# Interferometric Transmission Probing with Coded Mutual Intensity: Supplementary Material

ALANKAR KOTWAL, Carnegie Mellon University
ANAT LEVIN, Technion
IOANNIS GKIOULEKAS, Carnegie Mellon University

In this supplement, we provide additional details about the physical prototype we use to implement interferometry with coded mutual intensity.

CCS Concepts: • **Computing methodologies → Computational photography**.

Additional Key Words and Phrases: spatial coherence, mutual intensity, interferometry, light transport matrix, transmission matrix

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## 1 ACQUISITION SETUP

We discuss the engineering details of the setup implementing interferometry with coded mutual intensity. The schematic and a picture of the setup are shown in Figure 4 of the main paper.

*Light source.* We use two types of sources, for temporally coherent and temporally incoherent probing respectively. The first source is a single-frequency green (532 nm) polarized laser from Lasos that outputs a power of 52 mW. This laser has a very small beam diameter (approximately 0.7 mm), requiring that we use of a 5× beam expander to increase the diameter of the beam. The laser is rated to have a coherence length of the order of several meters with a relatively flat temporal coherence function.

The second source is a temporally incoherent supercontinuum laser, *SuperK* from NKT Photonics. The spectrum of this laser ranges from 390 nm to 2400 nm, therefore requiring a spectral filter for a feasible coherence length. We use a 1 nm spectral filter with a central wavelength of 532 nm to reduce the bandwidth of the output light.

*Electro-optic modulator.* We use an electro-optic modulator to perform amplitude modulation of the beam coming out of the laser. We take advantage of the fact that the beam is thin to pass it through the narrow (2 mm) EOM aperture to pass the beam through. The EOM requires an amplifier converting DC signals of 10 V into DC signals of 200 V. The EOM rotates the polarization of the light according to the signal that is applied to it, and requires the input light to be polarized, and a polarizer on its output. The temporally coherent laser is already polarized, but in the case of the supercontinuum laser, a polarizer needs to be placed after the EOM. We use a Glan Thompson polarizer on the far end of the EOM and a photographic polarizer in front of the laser if necessary.

*Mechanism for spatial incoherence.* We use two fast-rotating mirrors to scan the laser beam in a square angle at kHz frequencies to create spatial incoherence. An intermediate lens (a 35 mm Nikon prime lens) then maps angle into spatial position behind the illumination lens, creating the 'source'. A beam expander is placed before this entire configuration to expand the very thin beams that the lasers emit, in order to ensure that our final beam covers our field of view of 1 inch. The mirrors are operated by a function generator generating sinusoids at kHz frequency with a slight offset to create a dense Lissajous curve that spans a square. Controlling the size of the source is easy and lossless because that translates to decreasing the amplitude of one of the channels.

*Illumination lens.* We use a 200 mm Nikon prime lens to collimate light from the above 'source' for its superior performance over off-the-shelf AR-coated achromatic doublets in terms of spherical and chromatic aberration, improving light efficiency and collimation. The output of the scene is cropped to a 1 inch circular beam and is passed through the beamsplitter cube apertures.

*Interreflections.* Interreflections are especially problematic in the case of temporally coherent light because they introduce strong secondary fringes. For example, light paths passing through a beamsplitter, and those reflected twice inside the beamsplitter also passing through cause strong fringes because of spatial coherence. Such strong fringes in the scene-only and reference-only images essentially nullify our contrast. In the case of temporally incoherent light, this effect is not as severe, because these paths typically have different path lengths and thus do not interfere. We found that deliberately misaligning optics by a small amount (sub-degree) mitigates these effects.

*Beamsplitters.* We use thin plate 50:50 beamsplitters in all three locations needing beam splitting in our setup. We experimented with pellicle beamsplitters and they introduced strong fringes in the case of coherent light, which reduced our contrast. We did not use cube beamsplitters due to interreflections and the disadvantages discussed above. As above, we deliberately misaligned optics to avoid interreflection artifacts.

We found that in the long path lengths taken by light in our setup, the rough alignment provided by the approximate rigid positioning of the beamsplitters in standard cube mounts is insufficient to get

Authors' addresses: Alankar Kotwal, Carnegie Mellon University; Anat Levin, Technion; Ioannis Gkioulekas, Carnegie Mellon University.


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light through the system and into the camera. Therefore, we used cube mounts that provide control over three degrees-of-freedom of the beamsplitter pose, in order to accuarately set light paths.

*Mirrors.* We use high-quality mirrors of guaranteed $\lambda/4$ flatness when we do not need phase modulation on the reference arm. In the case of visualizing coherent probing patterns, we use a monolithic hollow mirror retroreflector (three mirrors forming a cubic corner). To create the mirror-diffuser corner in one of the examples, we use a hollow roof mirror and paste a diffuse flat spectral response paper on one of its sides.

*Translation stage.* We use a translation stage from Newport with an accuracy of upto 10 nm and low-noise operation. Vibrations affect interference contrast, which is why low noise operation is important.

*Spatial light modulator lens.* To match the lens and magnification of the source on the illumination side, we use another 200 mm Nikon prime lens in front of the phase spatial light modulator.

