

Supplementary Information for

Miniature computational spectrometer with a plasmonic nanoparticles-in-cavity microfilter array

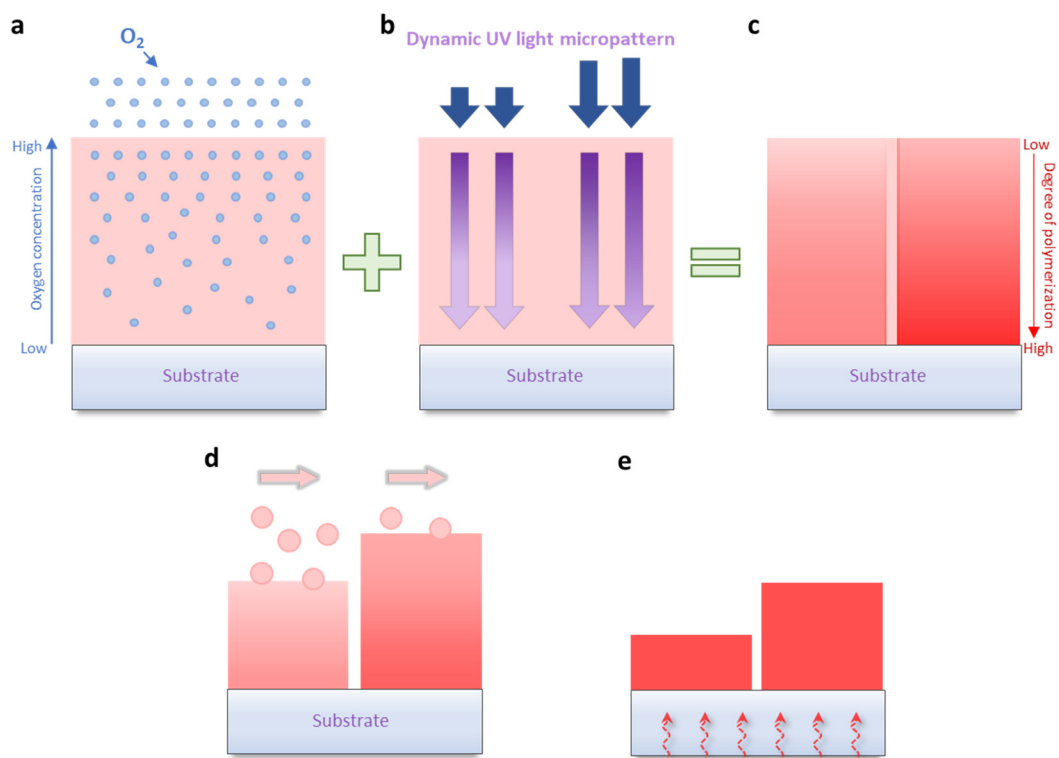
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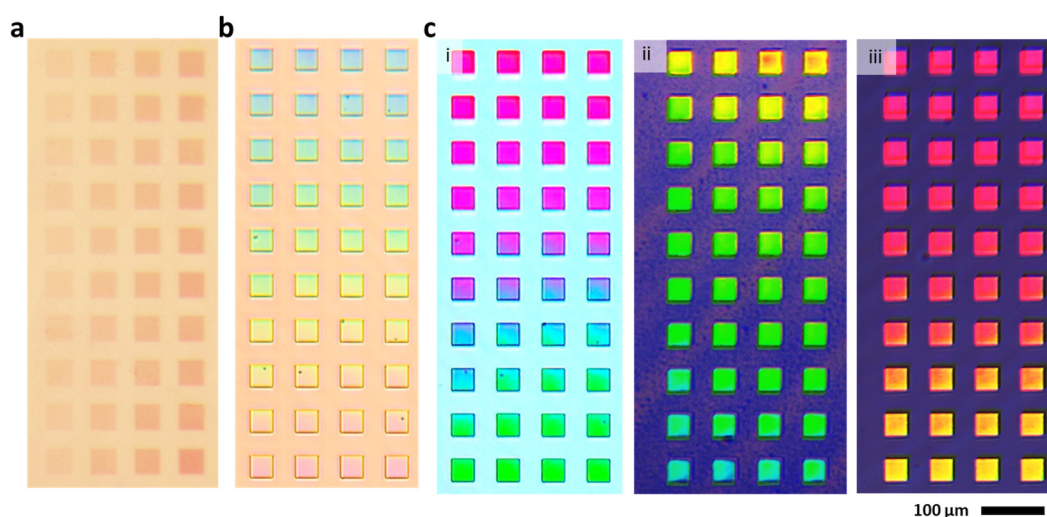
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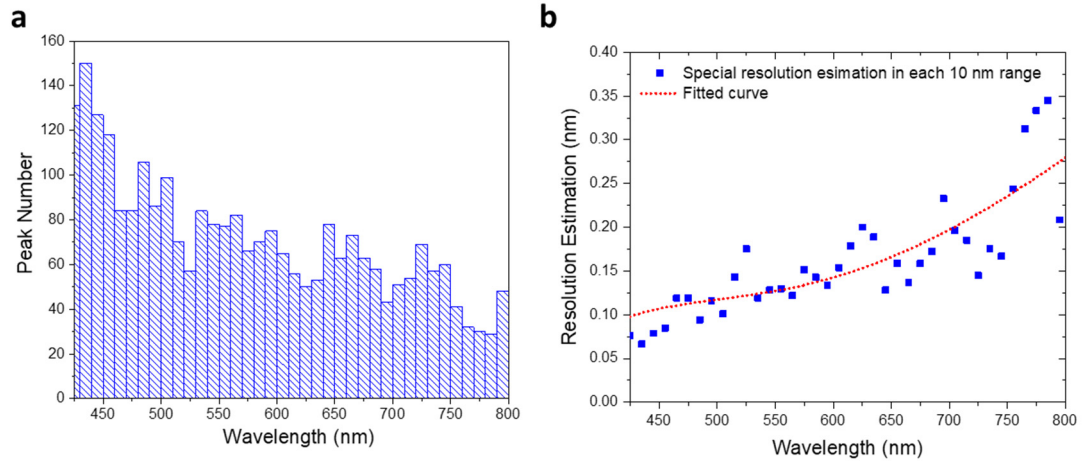
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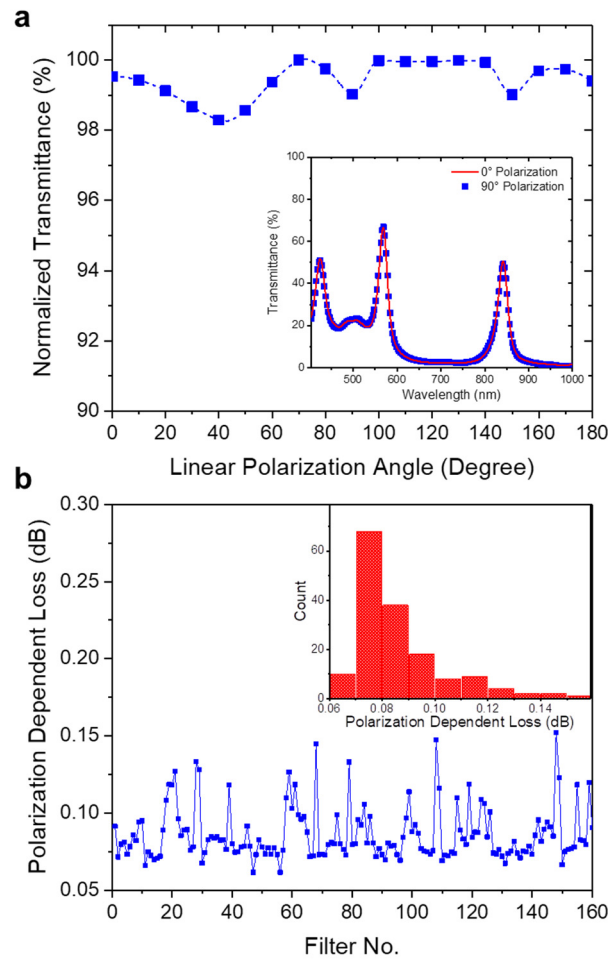
Supplementary Fig. 1 | Schematic diagrams and flowchart of digital grayscale photopolymerization technology for direct printing of length-varying polymer FP cavities. **a**, Formation of a gradient of oxygen inhibition degree by the diffusion of oxygen from the air into the film. **b**, Exponential attenuation of UV light due to absorption. **c**, Formation of a gradient of polymerization degree that is greater at the bottom. **d**, Creation of length-varying polymer FP cavities by the development of a less polymerized oligomer. **e**, Hard baking process.



