Spin Wave Reversible Logic

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Why spin waves?

Two men with laser pointers: 
EM goes through the intersection

Two men with spin waves: 
SW is reflected back in case of destructive interference

constructive
destructive
Spin Wave Interference in a Cross Junction

\[ H = -J \sum_{j} S_j S_{j+\delta} - 2\mu H_0 \sum_{j} S_{jz} \]

\[ \hbar \frac{d\vec{S}_j}{dt} = \vec{\mu} \times \vec{B}_j \]

Case 1: Two spin wave packets are excited in-phase: propagation without reflection

Case 2: Two spin wave packets are excited out-of-phase: 100% reflection
Numerical Modeling

Two waves are in phase: 100% Transmission

Two waves are out of phase: 100% Refraction

Billiard-ball model

There are two major, closely related, types of reversibility that are of particular interest for this purpose: physical reversibility and logical reversibility. There is no energy required for reversible computing.

Fredkin and Toffoli Gate billiard ball model of an AND gate. When a single billiard ball arrives at the gate through input 0-in or 1-in, it passes through the device unobstructed and exits via 0-out or 1-out. However, if a 0-in billiard ball arrives simultaneously as a 1-in billiard ball, they collide with each other in the upper-left-hand corner of the device and redirect each other to collide again in the lower-right-hand corner of the device. One ball then exits via 1-out and the other ball exits via the lower AND-output. Thus, the presence of a ball being emitted from the AND-output is logically consistent with the output of an AND gate that takes the presence of a ball at 0-in and 1-in as inputs.
Building Reversible Logic Gates

Cross-junction

Spin waveguide

Phase shifter

<table>
<thead>
<tr>
<th>Input A B</th>
<th>Output A B</th>
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<tbody>
<tr>
<td>0 0</td>
<td>1 0</td>
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<td>0 1</td>
<td>0 1</td>
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It is possible to build logic gates with unidirectional information flow by combining cross junctions with waveguides and phase shifters.

Case #1: A=B waves come through each junction without reflection

Case #2: A≠B there are multiple reflections before waves will come through
Experimental Setup

Test structure: four-terminal cross junction made of yttrium iron garnet $Y_3Fe_2(FeO_4)_3$. The length of the each waveguide is 3.65 mm; the width is 650 μm; the YIG film thickness is 3.8 μm; saturation magnetization of $4\pi M_0 \approx 1750 Oe$.

There are three micro-antennas fabricated at the edges of the cross arms. Spin waves are generated by RF current flowing through the antennas at ports 1 and 2. The output inductive voltage is detected by the micro-antenna at ports 3 and 4.
Searching for Symmetrical Output

Spin wave transport within the cross junction is efficiently controlled by the direction of the bias magnetic field. Symmetric output is expected at 45°.

On/Off ratio > 45 dB at Room Temperature
Phase noise: in YIG ~ -130 dBc/Hz
Numerical Estimates

\[ E_{out} = E_{in} \times \exp[-\alpha L] \times \beta^N \]

\( \alpha \) – spin wave attenuation per propagation length (e.g. \( \sim 25\text{dB per 3mm in YIG at RT} \))

\( \beta < 1 \) – spin wave losses per cross junctions

\( L \) – the length of the circuit

\( N \) – number of cross junctions per circuit

\( E_{out} \geq 100\ kT \)

**Number of operations** = \( N / \rho \),

\( \rho \) – number of junctions per logic circuit (e.g. 8 junctions for the described gate)

**Time delay** = \( L / v_g \), \( v_g \) – group velocity (e.g. \( 3 \times 10^4 \text{ m/s for magneto-static spin waves in YIG} \))
Key parameters:

\[ \alpha = 25 \text{dB per 3mm} \ (YIG \ at \ RT) \]

\[ \beta = \frac{P_0 - P_{\pi}}{P_0 + P_{\pi}} \]
Summary

- Spin wave interference for signal re-direction
- Reversible logic gates based on cross-junctions
- Numerical modeling on nanometer scale cross junction: infinite On/Off
- Experimental data on micrometer scale YIG cross junction: On/Off > 45 dB at Room Temperature
- Numerical estimates: less than 1kT per operation is possible in scaled spin wave reversible logic gates

Research Plans

- Demonstrate a prototype consuming less than $kT$ per operation at RT

- Design more functional phase-based logic gates

- Explore the thermodynamic limits of classical phase-based computing
THANK YOU FOR YOUR ATTENTION!