# Towards Synthetic Light-in-Flight

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**Abstract:** We present a method for the computational synthesis of a shaped, synthetic light pulse from interferometric measurements under CW illumination. The pulse can be manipulated to travel through a captured scene, demonstrating synthetic light-in-flight videos.

## 1. Introduction

Beginning in the 1970's, photographic methods were developed to capture representations of light as it propagates across a scene or through a (scattering) medium [1, 2]. Now known as light-in-flight (LiF), these techniques commonly rely on short light pulses, and/or high speed detector gating [3]. LiF imaging has found applications in the realms of metrology, medical imaging, laser pulse studies, and high speed image capturing [4, 5]. This paper introduces a method that allows for the computational synthesis of a synthetic light pulse traveling across a scene without the need of high-speed gating or pulsed lasers. The scene is illuminated with a tunable continuous wave (CW) laser at a multiple frequencies. Eventually, the phase and amplitude of each complex field $E(\lambda_n)$ at each wavelength is separately captured *in single-shot with an ordinary CMOS camera*, through our acquisition procedure introduced in [6]. Using the captured fields $E(\lambda_1),...,E(\lambda_N)$, different synthetic wave forms are created and manipulated computationally to form a shaped light pulse. We show the feasibility of our proposed method in simulation and real experiments.

## 2. Synthetic Wave Theory and Simulation

The goal of this project is the creation of a clearly defined virtual (synthetic) light pulse through the computational addition of optical fields at multiple frequencies. The basic idea is as follows: Combining two different optical fields $E(\lambda_1),E(\lambda_2)$ with slightly different wavelengths delivers a high frequency wave with a low frequency beat note (see Fig.1a). The wavelength of this beat wave can be described by the "synthetic wavelength" $\Lambda = \frac{\lambda_1\lambda_2}{\lambda_1-\lambda_2}$ [7, 8]. Depending on the selection (spacing) of $\lambda_1$ and $\lambda_2$, the computationally generated synthetic field is largely robust to the phase perturbations in an optical speckle field, and hence can be used for interferometric "ToF-measurements" of objects with rough surfaces [6, 8]. Moreover, we can generate periodic "synthetic pulses" by combining multiple fields $E(\lambda_n)$ of different wavelengths, as illustrated in Fig. 1a. The pulse distance is dictated by the smallest wavelength difference $\Delta\lambda_{min}$. As more fields are computationally added, the line width of the synthetic pulse decreases. For a first simulation of the basic concept, we computationally added $N = 21$ optical fields $E(\lambda_n) = A \cdot e^{i(2\pi x/\lambda_n - \omega_n t)}$ starting at $\lambda_1 = 854.2nm$, and raised in increments of $\Delta\lambda = 02.889pm$ until $\lambda_{21} = 854.2577nm$. After the computational superposition, the real part of the resulting field is used to simulate a synthetic light pulse reflected off a 3D model (see Fig. 1b). This synthetic pulse can be shaped through wave selection and advanced by adjusting the time value of the phase term. As time is incremented, the pulse travels across the 3D scene virtually "sectioning" the 3D model (see Fig. 1b).

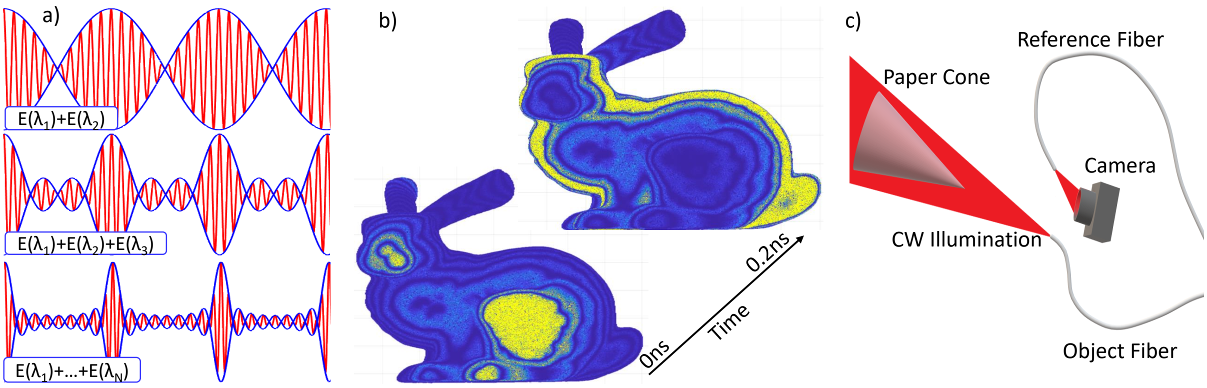


Fig. 1: a) Schematic: Real parts of synthetic fields created by addition of multiple optical fields $E(\lambda_n)$. b) Simulation: Synthetic pulse traveling across a 3D model c) Schematic of our experimental setup: A CW tunable laser illuminates a paper cone. The camera captures different optical fields $E(\lambda_n)$ via single-shot interferometry [6].

