Metasurface-enhanced spatial mode decomposition

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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, such as spatial light modulators, allow a fast, direct measurement of the mode content, but they have limited precision due to cross coupling between modes. Here, we report a proof-of-principle demonstration of mode decomposition with a metasurface, resulting in significantly enhanced precision. A mode-weight fluctuation of $6 \times 10^{-7}$ was measured with 1 s of averaging at a Fourier frequency of 80 Hz, an improvement of more than three orders of magnitude compared to the state-of-the-art spatial light modulator decomposition. The improvement is attributable to the reduction in cross coupling enabled by the exceptionally small pixel size of the metasurface. 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.

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I. INTRODUCTION

A monochromatic laser field is uniquely described by its power and 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 wave fronts. Precise determination and manipulation of the mode content can lead to a vast range of new applications, such as spatial light modulators for mode decomposition [9,11] and quantum communications [4,5]. Even applications that require extremely stable wave fronts, such as laser interferometric gravitational-wave detection, will also benefit from accurate information about the mode content [6,7].

One direct and robust approach to determine the mode content is using correlation filters based on Fourier optics [8,9]. 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 [8]. 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, not only measuring the ideal on-axis intensity [10]. The undesired measurement of some off-axis intensity induces an error, which in this paper we refer to as the cross coupling.

Previous work has demonstrated the success of using spatial light modulators for mode decomposition [9,11] and showed an accuracy of mode weighting around 1% [12]. This work found $S^2$ imaging to be $\sim 3$ times more precise than correlation filters. Recent work shows that the correlation filter approach can be improved by a factor $\sim 5$ by using a pinhole to reduce cross-coupling errors [10,13].

The cross-coupling effect has been analyzed and is limited by the beam size on the sensor [10,13]. More precisely, it scales as [10]

$$\rho_{\min} \approx \frac{r_a^2}{4w_S^2} + O\left(\frac{r_a^4}{w_S^4}\right),$$

where $r_a$ is the radius of the sensing aperture and $w_S$ is the Gaussian beam radius on the sensor. Henceforth, to ultimately suppress the cross coupling, larger beams on the sensor are preferred. As a fact of a Fourier imaging systems [14] this implies a small incoming beam interrogating at the diffractive optical element, which exhibits a challenging requirement. For example, spatial light modulators have a fundamental limit of the pixel resolution. Recent developments in the field of optical metasurfaces have led to a novel platform for controlling the multiple degrees of freedom of light at the subwavelength scale [15]. The metasurface is an ultrathin structured medium composed of spatially variant plasmonic or dielectric meta-atoms, which can be fabricated by using
FIG. 1. Mode decomposition apparatus. The incoming laser strikes the metasurface 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 Fig. 3(a).

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, the metasurfaces, as new kinds of planar and multifunctional diffractive optical elements, have been extensively explored in the field of planar metalens [16,17], high-efficiency optical holography [18,19], vortex beam generation [20,21], and quantum information processing [22–26]. One recent proposal uses a highly transmissive dielectric metasurface for spatial mode multiplexing on optical fibers (see Ref. [27] and references therein).

In our paper, we propose to use a metasurface as the diffractive optical element for mode decomposition. We experimentally addressed the cross-coupling effect and noise issues by encoding three correlation filters for HG00, HG01, and HG10 on one metasurface chip, which allows for a simple calibration procedure and can be easily extended to include more spatial modes. These modes were chosen, as they permit the use of quadrant photodiodes (QPDs) as witness sensors. With the exceptionally small pixel size of the metasurface, we are able to measure the first-order mode content with a noise floor \(<10^{-6}/\sqrt{\text{Hz}}\) above of 25 Hz.

