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Multimaterial photosensitive fiber constructs enable large-area optical sensing and imaging

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Abstract
The process of optical imaging and the use of a glass lens have been hitherto inseparable since it is the lens that is responsible for mapping incoming rays to form an image. While performing this critical role, the lens, by virtue of its geometry and materials composition, presents constraints on the size, weight, angular field of view, and environmental stability of an optical imaging system as a whole. Here, a new approach to optical imaging is presented. Tough polymeric light-sensing fibers are suspended on a frame to form large-scale, low-density, two- and three-dimensional photonic meshgrids. While a single grid can indeed locate a point of illumination, it is the stacking of a multiplicity of such grids, afforded by their essential transparency, which allows for the detection of the direction of illumination with a wide angular field of view. A surface-spanning-arrangement of such fibers is used to extract an arbitrary optical intensity distribution in a plane using a tomographic algorithm. Lensless imaging is achieved by a volumetric fiber assembly that extracts both the phase and intensity distributions of an incoming electromagnetic field, enabling one to readily determine the object from which the field originally emanated.

The use of lenses for optical imaging has dominated optics since antiquity with no fundamental changes since, except for improvements in design and fabrication. The performance and size of any optical imaging system is usually determined by the quality and size of the lens(es) included in that system. The search for alternative approaches to optical imaging that do not rely on lenses, so-called lensless imaging, has had a venerable history. The common factor amongst all previous attempts is the introduction of a new optical system, usually an interferometer, which transforms the optical field before recording the intensity using a conventional optical-detector array. A recent attempt demonstrated three-dimensional lensless imaging using a sophisticated interferometric arrangement and a novel computational algorithm [1]. In this paper we demonstrate a distinct, non-interferometric approach to lensless optical imaging that relies on a volumetric sampling of the electromagnetic field that is enabled by semitransparent 3D arrangements of photodetecting fibers.
In the limit of geometric optics, where diffraction and interference effects are negligible, light is described by rays. A complete description of a ray is given in terms of a direction of propagation vector and a point of intersection with a plane [2]. The function of an optical component, such as a lens (shown schematically in Fig. 1A), may be represented in this limit by a matrix which maps the incoming rays to outgoing ones. In other words, a lens is an analog computer that applies a specific transformation, determined by the shape and index of refraction of the lens, to the parameters representing each ray. One of the main goals of this paper is to demonstrate that complete identification of the parameters describing the rays enables one to replace this analog computer (lens) with a digital computer. This is of importance for the long-standing effort in microscopy devoted to improving the resolution of diffraction-limited imaging [3]. However, optical detectors normally register only the location of an incident ray, but not its direction. An optical detector capable of registering both, in other words a directional light detector, would then acquire all the parameters needed to implement the...
effect of any optical device or process *computationally* by simply performing the corresponding transformation (not necessarily restricted to being linear) or series of transformations.

In the wave-optics formulation of optical imaging, light is represented with a complex field distribution. The intensity of the diffracted field transmitted or reflected by an object, and recorded by a 2D optical-detector array, has little resemblance to the object at distances much larger than the wavelength of light. A lens, in this case, provides a phase modulation to the incident diffracted field that leads to the formation of a sharp image when combined with the effect of free-space propagation for a specified distance after the lens [2]. While conventional optical detectors measure the amplitude (intensity) of the field, there is no direct access to the phase. However, if the amplitude and phase of the diffracted field are detected, one could simply ‘back-propagate’ the optical field computationally (by implementing the Hermitian conjugate of the propagation operator) until a sharp image is formed at the correct distance separating the object from the detection plane. In X-ray imaging, similar lensless approaches have recently been demonstrated [4, 5] motivated by the lack of large-numerical-aperture X-ray lenses. Optics, however, cannot benefit from this class of lensless approaches since an extremely large detector array would be required at optical wavelengths.

