authors note that graphene properties may be sensitive to water vapor or adsorbed gas molecules, especially when the graphene surface is not passivated. How does the device manage the potential noise and signal degradation issues that could arise from using dual-arm plasmonic nanostructures on a graphene platform?

9. They claim machine learning further enhances the device's ability to predict and differentiate optical signals over a broad wavelength range. The wavelength precision presented in this paper was obtained using machine learning models. Many other works share their algorithms publicly in similar studies.This is an excellent example of a virtuous cycle in the research world. Likewise, I encourage the authors to open the code of their developed algorithm public for the benefit of other subsequent researchers. Suppose these two algorithm codes are publicly archived on Github and Zenodo. In that case, they will benefit many researchers, and this paper will attract many readers if it gets publication.

10. How does the use of machine learning in this photodetector compare to traditional signal processing methods in terms of accuracy, speed, and computational requirements?

11. What specific optical communication and computing applications would benefit most from this technology, and what are the anticipated improvements over current systems? What further developments or optimizations are necessary to make this technology viable for commercial deployment, particularly in terms of cost-effectiveness and ease of integration?

12. What challenges might arise in scaling the device for practical applications, particularly manufacturing and integration? Rather than highlighting the advantages of their design in these aspects, I hope that the authors will also present relevant current technologies or technologies needed in the future to show how the disadvantages in their design can be improved in the future.

Reviewer #2 (Remarks to the Author):

The authors have explored the use of a small array of graphene detectors, made polarisation sensitive by tailored metasurfaces, to provide a crude determination of the polarisation state and wavelength of incoming illumination. The work builds on previous studies, but includes novel aspects. The manuscript has issues that would need to be resolved before publication.

The authors should clarify the novelty of their study. For example, in some sections language such as "This design only requires a single measurement of a three-port metasurface" may mislead the readership. In reality, measurement of three separate devices (i.e. using six electrodes) is required to extract this information so the terms "single measurement" and "three port" are likely to confuse. I suggest the authors remove or rewrite such statements to avoid confusion.

The main text focuses on qualitative analysis, and more quantitative information should be added into the main text to provide the readership with a realistic picture of the impact of this demonstration. For example, information on the responsivity/detectivity of the sensors is relegated to the SI and not mentioned in the main text. This is very important given that the magnitude of the detectivity is quite low (i.e. 10^6 Jones scale) compared to state-of-the-art IR sensors. This means that the proposed sensor array would only be useful under very intense infrared light and is unlikely be usable in, for example, real world sensing applications. As such, it is important for the authors to clearly acknowledge this shortcoming as a limitation of their proposed system.

Can the authors provide information on the linearity of their photovoltage with illumination intensity?

Related to the above points it is not clear what application the authors foresee this detector array as being useful for? As discussed above, the low sensitivity would preclude usage for most sensing/imaging applications. Similarly, the μs detector speed documented in the SI would prevent usage for communication applications (which require >GHz bandwidths). Given the detection mechanism, it is unlikely that these metrics will improve significantly. Hence, the readership will want a clearer statement about the potential application of this sensor array, and removal of mention of other infeasible applications.

Reviewer #3 (Remarks to the Author):

This manuscript reports a metasurface-assisted graphene photodetector, which can achieve the simultaneous detection and distinction of various polarization states and wavelengths of broadband light (1-8 μm) at the wavelength resolution of 0.5 μm. By designing a set of integrated dual-arm plasmonic nanostructures, multidimensional information can be decoupled by encoding vectorial photocurrents with varying polarities and amplitudes. Furthermore, machine learning techniques are leveraged to reconstruct and boost the cooperate multiport metasurfaces. This work provides a solution for highly compact and multi-dimensional spectral-polarization detection. I therefore recommend the current manuscript to be published in Nature Communications. However, the following comments should be addressed before publication.

1.The metasurface-assisted graphene photodetector can achieve spin-wavelength differentiation over the infrared range (1~8 μm). Could the current design be employed to the spectral-polarization co-detection in visible and ultraviolet ranges? The authors should provide experimental result or simulation model to discuss the subject.

2.In the manuscript, the dual-arm nanoantennas were designed to be parallel with the source/drain electrodes. If varying the angles between the dual-arm nanoantennas and electrodes, what happens to the spin-wavelength differentiation by the graphene photodetector?

3. Due to the gapless properties of graphene, the photocurrents were considered to be originated from the photothermal effects. More discussions are suggested to provided to help the readers understand the generation of photocurrents of varying magnitudes and directions.

4. The wavelength resolution is 0.5 μm in the current dual-arm nanoantennas, which is expected to be further improved by the machine learning techniques. The reviewer wonder that what is the limit of wavelength resolution in experiments by adjusting the structural dimension of the dual-arm nanoantennas?

Reply to the reviewers:

Reviewer 1

Comments:

A broadband multidimensional photodetector simultaneously detects polarization-sensitive spectral information on a single integrated chip, which may inspire many researchers in broad fields across academia and industry. This article presents a novel metasurface-enabled graphene photodetector capable of various polarization states and wavelengths of broadband light from 1 to 8 micrometers. They suggest precise spin-wavelength differentiation by utilizing dual-arm plasmonic nanostructures and machine-learning techniques. The device exhibits vectorial photocurrents with varying polarities and amplitudes based on light's wavelength and polarization, allowing for efficient encoding and decoding of optical information. The authors claim significant advancements in optical sensing, communication, and computing, offering a compact and reliable solution for high-dimensional spectral-polarization co-detection. Their efforts should be deserved, but their demonstrations are pretty predictable, considering the graphene photodetector coupled with plasmonic nanoantennas, and the new findings are not very recognizable. This work with comprehensive experimental datasets has scientific value for photonic and optoelectronic scientists in the relevant community. However, considering the novelty and advancement, I cannot recommend that Nature Communications accept this paper for publication. At least, I would like to check the author's answers to the following questions and suggestions.

Author Reply: We are grateful to you for your questions and suggestions, which will greatly enhance the quality of our manuscript. These suggestions have also reminded us to refine and deeply explore the practical potential applications of our work. We have carefully considered each question and suggestion, supplementing with extensive data and statements. We hope to address your concerns and facilitate the publication of our work in this journal.

Firstly, please allow us to elaborate on the novelty of this paper. The highlight of our work is the use of metasurface design to simultaneously achieve the detection and discrimination of polarization information and wavelength information, thereby achieving high-dimensional detection. This means that while achieving wavelength spectral resolution, we can also extract the polarization information of light, especially the highly challenging circular polarization information. Although there is still room for improvement in spectral detection capability compared to many on-chip spectrometers currently proposed, the ability to recognize polarization information is unique to our work. In other words, while spectrometers or polarimeters typically achieve two-dimensional information detection (wavelength/polarization—photoresponse), our strategy attempts three-dimensional/high-dimensional information detection (wavelength + polarization—photoresponse). However, as you mentioned, there are still issues in statements or performances. We have made extensive revisions and provided detailed responses as follows.

Comment 1. The authors mentioned "the wavelength resolution of 0.5um," but I think they must change it to "the wavelength prediction accuracy of 500nm" based on Supplementary Note 6. Note that the spectral wavelength) resolution indicates the ability to distinguish two narrow spectral peaks separated by fine wavelength intervals. Since their wavelength prediction relies on the confusion matrix of machine learning and they did not extract the resolution from two narrow spectral peaks from the measured or reconstructed spectra, the authors cannot mention the "wavelength or spectral resolution" in this work.

Author Reply 1: We appreciate you pointing out the issue. We carefully evaluated and differentiated these two concepts. Specifically, resolution indicates the ability to distinguish two narrow spectral peaks separated by fine wavelength intervals. This requires testing the device using monochromatic light and reconstructing and analyzing the results. However, in this experiment, as we attempt to collect spectral data over an ultra-wide wavelength range (1-8 μm), and since the light we apply needs to simultaneously carry polarization information, it is not feasible to test with such densely narrowband monochromatic light. Therefore, we reconstruct, analyze, and predict the spectral data. In our case, we agree that the wavelength prediction accuracy, relying on machine learning, should be referred to as "500 nm wavelength prediction accuracy."

Author action 1: We have corrected all relevant descriptions in the revised manuscript.

Comment 2. Can the current design effectively differentiate between closely spaced wavelengths within the 1-8 micrometer range? Since we cannot confirm the "spectral resolution" in this work, how does it handle potential signal overlap or interference?

Author Reply 2:

1. Thank you for raising the question. Within the range of prediction accuracy, the revised design can effectively distinguish densely spaced wavelengths ranging from 1 to 8 micrometers with a 0.1 micrometer interval, as a further improvement as compared to previous model. This is an attempt to apply machine learning to spectral information over an ultra-wide wavelength range (1-8 μm) that also includes polarization information. Due to experimental limitations, the density of the obtained data is limited. The wavelength prediction accuracy of our machine learning model is constrained to 0.5 micrometers. However, when we have sufficient training samples, our machine learning model can further improve the wavelength prediction accuracy. In the Supplementary Information (SI), we have demonstrated that the precision of wavelength can be reduced to 0.1 micrometers. Theoretically, with a sufficient number of data samples, the wavelength prediction accuracy can be improved to any desired range.

2. The system design in this paper is aimed at detecting and identifying a single beam of light with

wavelength and polarization information. Due to the need to simultaneously discern high-dimensional information, the processing method is more complex compared to typical miniature computational spectrometers. Model construction and processing as shown in Figure R1.1. To process and distinguish high-dimensional information from two or more beams of light, measurements need to be taken sequentially. However, since the machine learning model we used can output a result within 0.1 seconds for any given input, there is minimal sacrifice in time resolution.

