Holographic Algorithms for On-Chip, Non-Boolean Computing

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INTRODUCTION

It is widely believed that the established route of microelectronic scaling is approaching its end: further downscaling of semiconductor devices carries disproportionate penalties in power consumption and poses fundamental fabrication challenges. Instead of scaling of devices, Moore's law is now increasingly about scaling computing systems: single-core devices toward larger, multi-core systems.

While there are known programming methodologies for parallelizing program codes to a few threads, only a very few, special-purpose applications lend themselves to parallelization on really large number of cores. This motivates our quest for studying computing paradigms and algorithms that are inherently parallel [1]. Holographic / optical computing is a perfect example of such algorithms: the results of a computation are given by an interference pattern formation of many light rays (see Fig. 1 for an illustration [1]). Optical systems are impractical to realize on-chip. For this reason we explore routes to design holographic algorithms that can be naturally integrated with microelectronic technologies and require no optical hardware. Two approaches will be discussed below.

IMAGE VECTOR TRANSFORMATIONS USING SPIN WAVES

It is known that magnetic excitations in thin magnetic films behave analogously to optical waves but at much shorter wavelengths ($\lambda < 100$ nm), and spin waves also more straightforwardly generated on-chip, and interfaced to CMOS circuitry [2]. Figure 2 shows a spin-wave mirror that generates the Fourier transform of an input image vector. The device takes an analog vector as input, which is used to generate a given spin-wave distribution. This can be done by spin-torque oscillators [3]. The generated spin wave pulses are reflected back from the curved boundary (i.e. the mirror) and 3 ns later the intensity distribution at the bottom of the film becomes the Fourier transform of the input vector, which may be read-out.

Many image processing algorithms rely on manipulating the image in the Fourier domain (FD). Figure 3 is a simulation of a two-mirror system, where the vector image (i.e. the spin-wave distribution) is Fourier-transformed and subsequently transformed back by a second mirror. A filter can be placed in the Fourier plane to perform lowpass / highpass filtering in the FD [4]. The energy propagating in the spin-wave excitations is in the order of few hundred electronvolts for the entire operation, enabling, in principle, very low-energy computation.

CIRCUIT REALIZATION OF 2D IMAGE PROCESSING FUNCTIONS

Voltage and current distributions in an electrical circuit may mimic electromagnetic field distributions in a light beam. In particular, we found that the dynamics the circuit of Fig. 4 can approximate solutions of the paraxial Helmholtz equation [5], which describes wave propagation through an optical system. A two-dimensional input image is given by the nodal voltage distribution of the circuit at t=0. At the end of the computing process (say at $t=t_{\mathrm{end}}$) the distribution gives the processed / filtered image.

LC oscillators are hard to realize in microelectronic technologies and our presentation will explore more practical implementations, such as MEMS-based oscillators.

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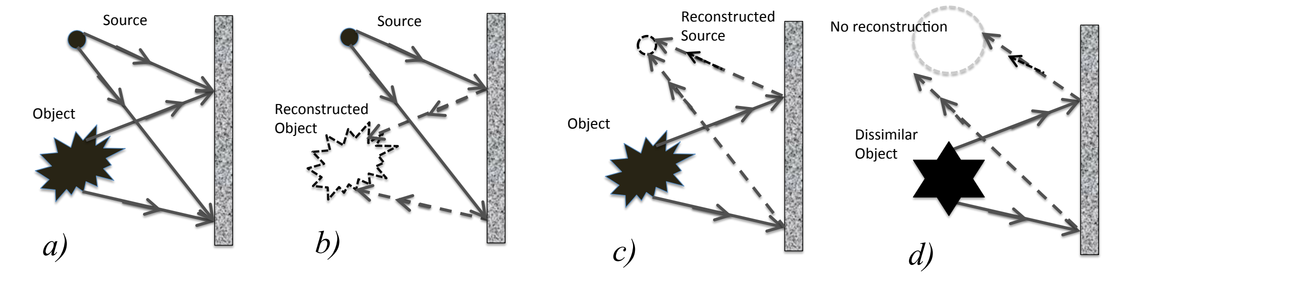

