OPTICAL PROCESSING

Coherent Optical Wavelet Transforms

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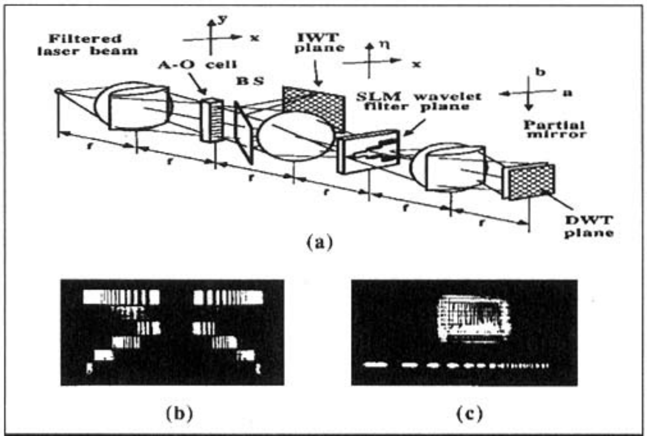
After a successful application to the analysis of seismic data in 1984, geophysicist J. Morlet[1] formalized the concept of wavelets by generalizing similar mathematical and physical decomposition concepts from the previous works of Harr (1910), Gabor (1946), Calderon (1964), etc.. Closely related to the concept of pyramids, the key component of the wavelet theory is a set of look-alike functions called wavelets that can form an efficient and powerful decomposition basis. Any square-integrable signal can be selected as the so-called mother wavelet that, in turn, generates a family of daughter wavelets by dilations.

An unique feature of the wavelet processing is that not only a multi-resolution signal decomposition can be achieved through a set of linear correlation operations between the input signal and the wavelets, but also the original signal can be reconstructed from the decomposed signals through their convolutions with the same set of wavelets. One other interesting feature of the wavelet processing is its capability of forming an orthonomal decomposition basis allowing for an efficient sampling, which could not be achieved by other existing windowed Fourier transforms, such as the Gabor transform. In addition to a successful application to the seismic and geological data, the usefulness of the wavelets to the fractal, turbulence, speech, and vision analysis, as well as to other industrial and military signal and image processing applications, has also been recognized recently.

Since a complete wavelet process consists of a direct (DWT) and an inverse (IWT) wavelet transform characterized by a set of parallel linear correlation and convolution operations, extensive computations are expected. Furthermore, the coordinate expansion and reduction required by the transforms may add computational complexity to digital electronics. Free-space optics, which is inherent to massively parallel linear operations, is expected to have solutions to these problems.[2,3]

Research on optical wavelet processing has been initiated at various institutions, industrial, and government laboratories. We recently reported a coherent optical method of generating DWT and IWT of one dimensional signals through parallel band-pass filtering.[2] In part (a) of the figure, a compact version of such a setup is sketched. The 1D signal is entered through an acousto-optic device and is spatially filtered through a set of wavelet filters generated at a spatial light modulator (SLM). The filtered signals are inversely Fourier transformed and imaged along the b- and a-axes to complete the parallel spatial correlation operations to obtain the DWT. What is more interesting is that the same setup could be used to obtain the IWT by inserting a partial end mirror to reflect the DWT wavefront back into the system. The mirror reflected signal is filtered again through the wavelet filters (but resulting in parallel convolution opera-



(a) A compact optical wavelet processor that generates direct (DWT) and inverse (iwt) wavelet transforms in parallel, (b) a 1D input chirp signal (top) and its five channel optical wavelet decompositions, (c) the optically reconstructed original chirp using the decomposition results of (b).

tions) and is separated by a beamsplitter to a second output plane to complete the IWT production. Thus, in a natural and compact way, optics lends itself to processing the wavelet transforms of 1D signals.

In part (b) and (c) of the figure, experimental data of optical DWT and IWT of a spatial chirp-signal are displayed. Using a more complicated geometry, optical DWT and IWT of 2D images is also implementable and was experimentally tested by us and by other groups of researchers.[4] The successful applications of optical wavelet transforms could generate a great impact on the future research in the areas of optical signal and image processing, pattern recognition, data compression and communication, machine vision, and artificial intelligence.

