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Compact discrete correlators with improved design

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Abstract

Optical correlators are of interest for a variety of signal processing tasks. In a recent paper [Appl. Opt. 39 (2000) 759–765], we described an approach to build discrete correlators for spatially incoherent signals using planar-integrated free-space optics. In that paper, input and output array were spatially interlaced in the same area. Here, we present an improved design with separated input and output. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Optical correlation is a widely used operation in signal processing for object recognition, classification, and address decoding in optical communication systems. The latter application is of concern to us, for example, in context with optical data buses using free-space optical interconnections. For this purpose, discrete arrays of “smart pixels” have been discussed as input/output devices. Of particular interest are arrays of VCSEL-based devices (VCSEL: vertical cavity surface-emitting laser) directly located on a silicon chip [1] which can serve as emitters in 3-D optical interconnects. Particular requirements to inter-

connections are the need for compact size and robustness as well as potentially low cost. The concept of planar-integrated free-space optics [2] satisfies these requirements. It has been suggested earlier to use this concept for the implementation of joint transform correlators [3–5].

In a recent article, we presented an integrated version of a VanderLugt correlator for discrete input signals [6]. The specific application in mind is the address header recognition in an optical data bus with 2-D VCSEL arrays as light sources. For this case of spatially incoherent objects, the VanderLugt correlator appears to be better suited than the joint transform correlator. In Ref. [6], a specific optical design was demonstrated where the input array I and the output array O are located not only in the same plane, but also interlaced which simplifies the optical system. Here, we want to discuss the case where I and O are also spatially separated by a lateral offset (Fig. 1b). Two different optical designs were realized and will be described in the following Sections 2 and 3.

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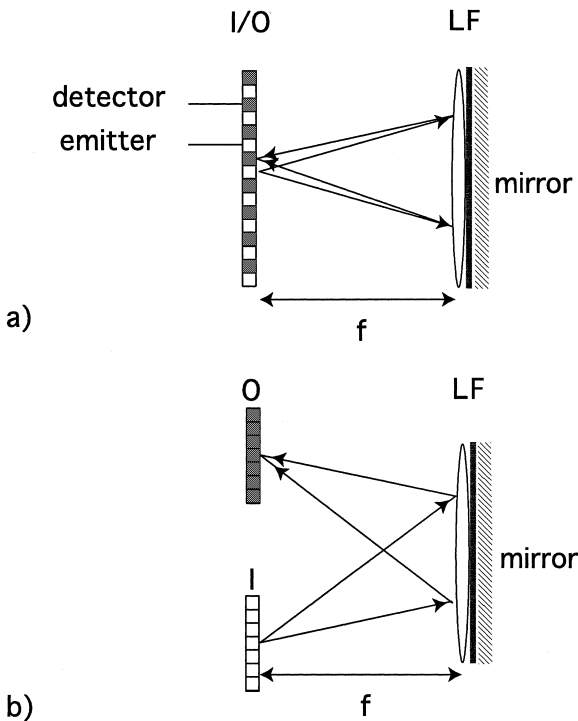


Fig. 1. Arrangements for an optical correlator using reflective optics: (a) with interlaced input and output, (b) with spatially separated I/O.

2. Optical design

For our design, the input object is assumed to be, for example, a 2-D VCSEL array. In other words, we assume an array of discrete, mutually incoherent light sources emitting at nearly the same wavelength. The discreteness of the input arrays is a useful feature to implement special optical designs, as will be discussed below. Furthermore, it allows one to obtain a correlation result with a high signal-to-noise ratio. Finally, the fact, that the light sources operate essentially at the same wavelength allows one to use specially designed diffractive optics. In the experiments, the VCSEL array was simulated by a binary mask pattern illuminated with light from a HeNe laser with a rotating ground-glass which was used to destroy the spatial coherence. A more detailed discussion of design considerations can be found in Ref. [6].

2.1. “Light pipe” design

The first correlator design we consider is based on an optical imaging system known as “light pipe” [7] (Fig. 2a). Lenses L_1 and L_4 act as field lenses, L_2 and L_3 as imaging lenses. The system can be used for coherent and incoherent input signals. In the latter case, the field lenses may not be necessary. However they help to improve the imaging by assuring uniform illumination of the whole aperture of the imaging lenses. Fig. 2b shows the integrated system schematically. It is realized with an oblique optical axis to “fold” the system into a substrate according to the idea of planar-integrated free-space optics. Lenses L_2 and L_3 and the filter F are integrated in a single element CE. Input and output arrays are virtually “in contact” with the field lenses. CE combines two functions: that of an imaging lens and the filter function for the correlation operation.