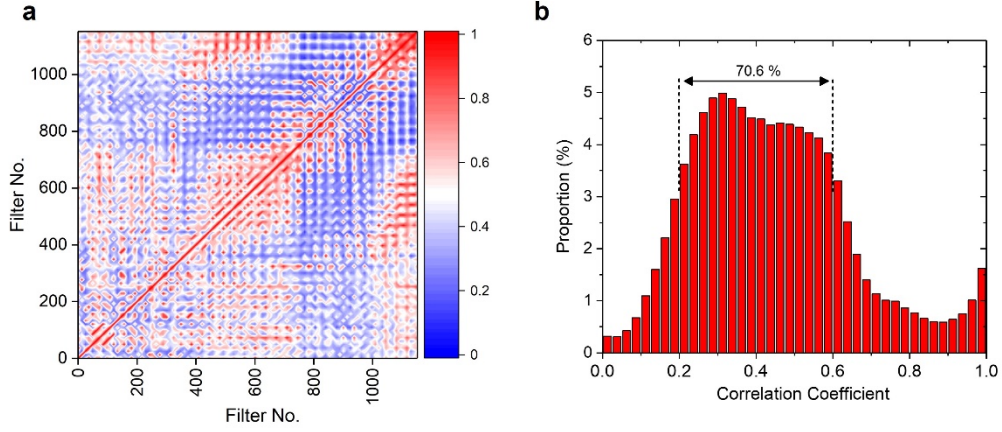
Supplementary Fig. 2 | Colour transmission optical microscopy images of the fabricated samples at different stages. **a**, Optical microscopy images after printing the micropatterns of the printed AgNPs on a TiO_2 layer (as well as the bottom Ag mirror and protective silica layers). **b**, Optical microscopy images after printing the polymer FP microcavities. **c**, Optical microscopy images of three groups of plasmonic nanoparticles-in-cavity microfilters fabricated from different sizes of AgNPs and FP cavities of different lengths. The scale bar is 100 μm .



