Optical time-domain analog pattern correlator for high-speed real-time image recognition

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The speed of image processing is limited by image acquisition circuitry. While optical pattern recognition techniques can reduce the computational burden on digital image processing, their image correlation rates are typically low due to the use of spatial optical elements. Here we report a method that overcomes this limitation and enables fast real-time analog image recognition at a record correlation rate of 36.7 MHz—1000 times higher rates than conventional methods. This technique seamlessly performs image acquisition, correlation, and signal integration all optically in the time domain before analog-to-digital conversion by virtue of optical space-to-time mapping.

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In real-time optical imaging, the speed of image processing is limited by the image acquisition circuitry, including the conversion rate of analog-to-digital converters and the throughput of digital processors [1]. Although digital processors exemplified by the state-of-the-art field programmable gate arrays [2] boast tens of gigbits per second throughput, real-time image processing with such systems is currently limited to ~1000 frames/s because of the bottleneck associated with the storage and access of the massive amount of digital data that is produced during high-speed imaging. As a result, the throughput of commercially available automated microscopes and imaging flow cytometers is constrained to ~1000 cells/s [3]—a few orders of magnitude smaller than that of conventional scattering-based flow cytometers. Furthermore, digital image processing cannot be performed in real time due to the massive amount of data and hence requires offline processing.

For high-throughput image recognition, various optical techniques have been developed to reduce the computational burden on the digital electronics. The most commonly used method is spatial-domain correlation detection based on the use of Fourier optics in conjunction with spatial light modulators or holographic elements known as the Vander Lugt correlator [4,5] or the joint transform correlator [5,6]. These techniques have successfully been applied to fingerprint and face identification, medical imaging, and robotics [4–7]. While they take advantage of massive parallelism inherent in Fourier optics for high-precision image correlation, their correlation rate is typically limited to ~10 kHz due to the response time of the spatial optical elements (e.g., the liquid crystal modulator) or the download data rate of the digital holographic elements (e.g., the complementary metal-oxide semiconductor camera).

In this Letter, we propose and demonstrate a new method that performs fast real-time optical image correlation detection at a record correlation rate of 36.7 MHz—about 1000 times faster than the conventional methods. This technique is based on the recently developed ultrafast imaging technology known as serial time-encoded amplified imaging/microscopy (STEAM) [8,9]. The imager's ability to perform optical image serialization and amplification enables optical image recognition *in the time domain*, in contrast to the conventional methods that operate *in the spatial domain*. This system, hence, eliminates the need for the spatial optical components and enables fast real-time frame-by-frame image recognition at much higher correlation rates.

The concept of our method, which we refer to as the optical time-domain analog image correlator (OTAIC), is shown in Fig. 1. The goal of the OTAIC is to optically compute the inner product of test and reference image patterns in the time domain. Assuming that the two

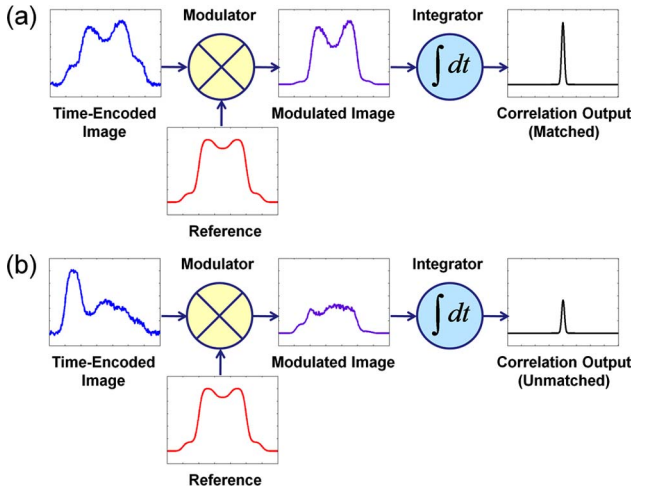

Fig. 1. (Color online) Concept of the OTAIC. Large and small correlation output values are generated in (a) matched and (b) unmatched cases, respectively. In both cases, the test time-encoded image is modulated by the reference image to obtain a modulated image, which is integrated over time to yield the inner product of the test and reference images, which is used as a correlation output.

patterns are both real, its operation can be expressed as their cross correlation:

$$(T * R)(t) = \int_{-\infty}^{\infty} T(\tau)R(t+\tau)\mathrm{d}\tau, \qquad (1)$$

where t is the time delay of the reference pattern, $R(\tau)$, with respect to the temporal representation of the test image pattern produced by the imager, $T(\tau)$. In practice, the two patterns are multiplied and then integrated in the time domain (Fig. 1). Equation (1) indicates that $(T * R)(0)$ can be used as a decision metric for image identification.