II. EXPERIMENTAL APPARATUS

Figure 1 shows an overview of the mode decomposition apparatus (MODAN). Phase maps of HG00, HG01, and HG10 together with three different blazed gratings are encoded on the metasurface chip. The entire metasurface chip active area was 500 \(\mu\text{m} \times 500 \mu\text{m}\) with \(10^3 \times 10^3\) pixels for a 1064-nm laser beam. The incoming laser strikes the metasurface and is split into three beams, A, B, and C. The on-axis intensity 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 inexpensive standard small aperture photodiodes. This photodiode had a circular 250-\(\mu\text{m}\) aperture and a quantum efficiency of 70% [28]. Cross coupling could have been further suppressed by using a smaller aperture prior to the photodiode. A 10-\(\mu\text{m}\) aperture was tested but the dark noise of the photodiode was in excess of any measurable signal. The signal was digitized in real time using a state-of-the-art, low-noise multichannel digitizer [29]. This system is a clone of the digitizer used by LIGO. The combination of these technologies ensured that digital quantization noise was not limiting, while also permitting a measurement bandwidth from 1 mHz to 10 kHz.

Figure 2 shows the phase distribution of the MODAN metasurface. The phase map was computed by adding the phase of the Hermite-Gaussian mode profiles to blazed gratings, each rotated by 2\(\pi/3\). For mathematical details, see Appendix A. To achieve the required phase distribution, the meta-atom is designed based on the concept of a geometric Pancharatnam-Berry phase [30]. As shown in Fig. 2, the meta-atom has a Au nanorod/SiO\(_2\)/Au mirror trilayer configuration. The width, length, and height of the gold nanorod is 80, 210, and 30 nm, respectively. The thickness of the SiO\(_2\) spacer and gold reflector layer are 90 and 150 nm, respectively. Under the incidence of left or right circularly polarized (LCP/RCP, \(\sigma = \pm 1\)) light, the reflected light with opposite handedness (RCP/LCP) can be obtained by choosing the anisotropic meta-atom with appropriate geometrical parameters. By rotating the fast axis of the gold nanorod, the geometric phase experienced by the reflected light with the RCP/LCP polarization state can be described by \(\phi = 2\sigma \theta\), where \(\theta\) is the rotation angle.
where θ represents the in-plane orientation angle of the gold nanorod. It is found that φ can be continuously tuned from 0 to 2π. The period of the meta-atom is 360 nm. The tri-layer metasurface, which is shown by the scanning electron microscope image in Fig. 2, was fabricated by using the electron beam lithography and metal lift-off processes. The optical properties of a metasurface unit cell are calculated by using the commercial finite-difference time-domain (FDTD) software (Lumerical FDTD Solutions). As shown in Fig. 2, the cross-polarization conversion efficiency at a wavelength of 1064 nm reaches over 80% under the incidence of left circularly polarized light, which indicates the high optical efficiency of the trilayer metasurface device.

III. CALIBRATION AND VALIDATION

To validate our sensor, we first prepared a clean beam by polarizing and spatially and spectrally filtering the laser light through a rigid triangular mode cleaner cavity [31,32] as illustrated in Fig. 3(a). The metasurface and photodiodes were calibrated by injecting a small amount of HG10 at 318 mHz, realized by an angular modulation of steering mirror M1. This technique works as a shifted HG00 can be described as an addition of the HG10 mode. The modulated light was split with one branch going to a witness QPD, which required a 1.2-mm waist radius beam. The second branch was directed towards the metasurface, which required a 55-μm waist radius of elliptically polarized light. The amount of HG10 does not change on propagation, however, the QPD is only sensitive to the real component of the HG10. Therefore, Gouy phase information was required to convert the QPD signal into mode weight. Additionally, the origin of the coordinate system for the QPD and the metasurface did not coincide at the part-per-million (ppm) level. Since the QPD measures a mode amplitude rather than the power, this could be accounted for by a small offset during signal processing. MODAN channels A and C were used to compute the MODAN mode weight. Due to the exceptional metasurface resolution in nanoscale size, cross coupling was substantially suppressed. However, at the ppm mode weighting which we present in this paper, a residual leakage still occurred from the TEM00 mode. As a result, we subtracted some of the dc leakage from our results during analog signal processing, and the remaining offset was computed and subtracted in digital postprocessing. See Appendix B for more details on the calibration. After calibration, we recorded 150 s of data respectively and compared their performances. We found the coherence between the two devices was good, as shown in Fig. 3(b). However, noise in the power supply caused the offset to drift slightly during the measurement, leading to increased measurement uncertainty at low frequencies.