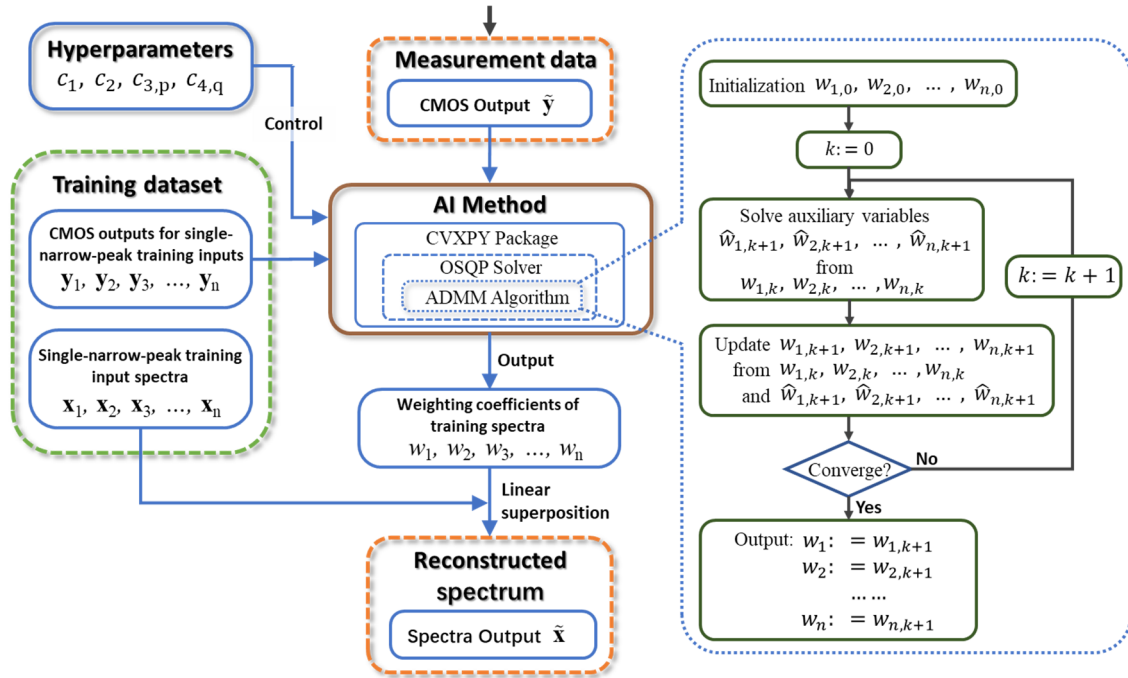
Supplementary Fig. 3 | **a**, Distribution of the transmission peaks of a fabricated plasmonic microfilter array. There are 2436 transmission peaks in the wavelength range from 425~800 nm. **b**, Estimation of the ideal spectral resolution using the transmission peak distribution.



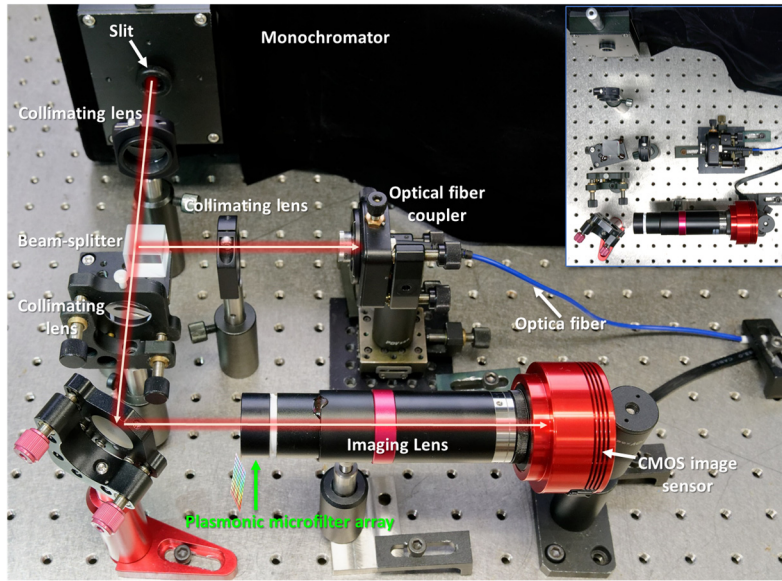
Supplementary Fig. 4 | **Polarization-dependence measurement results for plasmonic microfilters.** **a**. Normalized transmittance of a typical filter for 0° to 180° linearly polarized light. The inset shows the transmission spectra of a typical filter for 0° and 90° linearly polarized light. **b**. Measured polarization dependence loss of 160 filters. The inset is the statistical distribution of the polarization-dependent loss.



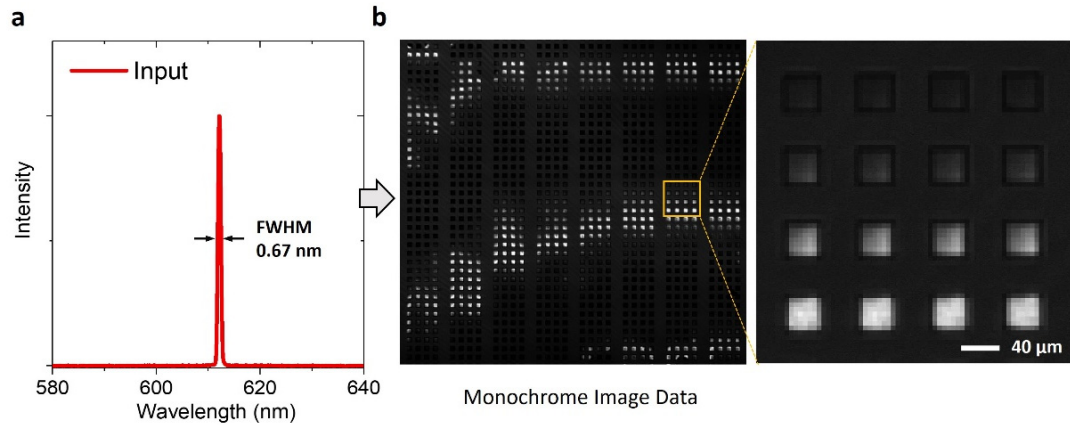
Supplementary Fig. 5 | **a.** Cross-correlation coefficients of the transmission spectra of a fabricated plasmonic microfilter array. **b.** Statistical distribution of the cross-correlation coefficients.