An optical detector obstructs the path of a ray since light detection is, in general, a destructive process. Nevertheless, an optical array made sufficiently sparse will offer little disturbance to the incident field. If one arranges for two such arrays to be placed in the beam path, the location and direction of a ray is easily determined. In Fig. 1B we show one possible implementation of a directional light detector in the geometric-optics limit that makes use of two transparent optical-detector arrays separated by a distance $d$. The first array registers the location of the input beam, which continues its path, only slightly perturbed, to the second web which records the new position of the beam. One may then easily compute the angle of the beam from knowledge of the two locations and the distance between the planes of the webs. The angular resolution of this arrangement is determined by the ratio of the spatial resolution of a web to $d$, and the angular bandwidth is limited by the ratio of the size of the array to $d$. 
Fig. 2. (A to C) (A) An optically sensitive fiber (diameter $D$) detects a line integral of the incident intensity distribution $I(x, y)$. The inset shows an SEM micrograph of the metal-semiconductor-metal fiber cross-section (1.25-mm outer diameter) showing four electrodes in contact with a photoconductive glass core. (B) An image of the letter ‘E’ is projected onto a 32×32 fiber web. The detected signal from the web rows and columns (constituting 2 orthogonal parallel projections) are also shown. The image of the letter ‘E’ itself is formed on a white sheet placed behind the essentially transparent web. (C) Reconstructing the image using the backprojection algorithm as a function of the number of angles the projections are taken at. These projections are obtained by rotating the object transparency (shown on the far right), 1 angle: 0°; 2 angles: 0°, 45°; 3 angles: 0°, 30°, 60°; 6 angles: 0°, 15°, 30°, 45°, 60°, 75°; and 18 angles: 0° to 85° in 5° steps.

Several obstacles, however, make the physical implementation of such a conceptually simple scheme prohibitive. One obstacle concerns the area of the optical-detector array. Typically, the array is constructed out of point, zero-dimensional (0D), detectors in the form of pixels integrated on a chip (such as CCD chips), which are limited to small areas, and a lens is required to collect the light and deliver a focused image to the chip. Alternatively, an arrangement of separate, individual point detectors can cover a larger area, but only a small portion of the field is intercepted by each detector. To obviate the above restrictions, we construct a transparent optical detector array that minimally impedes the propagation of the incident beam. The use of two such arrays, separated by some distance, allows one to easily determine the path that the light ray traversed. (Fig. 1C shows a photograph of such an arrangement.) Unlike other detectors, our arrays can be made arbitrarily large and hence have large angular bandwidth, corresponding to the numerical aperture having a value of 1. Our approach consists of constructing the array from one-dimensional (1D) light-sensitive elements in lieu of 0D elements. This is made possible by our recent success in fabricating a family of optoelectronic
fibers [6], constructed from insulators, semiconductors, and metals, which are particularly suitable for our purpose by virtue of combining optical and electrical functionalities. Specifically, the class of fibers that we make use of in this paper is that of fibers constructed of a photoconductive glass [7] core contacted to metal electrodes that run along the length of the fiber [8], and is then surrounded by a protective, transparent polymer cladding [9] (see the inset of Fig. 2A). When light impinges on the external surface of this fiber, an electrical signal is produced in the form of a change in current in an external circuit. This fiber structure offers several advantages that address the abovementioned difficulties of 2D arrays. First, the array consists of only $O(N)$ 1D elements that are sensitive to light along their whole length and collect a considerable amount of optical power, hence allowing the construction of sparse arrays. Second, these fibers can be of long length, resulting in large-area arrays. The fact that the electrodes run along the fiber in contact with the core alleviates the problem of electrical connections. Third, the fibers are mechanically tough, yet very flexible, which facilitates the construction of an optical array on a curved surface such as a sphere or a cylinder [10]. This also opens up the exciting prospect of incorporating such a fiber array in a fabric, thus producing optically functional clothing. Fourth, the fibers are essentially transparent, and an optical beam incident on an array of such fibers is only slightly perturbed. This advantage, when coupled with the flexibility of the fibers, allows the exploration of 3D arrays of arbitrary geometry which are capable of performing optical tasks beyond those of conventional 2D arrays, such as lensless imaging, for example. To distinguish our proposed optical-detector arrays constructed out of 1D optoelectronic fibers from conventional arrays, we call them ‘fiber webs’.

