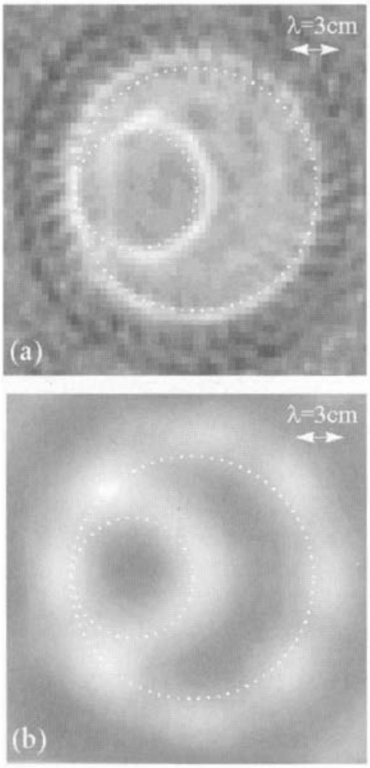
munity with the possibility to test imaging methods on experimental microwave data. Figure 1a is the image of the IPS007 object that can be recovered comparatively easy using the Born approximation. The IPS008 object with the same geometry but $k_0Va \approx 50$ represents a challenge for the whole community. Figure 1b, in fact, is a state-of-the-art reconstruction.

On the one hand, Figure 1b illustrates that a further sophistication of our method is necessary to permit quantitative imaging with acceptable resolution of strongly scattering objects. On the other, a comparison with competitive methods[4] proves that homomorphic filtering is a very promising approach to inverse scattering. It also supports our belief that signal processing techniques are well suited to provide fast, reliable, and numerically stable alternatives to iterative reconstruction methods.



Sanchez Figure 1. Reconstruction of objects from the Ipswich experiment: (a) IPS007 ($k_0Va < 0.01$) and (b) IPS008 ($k_0Va \approx 50$). Both targets have the same geometry (dotted lines), but different permittivity.

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References

1. J.B. Morris *et al.*, "Nonlinear filtering applied to single view backpropagated images of strong scatterers," J. Opt. Soc. Am. A **13,** 1506–1515 (1996).
2. A.V. Oppenheim and R.W. Schafer, *Digital Signal Processing* (Prentice-Hall, London, U.K., 1975), Chapter 10, pp. 480–531.
3. Measured data provided by the Electromagnetic Technology Division, AFRL/SNH, 31 Grenier St., Hanscom AFB, MA 01731–3010 (Ftp: ercthp1.rl.plh.af.mil).
4. D.A. Pommet *et al.*, "Imaging of unknown targets from measured scattering data," IEEE AP Magazine (1998), (accepted).

Application of Smart Pixels to Optical Implementation of the Wavelet Transform

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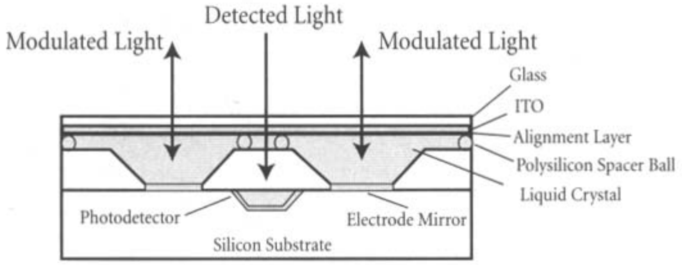
The concept of wavelets is based on fundamental ideas in transform domain processing, which were first expressed centuries ago in a variety of forms. However, it is only within the past decade, since the pioneering work of Daubechies demonstrated the relationship between wavelets and subband transforms, that significant progress has been made in applying wavelet theory to practical signal processing problems. Since then, there has been an explosion of interest in wavelets and subband transforms for wide-ranging applications in signal processing, communications, biomedical techniques, and many interdisciplinary fields.[1, 2] The wavelet transform can be implemented using any type of real-time optical correlator. Many optical architectures have been proposed for implementation of the wavelet transform; most of these are based on the Vander Lugt 4-f correlator, the joint transform correlator, or its derivatives such as the quasi-Fourier transform joint transform correlator.[1, 2] We propose to use the advantages of both optics and electronics by demonstrating the use of a smart pixel array as a reflective spatial light modulator (SLM) when implementing the wavelet transform architecture.

Smart pixels are a relatively new technology that closely integrates silicon electronic circuitry and optical devices on a common chip.[3, 4] A 2-D array of smart pixels, which potentially includes optical sources and modulators, detectors, and electronic gain or signal processing functions, can provide both electrical and optical inputs and outputs. The use of smart pixels as a high-speed, programmable SLM is well-suited to a broad range of signal processing problems. There have been many proposed fabrication methods for smart pixels, including monolithic integration, direct epitaxy, epitaxial liftoff, and other hybrid techniques. In particular, liquid crystal on silicon (LCOS) is a hybrid approach with tremendous potential for smart pixel applications.

As illustrated in the cross-section view of Figure 1 (page 48), electronic circuitry is first fabricated on a conventional complimentary metal oxide silicon (CMOS) substrate, including regularly spaced metal contact pads on the chip surface. A cover glass coated with a transparent conductive material such as indium tin oxide (ITO) is then placed on polysilicon spacers and mounted on top of the silicon circuitry (alternately, the cover glass may be mounted atop the natural contours of the processed circuitry). This creates a cavity between the cover glass and the silicon circuitry, which is filled with liquid crystal material. A thin layer of obliquely evaporated silicon monoxide or rubbed polyvinyl alcohol is deposited on the ITO; this makes contact with the liquid crystal material and induces spatial alignment of the liquid crystal molecules.

