Non-Boolean Computing Using Spin Waves

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INTRODUCTION

Spin waves display similar interference behavior as optical waves, but at much shorter wavelengths (<100 nm), and they are also more straightforwardly generated on-chip. This gave rise to a number of proposals for ‘spin wave computing’ devices [1][2], aimed at mimicking on the nanoscale the behavior of optical logic gates, switches, and interconnections.

Moreover, spin waves could be well-suited for non-Boolean algorithms as well, such as pattern recognition using interference [3][4]. By means of micromagnetic simulations, we show that spin-waves can perform computational primitives that are well established in optics. Spin-wave based computing media can be straightforwardly integrated with CMOS units to form a general-purpose signal processing system.

SPIN-WAVE OPTICAL ELEMENTS

The system that motivates this work is sketched in Fig. 1. The spin-wave sources and the phase shifters can create an arbitrary wavefront (just as in the in-line holography scheme of Gabor [3]), and the interference pattern is read out at the opposite boundary of the device.

For spin-wave sources we use AC driven spin-torque sources, where a locally-oscillating magnetic moment injects spin waves into a thin Permalloy film (Fig 2). The physical structure of the spin-torque sources is identical to that of a spin-torque oscillator, but they are not used in the self-oscillating regime. For self-oscillating sources the phase is difficult to control, while for the driven oscillators it is straightforwardly linked to the driving source.

Multiple, coherently-driven spin-torque sources can realize line sources (Fig 3.), akin to a laser source in a real optical system. Placing slits (Fig 4.) or a lens (Fig 5.) in the path of the wave, one can imitate interference and focusing phenomena known from optics. Most importantly, a phase shifter (Fig. 6) can be realized by applying a local magnetic field, which changes the phase velocity of the wave.

NON-BOOLEAN COMPUTING USING SPIN WAVES

Placing the above-simulated optical components in the system of Fig. 1, one arrives at a device that can execute a sequence of optical processing steps, such as holographic pattern recognition or Fourier transformation. CMOS circuitry can control the flow of the optical primitives and perform additional (Boolean-based) pre- and post-processing steps.

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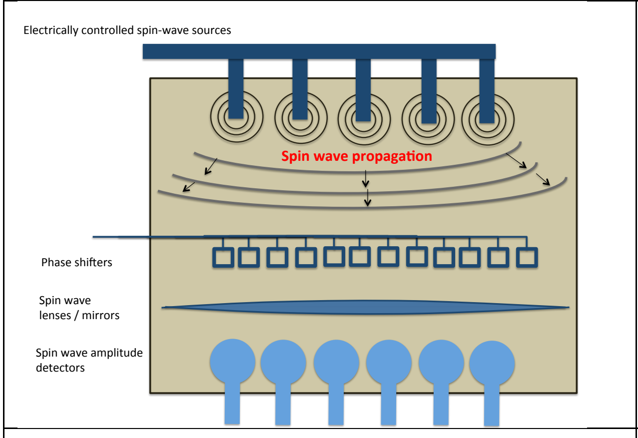

Fig. 1. Sketch of a spin-wave based computing system, with sources, phase shifters and detectors. A standard CMOS circuitry is used to configure the input oscillators and read-out the resulting spin-wave amplitudes.

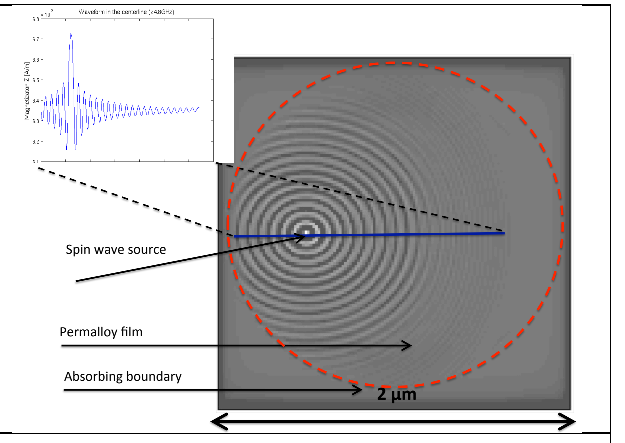

Fig. 2. Spin-wave distribution generated by a singe 30 nm diameter spin-torque source. The source is placed on a 5 nm thick Permalloy film. There is a constant 1.0 T magnetic film pointing 80^{o} to the film plane. The decay of spin wave intensity is close to a *1/r* law, as expected from a point source.

