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Adaptive spectra-selective imaging by real-time photoconductor bias modulation

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Modern multispectral / hyperspectral imaging systems provide vast amounts of information, but the subsequent data analysis requirements put an enormous strain on downstream data handling and digital signal processing resources. Since most spectral sensing tasks are decision-based and well defined, involving discrimination among a set of known spectral targets, ideally sensing systems would only detect spectra of interest and generate no other data. To that end, recent research has focused on developing new spectral information processing techniques for adaptive, real-time analysis in the optoelectronic domain. In previous work [1-2] we introduced the method of adaptive time-domain filtering (TDF) for real-time spectral discrimination. Instead of a typical filter or grating spectrometer, we implement a Fourier transform spectrometer (FTS) that generates a time-varying interferogram signal containing all spectral information in a pixel. Instead of sampling and digitally processing this signal, correlation with a set of known spectra is performed in the time-domain by measuring interferograms with a photodetector, multiplying them by electrical reference interferograms that represent the known spectra, and integrating. This inner product is recorded for each reference, and a simple comparison of the output values (the highest corresponds to the matching spectrum) completes the discrimination task. This method drastically reduces the data handling burden and the system can be readily adapted to wide range of sensing tasks by changing the reference functions serving as filters.

Here we present an improved TDF architecture that combines the photodetector and multiplier functions in a single optoelectronic element, a photoconductor (PC). The current output of a PC can be proportional to voltage bias as well as optical intensity, allowing for multiplication of electrical and optical signals. Real-time modulation of PC voltage bias, synchronized with interferogram generation, yields photocurrent proportional to the product of the optical input interferogram and bias modulation. This detector-multiplier stage is connected directly to an integrator stage, and at the end of the interferogram generation period the integrator output value is sampled; this completes the inner product calculation (see Fig. 1). Given the potentially simple fabrication of PC arrays and an integrator per pixel, a compact, completely parallel, spectra-selective imaging system would be possible.

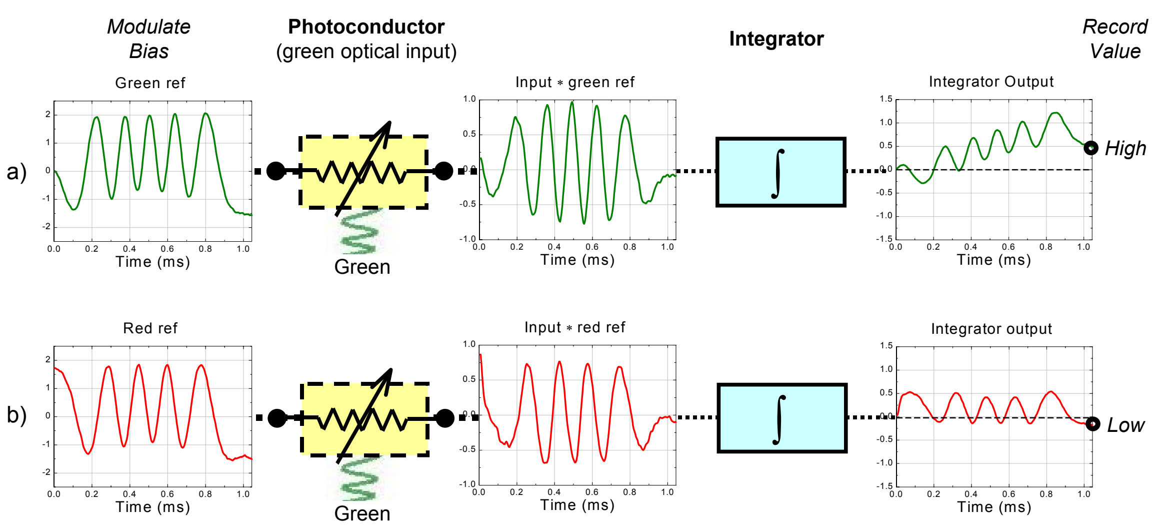
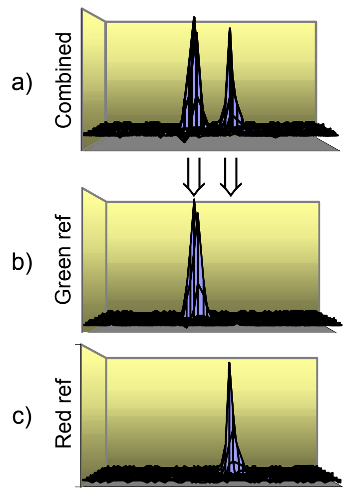


