Spectral Phase and Amplitude Retrieval and Compensation for Random Access Microscopy

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Abstract: Programmable, two-dimensional, spatial frequency modulation linear and non-linear imaging combined with a novel and remarkably simple, in-situ quantitative pulse compensation and measurement scheme is demonstrated for the first time.

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1. Introduction

Multifocal multiphoton microscopy (MPM) [1] makes efficient use of the multiwatt average powers available from femtosecond oscillators to produce high quality images at impressive frame rates (e.g. $\geq$ 30Hz). While the gain in image acquisition speed is substantial, it comes at a cost. Many of these systems must be used in conjunction with a 2D detector such as a CCD. Here, we use a spatial light modulator (SLM) to generate multiple foci along a line that passes through a SPatIal Frequency Modulation for Imaging (SPIFI) mask, [2] which renders the multifocal platform fully compatible with single element detection. SPIFI-MPM sweeps an amplitude modulation across the excitation source and maps a characteristic temporal frequency to each spatially distinct coordinate of the image plane, according to a designated linear modulation function. The image data is recovered by computing the power-frequency spectrum from the signal light; the frequency indicates a particular pixel position, while the magnitude is the shade of the pixel value. [2] In systems where photon economics play a vital role like SPIFI-MPM, efficiently reaching peak intensity is essential and requires a compressed pulse at the specimen. Furthermore, detailed knowledge of the pulse electric field is important in systems where material properties are of interest. To this end, we also introduce a novel pulse characterization technique called Spectral phase and amplitude reconstruction and compensation (SPARC). SPARC is similar to both FROG [3] and MIIPS [4] but has advantages compared to both, e.g. SPARC is the *only* self-referenced pulse measurement technique that links the pulse reconstruction to a physical quantity.

2. Frequency Multiplexing for Random Access Imaging

A series of measurements below demonstrates the capabilities of the method by comparison to analogous point-scan images. A pink auto-fluorescent microscope slide (Chroma p/n 92001), which emits two-photon excitation fluorescence (TPEF) signal within 600-700 nm, was laser-etched to have a series of vertical grooves across its width. A cosine mask was written to the SLM to create a 3-foci excitation geometry. The rotation mask spins and gives each foci a distinct temporal frequency, and subsequent signal detected with a PMT. This enabled simultaneous detection of the three images in Figure 1.c)

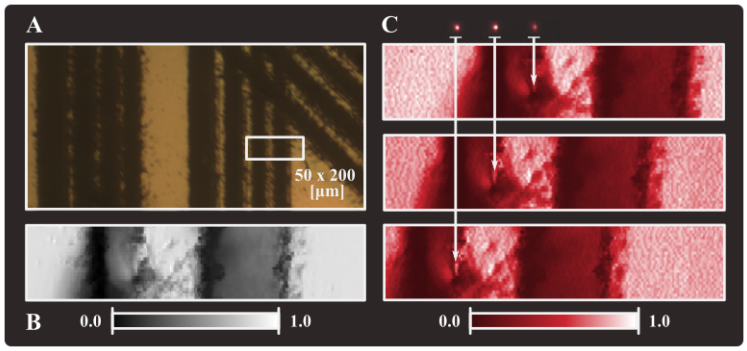

Fig. 1. Comparison of SPIFI and point scan A) white light image showing relative position of the etched features across a chromaslide, B) single point-scan TPEF image and C) TPEF images from the three foci collected simultaneously, and using the same set-up (for the point-scan the SLM is powered off and the mask removed) for a comparison between the techniques.

3. Spectral Phase and Amplitude Reconstruction and Compensation (SPARC)

While similar to MIIPS, where scanning a phase-only function locally cancels group-delay revealing overall spectral-phase, SPARC scans an ***amplitude*** function (i.e. a slit) inside a zero-dispersion stretcher. The slit in SPARC is a gate, like in FROG, but here the gating is in the spectral not the time domain. In Fig. 2 (I) reconstructed spectral amplitudes from FROG and SPARC are plotted along with the measured amplitude. In Fig. 2 (II), we used SPARC to remove excess chirp on the input pulse so the retrieved pulse from FROG and SPARC are plotted along with the transform limited pulse from FROG, showing good agreement. Fig. 2 (a-d) show a

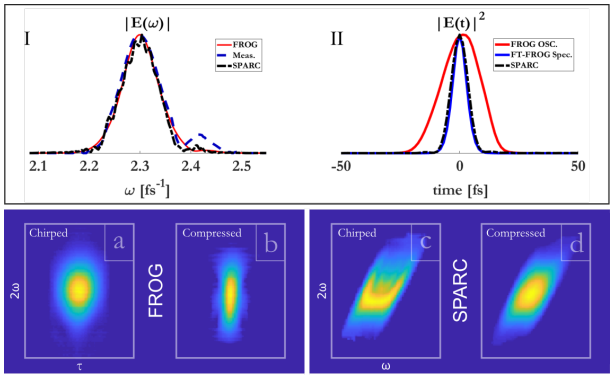

Fig. 2. (I) Spectral amplitudes reconstructed with FROG and SPARC plotted along with the measured spectrum. (II) Pulse intensity profiles reconstructed with FROG and SPARC plotted along with transform limited FROG spectrum. (bottom) (a) FROG trace taken directly at the output of an oscillator showing chirp. (b) FROG spectrogram taken at the output of the SPARC system showing a 4^{th} order limited trace. (c) SPARC trace of a pulse chirped by adding 10 cm of BK7 glass to the path. (d) SPARC trace of the same pulse in (c) after compensation of 2^{nd} order phase.

chirped FROG trace, compressed FROG trace (taken after the SPARC apparatus), Chirped SPARC trace, and a compressed SPARC trace respectively for comparison .

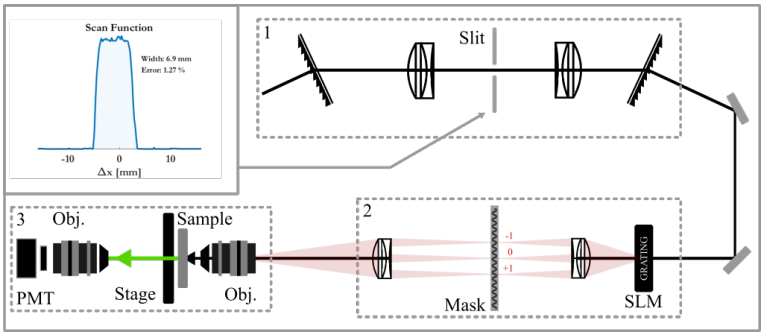

Fig. 3. SPARC reconstruction of the scanned slit showing percent error versus measurement with calipers. Schematic of the single-beam SPARC(1) + SPIFI-MPM(2/3) system. (Obj = objective lens)

For the first time, the combination of SPIFI-MPM with SPARC represents a new paradigm in nonlinear, single-element, multi-beam imaging; a system complete with a remarkably simple built-in pulse measurement and compensation system, that directly links the reconstructed field to a physical quantity i.e., the scanned slit.

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References

1. M.D. Young, J.J. Field, K.E. Sheetz, R.A. Bartels, J.A. Squier, Adv. Opt. Photonics vol. 7, pp. 276–378, (2015)
2. G. Futia, P. Schlup, D.G. Winters, R.A. Bartels, Opt. Express vol. 19, pp. 1626–1640 (2011)
3. D.J. Kane and R. Trebino, IEEE J. Quantum Electron., vol. 29, no. 2, pp. 571–579, (1993)
4. V. V. Lozovoy, I. Pastirk, and M. Dantus, Opt. lett., vol. 29, no. 7. pp. 775–777 (2004)