The system was integrated on a quartz glass substrate with a thickness of 8 mm. The layout of the system was chosen such that all alignment-critical elements are positioned on the same surface of the substrate to facilitate fabrication. Substrate thickness t , tilt angle α and the focal length of CE are related by $t = f / \cos \alpha$. In our case, the tilt angle is 2.93° . This is sufficiently small that astigmatism is the only aberration that needs to be corrected, as confirmed by ray tracing simulations. The compensation for astigmatism was achieved by scaling CE in y -direction by a factor of $1 / \cos^2 \alpha$ [4,8]. The combination element CE was implemented with a pixelated structure with eight discrete phase levels. In our experiment, it consists of 819×817 pixels. With a pixel size of app. $(1.42 \mu\text{m})^2$ the element covers an area of app. $(818 \mu\text{m})^2$. However due to the astigmatic correction neither the individual pixels nor the overall extension of the CE are exactly quadratic. These values corresponds to a numerical aperture of the lens of approximately $\text{NA} = n \sin u = 0.038$. The correlation filter which was superimposed with the lens function. It consists of a 2-D periodic structure (in order to generate a discrete point spread function (psf)) with 96^2 pixels per period. This means, that there are six periods of the filter within the aperture of CE. The filter function was

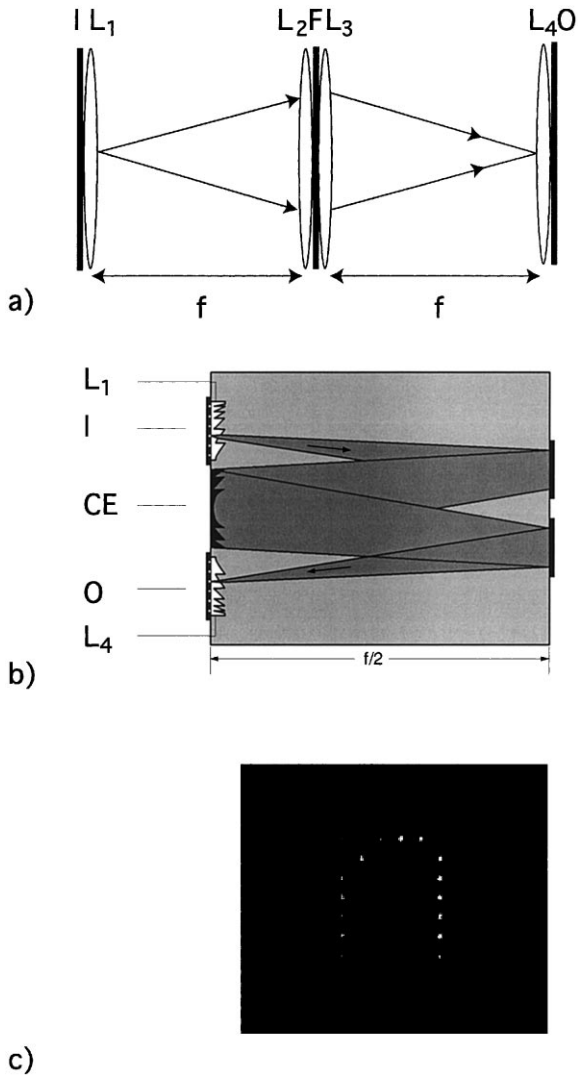


Fig. 2. “Light pipe” design: (a) Conceptual unfolded setup shown in transmission. All lenses have the same focal length f . F denotes the filter. (b) Schematic of the planar-integrated system. The functions of L_2 , F and L_3 are integrated in a combination element CE . (c) psf for a specific filter design.

calculated by using numerical optimization techniques.

For demonstration of this design, we consider its psf shown in Fig. 2c. In this case, the filter F was designed so that its Fourier transform would form the letter “n.” The separation of the spots in this pattern is approximately $51 \mu\text{m}$ in each direction. The uniformity of the spots in the psf is