Fig. 1. A green optical input is tested with prerecorded green (a) and red (b) reference interferograms, in series. For each case the PC bias is modulated with an AC-coupled reference (left graphs), multiplying the optical input and electrical reference (center). After integration over one interferogram length (right), the final value is recorded. Direct comparison of these output values completes the discrimination task.

This method was demonstrated with a single-pixel Michelson interferometer. The optical test sources were a 230 μW HeNe laser at 543 nm (green) and a 370 μW HeNe laser at 633 nm (red), focused to adjacent spots in an image plane. A 2-D galvomirror system scanned the image plane, allowing each pixel to be measured by the interferometer. The moving mirror was a 472 Hz continuous-scan Au-coated Si MEMS actuator with 1.4 μm scan length [3]. The detector was a 20 μm × 20 μm photoconductor with Au interdigitated fingers with 1 μm width and 1 μm spacing on semi-insulating GaAs. A constant PC bias of 0.5 V was used for recording reference interferograms, and a –2 V to 2 V range was used for bias modulation. Bias modulation functions must be AC-coupled; linearity and positive-negative symmetry of the photocurrent vs. bias voltage curve are required to perform multiplication with AC-coupled reference functions [3]. Fig. 1 shows experimentally measured electrical functions at each stage for discrimination between the red and green test sources. By measuring the real-time integrator outputs and comparing for each pixel in a 2-D plane, selective imaging was performed (Fig. 2). This system can also be used to sense non-laser sources; this method is valid for arbitrary target spectra.



	Sampling Rate	Samples	Time	Digital Processing
FTS	$\frac{1}{f} \cdot \frac{2\lambda_{min}}{\Delta\lambda}$	$\frac{2\lambda_{min}}{\Delta\lambda}$	$\frac{1}{f}$	• AC-couple • Nonlinearity compensation • Fourier transform • Matched filter
PC	$\frac{1}{f}$	n	$\frac{n}{f}$	• Threshold • Comparison of n values

f	Mirror scan frequency
1/f	Interferogram acquisition time
$\lambda_{min}/\Delta\lambda$	Spectral resolution (R)
n	Number of spectral references

Left: Fig. 2. Output amplitude across image plane. The combined output graph (a) simply shows the presence of two high intensity spots. However, scanning the image with PC bias modulation corresponding to the green (b) or red (c) reference tunes sensitivity specifically to green or red, allowing for selective imaging.

Right: Table 1. Comparison of key system requirements for selective imaging with FTS and PC methods.

Compared to the traditional FTS method of interferogram sampling and intensive digital processing, the PC method can drastically reduce sampling rate, sample number, and digital data processing requirements for a wide range of common multispectral sensing tasks (Table 1). Whereas the sampling requirements for FTS are dependent on desired spectral resolution and interferogram acquisition time, the PC method is only sensitive to interferogram acquisition time and number of spectral references. For typical required resolution (e.g. R = 50) and a moderate number of references (n ~ 10), our method requires a much lower sampling rate (100× lower), generates less data (10× less), and requires much simpler digital processing. Thus, when a sensing system is data storage / transfer / processing limited, as in many remote sensing, 2-D hyperspectral, and mobile systems, the PC method is preferable.

In conclusion, we have presented the first implementation of real-time adaptive TDF with only two stages—a photoconductor and integrator—for 2-D selective imaging. This architecture eliminates unnecessary data in the optoelectronic front end, enabling extremely simple spectra-selective detection arrays. For a wide range of common, well-defined sensing tasks, system sampling and data handling requirements are significantly reduced. The PC bias modulation method could enable a new class of compact, efficient, mobile spectral imaging systems.

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