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FREQUENCY COMBS

Full-color holography using combs

The three-dimensional images generated by digital holography are usually limited to a single color. A new technique exploiting frequency combs generates holograms with hundreds of colors at once.

Chao Dong and David Burghoff

In 1947, the Hungarian British physicist Dennis Gabor published his groundbreaking work on holography[1] that later earned him the 1971 Nobel Prize in Physics. While the original motivation was to improve the resolution of electron microscopes, the ability to record three-dimensional (3D) images using 2D photographs rapidly spread to other fields.

The invention of the laser allowed for holograms to be recorded with light[2], and it did not take long for holography to capture the public's imagination. In traditional holography, to make a recording of an object it is illuminated with laser light and the scattered light is mixed with light from the same laser, and the two beams are allowed to interfere on a photographic plate or a camera (Fig. 1a). This beating generates an interference pattern that encodes the entire light field — an entire 3D representation of the light coming from the object. However, because this process relies on interference, it requires narrow-linewidth coherent lasers. One cannot perform holography with broadband white light, as the different colors wash each other out.

In recent years, there have been many breakthroughs in photonics relying on frequency combs — a light source that features many perfectly evenly spaced laser lines[3]. In the visible region, such combs contain the many colours of traditional white light sources, but the different colours beat predictably instead of randomly. This beating mimics interference, and when they are used as sources, they can replace the concept of interference in many different measurements. Often, the measurements become simpler. The most famous example is probably dual-comb spectroscopy[4,5], an emerging spectroscopic modality that eliminates the moving mirror in Fourier-transform spectroscopy by replacing it with two combs.

Now, writing in *Nature Photonics*, Vicentini et al. have shown that holography can be efficiently performed at many wavelengths using two frequency combs[6]. The powerful method is extremely simple — no lenses needed — and essentially requires only the two combs and a camera. By shining one comb onto an object and mixing the scattered light with another comb, a hologram is recorded that beats predictably in time on a camera (Fig. 1b). By recording this beating and processing it, the authors show that a 3D representation of an object can be reconstructed and one that also encodes its spectrum. This 'dual-comb hyperspectral digital holography' method is essentially a 4D imaging technique, providing both 3D spatial information and spectral information. No sweeping is involved: all of the comb's lines are measured at once in a single shot.

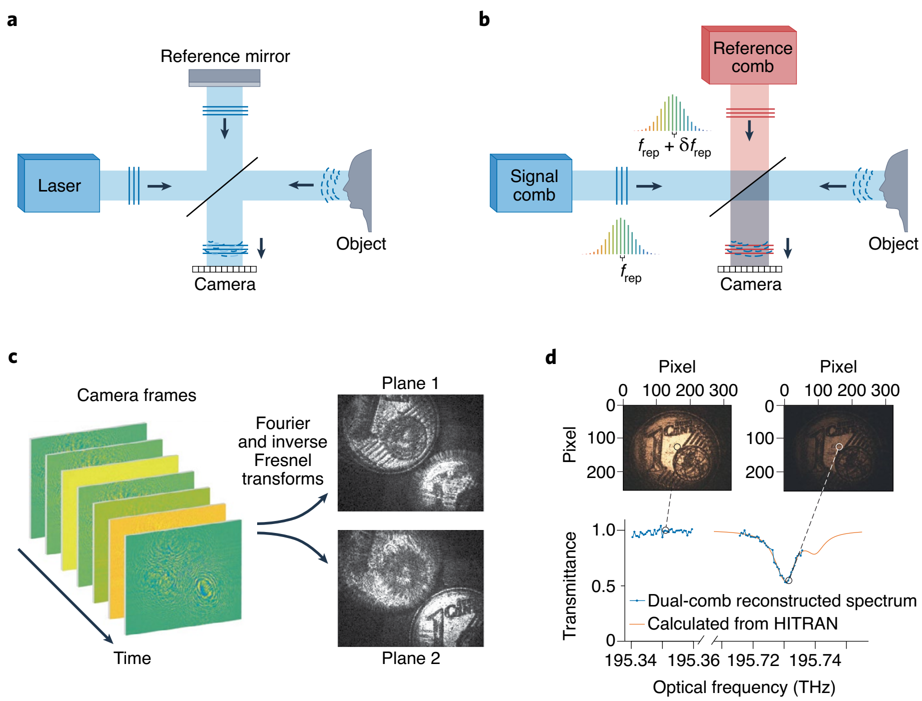

Fig. 1 | Overview of dual-comb holography. a, In conventional digital holography, light from a laser scatters off an object and is interfered with a delayed copy of itself, generating a hologram. **b**, In dual-comb holography, light from a comb scatters off an object and is interfered with light from a second comb with a slightly different repetition rate. The interference beats periodically in time. By recording and processing this beating, a 4D hologram is obtained (three spatial dimensions plus spectrum). **c**, Raw experimental data: frames are captured from a pair of coins and recorded sequentially in time. When processed, images are obtained at each plane and each wavelength. Two images at different reference planes and at a single wavelength are shown. **d**, When ammonia gas is placed in the beam path, each pixel of the image encodes the spectrum of the gas.

