Meta-Material Enhanced Spatial Mode Decomposition

Aaron Jones (✉ aaron.jones@uwa.edu.au)  
University of Western Australia  https://orcid.org/0000-0002-0395-0680

Mengyao Wang  
Beijing Normal University

Xuecai Zhang  
Southern University of Science and Technology,

Samuel Cooper  
University of Birmingham

Shumei Chen  
Harbin Institute of Technology Campus of University Town of Shenzhen,

Conor Mow-Lowry  
VU Amsterdam

Andreas Freise  
VU Amsterdam

Article

Keywords: meta-surface, cross-coupling, precision

DOI: https://doi.org/10.21203/rs.3.rs-892179/v1

License: ☑️ This work is licensed under a Creative Commons Attribution 4.0 International License.  
Read Full License
Meta-Material Enhanced Spatial Mode Decomposition

Aaron W. Jones\textsuperscript{1,2}, Mengyao Wang\textsuperscript{3}, Xuecai Zhang\textsuperscript{4}, Samuel J. Cooper\textsuperscript{1}, Shumei Chen\textsuperscript{5,†}, Conor M. Mow-Lowry\textsuperscript{1,6,7} and Andreas Freise\textsuperscript{1,6,7}

\textsuperscript{1}Institute for Gravitational Wave Astronomy, School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom
\textsuperscript{2}OzGrav, University of Western Australia, Crawley, Western Australia, Australia
\textsuperscript{3}Department of Astronomy, Beijing Normal University, Beijing 100875, China
\textsuperscript{4}Department of Materials Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China
\textsuperscript{5}Harbin Institute of Technology Campus of University Town of Shenzhen, Shenzhen 518055, China
\textsuperscript{6}Department of Physics and Astronomy, VU Amsterdam, De Boelelaan 1081, 1081, HV, Amsterdam, The Netherlands
\textsuperscript{7}Nikhef, Science Park 105, 1098, XG Amsterdam, The Netherlands

Acquiring precise information about the mode content of a laser is critical for multiplexed optical communications, optical imaging with active wave-front control, and quantum-limited interferometric measurements. Hologram-based mode decomposition devices allow a fast, direct measurement of the mode content, but they have limited precision due to cross-coupling between modes. Here we report the first proof-of-principle demonstration of mode decomposition with a meta-surface, resulting in significantly enhanced precision. A mode-weight fluctuation of 0.6ppm (-62 dB) can be measured with 1 second of averaging at a Fourier frequency of 80 Hz, an improvement on the state-of-the-art by more than three orders of magnitude. The improvement is attributable to the reduction in cross-coupling enabled by the exceptional phase accuracy of the meta-surface. We show a systematic study of the limiting sources of noise, and we show that there is a promising path towards complete mode decomposition with similar precision.

A monochromatic laser field is uniquely described by its power and the transverse profile. A standard approach to describe the transverse profile is to decompose it into an orthogonal mode basis, such as the Hermite–Gaussian (HG) or Laguerre–Gaussian (LG) basis. The mode content, the fractional weight and relative phase of different modes, completely describe the laser wavefronts. Precise determination and manipulation of the mode content can lead to a vast range of new developments in adaptive optics\textsuperscript{12}, quantum optics\textsuperscript{8} and quantum communications\textsuperscript{15}. Even applications that require extremely stable wavefronts, such as laser interferometric gravitational-wave detection\textsuperscript{17} will also benefit from accurate information about the mode content.

One direct and robust approach to determine the mode content is using correlation filters

\textsuperscript{*}aaron.jones@ligo.org
\textsuperscript{†}chenshumei@hit.edu.cn
based on Fourier optics. A particular mode pattern is encoded onto a diffractive optical element and a Fourier imaging system convolves this pattern with an incoming beam. In the far field, the mode weight is proportional to the on-axis intensity. For an orthogonal mode basis, several patterns can be spatially multiplexed by adding a blazed grating to the spatial carrier, allowing the simultaneous interrogation of multiple modes. In practice, the sensors that read the modal powers must have a finite aperture, inducing cross-coupling by measuring some off-axis intensity. The state-of-the-art accuracy of measuring the mode weighting is around 1%. These measurements are likely limited by this cross-coupling, once this effect is eliminated, mode weights of 0.2% can be demonstrated.

