All-Optical Integrated System for 2D Data Wavelet Transform and Compression

Giorgia Parca, Pedro Teixeira, António Teixeira

***Abstract*— Optical transform is considered as a powerful tool for optical signal/image handling. Efficient schemes for data compression at the speed of light can be implemented, enabling lower processing requirements, energy efficiency, lower latency (transmission time), reduced memory usage. The goal is the development of parallel processing systems for 2D optical data maintaining functionalities in the optical domain.**

In this paper we present an all-optical integrated system for wavelet based decomposition and compression of 2D optical data.

***Index Terms*— optical image processing, optical wavelet transforms, 3D interferometric structures, parallel processing.**

I. INTRODUCTION

The need to increase the capacity of information exchange motivates the efforts and the recent developments on exploiting the speed and the parallelism of the light for information processing at high data rate.

Reduction of redundancies or unnecessary information is crucial and enables faster data transmission, especially in case of large data amount to be processed and/or stored with real time processing requirements.

Information contained for example in high resolution images (for biology, medical diagnosis, environment monitoring, etc...), need to be processed and compressed, by removing the least significant elements, e.g. extracting only the visible ones.

New optical technologies have been developed in order to perform fast signal processing and compression directly in the optical domain, thus providing bit-rate and signal-format independent transmission schemes, almost preserving end-to-end optical transparency.

The total size of data can be reduced substantially, resulting in lower processing and transmission time, lower storage memory, better use of the transmission media.

Compression can be obtained through mathematical transformations followed by a thresholding operation. Namely, data reconstruction can be performed using only essential features extracted from transformed data and not directly achievable from the signal in its natural representation. An example of signal decomposition operation is the Discrete Fourier Transform (DFT), [1]; it allows calculating spectral distribution of stationary signals.

In literature, there are several studies on Fourier Optics showing the effectiveness of optically DFT implementation and signal processing, using only passive Planar Lightwave Circuit (PLC), [1], [2], [3].

Wavelet Transforms is another powerful tool commonly used for data compression, as in the JPEG 2000 standard, [4], pattern recognition, and subband coding, among others. The Discrete Wavelet Transforms (DWT), [2], can be implemented exploiting very simple optical passive architectures, as well as the DFT.

The non-stationary feature of involved signals, related to the nature of the image signals and the mechanisms of human vision, must be taken into account. Signals with space (or time)-varying spectra can be transformed considering the non-stationary hypothesis. In this case, image signals can accurately represented jointly in space and frequency domains.

WT overcomes the Fourier approach limitation in representing non-stationary signals, since the local spectral decomposition can be performed. It allows analyzing the incoming signal at different scales or resolutions, [5].

These powerful tools are supported by different technologies. The most explored approach is the free space image processing [6], [7], whose basic scheme is the one called 4f setup and depending on the specific processing to implement it exploits the spectral filtering and data manipulation through holograms and phase masks.

Besides the free space techniques, the availability of passive technologies, with low loss and dispersion, such as network of single mode fibers or planar lightwave circuits [1], [3] for the implementation of optical transforms, suggests the possibility to design optical integrated architecture for image data processing.

The state of the art shows the current development of 3D structures and material optimization for the implementation of planar waveguides layered structure for three dimensional interferometry, or direct 3D writings on materials, such as sol-gel or glass, through femtosecond laser [8].

These approaches are explored with the aim to perform the parallel processing through integrated optics, enabling the implementation of compact and robust schemes for all optical wavelet transforms.

The development of integrated 3D structures for all optical processing and image compression is considered in the framework of the project CITO – Optical Transform for Image Compression.

In this paper, we present the design of an all optical architecture for image compression and we demonstrate, through simulative approach, the implementation of the Haar wavelet transform of 2D image data, exploiting 3D integrated passive interferometric structure based on optical asymmetric couplers network.