IV. SPECTRAL NOISE ESTIMATE

One powerful way of understanding these noises is the amplitude spectral density (ASD) plot, shown in Fig. 4. This shows the noise in the HG10 mode-weight measurement by the MODAN and the QPD respectively, as a function of frequency, thus indicating what minimum mode weight is measurable with an appropriate bank of electronic filters. The noise on an arbitrary duration measurement is given by the integral of this curve, over the frequencies of interest.
The MODAN signal and QPD signal were measured simultaneously using the calibration described for Fig. 3(b). With no laser illumination, the dark noise gives the total noise floor of the MODAN photodiodes, signal processing, and digitizer electronics.

At high frequency, we see that the metasurface-based sensor outperforms the QPD, achieving a sensitivity of $6 \times 10^{-7}/\sqrt{\text{Hz}}$ at 80 Hz. Another way of writing this is that the mode-weight fluctuation at 80 Hz can be measured down to 0.6 ppm with a signal-to-noise ratio of 1 and 1 s averaging. At these high frequencies, the measurement is limited by a white electronic noise. We expect that the photodiode’s self-noise (shown in orange) 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 digitizer antialiasing filter.

At lower frequencies, the measurement is limited by an optical effect. We expect that this noise is residual beam drift, possibly caused by seismic, thermal, and air pressure fluctuations causing an apparent motion of the lens, with respect to the beam axis defined by the metasurface and aperture. This effect shifts the center of the beam away from the aperture, thus increasing cross coupling. This means that over long timescales ($t > 100$ s) the rms error is $<500$ ppm with no averaging, and adding 100 s of averaging reduces this to $<200$ ppm.

V. CONCLUSIONS

In this paper, we demonstrate a metasurface enhancement to correlation filter mode decomposition. This enhancement permits 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, submicron pixels enable a reduction in unused diffraction orders, improving power efficiency, thus reducing the shot noise and increasing the available spatial multiplexing. Therefore the signal-to-dark-noise ratio is increased. In contrast to QPDs and bullseye photodetectors, correlation filters can be trivially engineered for the measurement of an arbitrary mode pattern [11]. However, due to power conservation, the simultaneous interrogation of multiple modes reduces the power on each branch, thus decreasing the signal-to-noise ratio.

Applications requiring high-frequency mode decomposition, such as mode-division multiplexing and characterization of single-mode fibers, may reduce crosstalk using the metasurface enhancement. These systems are likely to be limited by electronic noise in the photodiode. An improved photodiode may permit shot-noise-limited sensitivity.

Applications requiring a low-frequency mode analysis, such as the correction of thermally induced mode mismatches in high-power systems, will need to carefully consider the low frequency of the stability of the phase plate, lens, photodiode, 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 combine the advantages of metasurfaces with adaptive optics, in the context of mode decomposition.

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A.J., A.F., and M.W. designed the study and developed the phase pattern; X.Z. and S.Ch. developed and fabricated the metasurface surface, and A.I. the design, assembly, and operation of the optical testing apparatus; A.I. and C.M. designed the analog signal processing and data analysis; S.Co. developed, built, and operated the digital acquisition; A.J., C.M., and M.W. drafted the manuscript.

APPENDIX A: DETERMINATION OF PHASE PATTERN

The phase map was computed from the Hermite-Gaussian amplitude functions $u(x, y, z)_{n,m}$ and blazed gratings. The equation for the blazed grating is

$$B(x, y)_{n,m} = \frac{2\pi}{\Lambda} \left[ \cos(\gamma_{n,m}x + \sin(\gamma_{n,m})y) \right],$$  \hspace{1cm} (A1)

where $\gamma_{n,m}$ is the rotation angle for this branch and $\Lambda$ is the grating period. The complete phase map is then given by

$$P_c(x, y) = \pi \arg \left[ \sum_{n,m} \exp \left( i \left\{ \arg(u_{n,m}(x, y)_{|z=0}) + B(x, y) \right\} \right) \right],$$  \hspace{1cm} (A2)

where the mode function is evaluated at the waist position, $z = z_0$. In this work, $\gamma_{0,0} = 0$ $\gamma_{1,1} = \frac{2\pi}{\Lambda}$, $\gamma_{0,1} = \frac{4\pi}{\Lambda}$.