The cross coupling effect has been analysed and is limited by the beam-size at the sensor. More precisely, it scales as square of the ratio of the sensor aperture to beam diameter. Henceforth, to ultimately suppress the cross coupling, larger beams on the sensor are preferred. As a fact of a Fourier imaging system, this implies a small incoming beam interrogating at the diffractive optical element, which exhibits a challenging requirement. For example, spatial light modulators have fundamental limit of the pixel resolution.

Furthermore, both of the spatial light modulators we tested exhibited noise at half integer multiples of the display frequency, rendering the device useless for modal measurements between 25-250 Hz—essential frequencies in audio band applications such as laser interferometric gravitational-wave detection.

Recent developments in the field of optical metasurfaces have led to a novel platform for controlling the multiple degrees of freedom of light at subwavelength scale. In our work, we propose a new meta-surface approach to address the cross-coupling and noise issues. As a proof of principle demonstration, we encode three correlation filters for HG00, HG01, and HG10 on one meta-surface chip, which allows for a simple calibration procedure and can be extended to include more spatial modes. With the exceptionally high resolution of the meta-surface, we are able to measure the first-order mode content with a sensitivities in excess of 1 ppm above 25 Hz.

The metasurface, shown in Figure 1a, is an ultrathin structured medium composed of spatially variant plasmonic or dielectric meta-atoms, which can be fabricated by using the state of the art nanofabrication technologies. The electromagnetic response of each meta-atom can be engineered individually, which enables the precise and arbitrary manipulation of the polarization, phase and amplitude of light. In the past decade, metasurface, as a new kind of planar and multi-functional diffractive optical elements have been extensively explored in the field of planar metalens, high efficiency optical holography, vortex beam generation and quantum information processing.

Figure 1b shows an overview of the mode decomposition apparatus (MODAN). The incoming laser, strikes the meta-surface and is split into three beams, A, B and C. The on-axis intensity
(a) The Metasurface. A pixel of the metasurface consists of an Au rod on a SiO$_2$ spacer. The spacer sits above a Au mirror. A scanning electron microscope image of several unit cells is shown in the lower right.

(b) Mode Decomposition Apparatus. The incoming laser strikes the meta-surface and is split into three beams, A, B and C. The lenses focus this light to a large waist in the output plane. Preparatory optics are shown in Figure 2a.

Figure 1: Meta Enhanced Mode Decomposition Correlation Filter (MODAN)

of beam A corresponds to the power in the HG00 mode, while B and C correspond to HG01 and HG10 respectively. A lens focuses these beams to a large waist where the on-axis power is then measured using small aperture photo-diodes. The entire meta-surface is 500 µm × 500 µm with $10^3 \times 10^3$ pixels for 1064 nm laser beam.

To achieve the required phase distributions, the meta-atom is designed based on the concept of geometric Pancharatnam-Berry phase\textsuperscript{25}. It has an Au nanorod, SiO$_2$ spacer and Au mirror trilayer configuration, also shown in Figure 1a. Under the incidence of left- or right-circular polarized light, the reflected light with opposite handedness can be obtained by choosing the anisotropic meta-atom with appropriate geometrical parameters. By rotating the fast axis of the gold nanorod, the phase of the reflected light with opposite circular polarization state can be continuously tuned from 0 to $2\pi$\textsuperscript{16}.