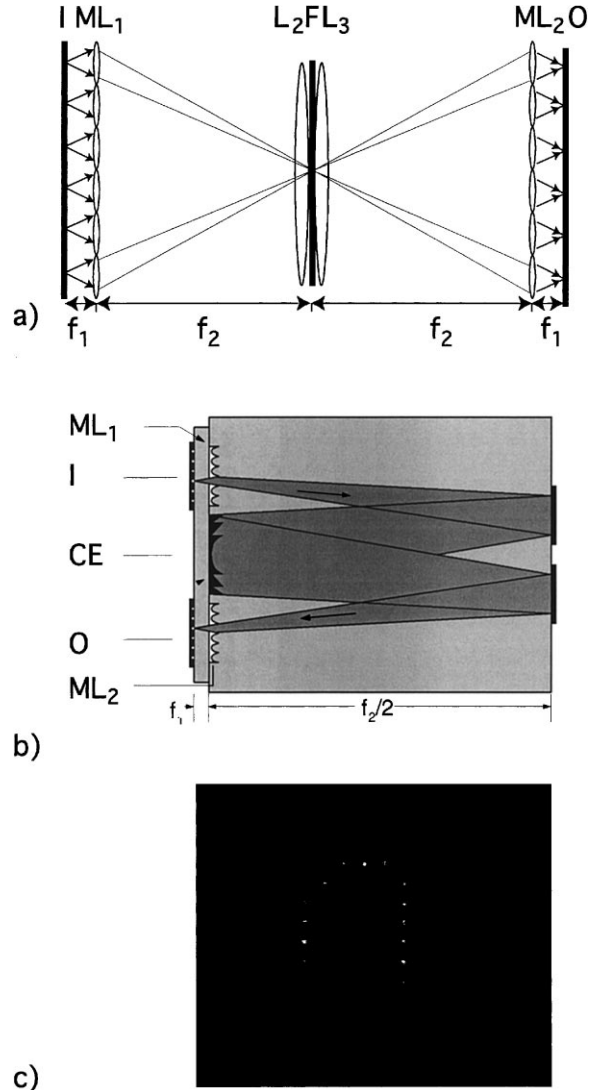


Fig. 3. “Hybrid” design: (a) Unfolded setup in transmission. (b) Integrated setup. ML : microlens array. (c) psf.

sufficient and no noticeable stray or background light (as, for example, unwanted diffraction orders) is observed. The size of the individual spots remains within the diffraction limit, as far as can be judged from the camera picture.

2.2. “Hybrid” design

The concept of “hybrid imaging” [9] means that a conventional (e.g., telecentric or $2f$ – $2f$) imaging

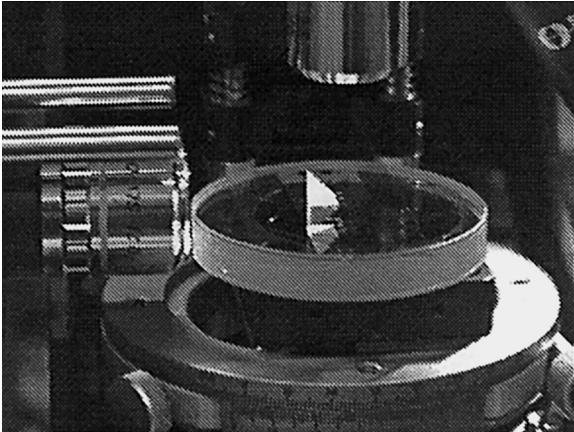


Fig. 4. Experimental setup to observe the psf. A prism with a 45° angle was used to couple the output signal to a CCD camera.

system is combined with microchannel imaging realized by microlens arrays (Fig. 3a). In the hybrid imaging scheme, the imaging task is split up conveniently between the microlenses (which provide high resolution due to a large NA) and the imaging lens(es) (formed by L_2 and L_3 in Fig. 3a) providing the beam translation. This approach can be used in an advantageous way for discrete objects in order to improve the imaging quality and/or simplify the optical system. Image quality is improved by reducing the NA of the imaging lens and thus aberrations. This feature has been proved to be particularly useful for planar-optical imaging systems where the tilted optical axis gives rise to inherent aberrations [10]. Here, we demonstrate the use of the hybrid imaging scheme for the implementation of our discrete correlator. The integrated system is shown in Fig. 3b, the resulting psf in Fig. 3c. As one can tell from the experimental result, the spot size is reduced yielding a “sharper” looking psf. This is due to the relatively large NA of the microlenses. In our experiments, the NA of the microlenses was 0.1 as compared to an NA of 0.051 for CE. The reduced spot size may be of advantage if one uses “smart pixel” device arrays for input/output and it might be critical to keep the light intensity to narrow regions.

The psf in Figs. 2 and 3 were obtained with an experimental setup shown in Fig. 4.

3. Conclusion

We have presented the design and demonstration of discrete correlators based on planar-integrated free-space optics. The experimental results demonstrate the feasibility of our approach. The array sizes were small, however, sufficient for potential applications in security systems or in optical data buses. So far, we have demonstrated different designs for the correlator. Further work will focus on the integration of a 2-D VCSEL array as the input device and a modulator (for example, LCLV) so that different correlation operations can be realized dynamically.

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