II. 3D SCHEME FOR 2D OPTICAL WAVELET TRANSFORM AND COMPRESSION

We present an architecture for all-optical image acquisition, processing and transmitting, whose building blocks are depicted in fig.1. This approach allows handling images with fast signal processing, maintaining all functionalities in the optical domain.

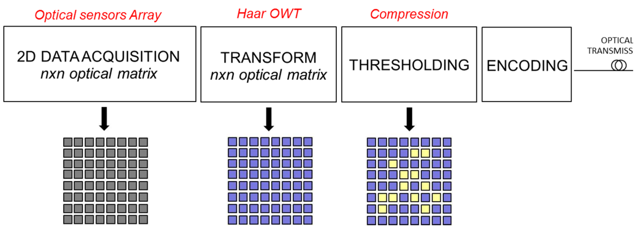


Fig.1 All-Optical System building blocks

The acquisition stage includes light detection, through optical sensor matrix, and image/2D data sampling, thus obtaining the nxn optical input data matrix.

First processing operation is used to properly represent the optical matrix in a transformed domain, with the aim to extract some specific features exploiting the energy compaction properties of wavelet decomposition.

Our approach for implementing the data decomposition, and reconstruction at the receiver side, is based on the Discrete Wavelet Transform (DWT).

Through the next functionality, corresponding to a thresholding operation, the precision reduction is performed selecting relevant portions within the coefficients set.

The selection of portions of interest from the signal decomposition can be implemented through Photonic Analog-to-Digital Converter or Non Linear devices (e.g. nonlinear crystals) and uses specific selection criteria related to the final applications and quality requirements.

Our focus is the implementation of compact and robust optical transforms exploiting integrated optics, in order to develop an alternative approach to the existing methods based on free space optical computing (e.g. holography).

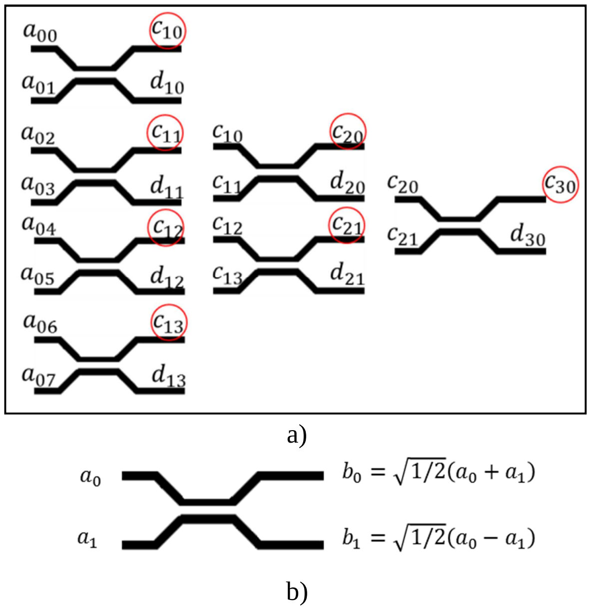
This is supported by the existence of methods and optical architectures able to implement the transform through integrated optics, namely interferometric structures based on asymmetric couplers networks.

DWT can be evaluated via recursively filtering a data array by halfband lowpass $H[n] = \sum_{k=-\infty}^{\infty} x[k]\, g[2n-k]$ and highpass $G[n] = \sum_{k=-\infty}^{\infty} x[k]\, h[2n-k]$ filters, which include subsampling of factor 2 following the Mallat pyramidal decomposition algorithm, [10].

The low-pass and high-pass filters associated with the Haar wavelet can be implemented through 3 dB asymmetric couplers [11], as shown in the next schematic of Fig. 2a), giving as outputs the scaling (c_{ij}) and detail (d_{ij}) coefficients of the input signal.

In order to implement the optical wavelet transform of a set of input data, a 3 dB asymmetric couplers network can be designed as in Fig. 2b); in this case the wavelet coefficients are computed up to the M=3 level.