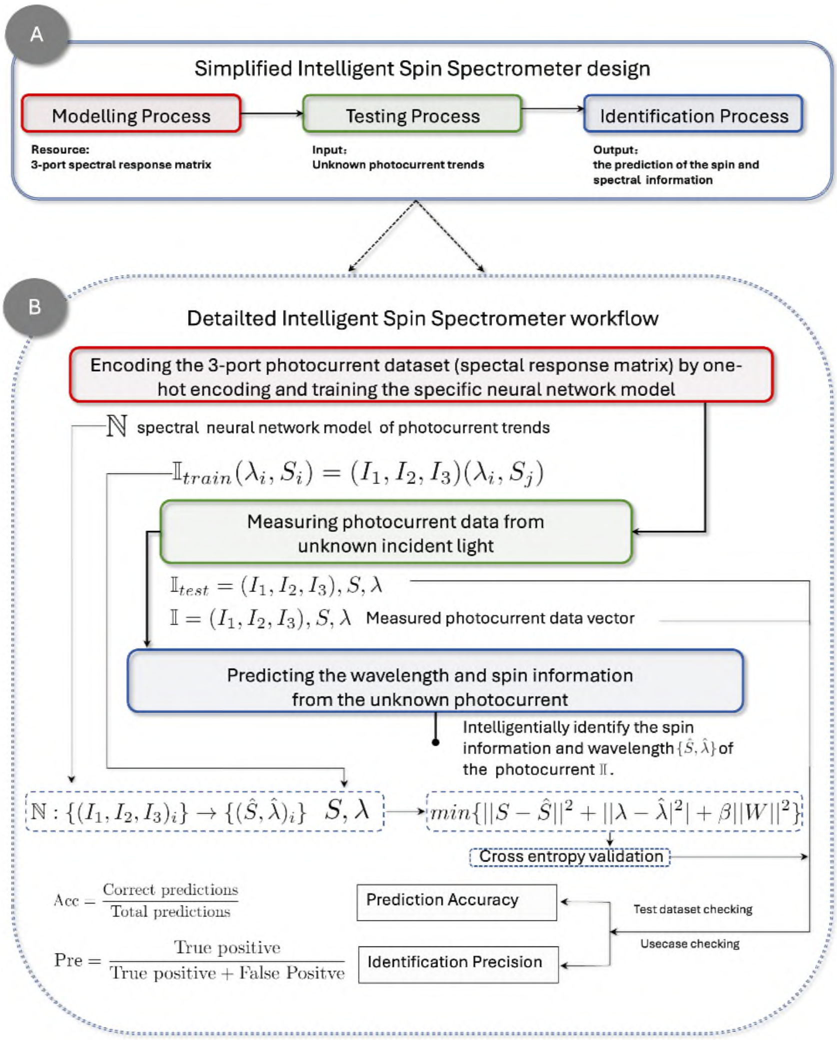


Figure R1.1. Summarized workflow diagram. A, Simplified version. B, Detailed version.

Author action 2: We have outlined the limitations of the machine learning model demonstrated in this work in the discussion section, setting these as targets for future efforts. We have added the working principle of the above model to Supplementary Fig. 27.

Comment 3. According to the state-of-the-art works recently reported on miniaturized computational spectrometers, their "spectral resolution" has already achieved a few nanometers to at least tens of nanometers. Regarding the "high peak wavelength accuracy," some works have achieved nanometers below the decimal point (like 0.Xnm or 0.0Xnm, *depending on their designs). In comparison, the authors could not demonstrate "wavelength or spectral resolution" but "the wavelength prediction accuracy of 500nm." How can we recognize this work's advancement?*

Author Reply 3: Thank you for highlighting the issues raised by the reviewers and mentioning works such as wavelength-scale black phosphorus spectrometer, miniaturized spectrometers with tunable van der Waals junction, tunable two-dimensional heterojunctions near-infrared spectrometers and Single-nanowire spectrometers, (*Yuan, S., Naveh, D. Nature Photonics* ***15****, 601-607 (2021); Yoon, H.H. et al. Science* ***378****, 296-299 (2022); Deng, W. et al. Nature communications* ***13****, 4627 (2022); Yang, Z. et al. Science* ***365****, 1017-1020 (2019).*). which have successfully achieved miniature computational spectrometers with high spectral resolution. Regarding the "high peak wavelength accuracy," due to the limited data in this experiment, the wavelength prediction accuracy of our machine learning model is constrained to 0.5 micrometers. However, when we have sufficient training samples, our machine learning model can further improve the wavelength prediction accuracy. In the Supplementary Information (SI), we have demonstrated that the precision of wavelength can be reduced to 0.1 micrometers. Theoretically, with a sufficient number of data samples, the wavelength prediction accuracy can be improved to any desired range.

Regarding the advancement of this work, it's important to note that these achievements are not contradictory to the breakthroughs and innovations emphasized in our work. I would like to elaborate on the advancements of our work from two perspectives:

1. High-dimensional detection capability that can simultaneously resolve wavelength and polarization information.

To facilitate explanation, we have summarized the advantages of our work in Figure R1.2. As can be seen, the works mentioned by the reviewers deal with two-dimensional information detection (wavelength information—photoresponse). They rely on materials or structures that are highly sensitive to wavelength information and cannot achieve polarization information resolution. Handling three-dimensional information relationships (wavelength information + polarization information—photoresponse) is extremely challenging. Therefore, the major difference and advancement of our work compared to the works mentioned by the reviewers is that, through the design of nanoantennas, our detector is capable of three-dimensional information resolution for the first time. On this basis, further research can be conducted to improve metrics such as wavelength resolution and polarization accuracy.

Two dimensional parameter detection (spectral detection)

[REDACTED]

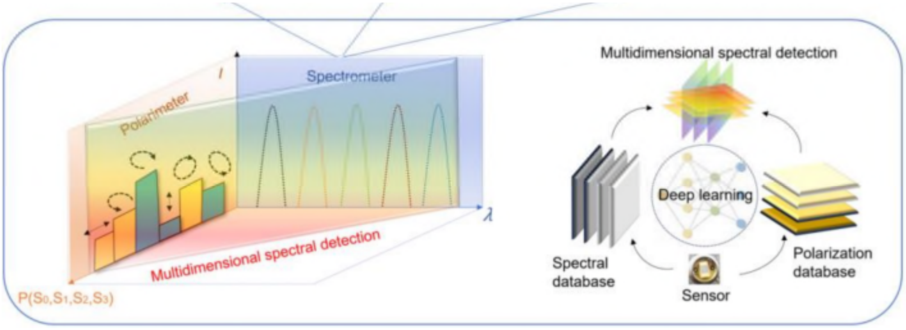


Figure R1.2. Schematic illustration of the high-dimensional detection innovation in this work

2. Breakthrough in wavelength detection limitations.

According to the works and reviews mentioned by the reviewers (Figure R1.3), current miniature computational spectrometers rely on the material's sensitivity to different wavelengths of light, making it extremely challenging to achieve ultra-wideband, especially infrared band resolution. Our work employs nanoantenna arrays to absorb infrared light, and the introduction of machine learning compensates for the nanoantenna's limitation of responding only to specific wavelengths. This enables wavelength resolution over a wide range (1-8 μm). The accuracy can also be further improved through the optimization of machine learning algorithms.

[REDACTED]

Figure R1.3. The field of miniaturized spectroscopic devices. Plot comparing the resolution, operational spectral range, and footprint for selected device demonstrations in the literature and those that are commercially available (indicated by asterisks), as categorized into their respective subfields (see color key). Footprint encompasses those elements of the device that are active in resolving and detecting light, and does not include accessory components such as the readout electronics or packaging. (*Yang, Z., Albrow-Owen, T., Cai, W. & Hasan, T. Science* ***371****, eabe0722*

(2021).)

Therefore, this work goes beyond simple spectral resolution and attempts high-dimensional information detection and resolution, achieving a breakthrough in spectral coverage. This is an innovative concept, albeit acknowledging various shortcomings in metrics, which we have addressed through supplementation and optimization in the revised manuscript. We aim to highlight the significance of this work.

Author action 3: We have objectively presented the advantages and areas for improvement demonstrated in this work in the discussion section, setting these as goals for future efforts.

Comment 4. I agree that traditional methods require multiple discrete optical components to extract such multidimensional information, but the proposed device integrates this functionality on a single chip. However, I guess the current design must have limitations regarding the "spatial resolution" of detected signals. In other words, even if their proof-of-concept claims the broadband photodetection of high-dimensional optical information with a single integrated on-chip detector, the trade-off between the footprint and spatial resolution might hinder performance and increase process cost when expanding them to a single integrated chip. Furthermore, how do they compare to existing state-of-the-art technologies?

Author Reply 4: Thank you for raising these questions. Here, we demonstrate a three-terminal device with a radius of approximately 20 μm, capable of reflecting both the wavelength and polarization information of light from a single current measurement. Compared to traditional discrete devices, this design reduces spatial occupancy in terms of dimensions. The detection of polarization and wavelength information does not require separation, extraction, and judgment through discrete components, but is directly reflected by the magnitude and polarity of the current. As you mentioned, further reducing the device size may impact its performance. However, this can be compensated by altering the device layout. For example, the device can be further miniaturized, as illustrated in Figure R1.4. Due to the increased length in the direction of the vector photocurrent, even with a channel width of only 10 μm, the signal strength increases fivefold. This indicates that device performance can be altered according to different requirements without sacrificing spatial resolution.

