A Two-Photon Shack-Hartmann Wavefront Sensor for The Near-Infrared Wavelength

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Abstract: We present a novel wavefront sensing scheme based on two-photon absorption in a conventional silicon camera for measuring aberrations of pulsed laser beams in the near-infrared wavelengths up to 2.0 μm.

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1. Introduction

Wavefront sensing is an important technique in beam characterization and adaptive optics (AO). In a common AO system, optical aberrations are measured by wavefront sensors and compensated actively by modulating devices such as deformable mirrors [1]. One of the most common instruments for measuring optical aberrations is the Shack-Hartmann wavefront sensor (SHWS) [2], where the local tilts of the wavefront are transformed by a lenslet array into a spot matrix on a detection camera and the tilts can be calculated from the deviation of the spots from their original position. An approximated wavefront can be reconstructed based on the sampling of the entire local tilts. The response spectrum of SHWS is largely determined by the material of the camera. Currently, the most common commercially available SHWS is silicon-based, i.e., it responds only to up to ~1.1 μm limited by the band gap of the silicon.

When working at wavelengths where array detectors are rare or very expensive, however, it becomes hard and costly to implement wavefront sensing using SHWS with the desired detector materials. At wavelengths in the near-infrared (NIR) region, commercial solutions based on either phosphorus up-conversion [3], or InGaAs camera [4] are both more expensive, and they cover only a small portion of the NIR spectrum. It is possible to use a mercury cadmium telluride (MCT) camera [5] as the detector for the wavefront sensor, which can cover a wider band, but again the cost is high due to the custom solution. Here, we propose a two-photon SHWS (2P-SHWS) that extends the working spectrum of the conventional SHWS from the visible range to the NIR. Our solution is based on two-photon absorption (TPA) in the silicon, and uses the fact that silicon-based camera can detect pulsed lasers even if the wavelength of the laser exceeds the linear spectral detection range of the material. In this way, by using a silicon based SHWS, it is possible to detect phases of pulsed laser beam up to ~ 2.1 μm with an off–the-shelf and cheap product.

2. Longer wavelength generation and wavefront detection

To demonstrate the wavefront sensing in the NIR, we first generated ultrashort pulses at longer wavelengths by delivering 380-fs, 4MHz pulses at 1550 nm from a commercial fiber laser (CAZADERO fiber laser, Calmar laser, Inc.) into a polarization-maintaining large mode area (LMA) photonic crystal fiber (LMA-25, NKT Photonics) with a mode-field diameter of ~21 μm. A half-wave plate is used to adjust the polarization of the input beam with the LMA fiber. Due to soliton self-frequency shift (SSFS) in the LMA fiber, the soliton continuously transfers energy from shorter wavelengths to longer wavelengths via intrapulse stimulated Raman scattering. The longest soliton wavelength depends on the input power, and it can be tuned from 1.58 μm to 2 μm. The input beam is coupled into the fiber by a C-coated lens with a focal length of 45 mm (Lens 1 in Fig. 1). The output light is collimated by a D-coated lens with a focal length of 50 mm (Lens 2 in Fig. 1). A long-pass filter (1720 LP, Omega Optical) and a bandpass filter (FB1750-500, Thorlabs) were used to select the most redshifted soliton centered at 1.75 μm. For selecting solitons centered at 2 μm, a long-pass filter (1950 LP, Omega Optical) and a bandpass filter (FB2000-500, Thorlabs) were used. To demonstrate the concept of 2P-SHWS, we used an off-the-shelf wavefront sensor (WFS150-7AR, Thorlabs) which consists a Si-CCD camera with ½" detector (pixel size of 4.65 μm×4.65 μm) and a

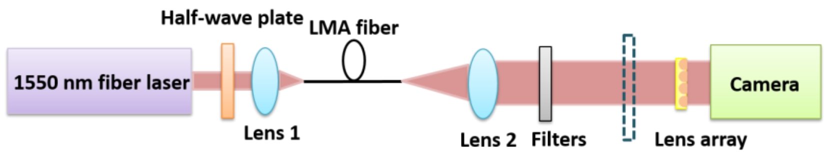

Figure 1. Schematic diagram for generating longer wavelengths for two-photon Shack-Hartmann wavefront sensor demonstration.

39×31 microlens array with an effective focal length of 5.2 mm and lenslet pitch of 150 μm. The responsivity of silicon limits the linear spectral response of the CCD camera, as shown in Fig. 2(a). We selected three wavelengths in NIR: 1.55 μm, 1.75 μm and 2 μm to measure the wavefront sensing performance, particularly, two of the wavelengths are outside the linear detection range of InGaAs camera (which is typically limited to 1.7 μm). The second-order interferometric autocorrelation traces for 1.55 μm, 1.75 μm and 2 μm are shown in Fig. 2 (b-d). We used the illumination source operated at three different NIR wavelengths with several cylindrical lenses for wavefront manipulation, as shown in Fig. 2 (e-m). The results Fig. 2 (k-m) match with the expected wavefront curvature which corresponds to a focal length ~ 200 mm. The minimal powers for each lenslet to obtain a stable tilt measured is also determined: 6.4 μW at 1.55 μm, 2.3 μW at 1.75 μm and 8.3 μW at 2 μm. These powers were measured under the setting with 56 ms exposure time, 5× gain and 100 frames average. Since the evaluation of the wavefront relies on geometrical calculation, the results are completely independent to the order of the detection process, which means that the same image processing and calibration used for linear detection can be used in 2P-SHWS without any need for special adjustments.