REFERENCES

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Femtosecond Waveform Processing via Spectral Holography

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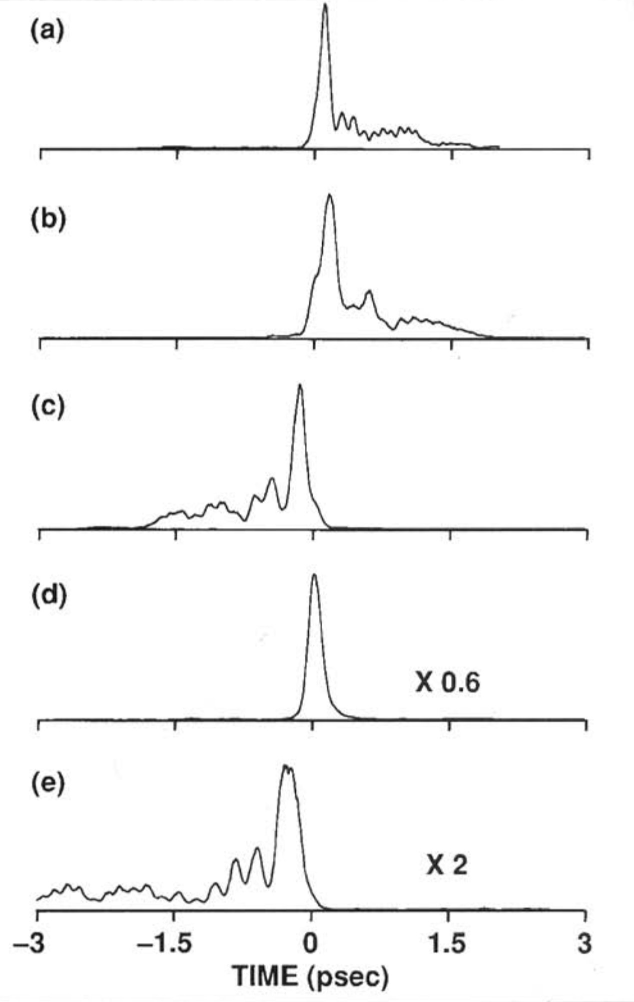
Although the technology of generating femtosecond optical pulses is now rather advanced, our ability to manipulate or process ultrashort pulses is still limited. Techniques for accomplishing linear filtering of ultrashort pulses have been developed and have been used to precisely synthesize femtosecond pulse waveforms.[1,2] Nevertheless, certain basic signal processing operations, such as time reversal, correlation, and convolution, cannot be achieved by linear filtering. In this summary, we describe the use of holographic processing techniques to perform nonlinear filtering of femtosecond waveforms.[3]

Our experiments constitute a temporal analog of off-axis, Fourier transform, spatial holography, in which information on a patterned signal beam is recorded as a set of fringes arising due to interference with a spatially uniform reference beam. In our temporal work, the reference is a short pulse with a broad and regular spectrum. The signal is a shaped pulse with information patterned onto the spectrum. The experiments are performed by directing reference and signal beams into a grating and lens apparatus that spreads the incident pulses into their constituent spectral components. Previously, pulse shaping was achieved by using spatially patterned masks to filter the individual optical frequencies.[1] Now the pre-patterned mask is replaced by a holographic recording material. Spectral holograms are written by recording the interference between matching frequency components from signal and reference beams.[4] Different frequency components are recorded at different spatial positions of the hologram, which in our experiments is a thermoplastic plate. Illumination of the spectral hologram with a short test pulse produces either a real or a time-reversed reconstruction of the initial signal waveform, depending on the experimental geometry, just as reconstruction of off-axis spatial holograms can yield either real or conjugate images.

Conceptually, our spectral holography experiments are related to previous work demonstrating storage and recall of optical waveforms by using photon echoes.[5] Recent experiments using direct time-domain holography have also demonstrated storage and recall of simple femtosecond waveforms.[6]

An example of our data is shown in the figure. Signal and reference pulses were derived from a CPM dye laser. An auxiliary pulse shaper was used to impose a cubic spectral



Intensity cross-correlation measurements, showing holographic storage and recall of a signal pulse distorted via cubic spectral phase modulation. (a) input pulse, (b) real reconstructed output pulse, (c) time-reversed output pulse, (d) autocorrelation of the signal field, obtained by using a shaped test pulse, and (e) time-reversed autoconvolution of the signal field, obtained by using a shaped test pulse.