Coherent Lensless Imaging

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Abstract: Coherent imaging has numerous advantages over incoherent imaging, but at a cost of requiring coherent laser illumination.

OCIS codes: (110.0110) Imaging systems; (090.1995) Digital holography; (110.1758) Computational imaging; (100.5070) Phase retrieval

1. Introduction

In many instances, coherent imaging can be similar to incoherent imaging – employing the same telescope, camera, or microscope as used for incoherent imaging, but for an object illuminated by coherent light. In that case the main difference between them is that for coherent light the transfer function describing the relationship between the optical fields in the image and the object planes is a scaled version of the exit pupil of the system, whereas for incoherent light the transfer function relating the object and image intensities is the autocorrelation of the exit pupil, i.e., the optical transfer function (OTF) [1]. Furthermore, for a rough object coherent light results in a speckled image. In this paper we will concentrate on aspects of coherent imaging which make it very different from incoherent imaging. One can do things with coherent light that are simply impossible with incoherent light.

2. Example: thin imaging system

As an example of what coherent imaging can do, consider the desire for an imaging system that is very thin (and perhaps could be conformal to the underside of the fuselage or a wing of an aircraft) for looking down at the ground with fine resolution [2]. This is impossible with conventional optics since even if the system has fast *f*/1 optics, it will typically be approximately as least as thick (in the axial dimension) as its diameter, *D*, making thinness and fine resolution, $\rho_x \sim \lambda R/D$ (where λ is the wavelength and *R* is the range to the target), mutually exclusive. With coherent illumination, on the other hand, it is possible to measure the optical field, scattered from the ground and propagated to the aircraft, in a plane with an array of detectors and no imaging optics. Then one can digitally propagate the field back to the ground and thereby form an image of the ground, in a computer. This was first accomplished in the laboratory in 1967 by Goodman and Lawrence [3], using a digital form of off-axis holography [4]: interfering the field from the object with the field from a coherent reference source, and performing the reconstruction of the image in a computer — digital holography. An alternative would be to measure fields using temporal heterodyne measurements with a frequency-offset reference (local oscillator) as are commonly used in synthetic-aperture radar. Phase retrieval [*e.g.,*2] is yet another way to acquire the field.

> A historical aside: Goodman and Lawrence [3] did not give the technique of digital holography a specific name, and did not call it “digital holography.” The title of their paper was “Digital Image Formation from Electronically Detected Holograms,” an excellent description. The earliest reference in OSA’s Optics Infobase to “digital holography” was not, however, to this technique, but was in reference to computer-generated holograms, that is, to the digital computation of the hologram which was then manufactured and read out optically (sort of the inverse of what we are here calling digital holography). The first reference to “digital holography” in OSA’s Optics Infobase in the sense used in this paper was Ref. 5, which used those words in reference to digital speckle pattern interferometry (DSPI). The term “digital holography” (or “digital holographic microscopy”) as an imaging technique, as well as referring to computer-generated holograms, is now entrenched on account of a series of OSA Topical meetings with that title that brought those two topics together. To draw the analogy to temporal heterodyne sensing, some have recently referred to digital holography as spatial heterodyne sensing. This is perhaps a good idea since it distinguishes it from computer-generated holograms. The earliest reference in OSA’s Optics Infobase to “spatial heterodyne” meaning digital holography imaging was Ref. 6 in 2001.

Temporal heterodyne (which can take the form of phase-shifting interferometry) requires three or more measurements of the interference between the local oscillator and the field from the object having different phase constants (which can be accomplished by having a frequency offset between the two fields), and requires very fast detectors, whereas digital holography requires a detector with a space-bandwidth product (number of pixels) that is two to four times greater, but can be slower.

3. Advantages of coherent imaging: using optical fields instead of just intensity

Once obtaining the field, one gains some significant advantages over imaging with incoherent light.

Having fields, if the object and coherent illumination are fixed but the receiver aperture (detector array) moves, then one can, in time, synthesize a larger aperture (giving correspondingly finer resolution) in exactly the same way as is commonly done in synthetic-aperture radar. Alternatively the object can rotate (in microwaves we would call that inverse SAR) or the illumination beam can rotate about the object to get the same effect.

If one illuminates the object with a series of finely-spaced laser frequencies (or wavelengths), and performs a Fourier transform in the frequency direction, one gets a 3D image consisting of voxels, with the third dimension being just like the range resolution one gets in chirped-frequency radar, with range resolution $\rho_z = c/(2\Delta\nu)$ where c is the speed of light and $\Delta\nu$ is the temporal bandwidth of the laser frequencies, or $\rho_z = \lambda^2/\Delta\lambda$, where $\Delta\lambda$ is the spread in wavelengths [7]. This axial resolution can be orders of magnitude finer than what one can achieve employing the depth of focus effect.