The liquid crystal is thus in contact with both the alignment layer beneath the conductive coating on the glass and the metal pads on the silicon circuitry. An electric field between these two defines individual pixels at the location of the metal pads. If the pixels are then illuminated, modulation of the electric field results in a corresponding modulation of the phase, intensity, or polarization of the optical signal. In practice, a polarized optical beam is imaged through the liquid crystal onto the metal pads, which also act as high-reflectivity mirrors for the modulated optical beam. In the case of photodetectors, the liquid crystal is not dynamically modulated and the incident optical beam is simply absorbed by the silicon detector.

For a proof-of-concept demonstration, an 8 × 8 LCOS smart pixel array was fabricated on a common substrate



Shoop Figure 1. Cross-section view of smart pixel devices.

with a 1 × 8 linear input photodetector array. The design was implemented using a 2.0-μm silicon CMOS process on a single 6900 × 6800 μm chip. The smart pixels used a liquid crystal material known as BDH SCE-13, which has a birefringence of 0.17 and a maximum polarization axis rotation of 22°. Results from characterizing the smart pixel photodetectors, replication circuitry, multiplication circuitry, and LCOS modulators have been reported previously.[4–6] A contrast ratio of about 25 has been measured, and theoretical switching speeds of 33 ms can be realized with an applied electric field of 10 V/m.

The results of this experimental characterization clearly demonstrate the applicability of this smart pixel technology to analog signal processing applications in general, including wavelet transform applications. The accuracy of the photocurrent representations internal to the electronic circuitry indicate that process uniformity did not adversely effect this functionality and that scaling to larger-sized arrays is possible. The multiplier circuit, which operated above threshold and over a restricted operating range of ± 100 mV, provides sufficient linearity for this analog application. The LCOS modulators provide sufficient speed and linearity to accurately represent the Fourier transform of the wavelet transform at speeds up to video frame rates. Together these results indicate that a larger smart pixel architecture could provide the functionality necessary for the real-time computation of the wavelet transform in a 4-f correlator architecture.

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References

1. A. Bruce *et al.*, "Wavelet analysis," IEEE Spectrum **33**, 26–35 (1996).
2. C. DeCusatis *et al.*, "Hybrid optical implementation of discrete wavelet transforms: A tutorial," Optics and Laser Tech. **28** (2), 51–58 (1996).
3. B.L. Shoop *et al.*, "New Devices for Optoelectronics: Smart Pixels," *Handbook of Fiber Optic Data Communication*, C. DeCusatis *et al.*, eds. (Academic Press, San Diego, CA, 1997), Chapter 20, pp. 705–758.
4. D.M. Litynski *et al.*, "Optical Implementation of the Wavelet Transform using Smart Pixels," SPIE Proc. International School-Seminar on Acousto-optics and Applications, Gdansk, Poland (1998), to be published.
5. B.L. Shoop *et al.*, "Smart Pixel Based Wavelet Transformation for Wideband Radar and Sonar Signal Processing," Proc. SPIE **3078**, 415–423 (1997).
6. D.A. Hall *et al.*, "Experimental Results From a Smart Pixel Implementation of the Wavelet Transform For Signal Processing," Proc. SPIE **3391**, 168–178 (1998).

SOLITONS

Dark Incoherent Solitons

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Dark beams are nonuniform optical beams that contain either a 1-D dark stripe or a 2-D dark hole resulting from a phase singularity or an amplitude depression in their optical field. Thus far, self-trapped dark beams (dark solitons) have been observed using coherent light only. Recently, however, we have demonstrated self-trapping of dark incoherent light beams (or, in a broader prospective, self-trapping of dark incoherent wave-packets in nature) for the first time.[1] Both dark stripes and holes (vortices) nested in a broad partially spatially incoherent wavefront were shown to self-trap and form incoherent dark solitons in a nonlinear photorefractive crystal. These self-trapped 1-D and 2-D dark beams induce refractive-index changes akin to planar and circular dielectric waveguides, which introduces the possibility of controlling high-power laser light with low-power incoherent optical sources such as LEDs.

A spatially incoherent beam is a "speckled" multimode beam of which the instantaneous intensity pattern contains many speckles that vary randomly in time. Such an incoherent beam cannot self-trap in a material with an instantaneous nonlinearity, as each individual speckle forms a small lens, which in turn captures a fraction of the beam and eventually causes the fragmentation of the beam's envelope. However, in a noninstantaneous nonlinearity, where the nonlinear medium responds to a time-averaged intensity, self-trapping of an incoherent beam is achievable. This was first demonstrated with bright incoherent beams by use of a photorefractive self-focusing nonlinearity.[2] The theory of bright incoherent solitons was subsequently developed.[3] Later on, our numerical simulations suggested that self-trapping of dark incoherent beams is also possible in photorefractive media.[4] Incoherent solitons are altogether new entities since their phase distribution is random. This is especially true for dark solitons for which the transverse phase is supposed to play a crucial role. In fact, dark incoherent solitons represent a fundamentally new concept, and their underlying mechanism has been investigated theoretically only very recently.[4]

Our experiments of dark incoherent solitons are performed with a quasi-monochromatic spatially incoherent light source, generated by passing a laser beam through a rotating diffuser.[1, 2] The rotating diffuser introduces a new speckle pattern every ~1 μs, much faster than the re-