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Optical Implementation of the Wavelet Transform By Using a Bacteriorhodopsin Film as an Optically Addressed Spatial Light Modulator

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The Fourier Transform (FT) is a powerful technique commonly used for the analysis and processing of signals. In the FT, sines and cosines are the basis functions used to represent an arbitrary signal. Fourier basis functions have the drawback of being localized only in frequency but not in time or space. In order to overcome the limitations of Fourier analysis with regard to the representation of transient signals, localized in time or space, the windowed FT and more recently the wavelet transform (WT) were introduced. Wavelet analysis represents a signal in terms of a family of functions derived from a single basic function called a wavelet. Signal analysis is accomplished by translating and scaling the wavelet function. While the FT gives global information about a signal, evaluating the WT at various scales and translations yields local frequency information about a signal. Optics with the inherent advantage of speed and ease of parallel processing has been utilized by several researchers¹ for implementation of WT. In the frequency domain, the WT is the product of the FT of a wavelet (wavelet filter) and the FT of a signal. The wavelet filters act as band pass filters, thus the WT in optics amounts to a spatial filtering operation. Since the FT is translation invariant, only scaling operations on the wavelets are required for spatial filtering. Scaling of the wavelets can be accomplished using a combination of lenses or a spatial light modulator. We implemented² optically the WT by using a Bacteriorhodopsin (bR) film as an optically addressed spatial light modulator, in which a computer generated wavelet can be imaged on a bR film. The bR film is kept at the FT plane in a 4f imaging system as shown in Figure 1. Dichroism induced by the wavelet filters displayed on the bR film leads to polarization rotation for wavelet selected Fourier components of an input image. The rotated Fourier components are analyzed to extract the wavelet transformed components.

In optical engineering, bR has several intrinsic properties of importance: it is more sensitive to light than inorganic crystals, thus the wavelet processor can be realized with very low light levels resulting in an extremely energy efficient device. The spectrum and kinetic aspects of the bR photocycle can readily be modified by replacing the retinal chromophore with natural and synthetic analogs which can shift the bR spectrum to virtually any color and by genetic mutations attained by biotechnological procedures. The cost of producing and its environmental friendliness make it an

Joseph Figure 1.

attractive material. A crystal like architecture makes bR very stable. Dry films of bR have been stored for several years without degradation and are structurally stable up to a temperature of 140°C. A unique feature of our method is that the WT is obtained in real time. As no interference is involved, vibration isolation and a coherent source are not required. We have thus demonstrated the feasibility of a real time, field deployable, efficient and environmentally friendly optical wavelet image processor.

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Solitons

Polarization-locked Temporal Vector Solitons In an Optical Fiber

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Temporal vector solitons have components along both birefringent axes. Despite different phase velocities due to linear birefringence, the relative phase of the components can be locked at $\pi/2$. These fragile polarization-locked vector solitons (PLVS) have been the subject of much theoretical conjecture,¹ but have previously eluded experimental observation.

Polarization preserving solitons occur due to interplay between birefringence and the nonlinear index of refraction (Kerr effect). In order for the nonlinear index of refraction to exactly cancel the linear birefringence, the soliton must have sufficient energy. Hence, polarization locked solitons appear above certain threshold that can be achieved inside the laser cavity. We have studied² the polarization evolution of solitons circulating in a mode-locked fiber laser and observed that PLVS form for low amounts of intracavity birefringence.

The experimental setup is shown in Figure 1a. The fiber laser consists of three pieces of single mode fiber fusion spliced together. By changing the angles of the two polarization control paddles, Θ_1 and Θ_2 , we can adjust the total cavity retardance (the total birefringence in the cavity) from zero to approximately a full wavelength. To measure the round trip retardance in the laser cavity, we pass the output

Cundiff Figure 1. (a) Experimental setup; (b) Measured polarization evolution frequency (Δ) as a function of the angles of the intracavity polarization controllers Θ_1 and Θ_2 . Colors represent Δ , which can be mapped into total cavity birefringence. (c) Same as (b) but at higher pulse energy.

tically polarized output observed in the gray regions in Figure 1b has nonzero components along both principal axes, a requirement for a PLVS. To verify that the pulse is a PLVS, we completely characterize the polarization state by measuring both the amplitude of the components along the principal axes and relative phase. It is also important that our laser is a low perturbation fiber laser, which provides a good approximation to a conservative system. Our numerical simulations show that the properties of PLVS in such a laser are very close to those described in Reference 1. On the other hand, when deviations of the laser system from the conservative limit are higher, theory shows³ that PLVS also exist.

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Soliton Effects in an AlGaAs Bragg Grating

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Experimental and theoretical research exploring the nonlinear properties of periodic structures has intensified over the past decade within a diverse range of materials utilizing both second and third order effects. Recently we studied the nonlinear transmission characteristics of high intensity pulses propagating through 4-10 mm long gratings etched into ridge waveguides formed in AlGaAs. In our experiments we were able to directly measure for the first time the nonlinear spectral broadening associated with significant nonlinear pulse compression from 400ps to 80ps, thereby providing an invaluable insight into the nonlinear pulse formation process. In addition we were

able to reproduce nonlinear effects previously demonstrated using Bragg fiber gratings,^{1,2} including the production of Bragg solitons and multiple gap solitons at considerably lower switching powers and for substantially shorter device lengths,³ thus enhancing the feasibility of ultrafast optical grating based switches.

The integrated waveguide filters were fabricated using a simple one step electron beam lithographic process,⁴ which allows the grating characteristics to be engineered and controlled with great accuracy. The MBE grown AlGaAs wafer consisted of the following layers: a 1.5 μ m thick AlGaAs guiding layer with 18% Al sandwiched between a 1 μ m thick AlGaAs top cladding with 24% Al and an AlGaAs bottom cladding 4 μ m thick with 24% Al. The grating period was 235 nm. The waveguides, 5 μ m wide, were etched to a depth of 0.9 μ m. The grating depth was approximately 0.3 μ m.

In the experiments we used 415 ps pulses with a repetition rate of 100 kHz and peak power of 1.4 kW. The pulses were coupled into and out of the waveguides using an end-fire rig. A high resolution commercial spectrum analyser and fast optical detector/sampling scope were employed to monitor the input and transmitted pulse shapes.

Figure 1a shows the grating transmission spectrum of a 1cm grating with a 0.2 nm stopband width and maximum reflectivity of 99%. We tuned the input pulse to lie outside the grating stopband and measured the transmission characteristics of the grating in the linear and nonlinear regime. We observed no significant temporal or spectral change in the transmitted pulse shape as the input power was increased. We then tuned the light to lie at various positions within and near the grating stopband. Figure 1a shows the transmitted pulse spectrum of a pulse tuned within the gap for both low and high input powers. Figure 1b shows the corresponding output temporal pulse shapes for the two input power levels. It is clear from Figure 1a that considerable spectral broadening occurs in the nonlinear regime and is decidedly asymmetric in nature. Distinct peaks observed in the spectrum were attributed to the formation of multiple gap solitons. As shown in Figure 1b the spectral broadening is associated with significant pulse compression. The results of numerical modelling of our devices using standard nonlinear coupled mode equations

Millar Figure 1. (a) shows the transmitted pulse spectrum of a pulse tuned within the gap for both low and high input powers. (b) shows the corresponding output temporal pulse shapes for the two input power levels.