To validate our sensor, we first prepared a clean beam by spatially, polarization and spectrally filtering laser light though a mode cleaner cavity. The phaseplate and photodiodes were calibrated by injecting a small amount of HG10 at 318 mHz, realized by an angular modulation of steering mirror M1. The modulated light was split with one branch going to a state-of-the-art witness QPD, which required a 1.2 mm waist radius beam. The second branch was directed towards phaseplate, which required a 55 µm waist radius of elliptically polarized light. Data was recorded using a state-of-the-art, low noise multi-channel ADC\textsuperscript{26}. For more details see Figure 2a and the Supplementary.
(a) Validation apparatus. Laser light is filtered through a mode cleaner cavity. A small angular modulation is applied at M1. The beam is then incident on the two devices under test: a QPD and the phaseplate.

(b) Calibration Signal. 150 s of data was gathered for the calibration procedure. This data shows excellent coherence between the QPD and MODAN based sensors at the 318 mHz modulation frequency.

Figure 2: Calibration and Validation

Material. We found the coherence between the two devices was superb, as shown in Figure 2b.

Due to exceptional meta-surface resolution in nano-scale size, cross coupling between all but the largest modes may be safely ignored. Pushing our experimental setup to its limit, we allowed the HG00 to become $10^6$ times larger than the HG10. Even at this level, fluctuations in the HG00 could be ignored and we only needed to take account of the DC effect, which was subtracted away during online signal processing.

Figure 3 shows amplitude spectral density of HG10 mode weight, computed from the correlation filter channels A and C, alongside the QPD signal for the same time period. During this time the beam alignment was not controlled, apart from an initial centering. At high frequency, the phaseplate based sensor outperforms our QPD, achieving the sensitivity of $6 \times 10^{-7}/\sqrt{\text{Hz}} \,(62 \text{ dB})$ at 80 Hz, meaning the mode weight fluctuation at 80 Hz can be measured down to 0.6 ppm with signal-to-noise ratio 1 and 1 s averaging. At these high frequencies, the measurement is limited by a white electronic noise. We expect that the photo-diodes self-noise was slightly in excess of that estimated by the manufacturer, which explains this limitation. The feature at 6 kHz in all three data traces is an artifact of the DAQ anti-aliasing filter.

At lower frequencies, the measurement is limited by an optical effect. We expect that this noise is beam jitter, possibly caused by seismic, thermal and air pressure fluctuations coupling into our in-air optical table. We anticipate that this affected the MODAN based sensor more severely than the QPD sensor due to the out-of-plane lens used by MODAN, which sat on longer lever arms than the optics in the QPD path. See Figure 4.4 of [11] for a photograph of these lens. This limitation means that measurements separated by 1000 s are comparable 0.1 % level.
Figure 3: Noise contributions. *MODAN Signal* and *QPD Signal* show the measured signals, whilst the beam is centered on the MODAN, but out of any alignment control loop. The manufactures photo-diode noise estimate from Channels A and C is shown by *PD Noise Projection*. *Dark Noise* shows the total noise of the MODAN photo-diodes, signal processing and DAQ electronics, with no laser illumination.
To date, the state-of-the-art mode weighting method is spatially and spectrally resolved ($S^2$) imaging, which offers a $\sim 40$ dB mode discrimination (and references therein). However, $S^2$ imaging requires an incoherent source and is therefore not suitable for in-situ diagnostics in many experiments. We show the meta-material enhancement allows correlation filter based imaging to surpass the $S^2$ technique, permitting the investigation of small mode weights among a larger carrier mode, in this case TEM00. This is particularly useful in precision metrology, where high levels of mode matching are required. Furthermore, sub-micron pixels enable a reduction in unused diffraction orders, improving power efficiency, thus reducing shot noise and increasing the available spatial multiplexing. Thus, increasing the signal to dark-noise ratio.

Applications requiring high-frequency mode-decomposition, such as mode-division-multiplexing and characterization of single-mode fibers, may reduce cross-talk using the meta-material enhancement. These systems are likely to be limited by electronic noises in the photo-diode. An improved electronic readout system may permit shot noise limited sensitivity.