Conceptually, the principle bears similarities to prior dual-comb techniques. The authors generate one comb with a repetition frequency f_{rep} and shine its beam on a 3D object. The light scattered off the object is combined via a beamsplitter with a second reference comb of slightly different repetition frequency $f_{rep} + \delta f_{rep}$, where δf_{rep} is the difference in repetition rates. The two beams interfere at a fast detector array, and their signal at each pixel is recorded as a function of time. These time-domain interferograms are Fourier-transformed to obtain a complex spectrum (with both amplitude and phase) at each pixel — a hologram-hypercube. To perform the holography reconstruction process, the authors use an inverse Fresnel transform, which lets them compute an image of the object at any depth of interest.

The authors implemented their scheme using two electro-optic frequency combs with 100 comb lines centred at 195 THz with slightly different repetition frequencies of $\delta f_{rep} = 2$ Hz. Because the cameras have a limited sampling bandwidth of 160 Hz, the two combs must be very mutually coherent in order to fit all of the beat tones into the bandwidth; the choice of electro-optic combs automatically provides this coherence. In the first experiment, the 3D character of the technique is proven by measuring holograms of two coins separated by 9 cm. After getting an interferogram-hypercube consisting of 81920 pixel-interferograms, the profile of the coins can then be reconstructed at an arbitrary depth of focus (Fig. 2a). The signal-to-noise ratio was limited by technical relative intensity noise.

In the second experiment, the authors illustrate their method's highly frequency-multiplexed character. When the object absorbs, or an absorber is located in the beam path, the reconstructed images will also reveal its spectral map, enabling identification and qualification of the object. The authors image a coin through an ammonia-filled gas cell, and by Fourier transforming in the time domain, holograms of all hundred comb lines can be obtained simultaneously (Fig. 2b). The intensity at a particular pixel matches the expected transmission of ammonia, and the spectrum is high-resolution (determined by the comb's repetition rate, $f_{rep} = 500$ MHz).

The work is the latest example of the exciting potential for dual-comb technology. For example, it was recently shown that a dual-comb system with a traditional lens-based imaging arrangement could perform hyperspectral imaging by having a video camera directly detects interferograms[7]. This provides an image with two spatial dimensions and a spectral dimension but has a fixed focus. Similarly, dual-comb ranging[8] can give the distance of a remote object along with its spectrum but requires an unambiguous pointwise mapping between the object and detector pixel. Holography combines the attractive features of both techniques, as well as the fast speed and high temporal resolution of comb spectroscopy, the ability to measure information over a large spectral bandwidth simultaneously, and the simplicity of a lens-free system.

The dual-comb digital holography method has excellent potential for further improvement. In the visible and near-infrared wavelength ranges, faster cameras with more pixels and larger sensors could dramatically increase the number, measurement speed, and spatial resolution of comb lines. Octave-spanning combs could be used to perform holography with broader spectral coverage, or the approach could be extended to other spectral regions, such as the mid-infrared or terahertz. With these improvements, hyperspectral 3D imaging could allow for the simultaneous realization of multiple types of optical diagnostics, such as optical contouring and deformation measurements, wavefront sensing, 3D profiling over relatively short distances, microscopy for life science, particle imaging velocimetry, tomography, and laser speckle contrast imaging. Furthermore, with the advent of chip-scale combs, these systems could be monolithic and compact.

At present, perhaps the most severe limitation of this approach lies in the speed of the cameras that are used to record the interferograms. Unlike single-pixel detectors, whose speeds can easily be in the tens of GHz, achieving multi-pixel cameras with speeds of more than kHz rates is difficult. As a result, scaling dual-comb holography to combs with hundreds of thousands of lines instead of hundreds of lines is difficult — it requires that the beating of many comb teeth pairs be compressed into a narrow camera bandwidth. For combs with thousands of teeth or more, this requirement can be severe, as it requires a high degree of mutual coherence between the comb teeth. While this could in principle be overcome with additional signal processing[9,10], in practice, processing this data for each pixel in real-time would be very demanding. Even if it could be done, resolving the comb lines would still require large measurement times, $(\delta f_{rep})^{-1}$, slowing down the measurement. The development of higher-speed cameras and real-time processors will be crucial for future applications.

In summary, the results by Vincenti and colleagues are impressive, and with the achievement of dual-comb digital holography, it is an exciting time for the development of this technology. The combination of digital holography and dual-comb interferometers will help to usher in a new frontier in scan-free 3D metrology, showing potential in spectroscopy, spectral imaging and ranging. ❐

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Competing interests

The authors declare no competing interests.