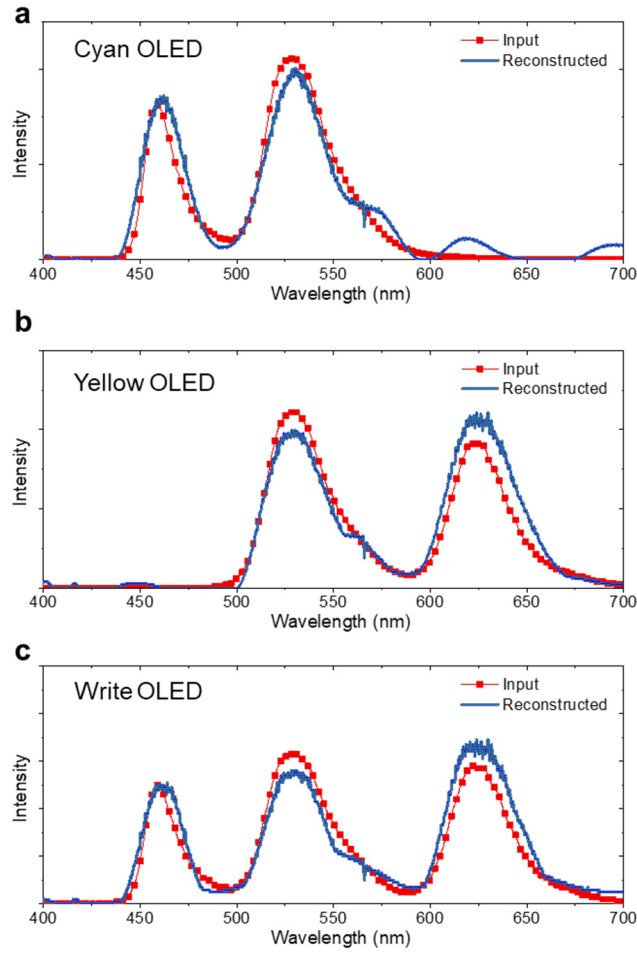
Supplementary Fig. 6 | **Diagram of the machine learning-based AI method for spectrum reconstruction.**



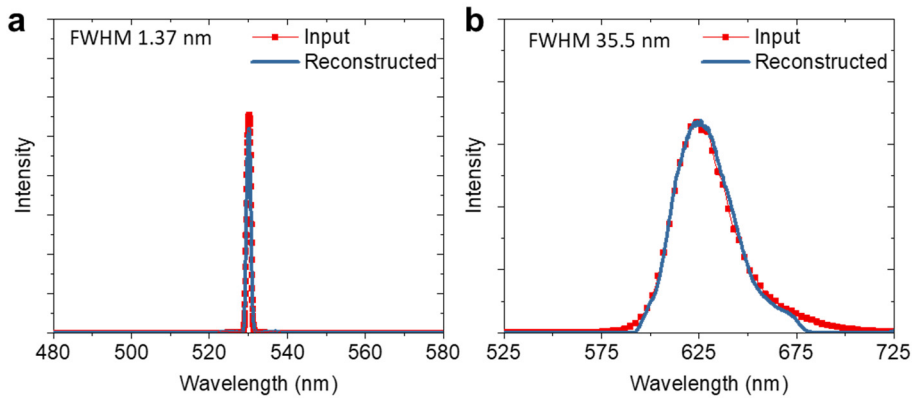
Supplementary Fig. 7 | Experimental setup for training and testing the plasmonic microfilter array-based computation spectrometer.



Supplementary Fig. 8 | Typical image data for spectrum reconstruction. a, The spectrum of an input light beam. **b,** Monochrome image data received by the CMOS image sensor. The scale bar in b(ii) is 40 μm .



Supplementary Fig. 9 | Testing results for the measurement of the broad light spectra of three different types of OLEDs. a, Yellow OLED. b, Cyan OLED. c, White OLED (from the AMOLED screen of Motorola Edge 20 Pro). The corresponding cosine similarities are 0.9774, 0.9693 and 0.9630, respectively.

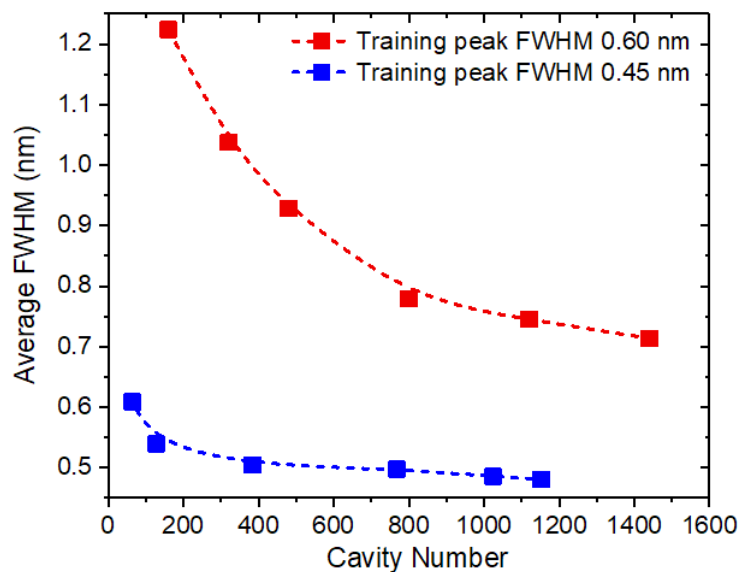


Supplementary Fig. 10 | Example of the reconstruction of narrowband (a) and broadband (b) input spectra using the same set of narrowband single-peak training spectra. The same training dataset but different hyperparameters are used to reconstruct these two input spectra. For the narrowband input spectrum (FWHM=1.37 nm), the hyperparameter settings are $c_1 = 600$, $c_2 = 0.1$, $c_{3,1} = 0.1$, $c_{3,5} = 0.02$, $c_{3,9} = 0.05$, and $c_{4,1} = 0.06$. For the broadband input spectrum (FWHM=35.5 nm), the hyperparameter settings are $c_1 = 5.8 \times 10^4$, $c_2 = 1900$, $c_{3,1} = 9.86 \times 10^4$, $c_{3,5} = 1.59 \times 10^7$, $c_{3,9} = 0.1$, and $c_{4,1} = 9430$. The other hyperparameters, i.e., $c_{3,p}$ ($p=2, 3, 4, 6, 7, 8$, or $p \geq 10$) and $c_{4,q}$ ($q \geq 2$), are all zero. The cosine similarities of the two reconstructed spectra are 0.9985 and 0.9977, respectively.

