Time-multiplexed spinwave Ising machines

in-depth report

A. Litvinenko[a], R. Khymyn[a], R. Ovcharov[a], V. Gonzalez[a], A. A. Awad[a,b,c], V. Tyberkevych[d], A. Slavin[d] and J. Åkerman[a,b,c]

a: University of Gothenburg, Gothenburg, Sweden;

b: Center for Science and Innovation in Spintronics, Tohoku University, Sendai, Japan;

c: Research Institute of Electrical Communication, Tohoku University, Sendai, Japan;

d: Oakland University, Rochester, USA.

We present a versatile platform for miniature low-power Ising machines that support and rapidly solve large-scale combinatorial problems [1]. The spinwave Ising Machines (SWIM) is a new class of time-multiplexed Ising machines [2,3] that are implemented with an arbitrary-interconnected array of spinwave radio frequency (RF) pulses propagating in a ring oscillator with additional measurement and control feedback system implemented with an FPGA (Fig. 1). Spinwaves propagate 5 to 7 orders of magnitude slower than the speed of light and can be easily interconverted into RF signals which are easily manipulated with off-the-shelf energy efficient electronic RF components. Altogether, the use of spinwaves allows for dramatic miniaturization, reduction of power consumption, and significant improvement of frequency stability in time-multiplexed Ising machines.

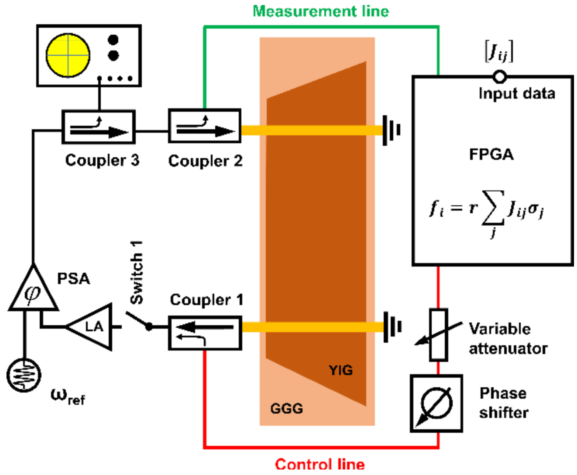

Fig. 1. Spinwave Time-multiplexed Ising machine.

Here, we present the design, the development, and the potential of the SWIM concept. The SWIM main loop consists of linear and parametric amplifiers, a YIG spinwave delay line where the spinwave RF pulses propagate, and an RF switch that controls the formation of RF pulses inside the ring. The feedback loop consists of the measurement and control block followed by a variable phase shifter and an attenuator. The feedback loop is connected to the main loop via microwave couplers. A phase-sensitive amplifier (PSA) limits conditions for stable oscillations in the SWIM ring circuit to only RF pulses at either phase 0 or π relative to a pumping reference signal.

We evaluated the computational performance of the SWIM with MAX-CUT optimization problems. Arbitrary combinatorial problems can be implemented with an FPGA control block. It takes around 5 µs for SWIM to evolve to a stable and optimal state for the MAX-CUT optimization problem. The SWIM consumes only 2W of power and, therefore, requires only 10µJ to compute the solution of arbitrary MAX-CUT problems.

Our work creates a pathway for miniature low-power and commercially feasible Ising machines for solving a wide range of large-scale optimization problems.

[1] A. Lucas. *Ising formulations of many NP problems.* Frontiers in physics **2**: 5. (2014).
[2] A. Litvinenko, et al, *A spinwave Ising machine*. arXiv preprint. arXiv:2209.04291. (2022).
[3] T. Honjo, et al. *100,000-spin coherent Ising machine*. Science advances **7**. 40: eabh0952. (2021).