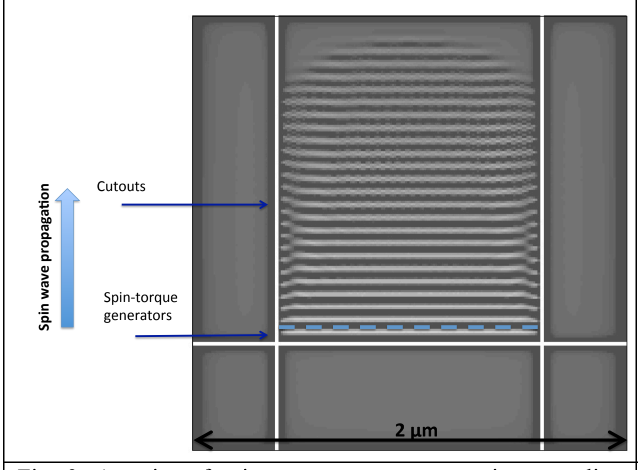

Fig. 3. A series of spin-torque sources are acting as a line source. The contour plot shows the out-of-plane component of the magnetization distribution.

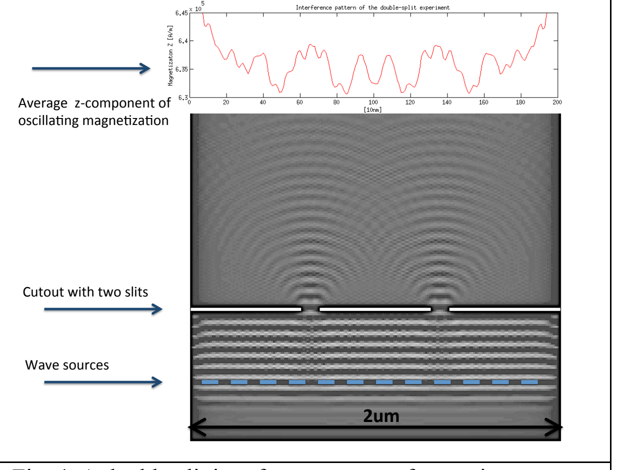

Fig. 4. A double-slit interference pattern from spin waves

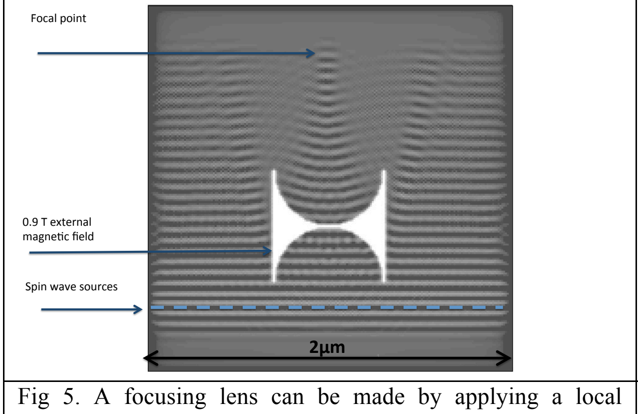

Fig 5. A focusing lens can be made by applying a local magnetic field, which changes the phase velocity of the spin waves. In this calculation the external field is altered in a 'negative lens' shape, focusing the waves.

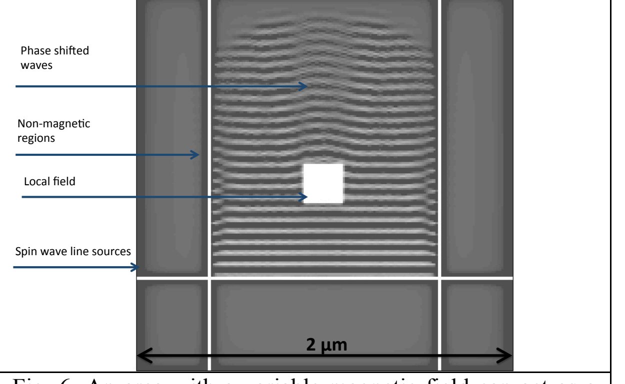

Fig. 6. An area with a variable magnetic field can act as a tunable phase shifter. A B_z = 0.7 T magnetic field applied in the white area in the center.