Consider a 2D web constructed of straight fibers on a square grid (although arbitrary grid geometries may also be constructed). The location of an incident ray of light, or any separable intensity distribution $I(x, y)$ in the form $I(x, y) = I_1(x)I_2(y)$, may be determined in a straightforward manner from the signals detected by the rows and columns. However, it is not obvious how such an array can determine the distribution of an arbitrary intensity distribution. An important observation brings to the fore which body of theoretical work is of relevance to this problem. Note that each fiber detects the incident intensity distribution along its whole length. A fiber, of length $L$ and thickness $\Delta$ ($\Delta \ll L$) placed along the line $x\cos\theta + y\sin\theta = t_1$ in an optical field having a two-dimensional intensity distribution $I(x, y)$, as illustrated in Fig. 2A, generates a photocurrent that is proportional to the intercepted optical power, $P_\theta(t_1)$, given by

$$P_\theta(t_1) = \int_{\text{fiber area}} dx dy I(x,y) \approx \Delta \int dx dy I(x,y) \delta(x\cos\theta + y\sin\theta - t_1);$$

where $t_1$ is the intercept of the fiber with the $t$ axis, which makes an angle $\theta$ with the $x$ axis. The intercepted power is thus a line integral of the intensity distribution along the fiber. Consequently, the measurements performed by a set of parallel photodetecting fibers form a parallel projection of the incident intensity distribution. The term ‘parallel projection’ is that used in the literature on computerized axial tomography
and refers to the measurements performed by a linear array of point detectors placed on one side of a 2D object of interest, when a linear array of point sources (e.g., X-rays) is placed on the opposite side of the object. Each point detector measures the line integral of the X-ray attenuation of the object along the line connecting it to the opposing point source. In our case, each fiber records the line integral of the intensity distribution of the optical field along its length. An example of a parallel projection produced by a fiber web is shown in Fig. 2B, where a $32 \times 32$ fiber web (of dimensions $24 \times 24$ cm$^2$) intercepts an image of a letter E. The image is produced by a white-light lamp (Xe-Hg) illuminating a transparency with dimensions $14 \times 14$ mm$^2$ placed at a distance of 1.2 m from the web. No lens is needed to form an image of the object transparency in this case because of the large dimensions (relative to the wavelength of light) used, highlighting the unique advantage of an array having such a large area. The two orthogonal parallel projections obtained by the rows and columns of the web are displayed, demonstrating the uniformity of the responses of the different fibers to the incident intensity distribution.

Although the physical mechanisms of X-ray detection in a CAT arrangement and the detection of light using a fiber web are completely different, they are, surprisingly, mathematically isomorphic, allowing us to import the theoretical foundations of CAT for use in the problem at hand. In particular, we may employ the backprojection algorithm [11], commonly used in CAT, to reconstruct an estimate of the impinging optical intensity distribution. This algorithm enables one to reconstruct an arbitrary two-dimensional distribution from one-dimensional parallel projections taken along different directions. In the case of X-ray CAT scans, the array of point sources and point detectors are usually rotated simultaneously around the object. In the case of fiber webs there are several strategies to achieve this: (1) rotating the fiber web; (2) using adjacent or interleaved fiber webs, each rotated by an angle with respect to each other; or (3) rotating the object that is imaged. In Fig. 2C we show the reconstruction results of the image, obtained using the backprojection algorithm, while increasing the number of projections recorded while rotating the object transparency. Note that the image, consisting of 1024 pixels, is produced by using 64 fibers only.