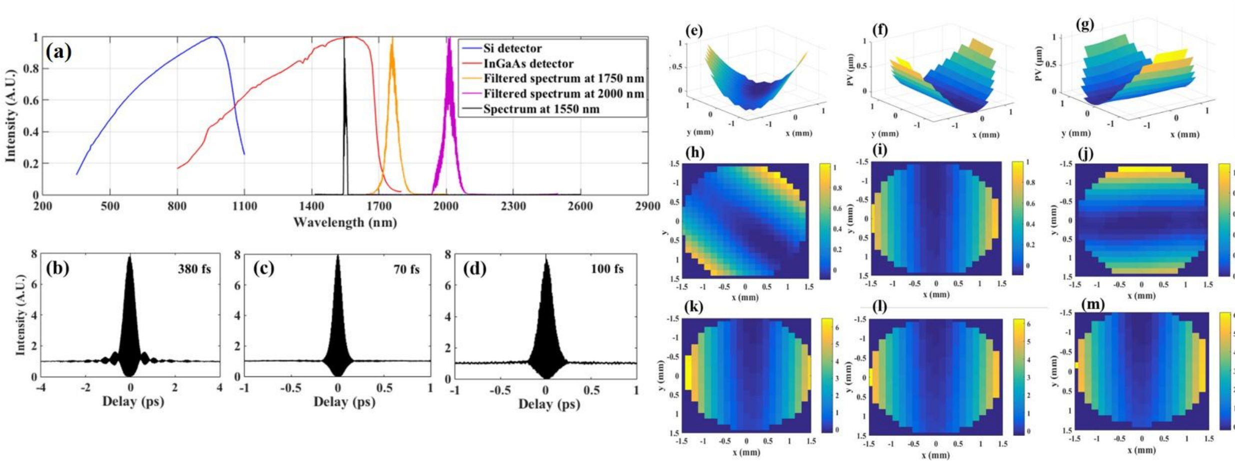

Figure 2. (a) Spectral response of the silicon-based detector (blue) and InGaAs detector (red), referred source: Thorlabs. Measured spectra of the fiber laser at 1.55 μm (black), the most redshifted soliton at 1.75 μm (orange) and 2 μm (purple) in large mode area photonic crystal fiber. The two-photon SHWS is demonstrated at 1.55 μm (black), 1.75 μm (orange) and 2 μm (purple). (b-d) Measured interferometric autocorrelation traces of the pulse from fiber laser at (b) 1.55 μm and the most redshifted solitons at (c) 1.75 μm and at (d) 2 μm. A deconvolution factor of 1.54 for sech function was used to obtain the indicated pulse durations. (e-m) Measured wavefronts of a 1000 mm-focal-length cylindrical lens at 2 μm in different orientations (e, h) 45 degrees; (f, i) 0 degree; (g, j) 90 degrees. PV: peak-to-valley value. Measured wavefronts are also demonstrated in both 3D (e-g) and 2D (h-j). Measured wavefront of a 200 mm-focal-length cylindrical lens at different wavelengths (k) 1.55 μm, (l) 1.75 μm and (m) 2 μm.

3. Conclusions and discussions

Although in this work we concentrated on the usage of an off-the-shelf product to exploit the TPA effect, a few modifications can easily be done to improve TPA signal, allowing the measurement of longer pulses width and lower power levels. For example, we can use thick enough silicon detector array, together with high NA lenslet array to maximize the signal of such 2P-SHWS. As the optical coating of the lenslet array was not optimized to the NIR wavelength, optimization of the optical coating is also desired.

The usage of a commercially available and cheap silicon-based camera as the detector of the wavefront sensor for wavelengths where there are no available array detectors can be valuable for many researchers. This concept is not limited just for NIR lasers, and can be used in the same way for longer wavelength wavefront detection such as measuring up to 3.4 μm mid-infrared laser sources with TPA in InGaAs based SHWS. 2P-SHWS effectively doubles the spectral range of a conventional SHWS when measuring the wavefront of a short pulse laser.

4. References

[1] R. K. Tyson, *Principles of Adaptive Optics* (CRC Press, 2011), pp. 111.
[2] B. C. Platt, and R. Shack. "History and principles of Shack-Hartmann wavefront sensing." Journal of Refractive Surgery **17**, 573-577 (2001).
[3] R.J. Meier, et al. "Background-free referenced luminescence sensing and imaging of pH using upconverting phosphors and color camera read-out." Analytical Chemistry **86**, 5535-5540 (2014).
[4] T. Martin, et al. "640x512 InGaAs focal plane array camera for visible and SWIR imaging." In Defense and Security, International Society for Optics and Photonics, 2005.
[5] P. Feautrier, and J.L. Gach. "State of the art IR cameras for wavefront sensing using e-APD MCT arrays." In Adaptive Optics for Extremely Large Telescopes 4–Conference Proceedings, **1**, 2015.