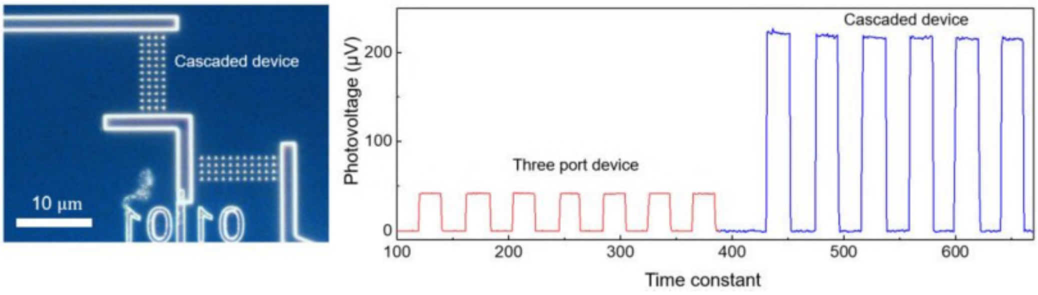


Figure R1.4. Performance comparison between three port devices and cascaded devices

To compare to existing state-of-the-art technologies, we have summarized and compared similar works. It can be observed that our work shows advantages in the detection wavelength range. Most importantly, the proposed high-dimensional spectral detection can capture polarization information in addition to wavelength. However, there is still room for improvement in terms of resolution.

Table R1.1. Comparison between this demonstration and other compact spectrometers

Method of spectral reconstruction	Footprint	Resolution /range	Spectral detection range	Spectral information	Ref.
Black phosphorus spectrometer	16 × 9 μm^2	1.19 %	2-9 μm	Wavelength	Nat. Photonics 15, 601–607 (2021)
Single-dot perovskite spectrometer	440 × 440 μm^2	1.28 %	350-750 nm	Wavelength	Adv. Mater. 34, e2200221 (2022)
ReS$_2$/Au/WSe$_2$ vdW spectrometer	6 × 4 μm^2	6.25 %	1150-1470 nm	Wavelength	Nat. Commun. 13, 4627 (2022).
MoS$_2$/WSe$_2$ vdW heterojunction	22 × 8 μm^2	0.68 %	405-845 nm	Wavelength	*Science.* **378**,296-299(2022)
This work	Radius~20 μm	1.42%	1-8 μm	Wavelength polarization	

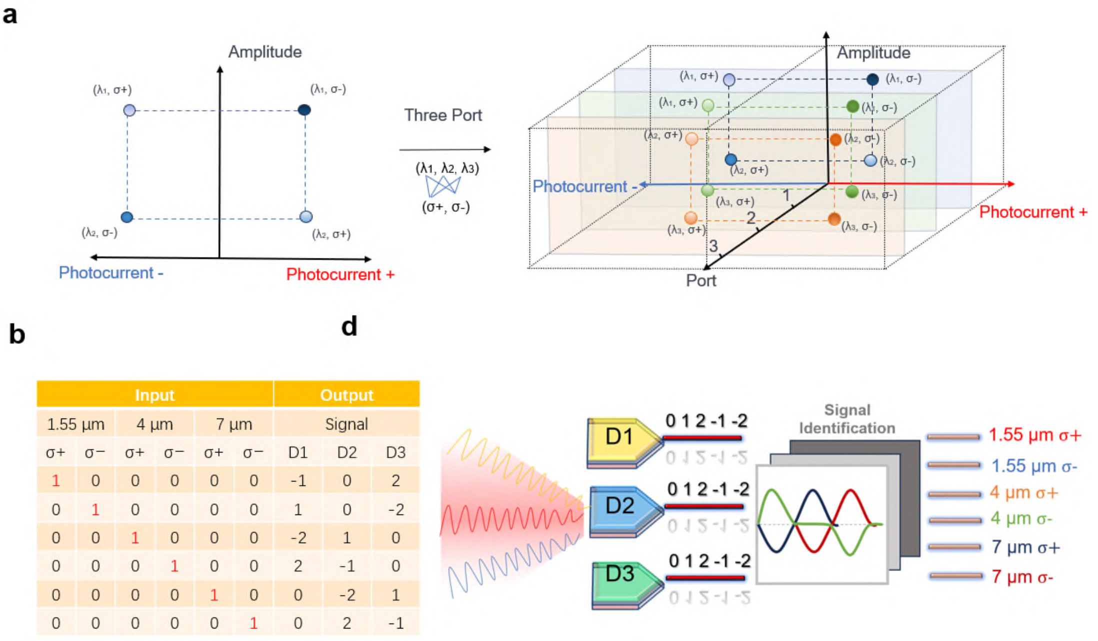
Author action 4: We have added the above discussion as an optimization method for device performance to Supplementary Figure 23 in the supplementary information. We have added the above comparisons to Supplementary Table 5.

Comment 5. The authors claim their design simplifies the detection process by eliminating the need for additional degrees of freedom like twists or gate control. Instead, their design relies on a plasmonic metasurface combined with the graphene film, and the metasurface area containing the nanoantenna array must be at least several tens of micrometers, which is a disadvantage in the device footprint. In particular, their three-port (or ports of any odd number) graphene photodetector design coupled with plasmonic nanoantennas further increases the device footprint when integrated on a chip for the exact spatial resolution. It seems they tried the two-port design presented in Supplementary Information. How about a four-port design to increase integration density, and why do they only highlight the three-port design? Can authors defend their design or suggest a better one?

Author Reply 5: Thank you for raising these questions.

First, we would like to address the reviewer's concerns regarding the simplicity and spatial occupancy of our device. The graphene device covered with a metasurface structure is very easy to fabricate, requiring only a single exposure and deposition using traditional processes. Large-area graphene growth and transfer techniques are also very mature. In contrast, the works mentioned (Tunable moiré quantum geometry sensing, miniaturized spectrometers with tunable van der Waals junction, tunable two-dimensional heterojunctions near-infrared spectrometers and Single-nanowire spectrometers, (*Ma, C. et al. Nature* ***604****, 266–272 (2022); Yoon, H.H. et al. Science* ***378****, 296-299 (2022); Deng, W. et al. Nature communications* ***13****, 4627 (2022); Yang, Z. et al. Science* ***365****, 1017-1020 (2019).*)) rely on mechanical exfoliation and transfer, especially for heterostructures and twist systems, which require strict control of interface contact and angles, making their fabrication far more challenging and time-consuming than our work. However, in terms of device area, they are similarly sized in the tens of micrometers and are controllable. Therefore, our device has advantages in terms of fabrication difficulty, cost, and integration complexity.

Secondly, we will explain the purpose of the three-terminal design. The reason for designing three terminals is based on the working mechanism of the double-arm plasmonic nanoantenna. Each size of nanoantenna can detect any two wavelengths of circularly polarized light and identify the four combinations of LCP λ1, LCP λ2, RCP λ1, and RCP λ3 based on the magnitude and polarity of the photocurrent. When the number of wavelengths increases to three, six combinations of light information will appear. To improve identification accuracy, each of the three terminals can be responsible for four of these combinations, and final encoding can be used to achieve precise differentiation (Figure R1.5). Additionally, the three wavelengths can be designed to span a wide range, such as 1.55 μm, 4 μm, and 7 μm. This facilitates the learning and prediction of photocurrent over a wide band (1-8 μm) using machine learning.



Input						Output		
1.55 μm		4 μm		7 μm		Signal		
σ+	σ−	σ+	σ−	σ+	σ−	D1	D2	D3
1	0	0	0	0	0	-1	0	2
0	1	0	0	0	0	1	0	-2
0	0	1	0	0	0	-2	1	0
0	0	0	1	0	0	2	-1	0
0	0	0	0	1	0	0	-2	1
0	0	0	0	0	1	0	2	-1

Figure R1.5. Three-port design for three-band circular polarization detection. a, Construction of the spatial model of the photocurrent. For a single-port device, it's possible to determine both the wavelength and spin information of light within a two-dimensional plane formed by the magnitude and amplitude of the photocurrent. Through the cooperative action of multiple devices, it is possible to establish a spatial photocurrent model with wavelength and spin resolution capabilities. b, Photovoltage encoding generated by the incidence of circularly polarized light with three different wavelengths. The combination of output signals from each channel allows for the identification of the wavelength and polarization information of the incident light. d, Schematic representation of the extraction of three-wavelength circularly polarized signals. In the case of mixed light incidence, the processing of photovoltage signal encoding allows for the extraction of the wavelength and circular polarization information of the incident light.

The layout of the three-terminal device is shown in Figure R1.6. Such a three-terminal layout is also beneficial for ensuring that the circular light spot can cover all the devices, making full use of the available space. When we aim to detect more wavelength information, more devices would be needed, occupying more space. Therefore, the introduction of machine learning here is intended to avoid sacrificing spatial resolution. By establishing a photocurrent learning model for three widely spaced wavelengths, we can predict more wavelength information.

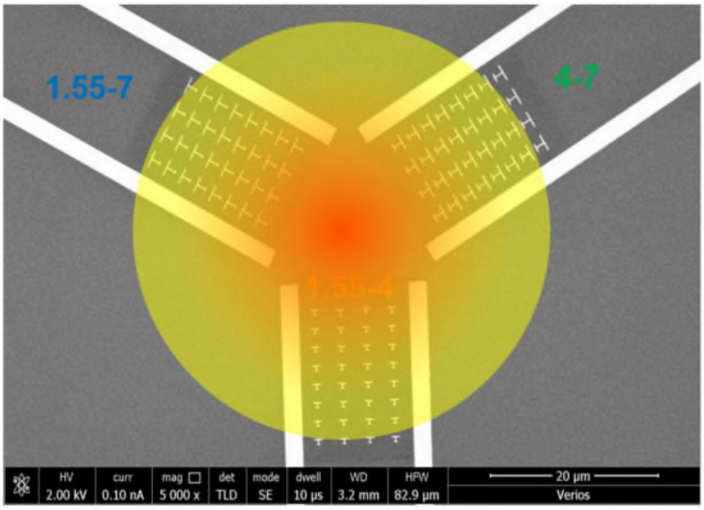


Figure R1.6. Microscopic image of the device and schematic of the spot coverage.