Having the intensity distribution in hand, we are now in position to discuss the general case of optical imaging using electromagnetic diffraction theory. We demonstrate that two fiber webs can be used to reconstruct an object from diffraction intensity measurements employing the phase retrieval algorithm [12-14]. In its simplest form, this algorithm iteratively obtains the phase of a wavefront if the amplitude is known in two different planes. The idea proceeds as follows. We use two planar fiber webs, located at two distinct diffraction planes, and obtain the incident 2D intensity distributions from both (by means of the CAT algorithm outlined above); we then implement the phase retrieval algorithm to retrieve the phase of the wave front [15]; knowing the complex field at the first web, we can ‘back-propagate’ the wave front computationally until an estimate of the object is obtained.
We demonstrate the feasibility of this approach by producing the image of a pattern consisting of three slits (of width 158 μm, separated by 158 μm each) illuminated with light at 830 nm. The 2D intensity distribution data obtained by a fiber web at two different locations in the far-field of the object is depicted in Fig. 3A. We implemented the phase retrieval algorithm on the two obtained intensity distributions to reconstruct the phase of the wave front, and subsequently we estimated the field at distances receding from the first web. A set of these estimates is shown in Fig. 3A. All the estimates are blurred until we approach the location of the object where a clear image is formed. Calculated fields back-propagated beyond this distance are blurred once again. Images of objects with more detail will require webs with a larger number of fibers. Note that this system has an infinite depth of focus, i.e., an image is formed of the object regardless of the distance of the object from the webs, provided that the diffracted field, at the locations of the two webs, is intercepted. Furthermore, the image reproduces the object with its real physical dimensions and also determines its physical distance from the webs. In Fig. 3B we plot the amplitude and phase of the optical field at three locations: the planes of the two fiber
webs and the object plane. The measured amplitudes at the planes of the two webs are compared to the amplitudes calculated using the object by employing diffraction theory and the reconstructed phases are compared to calculated phases. Note that discrepancy occurs between the reconstructed and calculated phases only at those locations where the amplitude is small, and the phase become less meaningful. Note that the reconstructed phase at the object plane reveals a linear phase distribution across the object plane instead of the expected zero phase, which indicates that the plane of the slits was slightly tilted with respect to the incident beam wave front.

It is important to stress that the amplitude and phase represent a complete representation of the optical field. The human eye, for example, implements a specific transformation (that of an iris followed by a lens) with variable parameters, before detecting a 2D intensity distribution. Any such optical process may be carried out on a digital computer by manipulating the full information about the field. One could, for example, prepare a hologram using this information. One may also implement object-recognition algorithms that will benefit from the availability of the complex optical field instead of relying on a 2D intensity image. Moreover, although the specific demonstration reported here makes use of a coherent light source (optical bandwidth of approximately 6 nm), a white light source could also be used. This would require using a generalized phase retrieval algorithm that formally handles broadband light, which has been explored and demonstrated in Ref. [16] for an approximately 200-nm wide optical spectrum.

In principle, by virtue of obtaining a complete description of the electromagnetic field, this approach may be used to image 3D objects that are translucent enough so that excessive occlusion does not occur. Furthermore, one can arrange for the photoconductive glass core in the fibers to be responsive in different regions of the optical spectrum [17]. One can also arrange to reduce the detected optical bandwidth by surrounding the fibers with resonant photonic-bandgap structures [6, 18, 19]. Using fibers provided with optical sensitivity at different wavelengths allows one to produce color images. Although the fiber webs used in this paper detect light and form an optical image (and in that sense can be said to ‘see’), one can substitute the photoconductive glass in the core with other families of glasses that are sensitive to other physical quantities, such as temperature or chemical contaminants [20]. Webs constructed of these fibers, coupled with the use of the same principles outlined above, will yield ‘images’ in these parameter spaces, and can thus be said to see, sense heat, and smell.

In conclusion, we have demonstrated non-interferometric lensless optical imaging using a three-dimensional photonic-fiber meshgrid. Such a meshgrid determines the position and direction of rays of light or the amplitude and phase of an electromagnetic field. Using a combination of a tomographic algorithm and the phase retrieval algorithm, a computational image of an object is formed with its physical dimensions and at its true location. Finally, one of the scientific objections to H. G. Wells’ 1897 novel, “The Invisible Man,” [21] was that such a man would necessarily be blind. Although our fiber meshgrids are not strictly invisible, we have shown that objects that are almost transparent may, in a meaningful sense, ‘see’.
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