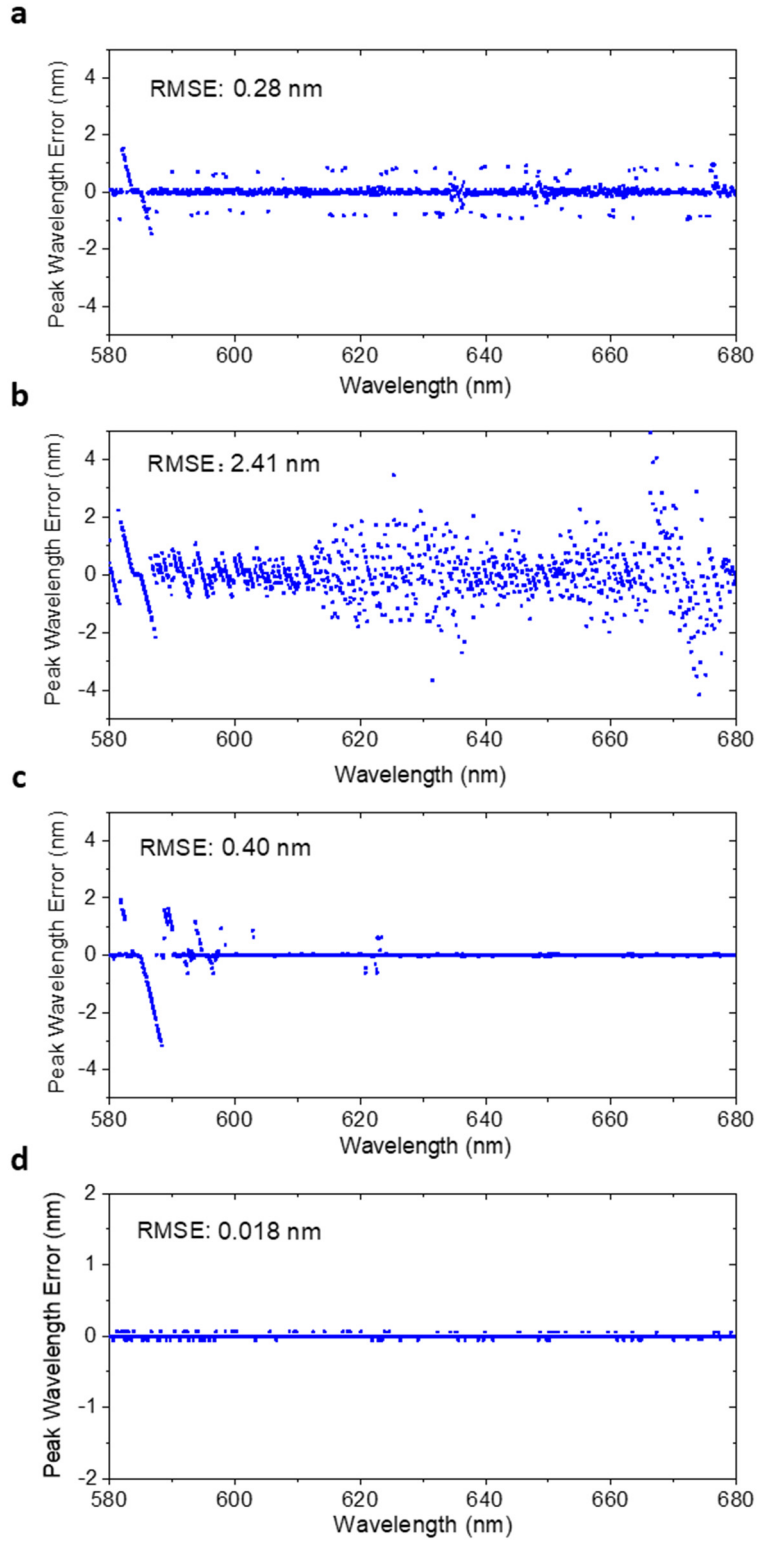
Supplementary Table 1. Comparison with recently reported computational spectrometers.