For the situation with more ports, wavelength resolution becomes denser, but the occupied space also increases accordingly. By leveraging machine learning algorithms, the detection information provided by the three wavelengths from the three-port setup is sufficient to meet the dataset requirements. Therefore, a four-port design is not necessary.

Author action 5: We have added the corresponding discussion in the three-port design section on page 10 and the discussion section on page 16 of the manuscript.

Comment 6. What are the additional potential trade-offs between achieving high-dimensional detection and maintaining spatial resolution or footprint?

Author Reply 6: Here, the device for high-dimensional detection encodes and analyzes the photocurrent from a single measurement to identify polarization and wavelength information, rather than using discrete devices for separate extraction and identification as in traditional methods. This greatly reduces spatial occupancy. Additionally, with the aid of machine learning, it is possible to recognize wavelength and polarization information across a wide band without sacrificing spatial resolution. If the device size is further reduced, there might be a trade-off with performance, but this can be balanced by altering the device layout.

Additionally, as the reviewer mentioned, further reducing the device size may impact its performance. However, this can be compensated by altering the device layout. For example, the device can be further miniaturized, as illustrated in Figure R1.7. Due to the increased length in the direction of the vector photocurrent, even with a channel width of only 10 μm, the signal strength increases fivefold. This indicates that device performance can be altered according to different requirements without sacrificing spatial resolution.

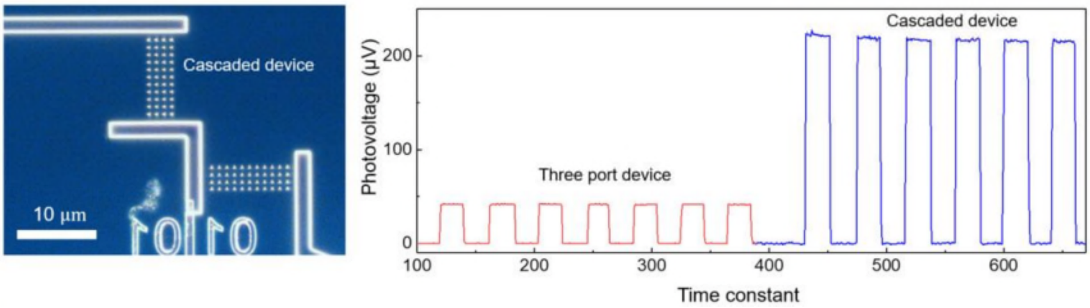


Figure R1.7. Performance comparison between three port devices and cascaded devices

Author action 6: We have added the above discussion as an optimization method for device performance to Supplementary Figure 23 in the supplementary information.

Comment 7. How does the proposed metasurface-enabled graphene photodetector ensure the stability and reliability of information detection without additional degrees of freedom? In terms of stability and noise, unlike what was shown in Supplementary Fig. 17, the photovoltage level in the switch signal in Supplementary Fig. 18 is weak, and the value appears to be unstable over time. Also, was the fitting done correctly when obtaining the Rising and Decaying times on the right side of Supplementary Fig. 18? Please express the general exp fitting.

Author Reply 7: Thank you for the questions. Since the rise and fall times of this device are shorter than the sampling limit of the source meter, we used an oscilloscope for sampling measurements. The noise, as supplemented in Figure 18, primarily originates from the testing system. For stability measurements, we present Figures R1.7, and 1.9 to demonstrate the reliability and stability of the device.

In previous evaluations of response time, we analyzed the time intervals corresponding to the 10% to 90% range of the total signal to obtain rise and fall times. Hereafter, we will employ the method provided by the reviewers for assessment as Figure R1.8. The fitting function is:

$$U = A \cdot \exp(-\frac{t}{\tau}) + \mathrm{U}_0$$

Where U is the photovoltaic voltage, t is the time, A is the coefficient, and τ is the extracted rising τ1 and falling edge time τ2.

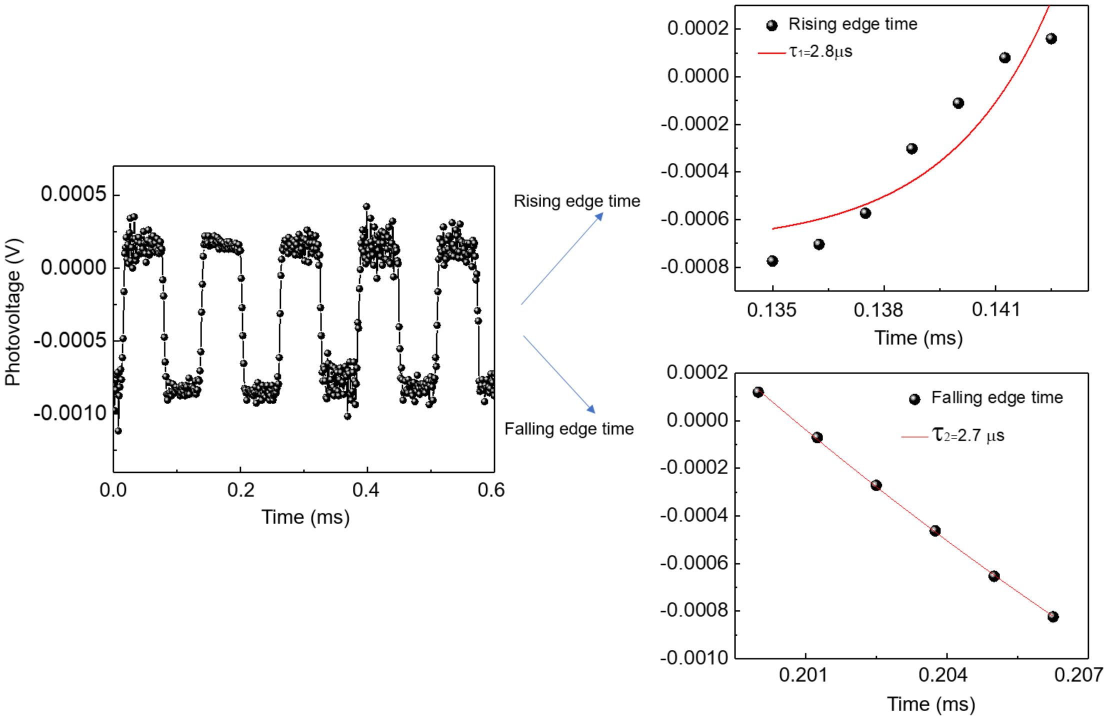


Figure R1.8. The optoelectronic switch signals of the device were collected by an oscilloscope, allowing for the measurement of both the rising and falling edge times.

Author action 7: We have updated the evaluation method for device response time and included it as Supplementary Figure 19 in the supplementary information.

Comment 8. How does the device perform under different environmental conditions, such as varying temperatures and humidity levels, which could affect the graphene and metasurface materials? The authors note that graphene properties may be sensitive to water vapor or adsorbed gas molecules, especially when the graphene surface is not passivated. How does the device manage the potential noise and signal degradation issues that could arise from using dual-arm plasmonic nanostructures on a graphene platform?

Author Reply 8: Thank you for raising these questions. All tests in this study were conducted at room temperature and exhibited consistent performance over different time periods. To investigate the stability conditions and protection methods of the devices, we prepared devices both with and without hBN (hexagonal boron nitride) coverage and measured the performance stability (chopped signal) of both types of devices after long-term room temperature exposure (Figure R1.9.). As the reviewer mentioned, the performance of bare graphene devices deteriorated significantly due to adsorption effects from water vapor and other factors. However, the devices covered with hBN did not show substantial performance degradation. Additionally, the plasmonic structure is made of gold material, which is resistant to oxidation. Therefore, covering the material with hBN effectively maintains the stability of the device. To further ensure performance stability, we also employed an encapsulation technique to store the devices in a vacuum environment, which greatly helps in maintaining the device performance.

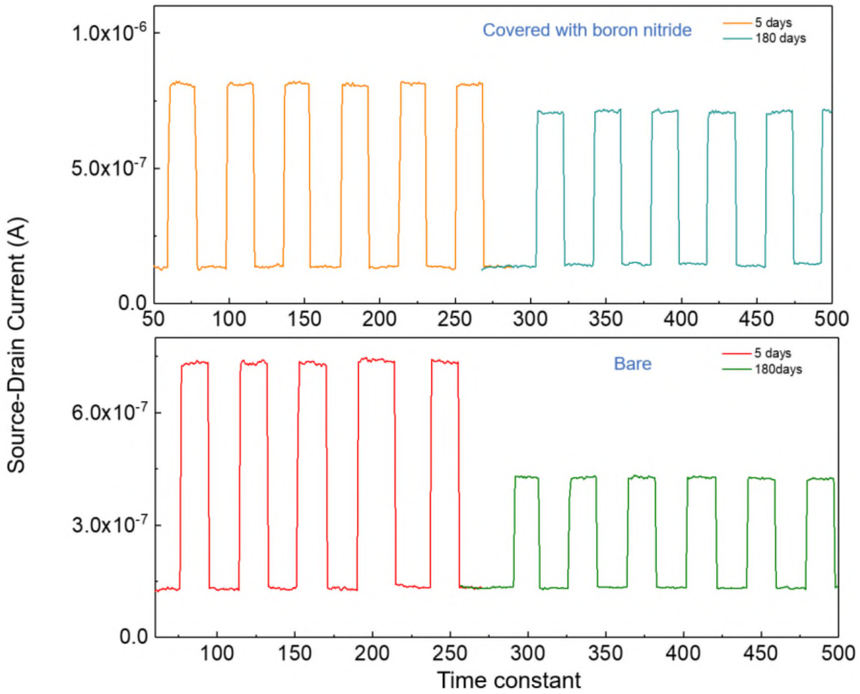


Figure R1.9. The performance stability (chopped signal) of devices with and without hBN after long-term room temperature exposure.