## 3. Real Experiment and Results

This section describes the application of our introduced method to a real-world experiment. The measured scene is comprised of a paper cone illuminated by a tunable CW laser. The selected wavelengths match the wavelengths used in the simulation above ( $N = 21$ different wavelength starting at $\lambda_1 = 854.2nm$, and raised in increments of $\Delta\lambda = 02.889pm$ until $\lambda_{21} = 854.2577nm$). For each wavelength $\lambda_n$, the optical field $E(\lambda_n)$ is interferometrically captured in single-shot with an ordinary CMOS camera (plus reference beam). We refer to [6] for details about the used "single-shot interferometry camera". Due to the optically rough surface of the cone, each captured optical field $E(\lambda_n)$ shows fully developed speckle (see Fig. 2a). The randomized phase $\phi(\lambda_n)$ makes it impossible to infer any ranging information. However, if multiple fields are combined, the microscopic path length variations in the speckle fields cancel each other out [7] and the macroscopic pathlength variations of the scene can be measured at the computationally generated synthetic wave/pulse. After capturing the different optical fields $E(\lambda_n)$, each field can be computationally manipulated. This means that the amplitude and phase of each field can be freely changed in the computer to generate different synthetic waveforms. For example, we compensate the drift of our laser in the shown experiment (Fig. 2) by computationally adjusting the phase of each optical field, i.e., by bringing all optical fields "in phase". Eventually, we let the resulting synthetic pulse advance through the scene by adjusting the time variable of the phase. The result is shown in Fig. 2b. It can be clearly seen that the synthetic pulse starts at the tip of the paper cone and travels towards its base. The full "synthetic light in flight video" can be found here.

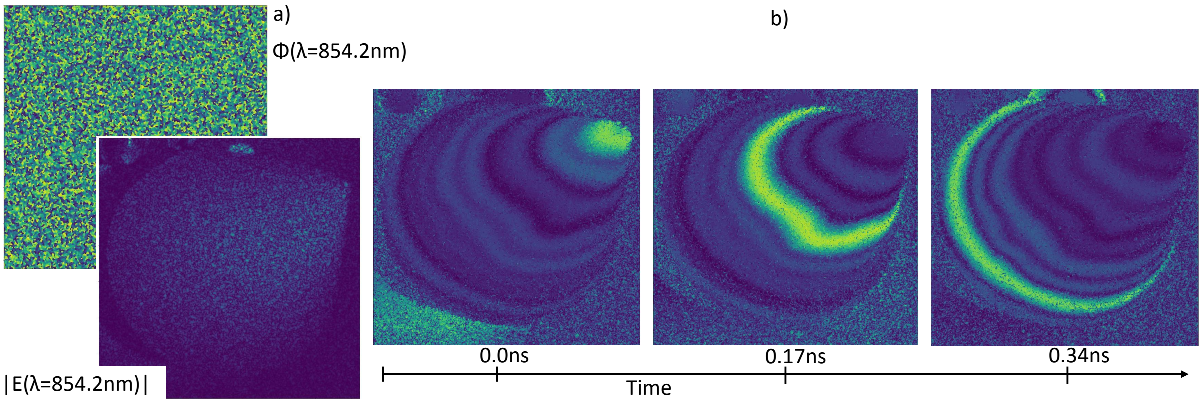


Fig. 2: Real world experiment (see Fig. 1c for setup description). a) Phase and amplitude of one single, captured optical (speckle) field ($\lambda = 854.2nm$). b) Synthetic pulse computed from $N = 21$ single optical speckle fields. The calculated intensity of the synthetic field is shown at three different time instances ($0ns$, $0.17ns$, $0.34ns$), while the synthetic pulse is advancing through the scene. Full video can be found here

## 4. Discussion and Outlook

We presented a method to computationally combine multiple optical fields at multiple optical wavelengths to form a synthetic pulse and perform "synthetic LiF measurements". Compared to hardware-based pulse measurements, our method does not require pulsed lasers or time-gated detectors. Moreover, we can computationally manipulate different quantities of our optical fields (such as phase and amplitude) *after* their acquisition. In the future, we plan to further explore this direction to produce different synthetic waveforms that can be tailored to different specific applications.

## References

1. N. Abramson, "Light-in-flight recording by holography," *Optics Letters*, vol. 3, p. 121, Oct. 1978.
2. G. Häusler, J. Herrmann, R. Kummer, and M. Lindner, "Observation of light propagation in volume scatterers with $10^{11}$-fold slow motion," *Optics Letters*, vol. 21, p. 1087, July 1996.
3. D. Faccio and A. Velten, "A trillion frames per second: The techniques and applications of light-in-flight photography," *Reports on Progress in Physics*, vol. 81, p. 105901, Oct. 2018.
4. T. Inoue, M. Sasaki, K. Nishio, T. Kubota, and Y. Awatsuji, "Analysis of the reconstructed images of light-in-flight recording by holographic microscopy when recording condition is changed," in *Frontiers in Optics + Laser Science 2021*, (Washington, DC), p. FW5B.3, Optica Publishing Group, 2021.
5. T. Kakue, T. Inoue, T. Shimobaba, T. Ito, and Y. Awatsuji, "FFT-based simulation of the hologram-recording process for light-in-flight recording by holography," *Journal of the Optical Society of America A*, vol. 39, p. A7, Feb. 2022.
6. M. Ballester, H. Wang, J. Li, O. Cossairt, and F. Willomitzer, "Single-shot tof sensing with sub-mm precision using conventional cmos sensors," *arXiv preprint arXiv:2212.00928*, 2022.
7. F. Willomitzer, P. V. Rangarajan, F. Li, M. M. Balaji, M. P. Christensen, and O. Cossairt, "Fast non-line-of-sight imaging with high-resolution and wide field of view using synthetic wavelength holography," *Nature Communications*, vol. 12, p. 6647, Nov. 2021.
8. F. Willomitzer, "Synthetic wavelength imaging – utilizing spectral correlations for high-precision time-of-flight sensing," 2022. arXiv preprint arXiv:2209.04941.