To prove the functionality of the OTAIC, we constructed a one-dimensional (1D) STEAM imager, as shown in Fig. 2(a). The optical source is a mode-locked femtosecond pulse fiber laser with a pulse repetition rate of 36.7 MHz. After supercontinuum generation and bandpass filtering, a nearly flat spectral shape with ~20 nm bandwidth centered at 1590 nm is produced for illumination. A pair of diffraction gratings with 1100 lines/mm converts a broadband pulse into a 1D spatial rainbow pulse, which is incident onto the test sample. The image of the test sample is encoded into the spectrum of the reflected 1D pulse, which is directed toward the OTAIC via the optical circulator. Pulses are repeated for repetitive scans (frames). The electrical pulse train from the mode-locked laser, which synchronizes with the optical pulse train, is used as a trigger for the OTAIC.

As a proof of concept, we used a test sample with a binary pattern (barcode) that consists of absorptive and reflective parallel lines. While the method described above can identify analog image patterns (e.g., fingerprints and cells), an additional component was added to the system for the unique recognition of digital (binary) patterns. More specifically, we employed a balanced (differential) detection scheme in which the difference between two complementary outputs of the OTAIC is used as a decision metric.

To optically simulate Eq. (1), we constructed the apparatus shown in Fig. 2(b). The electrical pulse train from the mode-locked laser is multiplied by the phase-locked frequency synthesizer by a factor of 88. The pulse pattern generator with 12.5 GHz pulse rate produces an electrical pattern based on the reference pattern, which is fed into a dual-output $LiNbO_3$ Mach–Zehnder modulator that produces complementary outputs. Preceding the modulator, a dispersive fiber with negative dispersion (−404 ps/nm) stretches the image-encoded spectrum into a temporal waveform [Fig. 2(c)] that is subsequently modulated by the reference pattern. To integrate the optical pulse in time, an SMF-28 fiber with a nearly equal amount of dispersion to the negatively dispersive fiber but with the opposite sign is used to compress the modulated image-encoded pulse. This is subsequently detected by the high-speed photodetector and further integrated in the low-pass filter with a cutoff frequency of 10 GHz. The integrated signal is digitized by the real-time oscilloscope with 16 GHz bandwidth and 50 GS/s sampling rate to yield the correlation output. In this fashion, both outputs of the modulator enter the same set of the fiber, photodetector, low-pass filter, and digitizer to generate the complementary outputs, the difference of which is computed in the digital domain to obtain the final correlation output. This balanced detection also eliminates common mode noise and distortion in the signal.

In the first experiment, we tested various test barcode patterns against a fixed reference pattern. Figure 3 shows the correlation output from the OTAIC for four different test patterns that consist of 10 bars against the fixed reference barcode. The separation between consecutive pulses (image frames) is 27.2 ns, which corresponds to a frame rate of 36.7 MHz. The OTAIC shows a large contrast in the correlation output between matched and unmatched cases, providing excellent discrimination.

In the second experiment, we tested real-time frame-by-frame correlation detection between a fixed test pattern and a reference pattern that is updated at every frame. This technique is not possible with the conventional methods at this speed due to the slow response of their spatial optical elements. The pattern generator was programmed to change the reference pattern at every frame for all possible $2^{10} = 1024$ reference patterns randomly. As shown in Fig. 4, the real-time frame-by-frame image cor-

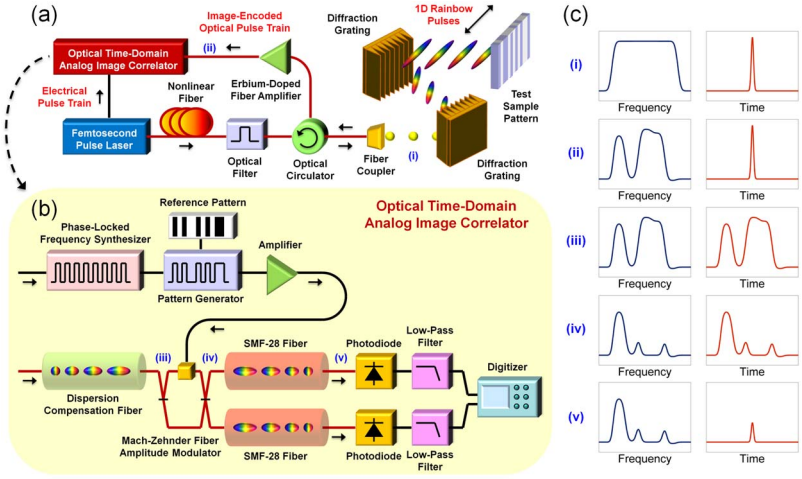

Fig. 2. (Color online) Schematic of the OTAIC on the STEAM platform. (a) STEAM with the OTAIC. (b) Details of the OTAIC that performs the optical analog image correlation detection. (c) Evolution of the optical pulse.