Author action 8: We have added the characterization of device performance stability to Supplementary Figure 20 in the supplementary information.

Comment 9. They claim machine learning further enhances the device's ability to predict and differentiate optical signals over a broad wavelength range. The wavelength precision presented in this paper was obtained using machine learning models. Many other works share their algorithms publicly in similar studies. This is an excellent example of a virtuous cycle in the research world. Likewise, I encourage the authors to open the code of their developed algorithm public for the benefit of other subsequent researchers. Suppose these two algorithm codes are publicly archived on Github and Zenodo. In that case, they will benefit many researchers, and this paper will attract many readers if it gets publication.

Author Reply 9: Thank you for the valuable suggestions. We have built a GitHub repository for our project to protect our copyright and the originality of our paper. It is currently a private repository. However, we are willing to make it public once our work is published. The address for our code of the developed algorithm and machine learning model is:https://github.com/vindolineKis/MOIR_photodecector.git. Anyone is welcome to access the code for academic purposes after obtaining permission from the authors.

Comment 10. How does the use of machine learning in this photodetector compare to traditional signal processing methods in terms of accuracy, speed, and computational requirements?

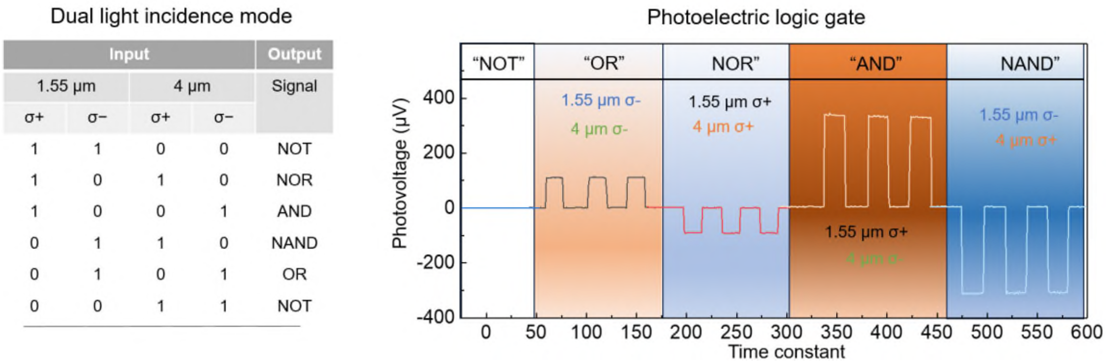
Author Reply 10: Traditional photoelectric detection and signal processing methods primarily rely on constructing and integrating wavelength- and/or polarization-sensitive elements in space (for example, spatially integrates different photonic crystal structures) or time (for example, changes active gating control and measures hundreds of times) to improve the wavelength/polarization detection ability (detection range and sensitivity). A machine learning-based photodetector only requires a certain amount of rough data collected from the laboratory. Once the photodetector is trained, you can input any legal photocurrent to get a qualified output of spin information and wavelength. the accuracy of the model can be tuned as desired. At the same time, the speed of the model is much faster compared to traditional photodetectors. In this paper, the machine learning model we used can output a result within 0.1 seconds for any given input. Regarding computational resource requirements, the machine learning-based photodetector has certain demands on computer hardware such as CPU, RAM, and storage devices.

Author action 10: We have added relevant discussions in Supplementary Note 6.

Comment 11. What specific optical communication and computing applications would benefit most from this technology, and what are the anticipated improvements over current systems? What further developments or optimizations are necessary to make this technology viable for commercial deployment, particularly in terms of cost-effectiveness and ease of integration?

Author Reply 11: Thank you for your constructive questions. Light possesses multiple degrees of freedom (such as wavelength, polarization, pulse length, etc.) that can be utilized for information encoding. The work presented here demonstrates the ability to detect both polarization and wavelength information simultaneously, enhancing the distinctive characteristics of light. The rich combination of high-dimensional information provides sufficient channel capacity. This is why researchers are exploring orbital angular momentum detection, despite the significant challenges involved (Ji, Z. et al. Photocurrent detection of the orbital angular momentum of light. *Science* **368**, 763-767 (2020)).

Here, we provide an example for application. In Figures 2 and 3 of this paper, the combination of optical circular polarization information with specific wavelength information provides numerous degrees of freedom for optical communication. Additionally, the dual optical incidence mode can lead to the superposition or cancellation of output signals, which can be utilized for the implementation of photonic logic gates. Today, the limitations of existing electronic logic gates in terms of precision and rapid computation, combined with the explosive demand for various data processing, have sparked interest in new logic gate platforms (Kim, W. et al. Perovskite multifunctional logic gates via bipolar photoresponse of single photodetector. *Nature communications* **13**, 720 (2022)). The devices proposed in this paper can convert optical inputs into electrical outputs and perform multiple Boolean logics to realize photoelectric logic gate, as shown in Figure R1.11.



Dual light incidence mode

Input				Output
1.55 μm		4 μm		Signal
σ+	σ−	σ+	σ−	
1	1	0	0	NOT
1	0	1	0	NOR
1	0	0	1	AND
0	1	1	0	NAND
0	1	0	1	OR
0	0	1	1	NOT

Figure R1.11. Demonstration of the photoelectric logic gate

Author action 11: We have added this potential application to Supplementary Figure 24 in the supplementary information.

As you noted, several improvements, developments, or optimizations are required to realize these applications. First, in terms of performance, enhancing the device's responsivity is necessary. This can be explored through the proposed methods, such as gate voltage mechanisms, layout optimization, and improvements in material quality. Second, regarding device response time, graphene has already demonstrated potential for ultrafast response speeds (500 GHz), which can serve as a reference for optimization and exploration (*Koepfli, S.M. et al. Metamaterial graphene photodetector with bandwidth exceeding 500 gigahertz. Science* ***380****, 1169-1174 (2023).*). Most importantly, in terms of cost-effectiveness and ease of integration, the large-scale growth technology for graphene films is now quite mature. Combined with high-precision lithography techniques, this reduces the cost-effectiveness of the device and ensures compatibility with CMOS technology. Therefore, it holds promising application prospects.

Comment 12. What challenges might arise in scaling the device for practical applications, particularly manufacturing and integration? Rather than highlighting the advantages of their design in these aspects, I hope that the authors will also present relevant current technologies or technologies needed in the future to show how the disadvantages in their design can be improved in the future.

Author Reply 12: Thank you for the valuable suggestions. In the current research on devices based on two-dimensional materials, many challenges are being addressed, but issues arise when scaling up to practical applications, particularly in manufacturing and integration. This paper attempts to achieve on-chip high-dimensional optical information detection through metasurface structures, yet there are still some problems that need further investigation to resolve. Firstly, regarding responsivity, performance can be further enhanced by applying gate voltage, improving material quality, and optimizing device layout. Secondly, to further enhance integration, single-unit devices can be expanded into array pixel devices, enabling multi-channel signal output and further reducing time resolution. Additionally, achieving high-resolution detection is also a future challenge that needs to be addressed. This requires mature machine learning algorithms and the implementation of monochromatic light testing in experiments.

Author action 12: We have addressed the limitations and optimization needs of this work in the discussion section on page 22 of the revised manuscript.

Reviewer 2

Comments: The authors have explored the use of a small array of graphene detectors, made polarisation sensitive by tailored metasurfaces, to provide a crude determination of the polarisation state and wavelength of incoming illumination. The work builds on previous studies, but includes novel aspects. The manuscript has issues that would need to be resolved before publication.

Author Reply: We appreciate your affirmations and constructive feedback. In response to the series of questions raised, we first provide a quantitative and systematic description of the device's performance. Secondly, we explore optimization strategies for the device's performance. Most importantly, regarding the feasibility of applications, we discuss the limitations of the work, improvement methods, application examples, and future work prospects. Please allow us to elaborate on these aspects in detail below.

Comments 1: The authors should clarify the novelty of their study. For example, in some sections language such as "This design only requires a single measurement of a three-port metasurface" may mislead the readership. In reality, measurement of three separate devices (i.e. using six electrodes) is required to extract this information so the terms "single measurement" and "three port" are likely to confuse. I suggest the authors remove or rewrite such statements to avoid confusion.

Author Reply 1: Thank you for pointing out these issues. Our initial idea was to use an integrated system that employs a three-channel source meter to obtain measurement information simultaneously. However, we acknowledge that these statements are not appropriate. We have followed your suggestion and have deleted and rewritten these statements accordingly.

Comment 2: The main text focuses on qualitative analysis, and more quantitative information should be added into the main text to provide the readership with a realistic picture of the impact of this demonstration. For example, information on the responsivity/detectivity of the sensors is relegated to the SI and not mentioned in the main text. This is very important given that the magnitude of the detectivity is quite low (i.e. 10^6 Jones scale) compared to state-of-the-art IR sensors. This means that the proposed sensor array would only be useful under very intense infrared light and is unlikely be usable in, for example, real world sensing applications. As such, it is important for the authors to clearly acknowledge this shortcoming as a limitation of their proposed system.

Author Reply 2:

Thank you for pointing out these issues. In the previous version of this paper, the focus was primarily on the realization and functional characterization of high-dimensional information detection, while the exploration of device responsivity was overlooked. Based on the reviewer's suggestions, we have investigated how to improve device responsivity. There are two main approaches:

1. By applying gate voltage to regulate the Schottky junction formed between graphene and

the metal structure, the responsivity of the device can be modulated, as shown in Figure R2.1. Compared to devices without gate voltage, the photoresponse can increase by approximately five times when a gate voltage of 150V is applied. This demonstrates that gate voltage regulation is an effective method for enhancing device responsivity.