Publication information	Working mechanism	CMOS/CCD or other detectors	Operation range	Spectral resolution
Compact spectrometer based on a disordered photonic chip ¹ (<i>Nature Photonics</i> 2013)	Plasmonic nanohole	Photodetector array	1500 ~ 1525 nm	0.75 nm
A colloidal quantum dot spectrometer ² (<i>Nature</i> 2015)	Perovskite quantum dot	CCD sensor (Transmission mode)	390 ~ 690 nm	3.2 nm
Single-nanowire spectrometers ³ (<i>Science</i> 2019)	Single compositionally engineered nanowire	Nanowire detector array	500 ~ 630 nm	7 ~ 8.5 nm
Single-shot on-chip spectral sensors based on photonic crystal slabs ⁴ (<i>Nature Communications</i> 2019)	Photonic crystal slabs	CMOS sensor (Transmission mode)	550 ~ 750 nm	1 nm
Compact CMOS spectral sensor for the visible spectrum ⁵ (<i>Photonics Research</i> 2019)	Photonic crystal slabs	CMOS sensor (Transmission mode)	400 ~ 700 nm	1 nm
Broadband perovskite quantum dot spectrometer beyond human visual resolution ⁶ (<i>Light: science & applications</i> 2020)	Perovskite quantum dot	CCD sensor (Transmission mode)	250 ~ 1000 nm	1.6 nm
Neural network-based on-chip spectroscopy using a scalable Plasmonic Encoder ⁷ (<i>ACS Nano</i> 2021)	Plasmonic nanohole	CMOS sensor (Transmission mode)	480 ~ 750 nm	<3.29 nm
A pearl spectrometer ⁸ (<i>Nano Lett.</i> 2021)	Naturally pearl nanostructure	CCD sensor (Transmission mode)	450 ~ 700 nm	7.4 nm
Deeply learned broadband encoding stochastic hyperspectral imaging ⁹ (<i>Light: science & applications</i> 2021)	Multilayer film filters (using SiO ₂ and TiO ₂ nanolayers)	CCD sensor (Transmission mode)	400 ~ 700 nm	5.2 nm
A wavelength-scale black phosphorus spectrometer ¹⁰ (<i>Nature Photonics</i> 2021)	Tunable black-phosphorus detector	Black phosphorus detector	2000 ~ 9000 nm	420 nm
3D-printed miniature spectrometer for the visible range with a 100 × 100 μm ² footprint ¹¹ (<i>Light: Advanced Manufacturing</i> 2021)	3D-printed micro-optics	CMOS sensor (Transmission mode)	490 ~ 690 nm	9.2 nm
A single-dot perovskite spectrometer ¹² (<i>Advanced Materials</i> 2021)	LiCl-doped perovskite film	Perovskite detector	350 ~ 750 nm	5.3 nm
Mass production-enabled computational spectrometers based on multilayer thin films ¹³ (<i>Scientific Reports</i> 2022)	Multilayer film filters (using SiO ₂ and TiO ₂ nanolayers)	CMOS sensor (Transmission mode)	500 ~ 849 nm	1 nm
Ultraspectral imaging based on metasurfaces with freeform shaped meta-atoms ¹⁴ (<i>Laser & Photonics Reviews</i> 2022)	Metasurfaces with freeform shaped meta-atoms	CMOS sensor (Transmission mode)	460 ~ 740 nm	0.5 nm
Dynamic brain spectrum acquired by a real-time ultraspectral imaging chip with reconfigurable metasurfaces ¹⁵ (<i>Optica</i> 2022)	Reconfigurable metasurfaces	CMOS sensor (Transmission mode)	450 ~ 750 nm	0.8 nm
Short-wave infrared chip-spectrometer by using laser direct-writing grayscale lithography ¹⁶ (<i>Advanced Optical Materials</i> 2022)	Directly written Fabry-Pérot cavities	Photodetector array	900 ~ 1700 nm	2 nm

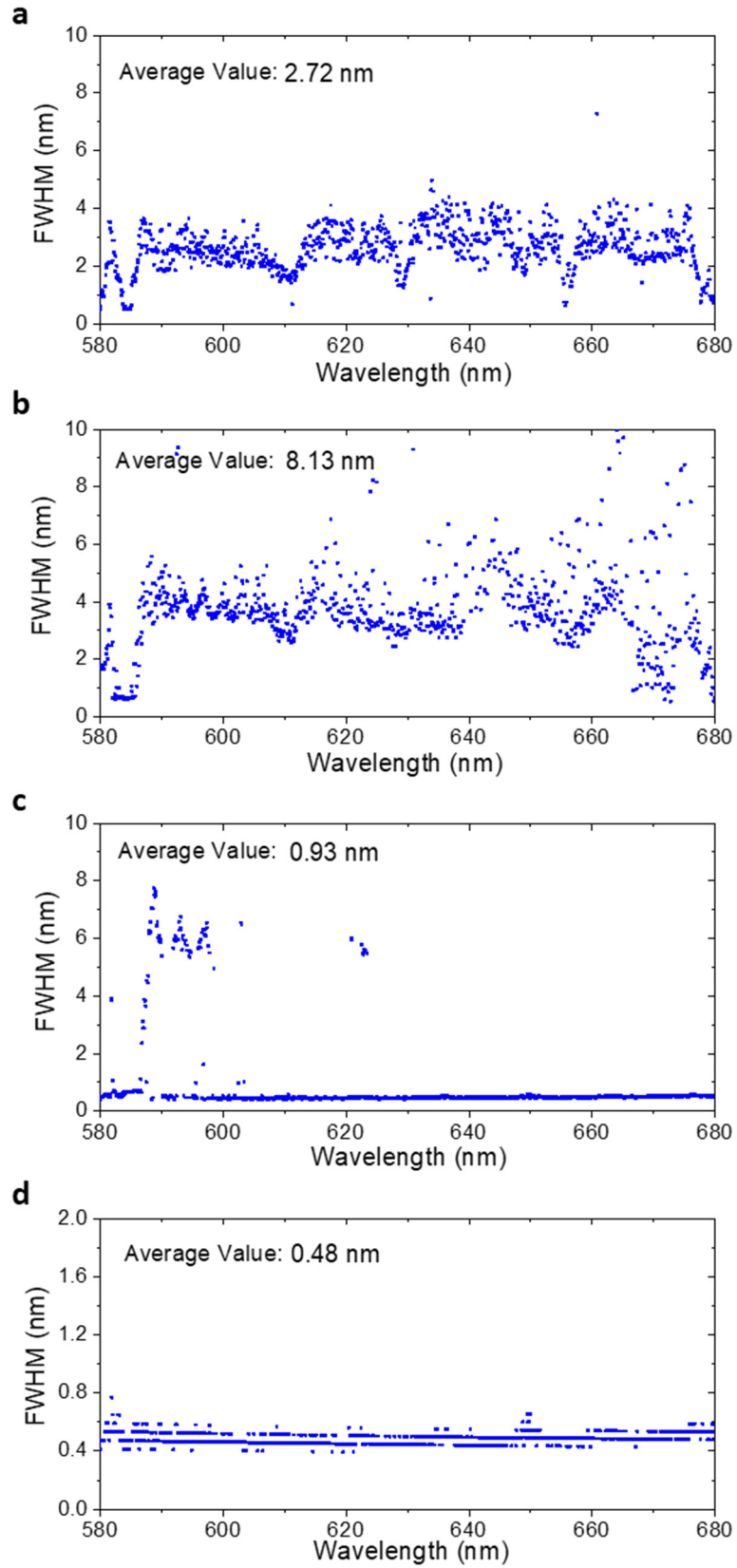
Miniaturized spectrometers with a tunable van der Waals junction ¹⁷ (<i>science</i> 2022)	Tunable van der Waals junction	MoS ₂ /WSe ₂ heterojunction detector	405 ~ 845 nm	3 nm
Deep learning-based miniaturized all-dielectric ultracompact film spectrometer ¹⁸ (<i>ACS Photonics</i> 2023)	Five-layer film stacks (using SiO ₂ and TiO ₂ nanolayers)	CMOS sensor (Transmission mode)	400 ~ 700 nm	5 nm (16 filters) or 3nm (64 filters)
Video-rate hyperspectral camera based on a CMOS-compatible random array of Fabry-Pérot filters ¹⁹ (<i>Nature photonics</i> 2023)	Fabry-Pérot filter array	CMOS sensor (Transmission mode)	400 ~ 700 nm	~20 nm
Imaging-based intelligent spectrometer on a plasmonic rainbow chip ²⁰ (<i>Nature Communications</i> 2023)	Plasmonic rainbow chip	CCD sensor (Reflection mode)	400 ~ 800 nm	2 nm
Folded digital meta-lenses for on-chip Spectrometer ²¹ (<i>Nano Letter</i> 2023)	Folded digital meta-lenses	Photodetector	1530 ~ 1565 nm	0.14 nm
Inverse-designed linear coherent photonic networks for high-resolution spectral reconstruction ²² (<i>ACS Photonics</i> 2023)	Integrated photonic chip	Photodetector	1515 ~ 1525 nm	0.1 nm
Integrated single-resonator spectrometer beyond the free-spectral-range limit ²³ (<i>ACS Photonics</i> 2023)	Single micro-ring resonator	Photodetector	1500 ~ 1600 nm	0.08 nm
Photon counting reconstructive spectrometer combining metasurfaces and superconducting nanowire single-photon detectors ²⁴ (<i>Photonics Research</i> 2023)	Metasurface array	Nanowire single-photon detectors	1500 ~ 1600 nm	2 nm
This work	Plasmonic nanoparticles-in-cavity microfilter array	CMOS sensor (Transmission mode)	395 ~ 725 nm	0.65 nm (0.49 nm for 580 ~ 680 nm)