*Phase spatial light modulator.* To code the reference beam's phase response, we use a phase spatial light modulator placed in the Fourier plane of the 200 mm Nikon prime lens. The phase spatial light modulator works on the principle of rotating LCD crystals to create a small phase shift on the signal applied to it. However, the input light needs to be polarized in a fixed direction with respect to the SLM to achieve pure phase modulation: we ensure this is the case by setting the polarizer in front of the supercontinuum laser or the orientation of the temporally coherent laser to match the required direction of polarization. For the temporally incoherent case, the entire phase SLM and lens system are placed on the translation stage.

*Camera lens.* Our scenes are sized at the order of 1 inch. Therefore, we benefit from a lens that achieves high magnifications (1:1). This also allows for better contrast due to lower averaging of speckle (interference signal is convolved with the pixel box when captured with the camera. We use a 180 mm Canon prime macro lens in front of the camera.)

*Camera.* We use a machine vision camera from AVT with a high sensitivity CCD sensor of resolution 8 MP, pixel size 3.5 µm, and a pixel pitch of 4 µm. Small pixel pitch, along with pixel size, increase the interference contrast because we average interference speckle over a smaller area.

*Color filters.* We use a 532±0.2 nm laser line-coated bandpass filter with 1 nm bandwidth and <0.01% transmission outside this range, to limit the bandwidth of the supercontinuum laser.

*Neutral density filters.* We use absorptive neutral density filters to make the intensities of both arms of the interferometer equal. Matching the brightness leads to an acquisition with optimal interference contrast.

*Mechanism for inverting the flip due to the lens-and-SLM system.* Coding the source with a lens and a phase spatial light modulator behaves as a retroreflector and not a mirror; the flip caused by this arrangement needs to be inverted. We achieve this is to get the reference arm light out of the main beam before the main beamsplitter, have it go inside the phase SLM system and then place a 4f system to flip the beam around before it going to the camera. This motivates the design of the setup in Figure 4 of the main paper.

*Alignment.* Due to the long paths that light takes in the setup and the small (1 inch) aperture, the optical setup requires very careful alignment that can often take hours. Therefore, as much as possible of the setup is built around a cage system that reduces alignment requirements. The optical configuration required to invert the flip, along with the main beamsplitter, can be mounted on a rectangular cage system and clamped down to the optical table for rigidity. The lenses (with the exception of the camera lens) are screwed into the apertures of the cage system with height-adjustable posts below them, and their heights are adjusted to ensure a smooth fit of the lenses in the aperture. Both the lasers are mounted so as to make their beams as parallel to one of the axes of the optical table as possible. The steering mirrors are aligned to make sure the beam at its zero position passes through the center of the beamsplitter box mounts. The beamsplitters are then aligned using a modified version of the alignment technique described by Gkioulekas et al. [2015].

*Vibrations.* The acquisition time of our temporally coherent system is small, because we need to capture either only a single shot or a few subwavelength shifts. Because of the high power of the laser, we need to expose the camera only for a few milliseconds, and therefore vibrations do not strongly affect our measurements. However, when we combine our system with temporally incoherent light (OCT), the inclusion of the polarizer and spectral filter results in reduced power. Combined with the need to perform a mechanical scan, the acquisition time becomes very long. As a result, in this case, vibrations become problematic, and we need to use a vibration-isolated optical table to conduct our experiments.

*Component list.* For easy reproducibility of the setup, we provide in Table 1 a list of the key components used in our implementation. We do not list standard parts used for mounting and positioning, commonly-available in optical labs.

## REFERENCES

Ioannis Gkioulekas, Anat Levin, Frédo Durand, and Todd Zickler. 2015. Micron-scale light transport decomposition using interferometry. *ACM TOG* (2015).

| description | quantity | model name | company |
|---|---|---|---|
| 8 MP CCD color camera with Birger EF mount | 1 | PRO-GT3400-09 | Allied Vision Technologies |
| 180 mm compound lens | 1 | EF 180mm f/3.5L Macro USM | Canon |
| 1 inch laser line bandpass filter, 532 ± 0.2 nm CWL, 1 nm BW | 1 | FL532-1 | Thorlabs |
| 25 mm × 36 mm plate beamsplitter | 3 | BSW10R | Thorlabs |
| motorized filter wheel | 1 | 84-889 | Edmund Optics |
| 1 inch round protected Aluminum mirror | 3 | ME1-G01 | Thorlabs |
| single-frequency laser, 532 nm CWL, 52 mW power | 1 | unknown | Lasos |
| broadband hollow retroreflector | 1 | UBBR2.5-1UV | Newport Corporation |
| ethernet driver for linear stage | 1 | XPS-Q2 | Newport Corporation |
| large tilt and rotation platform | 2 | 37 | Newport Corporation |
| ultra-precision linear motor stage, 16 cm travel | 1 | XMS160 | Newport Corporation |
| 200 mm compound lens | 2 | AF Micro Nikkor 200mm 1:4 D IF-ED | Nikon |
| phase spatial light modulator | 1 | Pluto | Holoeye |
| electro-optic modulator | 1 | EO-AM-NR-C4 | Thorlabs |
| Glan Thompson coated calcite polarizer | 1 | GTH5-A | Thorlabs |
| function generator | 2 | SDG1025 | Siglent |
| 2 inch absorptive neutral density filter kit | 1 | NEK01S | Thorlabs |

Table 1. List of major components used in the optical setup of Figure 4 of the main paper.