A numerical study of spin torque nano-oscillators based Ising machines

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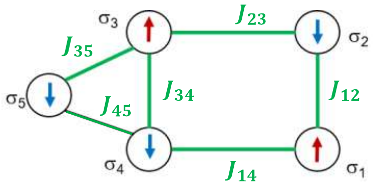
Abstract

Spin transfer torque nano-oscillators (STNO) generate microwave output voltage signals upon injection of a DC current. Potential applications are within wireless communication and unconventional computing [1]. One example of the latter are oscillators based Ising Machines (IM) [2] which are a promising route for solving combinatorial optimisation problems more efficiently in terms of time and energy with respect to traditional computing. They leverage the phase dynamics of an ensemble of coupled oscillators injection locked to an external signal source.
In this numerical study a STNOs based IM is considered. First, a verification is done to check that the phase state of the oscillators is binary as required by IM. Then, I find an operating point in terms of the applied dc voltage and magnetic field, that allows for enough stability to the system. After this, a pair of electrically coupled STNOs is implemented and different coupling strengths are employed in the simulations. The results demonstrate that the coupling can either enhance or dicrease the stability against temperature fluctuations and paves the way for the ensuing simulations that aim to understand the electrical coupling between STNOs and the solution of a optimisation problem.

Context

Ising Machines (IM)



- **Binary** valued units (spins σ_i)
- Some **controllable** interconnection (J_{ij})
- **Annealing** method
- **Switching** between spin values

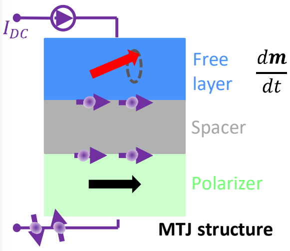
Ising Hamiltonian

$$H(\sigma) = -\sum_{\langle i\ j\rangle} J_{ij}\sigma_i\sigma_j - \mu \sum_j h_j\sigma_j$$

Mutual spin coupling — Individual bias

Many difficult **combinatorial optimisation problems** can be mapped to it and be solved by finding the Hamiltonian **global minmum** [2].

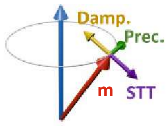
Spin torque nano-oscillators (STNO)



LLGS equation [3]

$$\frac{d\boldsymbol{m}}{dt} = -\gamma_0(\boldsymbol{m}\times\boldsymbol{H}_{eff}) + \alpha\left(\boldsymbol{m}\times\frac{d\boldsymbol{m}}{dt}\right) - \gamma_0 a_j(\boldsymbol{m}\times(\boldsymbol{m}\times\boldsymbol{p}))$$

Precession — Damping — Spin transfer torque



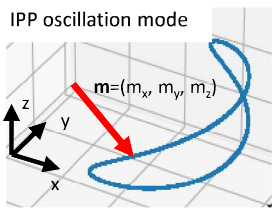
Intrinsic parameters	Value
Ms (A/m)	1e6
Size L_x,L_y,L_z (nm)	80, 90, 3.9
Damping (α)	0.02
K_u (J/m^3)	0
Polarizer azim angle (deg)	165

External parameters	Value
Field $\mu_0 H$ (T)	~0.04
H_{dc} direction (θ,φ)	90, 0
V_{dc} (V)	~1.50
T (K)	0 ; 10

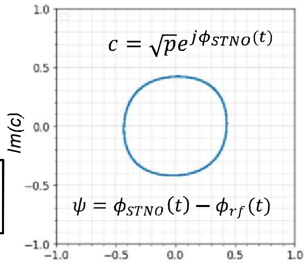
Method

Two main tools: numerical solver of the LLGS equation & analytical c-variable model [4]

IPP oscillation mode



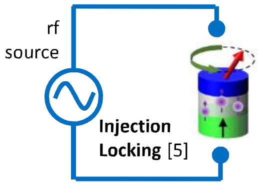
Non-linear oscillator model → c-variable transformation



$$\frac{dc}{dt} + i\omega(|c|^2)c + \Gamma_+(|c|^2)c - \Gamma_-(|c|^2)c = f(t)$$

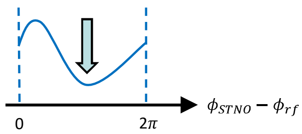
IM with STNOs

Key element : **synchronization**



1. Isolated STNO: $f_{STNO} = f_o$
2. Under external signal: $f_{STNO} = f_{rf}$

If $|f_o - f_{rf}|$ small enough



2*f* synchronization

$f_{rf} = 2 * f_{STNO}$

$\psi = \phi_{STNO} - \frac{\phi_{rf}}{2}$

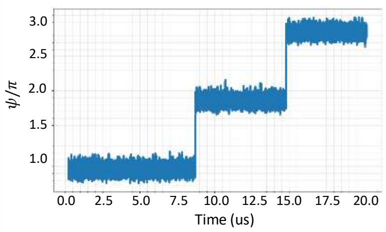
ψ has two stable values ≡ **ψ is binay**

Separated by π rad

Results

Verification of binary ψ

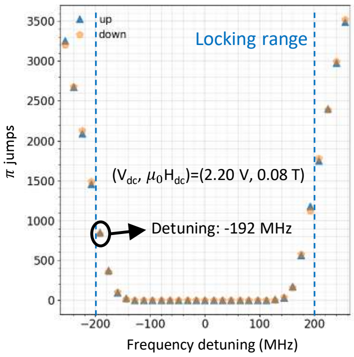
✓ *rf* field ($\mu_0 H_{rf} = 0.25$mT)
✓ non-zero temperature (10 K) for switching of binary state



✓ π jumps in ψ confirm it is binary
✓ Temperature fluctuations enable **switching** of ψ

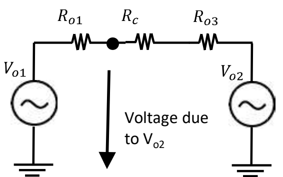
Seeking a stable operating point

Different operating points (V_{dc}, $\mu_0 H_{dc}$) explored



Electric coupling scheme model

First approach: resistive coupling between two STNOs



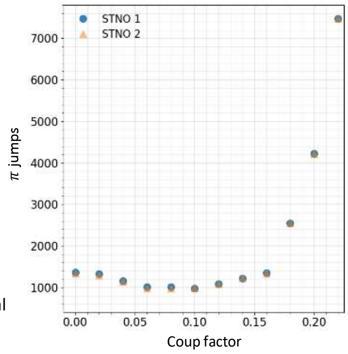
$$V_1 = \frac{R_{o1}}{R_c + R_{o3}} V_{o2}$$

Coupling factor $\mathcal{K}$

Vo1 and Vo2 represent the rf output signal from each STNO. In this case these were taken as m_{y1} and m_{y2} respectively

Effect of the coupling strength

Influence on ψ jumps for different coupling factors



Perspectives

- Developement of a deeper understanding of the electric coupling between two STNOs.
- Investigattion of the means for annealing scheme.
- Inclusion of more oscillators in the system.
- Implementation of an optimisation problem (NP complete problem).

REFERENCES

[1] M. Romera, P. Talatchain et al., Nature **563**, 230 (2018)
[2] T. Wang, J. Roychowdhury, arXiv:1709.08102v2 (2017)
[3] J. C. Slonczewski, J. Magn. Magn. Mater. **195**, 261 (1999)
[4] A. Slavin et al., IEEE Trans. Magn. 45, 1875 (2009)
[5] M. Quinsat et al., Appl. Phys. Lett. **98**, 182503 (2011)

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