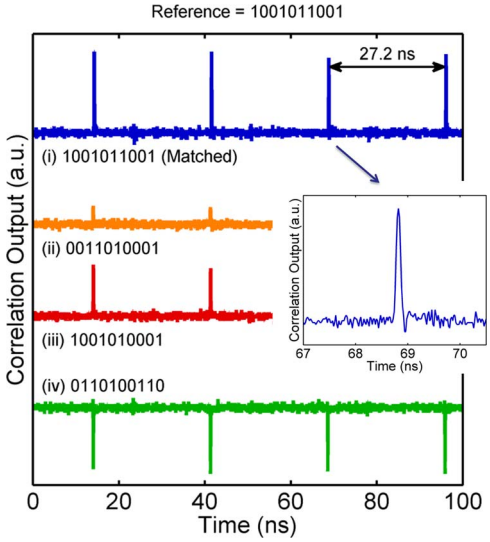

Fig. 3. (Color online) Correlation output for various test barcode patterns against a fixed reference pattern (1001011001): test patterns which are (i) equal to, (ii) very different from, (iii) only 1 bit different from, and (iv) completely opposite to the reference pattern. The largest peak (i) is produced when the test and reference patterns are matched, while the smaller peaks indicate the absence of a match. The largest peak with the opposite sign (iv) appears when the image and reference patterns are opposite.

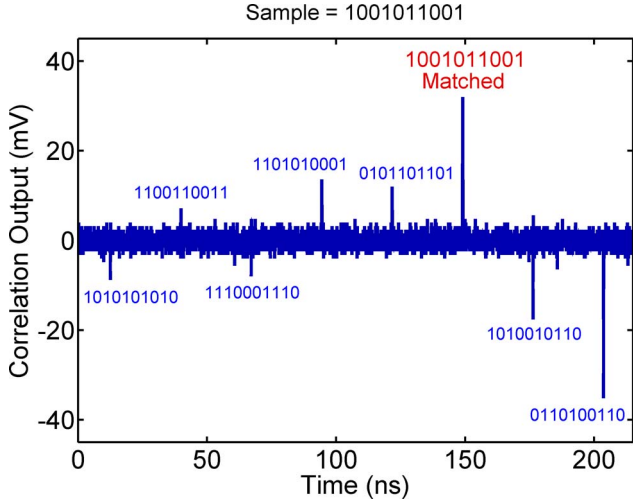

Fig. 4. (Color online) Demonstration of the real-time frame-by-frame analog image correlation detection. The correlation was obtained for a fixed test barcode (1001011001) against a reference barcode that is updated at every frame for all possible $2^{10} = 1024$ reference patterns randomly. The positively largest peak indicates the match between the test and reference patterns, while the smaller peaks show their disagreement.

relation detection at the record rate of 36.7 MHz was demonstrated.

The high-speed real-time operation of our system is made possible by its ability to seamlessly perform the image acquisition, correlation, and signal integration in the optical domain before the analog-to-digital converter. This reduces the image recognition to a simple threshold detection problem. It also significantly reduces the amount of information that must be stored and processed in the digital domain. This is the key to performing fast real-time image acquisition and processing. Also, the use of the time-domain modulation allows us to update the reference pattern in real time—a capability not shared by conventional spatial-domain correlators. Moreover, our method is advantageous over the delay lines correlator [10] and other fast spatial-domain optical correlators [11] in that it can uniquely recognize images and does not require any special preparation for reference patterns. While in this proof-of-principle demonstration, we used 10 bit barcodes for simplicity, the system is capable of processing up to 340 bars or image pixels per frame, which is constrained by the bit rate of the pattern generator (12.5 Gbit/s) in our system.

In summary, we have demonstrated a new method for optical analog image correlation detection that operates in the time domain at the record correlation rate of 36.7 MHz—about 1000 times faster than conventional methods. While in this demonstration, the image correlation was performed with 1D STEAM, it can naturally be extended to two-dimensional STEAM by replacing the 1D diffractive element with a pair of orthogonally oriented spatial dispersers [8]. Furthermore, if used with a flow cytometer, the combination of the STEAM and OTAIC has tremendous potential, as it can enable high-throughput identification of rare cells through their unique morphological and phenotype features [12].

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