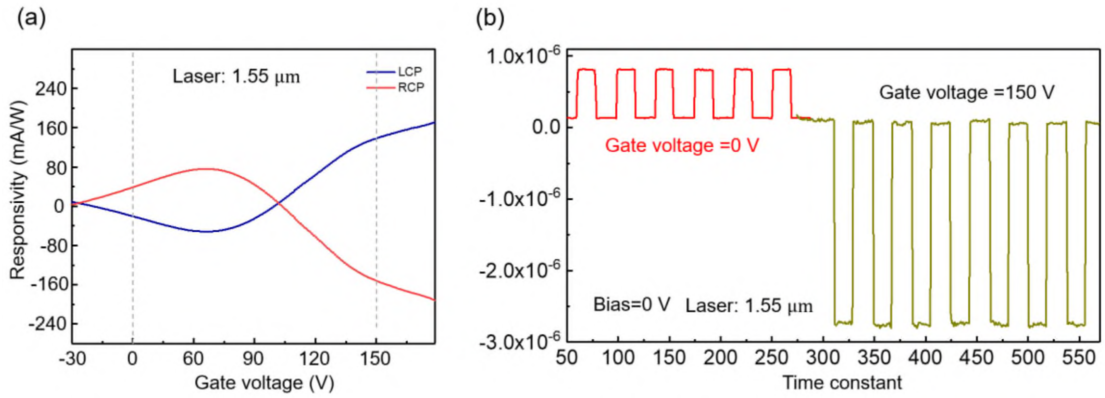


Figure R2.1. Performance comparison between three port devices and cascaded devices

2. We can play with the geometry of the graphene layer to increase the photoresponse. The device can be further miniaturized, as illustrated in Figure R2.2. Due to the increased length in the direction of the vector photocurrent, even with a channel width of only 10 μm, the signal strength increases fivefold. This indicates that device performance can be altered according to different requirements without sacrificing spatial resolution.

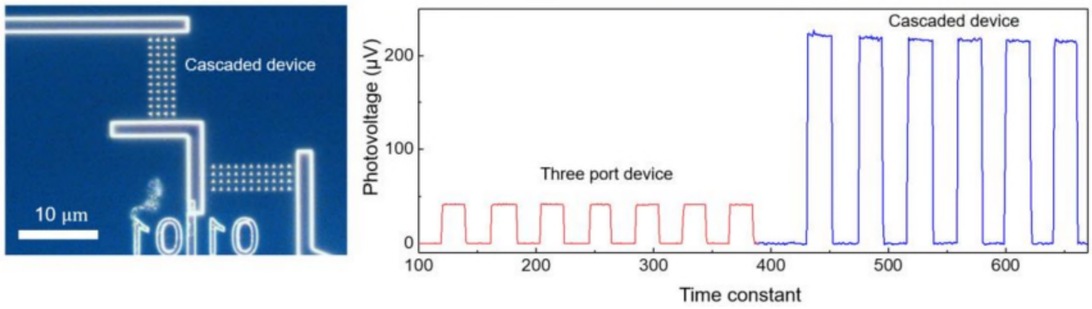


Figure R2.2. Performance comparison between three port devices and cascaded devices

In the process of exploring the aforementioned methods, the responsivity can be increased by approximately five times, and the corresponding detectivity can be enhanced to the order of 10^7. To evaluate the feasibility of our device for practical applications, we compared its performance with commercial detectors, as shown in Table R2.1. Compared to the zero-bias devices of current commercial detectors, our initial responsivity is not too low. By applying the aforementioned methods, we can further enhance the device's responsivity.

Table R2.1. Comparison with typical infrared detectors

Comparison with typical infrared detectors					
No	Description	Wavelength (μm)	Responsivity (V/W)	Bias Voltage	Ref. (with hyperlink)
1	Germanium photodiode	1.5	10	0-2 V	Nat. Photon. 15, 925 (2021)
2	InAsSb photovoltaic detector	4-5.9	21	0 V	P11120-201, Hamamatsu
3	Thermopile detector	0.19-20	0.1	0 V	TD10X, Thorlabs
4	Thermopile detector	3-5	50	0 V	T11361-01, Hamamatsu
5	This work	1.55-8	63	0 V	

Author action 2: We have added the above discussion as an optimization method for device performance to Supplementary Figure 23 in the supplementary information. Comparison with typical infrared detectors has been added as Supplementary Table 3.

Comment 3. Can the authors provide information on the linearity of their photovoltage with illumination intensity?

Author Reply 3: To explore the linearity of the photovoltage response to illumination intensity in the devices, we characterized them using a near-infrared test system with a spot size smaller than the area of the devices as shown in Figure R2.3. The measured power dependence of the polarization sensitivity indicates the extensive linear dynamic range of our device.

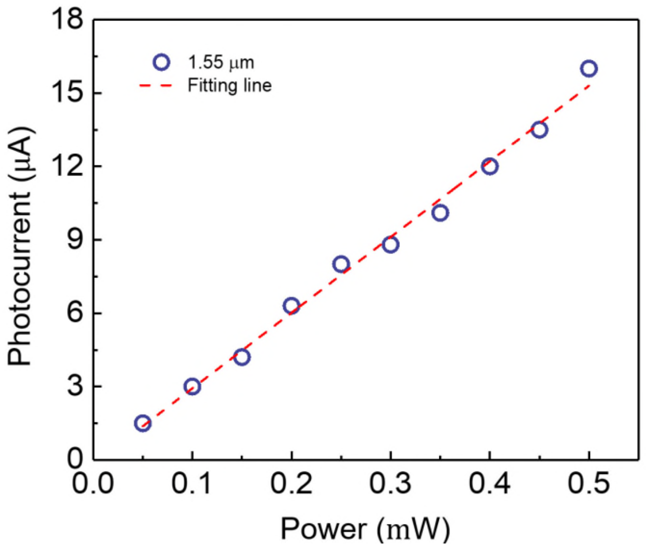


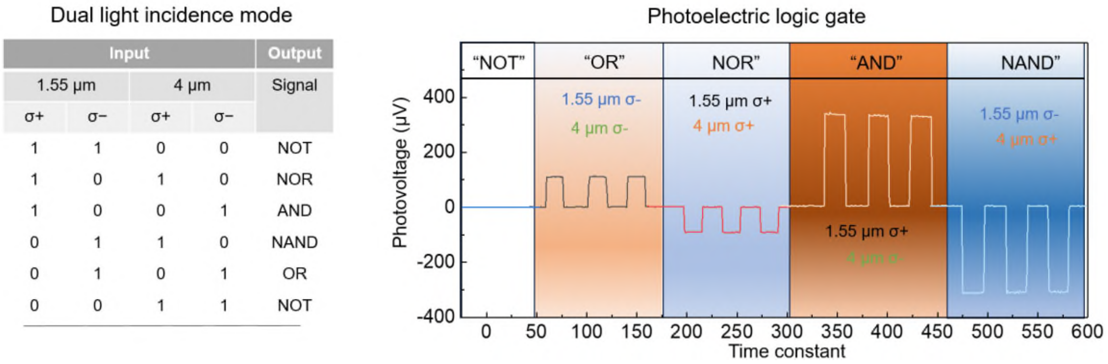
Figure R2.3. Measured correlation between responsivity and incident power dynamic range.

Author action 3: We have added the linearity of photovoltage with illumination intensity to Supplementary Figure 21.

Comment 4. Related to the above points it is not clear what application the authors foresee this detector array as being useful for? As discussed above, the low sensitivity would preclude usage for most sensing/imaging applications. Similarly, the μs detector speed documented in the SI would prevent usage for communication applications (which require >GHz bandwidths). Given the detection mechanism, it is unlikely that these metrics will improve significantly. Hence, the readership will want a clearer statement about the potential application of this sensor array, and removal of mention of other infeasible applications.

Author Reply 4: Thank you for your constructive questions. Light possesses multiple degrees of freedom (such as wavelength, polarization, pulse length, etc.) that can be utilized for information encoding. The work presented here demonstrates the ability to detect both polarization and wavelength information simultaneously, enhancing the distinctive characteristics of light. The rich combination of high-dimensional information provides sufficient channel capacity. This is why researchers are exploring orbital angular momentum detection, despite the significant challenges involved (Ji, Z. et al. Photocurrent detection of the orbital angular momentum of light. *Science* **368**, 763-767 (2020)).

Here, we provide an example for application. In Figures 2 and 3 of this paper, the combination of optical circular polarization information with specific wavelength information provides numerous degrees of freedom for optical communication. Additionally, the dual optical incidence mode can lead to the superposition or cancellation of output signals, which can be utilized for the implementation of photonic logic gates. Today, the limitations of existing electronic logic gates in terms of precision and rapid computation, combined with the explosive demand for various data processing, have sparked interest in new logic gate platforms (Kim, W. et al. Perovskite multifunctional logic gates via bipolar photoresponse of single photodetector. *Nature communications* **13**, 720 (2022)). The devices proposed in this paper can convert optical inputs into electrical outputs and perform multiple Boolean logics to realize photoelectric logic gate, as shown in Figure R2.4.


Dual light incidence mode

Input				Output
1.55 μm		4 μm		Signal
σ+	σ−	σ+	σ−	
1	1	0	0	NOT
1	0	1	0	NOR
1	0	0	1	AND
0	1	1	0	NAND
0	1	0	1	OR
0	0	1	1	NOT

Photoelectric logic gate

Figure R2.4. Demonstration of the photoelectric logic gate

Author action 11: We have added this potential application to Supplementary Figure 24 in the supplementary information.