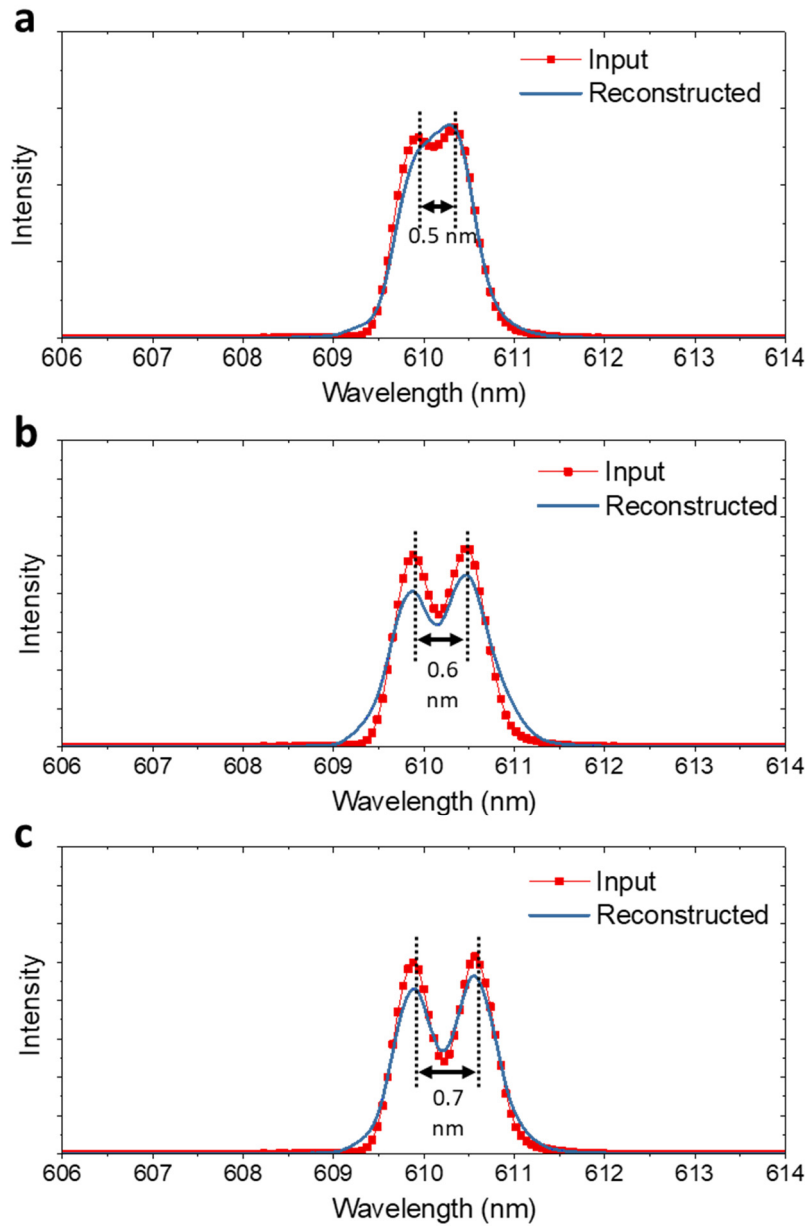
Supplementary Fig. 11 | Testing results for the effect of the microfilter number on the spectrometer resolution. Two groups of single-peak spectra with FWHMs of 0.61 nm (red) and 0.44 nm (blue) were used in the training and testing of the spectrometer.