Given the fields, one can perform phase-error correction in ways that are impossible with incoherent light, for example, using sharpness maximization after the data is collected [8]. Furthermore, in incoherent imaging, aberrations (from atmospheric turbulence, for example) cause a suppression of the modulation transfer function (MTF) of the system [1], which can cause a severe reduction of the signal-to-noise ratio (SNR), which is not recovered by deconvolution (by a Wiener-Helstrom filter, for example). In that case, deconvolution amplifies the noise. The MTF is the magnitude of the optical transfer function, which is proportional to the autocorrelation function of the exit pupil (including the phase errors) of the imaging system. For coherent imaging, on the other hand, the coherent transfer function is simply proportional to the (usually binary) pupil itself [1], and there is no SNR penalty associated with aberrations. Hence one can successfully correct large phase errors and achieve image quality comparable to what one would have gotten had there been no aberrations at all. Furthermore, it is possible to correct, in the computer after the fact, for aberrations in multiple planes [9], with similar avoidance of noise amplification, and without using the hardware of real-time multi-conjugate adaptive optics [10]. Coherent imaging naturally provides extremely large depth of field, since the optical fields can be digitally propagated to any axial distance in object space after the fact.

For a conventional imaging system, off-axis aberrations limit the field of view over which one can obtain diffraction-limited performance. Hence telescopes that have few optical surfaces tend to have small fields of view. Only such optics as microlithography lenses have diffraction-limited performance over wide fields of view, but at the expense of requiring a system having dozens of optical surfaces making up an axially thick optical system. Since the optics of coherent lensless imaging is free-space propagation, we know how to propagate the fields back to the plane of the object to achieve diffraction-limited images over a wide field of view.

With fields, one can perform holographic interferometry that can sense sub-wavelength changes in a time-changing scene, such as measuring tiny deformation. Similarly, through coherent change detection one can also determine that a surface was disturbed on a sub-micron level by the decorrelation of the phase between two data collections separated in time.

With laser illumination, one can image day or night.

4. Disadvantages of coherent imaging

With all these great properties, why is coherent lensless imaging not more widespread? First, although it is not a problem with microscopy, where digital holography is more widely used, one must have a laser that has long coherence length (at least twice the depth of the object being imaged), and high power for imaging outdoor scenes. During daylight, one would want the power of the laser to be (at least instantaneously) considerably brighter than the sun. To help accomplish this, one would prefer a pulsed laser to allow for time gating as well as a narrowband spectral filter to filter out the vast majority of the sunlight. Whereas in incoherent imaging sunlight is usually needed, in coherent imaging it is something one must fight to overcome. Second, getting the light from the object to interfere properly with the reference beam or local oscillator at the detector can be difficult. The two sources of light must arrive on the detector at the same time, which can be difficult for pulsed lasers, for long propagation distances, and for dynamic objects. Radial velocities cause Doppler shifts; transverse velocities may change the angle of the beam with respect to the reference beam.

Images of rough objects (most things are rough on the scale of an optical wavelength) in coherent light have the problem of producing speckled images, which can be thought of as a multiplicative noise. While an image of an isolated point-like object looks the same irrespective of the type of illumination, speckle in an image of an extended object reduces the effective resolution by about a factor of three. Speckle contrast can be reduced by a factor of $K^{1/2}$ by summing together K images of the same object having independent speckle realizations. For large K the resulting image approaches an incoherent image. Note, however, that to reduce the speckle contrast to, say, 10%, one needs $1/(0.1)^2 = 100$ independent speckle realizations. Images having independent speckle realizations can most easily be obtained by translating the sensor aperture by its own width, or changing the angle of the coherent illumination beam, or rotating the object, or any combination of these three. Wavelength diversity can also be used to reduce speckle.

5. Phase retrieval

Given the potential difficulty of interfering the field from the object with the reference beam, an alternative to consider is to dispense with the reference beam or local oscillator and simply measure the intensity of the field from the object. This greatly simplifies the detection hardware and reduces sensitivity to vibration. Without the phase of the field, however, an image cannot be readily computed. If, on the other hand, one has some *a priori* information about the object, then the unmeasured phase can be retrieved by a computer algorithm. Ref. 2 shows an example of employing phase retrieval when one uses an illumination pattern on the ground as a constraint: the retrieved phase must be consistent with an image being dark in the areas not illuminated. For that to work, the illumination pattern should have reasonably sharp edges (not just be Gaussian pattern). For coherent imaging, bright objects on dark backgrounds, e.g. ground-based imaging of aircraft or earth-orbiting satellites, the edges of the object itself are naturally sharp, which helps phase retrieval, but then the outline of the object is typically not known *a priori.* The outline or support of the object can be estimated from the support of its autocorrelation function, which can be computed from the measured data [11,12]. Phase retrieval is computationally very demanding and not always guaranteed to work, but it allows for simple optical hardware which, for some applications, is the overriding concern. Besides imaging remote objects, another application is coherent diffractive imaging with x-rays, where current technology does not give us good enough lenses that operate at that wavelength, and heterodyne sensing is also difficult; then using phase retrieval is an attractive way to form images of microscopic objects.

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