Figure 1. Schematics for illustrating holographic pattern recognition. In a, an interference pattern is created between waves emanating from a point source and an object. This interference pattern (a.k.a hologram), can be used to recreate a (virtual) image of the object upon illumination from the source (b)) - this is the commonly used method to reconstruct an image of the object. Figure 1c) and Fig. 1d) exemplifies two cases when the hologram is used for recognizing the original object. If the original object illuminates the hologram (Fig. 1c)), then the hologram reconstructs the source. If waves from a dissimilar object fall on the hologram (as shown in Fig. 1d)), the source will not reappear. In the scenarios of Fig. 1c) - d), the wave intensity at the position of the reconstructed source measures the similarity of the new object to the one that was used for recording.

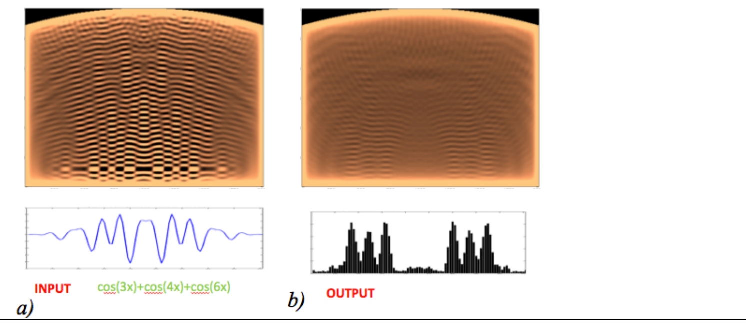

Figure 2. Fourier transform by a spin-wave mirror. a) A snapshot of spin waves in a 2 μm by 1.5 μm permalloy film, when the input waveform is emitted toward the mirror b) when the wavefront bounces back from the mirror, the reflected wave's intensity distribution yields the Fourier transform of the input waveform.

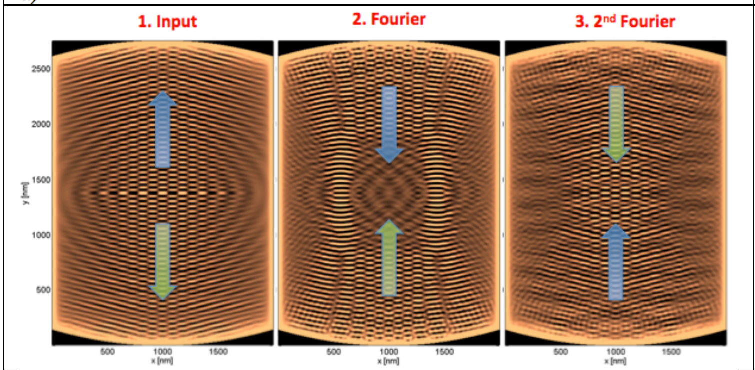

Figure 3. Fourier transform and inverse Fourier transform by a double-spin wave mirror. In these simulations, the original spin vector reappears at the end of the computation. For a practical application, a spin-wave scatterer can be placed in the Fourier plane – this performs a linear transformation on the input vector.

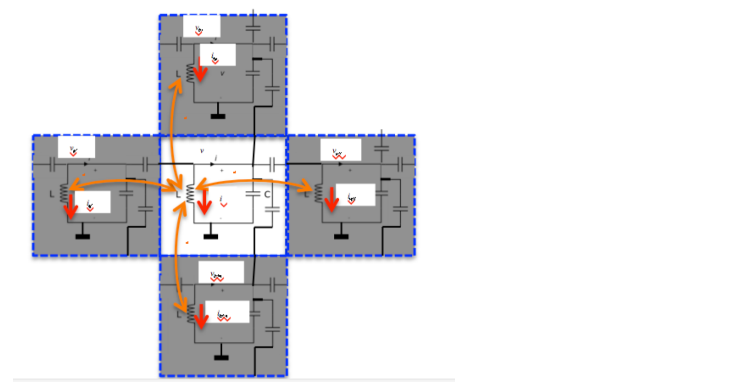

Figure 4. Capacitively and inductively coupled LC oscillators – with appropriately chosen circuit parameters this circuit can solve the Paraxial Helmholtz Equation and reproduce the behavior of an optical computing system. This points toward the possibility of realizing optical computing algorithms by coupled oscillators.