As you noted, several improvements, developments, or optimizations are required to realize these applications. First, in terms of performance, enhancing the device's responsivity is necessary. This can be explored through the proposed methods, such as gate voltage mechanisms, layout optimization, and improvements in material quality. Second, regarding device response time, graphene has already demonstrated potential for ultrafast response speeds (500 GHz), which can serve as a reference for optimization and exploration (*Koepfli, S.M. et al. Metamaterial graphene photodetector with bandwidth exceeding 500 gigahertz. Science **380**, 1169-1174 (2023).*
). Most importantly, in terms of cost-effectiveness and ease of integration, the large-scale growth technology for graphene films is now quite mature. Combined with high-precision lithography techniques, this reduces the cost-effectiveness of the device and ensures compatibility with CMOS technology. Therefore, it holds promising application prospects.

Author action 4: We have added this potential application to Supplementary Figure 24 in the supplementary information. We have removed references to infeasible applications and discussed the areas for improvement and future prospects in the discussion section.

Reviewer 3

Comments:

This manuscript reports a metasurface-assisted graphene photodetector, which can achieve the simultaneous detection and distinction of various polarization states and wavelengths of broadband light (1-8 μm) at the wavelength resolution of 0.5 μm. By designing a set of integrated dual-arm plasmonic nanostructures, multidimensional information can be decoupled by encoding vectorial photocurrents with varying polarities and amplitudes. Furthermore, machine learning techniques are leveraged to reconstruct and boost the cooperate multiport metasurfaces. This work provides a solution for highly compact and multi-dimensional spectral-polarization detection. I therefore recommend the current manuscript to be published in Nature Communications. However, the following comments should be addressed before publication.

Author Reply: We appreciate your positive feedback on this work and the valuable suggestions provided. We have made revisions and additions as per each point, including the inclusion of necessary figures and tables, as detailed below.

Comment 1. The metasurface-assisted graphene photodetector can achieve spin-wavelength differentiation over the infrared range (1~8 μm). Could the current design be employed to the spectral-polarization co-detection in visible and ultraviolet ranges? The authors should provide experimental result or simulation model to discuss the subject.

Author Reply 1: The response range of the device described in this paper is determined by the design of the plasmonic structure, which is primarily intended for the infrared spectrum. In response to the reviewers' comments, we explored the design of structures that operate in the visible/ultraviolet spectrum. Ultimately, with aluminum as the plasmonic material and dimensions as shown in Figure R3.1, we achieved a device capable of responding to circularly polarized light at a wavelength of 400 nm. Therefore, the operational wavelength range of this device is indeed designable.

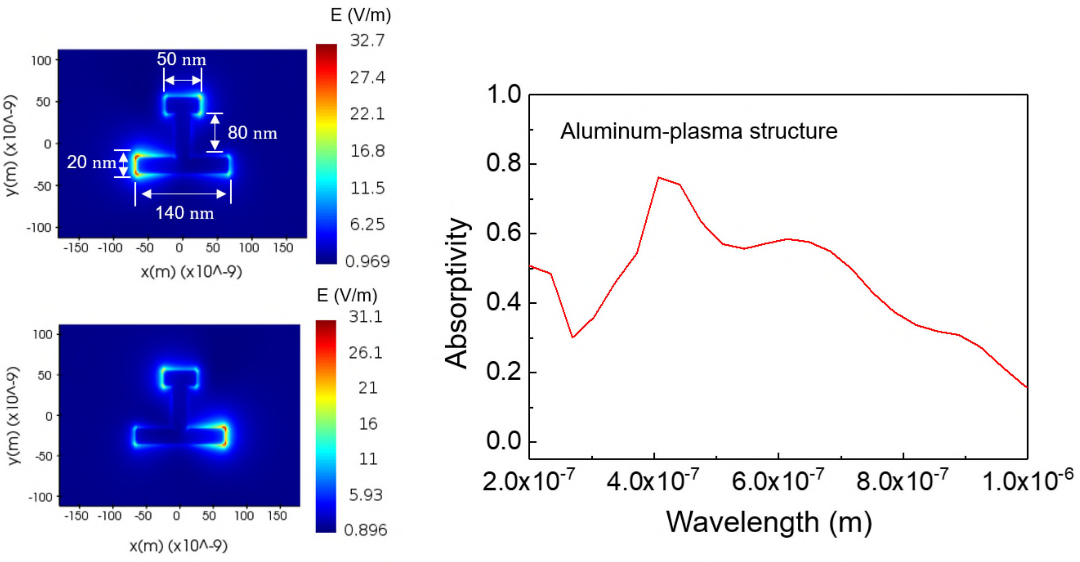


Figure R3.1 Design of a dual-arm plasmonic structure for the ultraviolet/visible light spectrum

Author action 1: We have added this supplementary design to Supplementary Figure 11 in the supplementary information.

Comment 2. In the manuscript, the dual-arm nanoantennas were designed to be parallel with the source/drain electrodes. If varying the angles between the dual-arm nanoantennas and electrodes, what happens to the spin-wavelength differentiation by the graphene photodetector?

Author Reply 2: The differentiation of wavelength and polarization information by the plasmonic structure is attributed to the vector photocurrent generated by the non-uniform field strength distribution. As shown in Figure R3.2, the 1.55 µm LCP induces a field localization effect on the lower right side of the dual-arm structure, resulting in a horizontally rightward current due to the near-field gradient, with the corresponding current distribution illustrated next to it. Similarly, the 1.55 µm RCP induces a horizontally leftward current. Furthermore, the near-field distribution of the 4 µm circularly polarized light, as shown in Figure R3.2b, follows the same pattern. Therefore, by placing the electrodes on both sides along the horizontal direction of the current, the electron collection efficiency can be maximized, leading to the largest possible photocurrent.

Changing the angle between the dual-arm nanoantenna and the electrodes would result in a loss of photocurrent, which is detrimental to the detection of polarization and wavelength information.

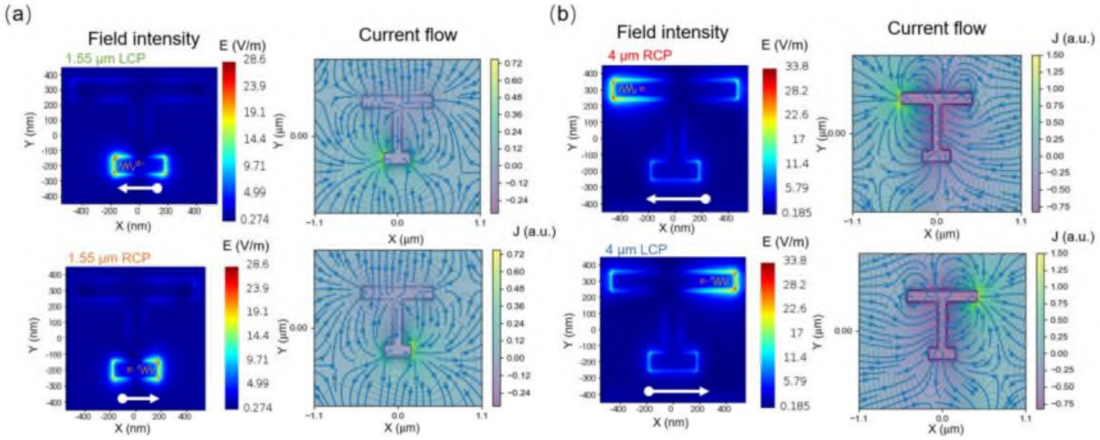


Figure R3.2 Simulated near-field distribution and predicted vectorial photocurrent in a unit cell at different wavelengths and circular polarization states of incident light. *J* represents the current density formed by the near-field distribution.

Author action 2: We have discussed this process in detail in Supplementary Note 2.

Comment 3. Due to the gapless properties of graphene, the photocurrents were considered to be originated from the photothermal effects. More discussions are suggested to provided to help the readers understand the generation of photocurrents of varying magnitudes and directions.

Author Reply 3: The role of the plasmonic nanostructure is twofold. First, it spatially modulates the optical field, leading to an inhomogeneous field profile: $\boldsymbol{E}(x, y)$. Second, the metallic nanostructures spatially modulate the doping level of the graphene sheet [5,6] and hence the Seebeck coefficient, $S(x, y)$. Upon optical illumination, a local photoresponse will be established through the photothermoelectric effect, $\boldsymbol{J}(x, y) \propto |\boldsymbol{E}|^2(x, y)\cdot\nabla S(x, y)$. After that, the transport of the local photoresponse is affected by many factors, such as the inhomogeneous conductance of the device channel. As a result, the calculation of the overall photoresponse, $\boldsymbol{J}_{\text{tot}}$, is complicated and only possible through numerical modeling. However, we can write the analytic expression of $\boldsymbol{J}_{\text{tot}}$ by defining a vectorial local responsivity, $\boldsymbol{\sigma}(x, y)$, as:

$$\vec{J}_{tot} = \iint_{x,y} \left|\vec{E}(x,y)\right|^2 \cdot \vec{\sigma}(x,y)dxdy \tag{S1}$$

Without loss of generality, we can assume a rectangular range of integrals, $x \in (-x_0, x_0)$ and $y \in (-y_0, y_0)$.

Since our plasmonic nanostructure is achiral, $\boldsymbol{\sigma}(x, y)$ should be parity-odd regarding the reflection operation, $x \rightarrow -x$, meaning that $\boldsymbol{\sigma}(-x, y) = -\boldsymbol{\sigma}(x, y)$. The equation of $\boldsymbol{J}_{\text{tot}}$ can then be rewritten:

$$\vec{J}_{tot} = \iint_{x,y} \left(\left|\vec{E}(x,y)\right|^2 - \left|\vec{E}(-x,y)\right|^2\right) \cdot \vec{\sigma}(x,y)dxdy \tag{S2}$$

In the above equation, the range of the integral is halved, $x \in (0, x_0)$ and $y \in (-y_0, y_0)$. Note that the term $|\boldsymbol{E}|^2(x, y) - |\boldsymbol{E}|^2(-x, y)$ is indeed the near-field asymmetry. Therefore, the CPL-sensitive vectorial photoresponse scales with the near-field asymmetry.