This planar structure can be stacked in order to create a 3D interferometry device which is able to receive a set of input fields distributed all over a 2D pattern (e.g. pixelated image). The data decomposition can be implemented by properly coupling along the two spatial coordinates, one at time (i.e. horizontally, vertically), allowing the parallel processing of the 2D coefficients.



$$S = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \qquad (1)$$

Fig.2 a) Optical 3 dB asymmetric coupler (planar) network for 1D DWT evaluation;b) 3 dB asymmetric coupler and scattering matrix S;

For 2D data/images and higher dimensional signal processing, this network can be expanded in order to obtain a 3D integrated passive structure for parallel data processing.

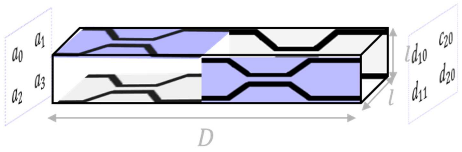
In Fig. 3a) is presented a 3D basic module with a 2x2 optical matrix as input, which perform 1 Level DWT.

First asymmetric couplers pairs will produce the first high/lowpass filtering along one dimension (e.g. horizontal). The four outputs will undergo a further stage of high/lowpass filtering along the other dimension (i.e. vertical), producing the scaling and detail coefficients of the 1 Level Haar DWT.

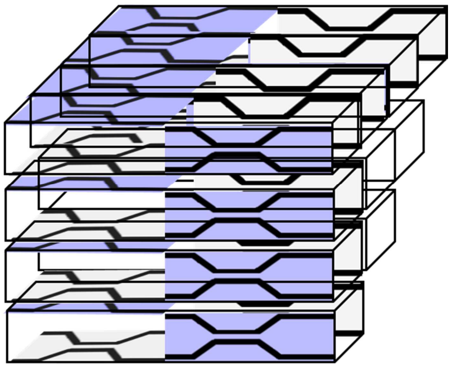
Increasing the input data set, this structure can be scaled by means of repeating and stacking the basic module presented, in order to build a NxN 3D integrated passive scheme for all optical DWT, as shown in Fig. 3 b).

The whole volume will scale with the input data set, depending basically on the length and section area of the basic module.

As instance, in case of larger images size, further DWT computation levels are needed; m 2D levels can be implemented by m layers (each one with length D) of basic stacked modules.



a)



b)

Fig.3 a) 3D basic module for parallel 2x2 data matrix optical 1 level DWT; b) NxN 3D integrated passive scheme for all optical DWT.

III. 3D OPTICAL TRANSFORM SIMULATIONS

3D module with 2D data as input was designed and emulated through Matlab simulations and one level Haar DWT based on the optical asymmetric couplers network was performed.

We considered a grey scale processing of the optical input matrix.

Fig. 4 shows the 256x256 sample image and the obtained 1 Level Haar wavelet, computed through applying the asymmetric coupler network scattering matrix derived from expanding Eq (1).

Considering the schemes presented in Fig. 3 as basic reference, first asymmetric couplers pairs will produce the first high (H) and low (L) pass filtering along the horizontal dimension. As described in Fig.4, the obtained coefficients will undergo a further stage of high/lowpass filtering along the vertical dimension, producing the scaling and detail coefficients of the 1 Level Haar DWT.

The thresholding operation was also tested for the compression data simulation, setting different amplitude threshold levels defined as a percentage of the maximum intensity value possible for the sample image.