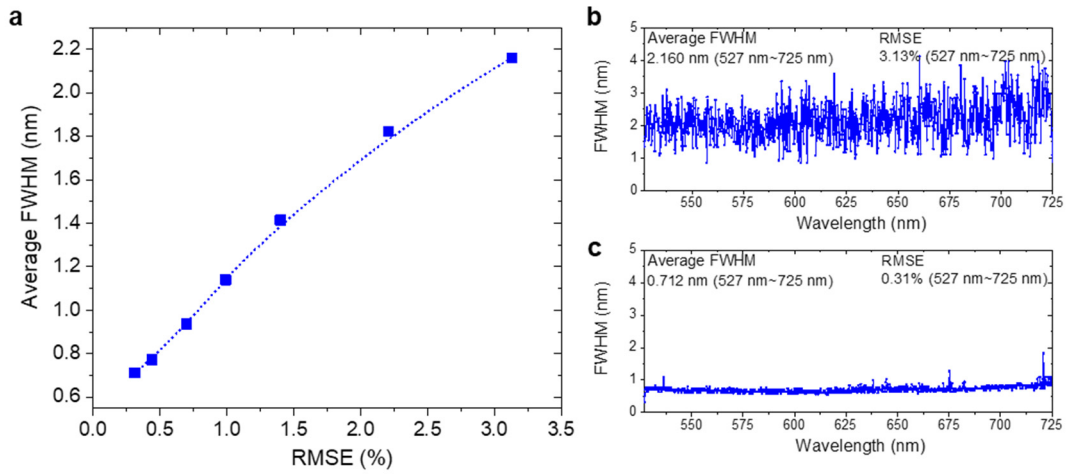
Supplementary Fig. 12 | Peak wavelength errors of the single-peak optical spectra reconstructed by using different algorithms. a, Ridge, b, TV, c, LASSO, d, Hybrid algorithm.



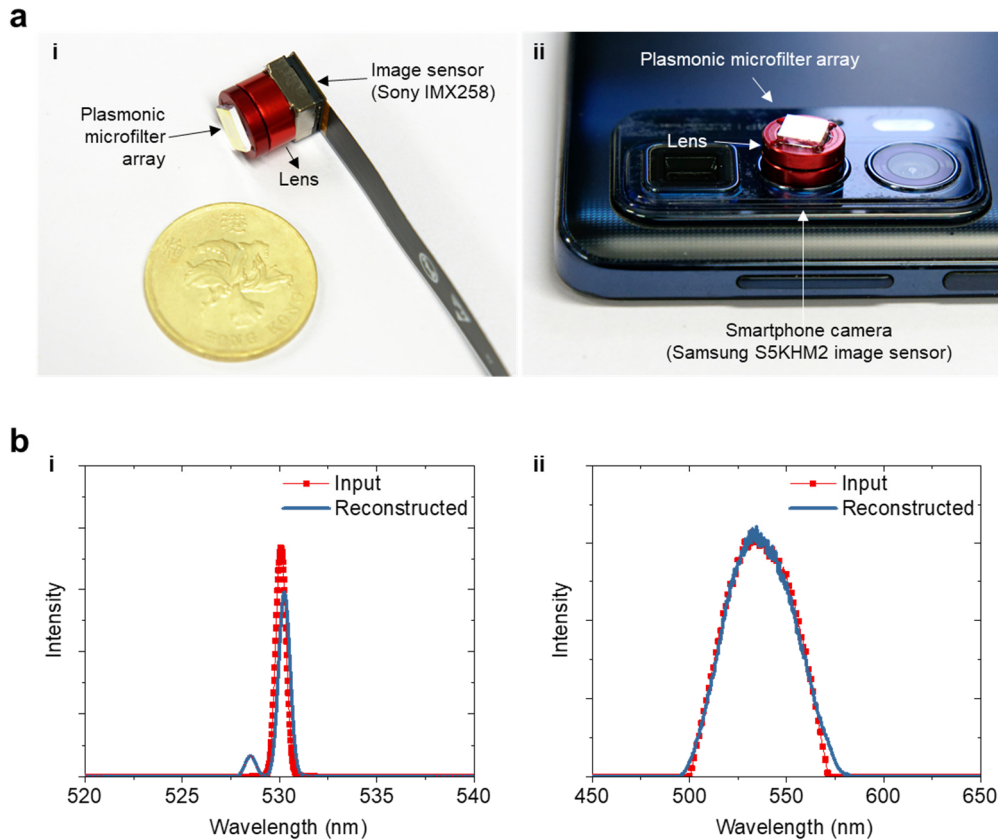
Supplementary Fig. 13 | Calculated FWHMs of single-peak optical spectra reconstructed by using different algorithms. a, Ridge, b, TV, c, LASSO, d, Hybrid algorithm.



Supplementary Fig. 14 | Spectral resolution testing of the computational spectrometer by using two-peak input spectra. a, Results for two spectral peaks with a wavelength separation of 0.5 nm. **b,** Results for two spectral peaks with a wavelength separation of 0.6 nm. **c,** Results of two spectral peaks with a wavelength separation of 0.7 nm. The results were achieved by using a series of input spectra with ~ 0.44 nm FWHM as training data scanned with a 0.1 nm step.



Supplementary Fig. 15 | Testing results for the effect of measurement noise on the spectrometer resolution. **a**, Average FWHM as a function of the RMSE. **b**, Reconstruction result with an RMSE of 3.13%. **c**, Reconstruction result with an RMSE of 0.31%. The spectrometer was trained with single-peak light spectra with a FWHM of 0.61 nm in the 525~675 nm range.



Supplementary Fig. 16 | Demonstration and testing of CMOS image sensor-based portable spectrometers with plasmonic microfilter arrays. **a**, Photos of the CMOS image sensor-based spectrometer (i) and the smartphone-based portable spectrometer (ii). **b**, Results of the homemade portable spectrometer shown in a(i) for the measurement of a single-narrow-peak spectrum (i) and broadband light input (ii).

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