Dual-comb digital holography with high spectral resolution

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Abstract: The many evenly-spaced lines of a frequency comb are harnessed for a new approach digital holography, using dual-comb interferometry. A "movie" of recorded holograms enables 3-dimensional hyperspectral imaging with high spatial and spectral resolution.

Introduction

Digital holography emerges as a powerful tool with applications ranging from the measurement of the three-dimensional morphology and shape of macro- and micro-samples to augmented-reality/virtual-reality display technologies. Here we demonstrate a new technique of digital holography based on a hyperspectral dual-comb imager. We explore the potential of our technique for volume metrology.

Experimental set-up and results

The principle of our experiment of inline transmission holography is sketched in Fig. 1. A frequency-comb, generated with an electro-optic intensity modulator, passes through an absorbing sample (Fig.1). It is then transmitted through and scattered by an object which has a three-dimensional structure. The scattered light is combined on a beam-splitter with that of a reference comb generator. The time-domain interference pattern is recorded for each pixel of a camera. In detail, in our set-up, a continuous-wave laser emitting at 195.73 THz is split into two beams. Each beam passes through an acousto-optic frequency shifter and the difference in frequency shifts is 80 Hz. Each beam is then modulated by an intensity modulator, so that two trains of 50-ps pulses are generated at repetition frequencies of 500 MHz and 500 MHz + 2 Hz, respectively. Each comb has about 50 individual lines. The absorbing sample is ammonia vapor provided in an 80-cm-long box with ammonia water in the bottom and holes for letting the beam in and out. The object is a positive 1951 USAF resolution test target. The InGaAs camera has 320x256 pixels and a frame rate of 320 Hz. The slow frame rate of the camera dictates the slow interferometric modulation and the small number of comb lines. Faster cameras will therefore enable a broader span and a higher measurement speed, thus increasing the power of the technique.

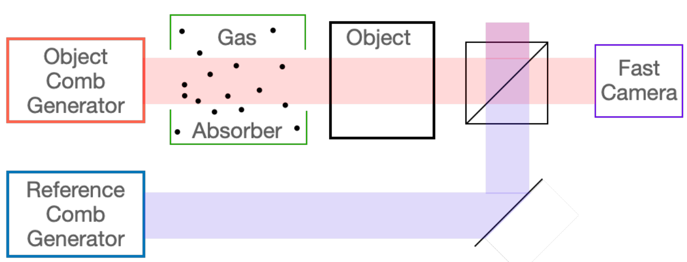

Figure 1: Sketch of the hyperspectral dual-comb system for digital holography

Each time-domain interferometric sequence is measured during 3.5 s. As many interferograms as there are pixels are measured. Each of them is Fourier transformed with a complex Fourier transform to provide spectra. In the examples given here, 27 spectra are averaged, leading to a total experimental time of 94.5 s. The amplitude spectra show well-resolved comb lines. For each comb line, the amplitude and the phase maps across the pixels generate a hologram at a given optical frequency. As many holograms as there are optical comb lines are measured. The images are reconstructed assuming Fresnel holograms with spherical waves. A reconstructed image of the hologram of the resolution test target at the frequency of 195.745 THz is shown in Fig. 2 for a focusing distance of 24 cm.

Using the hologram hypercube, made of all the amplitude and phase maps at different optical frequencies, all the tools developed for multi-wavelength holography can be employed for all the available comb lines. This includes hierarchical phase unwrapping which extends the ambiguity range of the quantitative phase derivations. Simultaneously, the absorption experienced by the object comb beam across its propagation is measured at resolved-comb-line spectral resolution (Fig.3a) with all the benefits of imaging high-resolution dual-comb spectroscopy [1], including the possibility to precisely measure spectral profiles (Fig.3b) and to determine the spatial map of the concentration of the absorber. Other reports [2,3] have illustrated other interesting features of hyperspectral imaging with a dual-comb spectrometer [4].

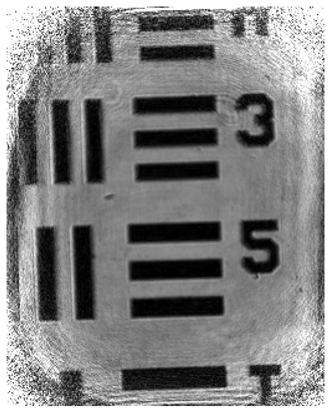

Figure 2: Reconstructed image of the resolution test target, measured by dual-comb digital holography.

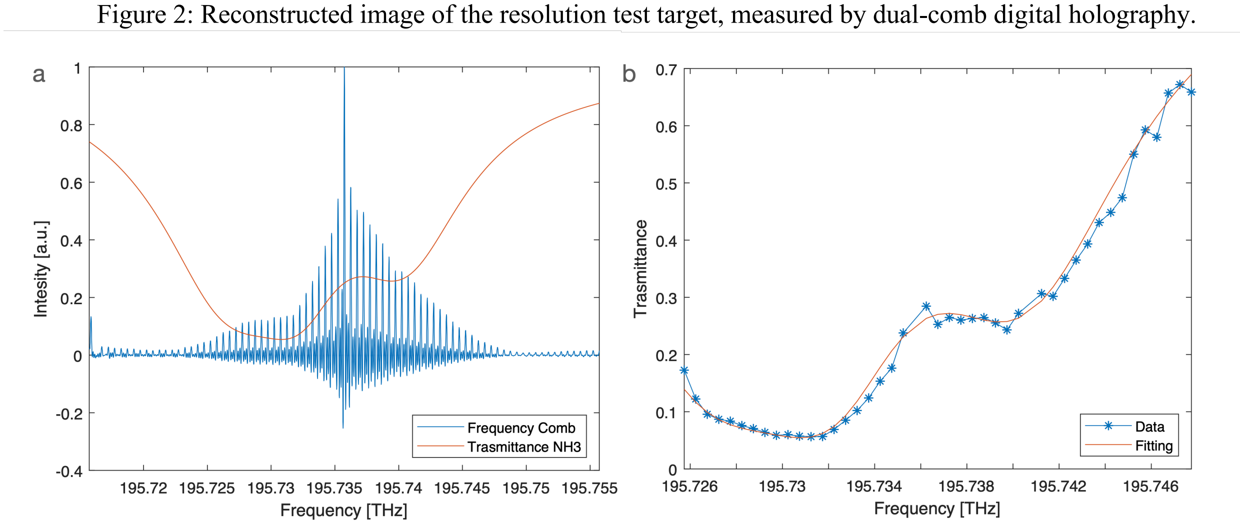

Figure 3. (a) Amplitude spectrum of pixel (128,160) measured with the dual-comb hyperspectral digital holography instrument. The intensity of the well-resolved comb lines is attenuated by ammonia absorption. (b) Detail of the experimentally-observed *P*(5) line of the $\nu_1+\nu_3$ band in ammonia and its fit, in good agreement.

Hyperspectral digital holography using frequency combs benefits from the multi-frequency character of our technique, which provide as many high-coherence narrow laser lines as there are comb modes. Furthermore, a fast measurement time and precise frequency referencing open up intriguing new opportunities.

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