Performance evaluation is based on the Mean Square Error MSE and Peak Signal to Noise Ratio PSNR calculation:

$$MSE\left(I_{orig}, I_{dec}\right) = \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\left|I_{orig}(i,j) - I_{dec}(i,j)\right|^2 \quad (2)$$

$$PSNR\left(I_{orig}, I_{dec}\right) = 10log_{10}\left(\frac{p^2}{MSE\left(I_{orig}, I_{dec}\right)}\right) \quad (3)$$

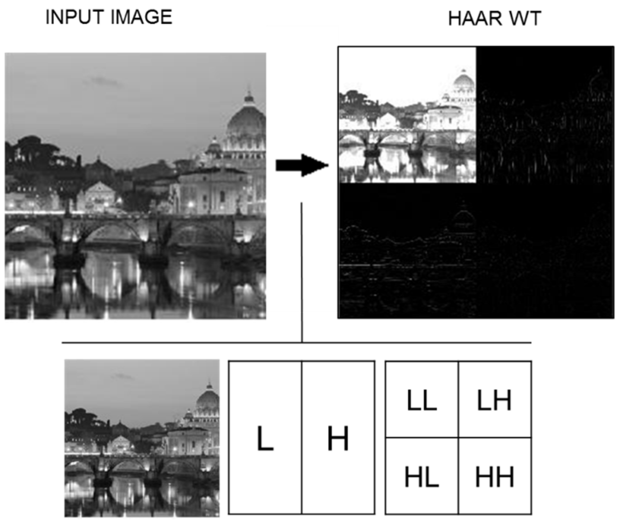


Fig. 4: Sample image (256x256) as 2D input data, 2D processing with high/lowpass filtering and obtained 1 Level Haar Optical WT.

Where I_{orig} is original optical matrix, I_{dec} is the reconstructed image after compression,p is the maximum possible intensity value for a pixel.

MSE and PSNR are evaluated for different cases, as reported in Fig. 5 and Table I, using a set of threshold values, from 10% to 90% of the parameter p. Fig.5 shows degradation due to the compression process.

In Table I we present some of the simulation results obtained for our compression test on 1 Level Haar Optical DWT. The output images correspond to the Inverse DWT performed for the synthesis procedure and image reconstruction after applying the thresholding on the DWT coefficients.

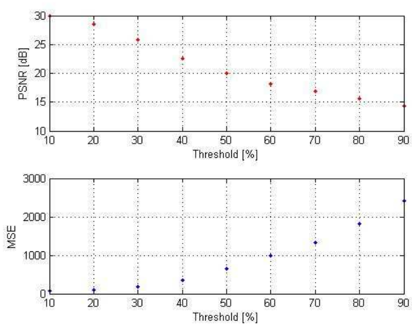


Fig. 5: PSNR and MSE as function of Threshold percentage, respect to the parameter p.

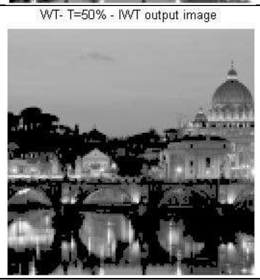
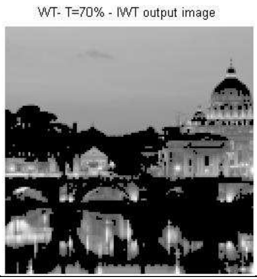
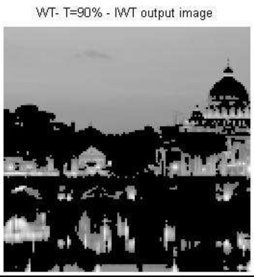
Reconstructed image	Threshold	PSNR	MSE
	10%	29.86	67.14
	30%	25.76	172.57
	50%	20.03	646.50
	70%	16.88	1.33e3
	90%	14.29	2.42e3

Table I: Reconstructed images and performance evaluation. Threshold % is referred to the maximum intensity value present in the image.

IV. CONCLUSION

We have investigated an alternative approach for the implementation of all optical 2D data processing. Wavelet transform and image compression can be accomplished exploiting an integrated scheme based on asymmetric couplers 3D network and a proof of concept is presented through simulations results.

This approach enable the parallel processing and offer potential in terms of integrability and robustness, to mechanical perturbation or vibrations, especially if compared to the free space optics approaches. Important practical evaluations will be needed be about losses, crosstalk, resolution range (image data), and architecture scalability.

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