Applications requiring low frequency mode analysis, such as correction of thermally induced mode mismatches in high power systems, will need to carefully consider the low frequency the stability of the phase-plate, lens, photo-diode and electronics to achieve the very highest dynamic ranges. Gravitational wave detectors may implement this technique to monitor parametric instabilities.

Future work may wish to consider adaptive sub-micron phase-pattern imaging techniques (e.g. Takagi et. al) which could combine the benefits of meta-material enhancement with adaptive phase-pattern imaging.

1. Pastrana, E. Adaptive optics for biological imaging. *Nature Methods* **8**, 45 (2011). URL https://doi.org/10.1038/nmeth.f.333.

2. Davies, R. & Kasper, M. Adaptive optics for astronomy. *Annual Review of Astronomy and Astrophysics* **50**, 305–351 (2012). URL https://doi.org/10.1146/annurev-astro-081811-125447.

3. Wagner, K. *et al.* Entangling the spatial properties of laser beams. *Science* **321**, 541–543 (2008). URL https://science.sciencemag.org/content/321/5888/541.

4. Wang, A. *et al.* Directly using 8.8-km conventional multi-mode fiber for 6-mode orbital angular momentum multiplexing transmission. *Opt. Express* **26**, 10038–10047 (2018). URL http://www.opticsexpress.org/abstract.cfm?URI=oe-26-8-10038.

5. Richardson, D. J., Fini, J. M. & Nelson, L. E. Space-division multiplexing in optical fibres. *Nature Photon* **7**, 354–362 (2013). URL https://www.nature.com/articles/nphoton.2013.94.
6. Adhikari, R. X. Gravitational radiation detection with laser interferometry. *Rev. Mod. Phys.* **86**, 121–151 (2014). URL https://link.aps.org/doi/10.1103/RevModPhys.86.121.

7. Brooks, A. F. *et al.* Overview of advanced ligo adaptive optics. *Appl. Opt.* **55**, 8256–8265 (2016). URL http://ao.osa.org/abstract.cfm?URI=ao-55-29-8256.

8. Golub, M. A., Prokhorov, A. M., Sisakyan, I. N. & Soifer, V. A. Synthesis of spatial filters for investigation of the transverse mode composition of coherent radiation. *Soviet Journal of Quantum Electronics* **12**, 1208–1209 (1982). URL https://doi.org/10.1070/QE1982v012n09abeh005998.

9. Schulze, C. *et al.* Wavefront reconstruction by modal decomposition. *Opt. Express* **20**, 19714–19725 (2012). URL http://www.opticsexpress.org/abstract.cfm?URI=oe-20-18-19714.

10. Forbes, A., Dudley, A. & McLaren, M. Creation and detection of optical modes with spatial light modulators. *Adv. Opt. Photon.* **8**, 200–227 (2016). URL http://aop.osa.org/abstract.cfm?URI=aop-8-2-200.

11. Jones, A. *Impact and Mitigation of Wavefront Distortions in Precision Interferometry*. Ph.D. thesis, University of Birmingham (2020).

12. Jones, A. W., Wang, M., Mow-Lowry, C. M. & Freise, A. High dynamic range spatial mode decomposition. *Optics Express* **28**, 10253–10269 (2020).

13. Yu, N. & Capasso, F. Flat optics with designer metasurfaces. *Nature Materials* **13**, 139–150 (2014).

14. Khorasaninejad, M. *et al.* Metalenses at visible wavelengths: Diffraction-limited focusing and subwavelength resolution imaging. *Science* **352**, 1190–1194 (2016). URL https://science.sciencemag.org/content/352/6290/1190.