APPENDIX B: CALIBRATION PROCEDURE FOR METAPHASE PLATE

The measurement of modal weight presented in the main text uses a photodiode to determine the amount of optical power in a small region close to the axis of propagation. This photodiode outputs a current, which is proportional to the optical power illuminating the diode. This current must be amplified, converted into a voltage, filtered, digitized, and analyzed spectrally to produce the data we present. These steps must be carefully understood to convert the resulting digital data back into a meaningful mode weight. We refer to this process as sensor calibration.

A detailed calibration procedure, from first principles, with a different modulation frequency (20 Hz) and different digitizer, can be found in Ref. [13]. In this, Jones demonstrates that the calibration obtained from first principles and the calibration against the witness QPD are consistent. However, during such a calibration errors on the photodiode aperture and electrical gains dominate the uncertainty on the calibration. For this reason, we opted to calibrate against the witness sensor.

Contrary to the experimental description in Ref. [13], for this work we used a clone of the LIGO CDS system [29] to simultaneously record several data channels from the experiment. With this system, all data were gathered at the
same clock rate, simplifying the analysis and allowing witness channels for diagnostics. The CDS system itself had been precalibrated to output four voltages of interest; the difference in the left and right halves of the QPD, $V_{dx}$, the total power on the QPD, $V_{SUM}$, and the voltage output by the MODAN photodiodes, $V_{10}$ and $V_{00}$.

These data were taken in three conditions: *modulated*, where the alignment of the input beam was modulated at 318 mHz, denoted by superscript $M$; *unmodulated*, where the beam was still side from beam jitter, denoted by superscript UM; and *dark* where the laser was switched off, but all other electronics was active, denoted by superscript $D$. The dark data were used to compute electrical offsets and noise levels. The modulated QPD data were used to produce a calibration factor for the MODAN. Finally, we use this calibration factor to produce the unmodulated MODAN data.

1. Removal of offsets

The photodiode and amplification stages contain some small voltage offsets. These offsets could trivially be calculated for the HG10 and HG00 channels from the average value of the dark noise,

$$O_{PD} = \frac{\sum_{i=0}^{N^D} V_{PD}^{i}}{N^D},$$

where $N^D$ is the number of elements in the dark data trace and $PD = \{01, 00\}$.

2. Mode power to mode weight

The MODAN photodiodes produce a current which is proportional to mode power. In this case, we remove power fluctuations and present a mode weight. Since the modulation is small, we can approximate that the power on the HG00 sensor depends only on laser power. Therefore, the mode HG10 mode weight measured by the MODAN is

$$\rho_{10}^{MD} = C_{calib.} \frac{V_{10} - O_{10}}{V_{00} - O_{00}},$$

where $C_{calib.}$ is the calibration factor we need to compute.

3. Calibration

As shown in Sec. 4.3.2 of Ref. [13], the HG10 mode amplitude is given by

$$a_{10}^{QPD,M} = \frac{V_{M}}{V_{SUM}} \frac{\pi}{2\sqrt{2} \cos(\alpha)}$$

where $40^\circ$ degrees is the Gouy phase difference between the point of angular actuation and the QPD. Comparing the above two equations, $C_{calib.}$ is then

$$\frac{1}{C_{calib.}} \bigg( a_{10}^{QPD,M} - \Delta a \bigg)^2 \Rightarrow \frac{V_{M}^{10} - O_{10}}{V_{M}^{00} - O_{00}},$$

where $\Delta a$ is a dc alignment offset between the sensors in units of mode amplitude.