Therefore, the differentiation of wavelength and polarization information by the plasmonic structure is attributed to the vector photocurrent generated by the non-uniform field strength distribution. According to Figure R3.2, the 1.55 µm LCP induces a field localization effect on the lower right side of the dual-arm structure, resulting in a horizontally rightward current due to the near-field gradient, with the corresponding current distribution illustrated next to it. Due to a similar mechanism, the 1.55 µm RCP induces a field localization effect on the lower right side of the structure, resulting in an opposite current direction. Therefore, the 1.55 µm LCP and RCP can be distinguished by the sign of the current. Although the 4 µm RCP and LCP also generate opposite currents, the field localization effect induced by the 4 µm circularly polarized light occurs at the ends of the long arms and is stronger. Based on the above deduction, the photocurrent generated by the 4 µm circularly polarized light is significantly larger than that generated by the 1.55 µm circularly polarized light. Hence, we can simultaneously distinguish wavelength and polarization information by analyzing the magnitude and direction of the photocurrent.

Author action 3: We have discussed this process in detail in Supplementary Note 2.

Comment 4. The wavelength resolution is 0.5 µm in the current dual-arm nanoantennas, which is expected to be further improved by the machine learning techniques. The reviewer wonder that what is the limit of wavelength resolution in experiments by adjusting the structural dimension of the *dual-arm nanoantennas?*

Author Reply 4: We explored and experimented with different precision levels of machine learning models for the photodetector, ranging from 0.1 to 1 μm. We ultimately decided that the wavelength resolution for the machine learning model in this work would be 0.5 μm. The main limitation and requirement for further resolution improvement is the variety of the training dataset collected in the lab. In this paper, we mainly argue the advantage and possibility of using the machine learning model for photodetectors. The resolution of 0.5 μm is sufficient to demonstrate our claims.

We have illustrated methods to increase the wavelength resolution in the Supplementary Information. In practical terms, the portability and time cost of data collection, along with the practical requirements of the detector, will all to some extent impact the wavelength resolution. We also suggest that researchers adjust and choose the appropriate resolution based on their specific circumstances.

Author action 4: We have added relevant discussions in Supplementary Note 6.

REVIEWERS' COMMENTS

Reviewer #1 (Remarks to the Author):

I respect the authors' efforts in adding various contents to the Supplementary Information during the review process. However, regarding the updated contents, I am curious about the lack of updates to the References in the Supplementary Information (as well as the Manuscript). I hope the authors will add or update the References during the proof stage. Also, here is my feedback for each comment below:

Reviewer #1-1
The term "wavelength resolution" used in this paper was inappropriate, but now I think it is well addressed. The authors correctly indicated the term "wavelength prediction accuracy of 500㎚" here.

Reviewer #1-2
I have asked how to handle signals that are overlapped or interfered with due to the absence of spectral resolution. However, the responses provided in points 1 and 2 seem inadequate answers to this question.
In the first response, the author refers to the data presented in Supplementary Note 6, mentioning that the data with a 0.1-micrometer interval has better accuracy. However, this response is not an appropriate answer to the question. It is widely known that the accuracy improves as the training data set increases during the machine learning process, so this aspect does not need to be emphasized. The author was attempting to highlight, once again, the high prediction accuracy across the ultra-wide wavelength range and the inclusion of polarization information (the key points they wanted to emphasize in the paper) due to the absence of spectral resolution.
In the second response, the author further supplements the key points emphasized in the paper as mentioned above. Re-emphasizing the advantages to the reviewer through this content seems like a good reply. However, I don't believe that measuring polarization through the photocurrent flowing through each port in the three-port device, based on incident light, and predicting wavelength through machine learning is more complex than the typical processing methods of miniature computational spectrometers. The polarization measurement is due to the inherent characteristics of the metasurface, resulting in different photocurrents in each port, and the overall machine-learning process does not appear to involve a more complex implementation at the coding level compared to typical miniature computational spectrometers.
Although my question was not addressed thoroughly here, I appreciate the author's responses.

Reviewer #1-3
I like the response that the significant difference and advancement of the author's work compared to the work is that, through the design of nanoantennas, their detector is capable of three-dimensional information resolution for the first time. I agree that achieving high resolution in the ultra-wide infrared band is exceptionally challenging. I recognize the author's efforts in introducing

machine learning to compensate for the nanoantenna's limited response to specific wavelengths.

Reviewer #1-4
I appreciate the comparison table and their highlight on the proposed high-dimensional spectral detection that can capture polarization information and wavelength.

Reviewer #1-5
Although large-area graphene growth and transfer techniques have matured, multiple ports of plasmonic nanoantenna and the graphene channel may still have some fabrication difficulty, cost, and integration complexity issues. I can recognize the purpose of the three-terminal design, but its comparison to a four(or more)-port design is missing. Nevertheless, I like their updated discussion sections.

Reviewer #1-6,7,8
I respect their updated characterization of their device's performance, stability, and potential trade-offs.

Reviewer #1-9
I appreciate their determination to share their algorithms publicly.

Reviewer #1-10,11,12
I like their detailed discussion and updates to the Manuscript and Supplementary Information.

I appreciate the author's humble attitude of acknowledging various shortcomings in metrics and efforts to address some of them through supplementation and optimization in the revised manuscript. Therefore, I recommend that Nature Communications accept this paper for publication after updating my minor comments, which can be addressed during the proof stage.

Reviewer #2 (Remarks to the Author):

They authors have addressed my main comments

Reviewer #3 (Remarks to the Author):

The authors have addressed my comments. I recommend the current manuscript to be accepted now.

Reply to the reviewers:

Reviewer 1

Comments:

I respect the authors' efforts in adding various contents to the Supplementary Information during the review process. However, regarding the updated contents, I am curious about the lack of updates to the References in the Supplementary Information (as well as the Manuscript). I hope the authors will add or update the References during the proof stage. Also, here is my feedback for each comment below:

Author Reply: We are greatly appreciative of your positive assessment of our work. Your recommendations are of great significance for the perfection of our endeavors. With regard to the remaining concerns, we are more than happy to address them point by point for modification.

Comment 1. I have asked how to handle signals that are overlapped or interfered with due to the absence of spectral resolution. However, the responses provided in points 1 and 2 seem inadequate answers to this question. In the first response, the author refers to the data presented in Supplementary Note 6, mentioning that the data with a 0.1-micrometer interval has better accuracy. However, this response is not an appropriate answer to the question. It is widely known that the accuracy improves as the training data set increases during the machine learning process, so this aspect does not need to be emphasized. The author was attempting to highlight, once again, the high prediction accuracy across the ultra-wide wavelength range and the inclusion of polarization information (the key points they wanted to emphasize in the paper) due to the absence of spectral resolution. In the second response, the author further supplements the key points emphasized in the paper as mentioned above. Re-emphasizing the advantages to the reviewer through this content seems like a good reply. However, I don't believe that measuring polarization through the photocurrent flowing through each port in the three-port device, based on incident light, and predicting wavelength through machine learning is more complex than the typical processing methods of miniature computational spectrometers. The polarization measurement is due to the inherent characteristics of the metasurface, resulting in different photocurrents in each port, and the overall machine-learning process does not appear to involve a more complex implementation at the coding level compared to typical miniature computational spectrometers. Although my question was not addressed thoroughly here, I appreciate the author's responses.

Author Reply 1: Thank you for bringing this issue to our attention, and we have indeed conducted a substantial amount of literature research on the topic. For miniaturized spectrometers, the treatment of signals that are overlapped or interfered due to the lack of spectral resolution requires intensive narrow-band monochromatic light for testing and reconstruction. This involves the use of monochromator testing equipment to test the device and reconstruct the data model.

However, in this experimental context, we require the collection of spectral data within an ultra-wide wavelength range of 1-8 micrometers that carries both polarization and wavelength information. Due to the lack of testing conditions such as a dense array of narrow-band polarized monochromatic light sources, the implementation of narrow-band monochromatic light testing is not feasible. Consequently, we are only able to reconstruct, analyze, and predict the spectral data, which restricts further refinement of the resolution.

This point will serve as a focus for our next phase of research efforts. On one hand, we need to combine wide spectral data with monochromatic light data to construct an optical current model. On the other hand, we need to further optimize machine learning algorithms to enhance the accuracy of predictions and the ability to handle overlapping signals

Author action 1: We have added relevant descriptions to the discussion section of the manuscript.

Comment 2. Although large-area graphene growth and transfer techniques have matured, multiple ports of plasmonic nanoantenna and the graphene channel may still have some fabrication difficulty, cost, and integration complexity issues. I can recognize the purpose of the three-terminal design, but its comparison to a four (or more)-port design is missing. Nevertheless, I like their updated discussion sections.

Author Reply 2: Thank you for your insights. Indeed, the plasmonic structure processing technology based on electron-beam direct writing currently requires higher precision compared to the simpler photolithographic techniques used in laboratories. We are working hard to simplify the preparation process as much as possible to reduce complexity.

Additionally, the multi-port design helps us to gain more recognition of polarization information for different wavebands of light, as mentioned in the previous question. The increase in ports is expected to improve the resolution of signal collection, however, it will also increase the complexity of device fabrication. This issue will also become a key problem that we need to address in the next phase of our research.

Author action 2: We have added relevant descriptions to the discussion section of the manuscript.