15. Wang, S. *et al.* A broadband achromatic metalens in the visible. *Nature Nanotechnology* **13**, 227–232 (2018).

16. Zheng, G. *et al.* Metasurface holograms reaching 80% efficiency. *Nature Nanotechnology* **10**, 308–312 (2015).

17. Arbabi, A., Horie, Y., Bagheri, M. & Faraon, A. Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission. *Nature Nanotechnology* **10**, 937–943 (2015). 1411.1494.

18. Chen, S., Cai, Y., Li, G., Zhang, S. & Cheah, K. W. Geometric metasurface fork gratings for vortex-beam generation and manipulation. *Laser & Photonics Review* **10**, 322–326 (2016). 1605.00831.
19. Devlin, R. C., Ambrosio, A., Rubin, N. A., Mueller, J. P. B. & Capasso, F. Arbitrary spin-to-orbital angular momentum conversion of light. *Science* **358**, 896–901 (2017).

20. Wang, K. *et al.* Quantum metasurface for multiphoton interference and state reconstruction. *Science* **361**, 1104–1108 (2018). [1804.03494]

21. Stav, T. *et al.* Quantum entanglement of the spin and orbital angular momentum of photons using metamaterials. *Science* **361**, 1101–1104 (2018).

22. Georgi, P. *et al.* Metasurface interferometry toward quantum sensors. *Light: Science & Applications* **8**, 70 (2019).

23. Zhu, L. *et al.* A dielectric metasurface optical chip for the generation of cold atoms. *Science Advances* **6**, eabb6667 (2020).

24. Li, L. *et al.* Metalens-array-based high-dimensional and multiphoton quantum source. *Science* **368**, 1487–1490 (2020).

25. Berry, M. The adiabatic phase and pancharatnam’s phase for polarized light. *Journal of Modern Optics* **34**, 1401–1407 (1987). URL [https://doi.org/10.1080/09500348714551321](https://doi.org/10.1080/09500348714551321).

26. Bork, R. *et al.* advligorts: The advanced ligo real-time digital control and data acquisition system. *SoftwareX* **13**, 100619 (2021). URL [https://www.sciencedirect.com/science/article/pii/S2352711020303320](https://www.sciencedirect.com/science/article/pii/S2352711020303320).

27. Jollivet, C., Flamm, D., Duparré, M. & Schülzgen, A. Detailed characterization of optical fibers by combining $s^2$ imaging with correlation filter mode analysis. *J. Lightwave Technol.* **32**, 1068–1074 (2014). URL [http://jlt.osa.org/abstract.cfm?URI=jlt-32-6-1068](http://jlt.osa.org/abstract.cfm?URI=jlt-32-6-1068).

28. Takagi, H., Nakamura, K., Goto, T., Lim, P. B. & Inoue, M. Magneto-optic spatial light modulator with submicron-size magnetic pixels for wide-viewing-angle holographic displays. *Opt. Lett.* **39**, 3344–3347 (2014). URL [http://ol.osa.org/abstract.cfm?URI=ol-39-11-3344](http://ol.osa.org/abstract.cfm?URI=ol-39-11-3344).

**Acknowledgements** The authors jointly thank John Bryant and David Hoyland for developing the low noise QPD and modifications to the EUCLID DAQ, used in precursor experiments. The authors thank Dr Artemiy Dmitriev for developing CDS units at Birmingham. A. W. Jones was supported by an EPSRC studentship and ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav), project number CE170100004.

**Author contributions** A.J., A.F. and M.W. designed the study and developed the phase-pattern. X.Z. and S.Ch. developed and fabricated the nanoscale surface. A.J. design, assembly and operation of optical testing apparatus. A.J. and C.M. designed the analogue signal processing and data analysis. S.Co. developed, built and operated the digital acquisition. A.J., C.M. and M.W. drafted the manuscript.
Competing Interests  The authors declare that they have no competing financial interests.

Correspondence  Correspondence and requests for materials should be addressed to A. W. Jones (email: aaron.jones@ligo.org).

Supplementary Material  Section 1 details how we calibrated the MODAN.
Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- supplementary.pdf