Computing with Coupled Spin Torque Oscillator (STO) Arrays

IEEE CAS DL program

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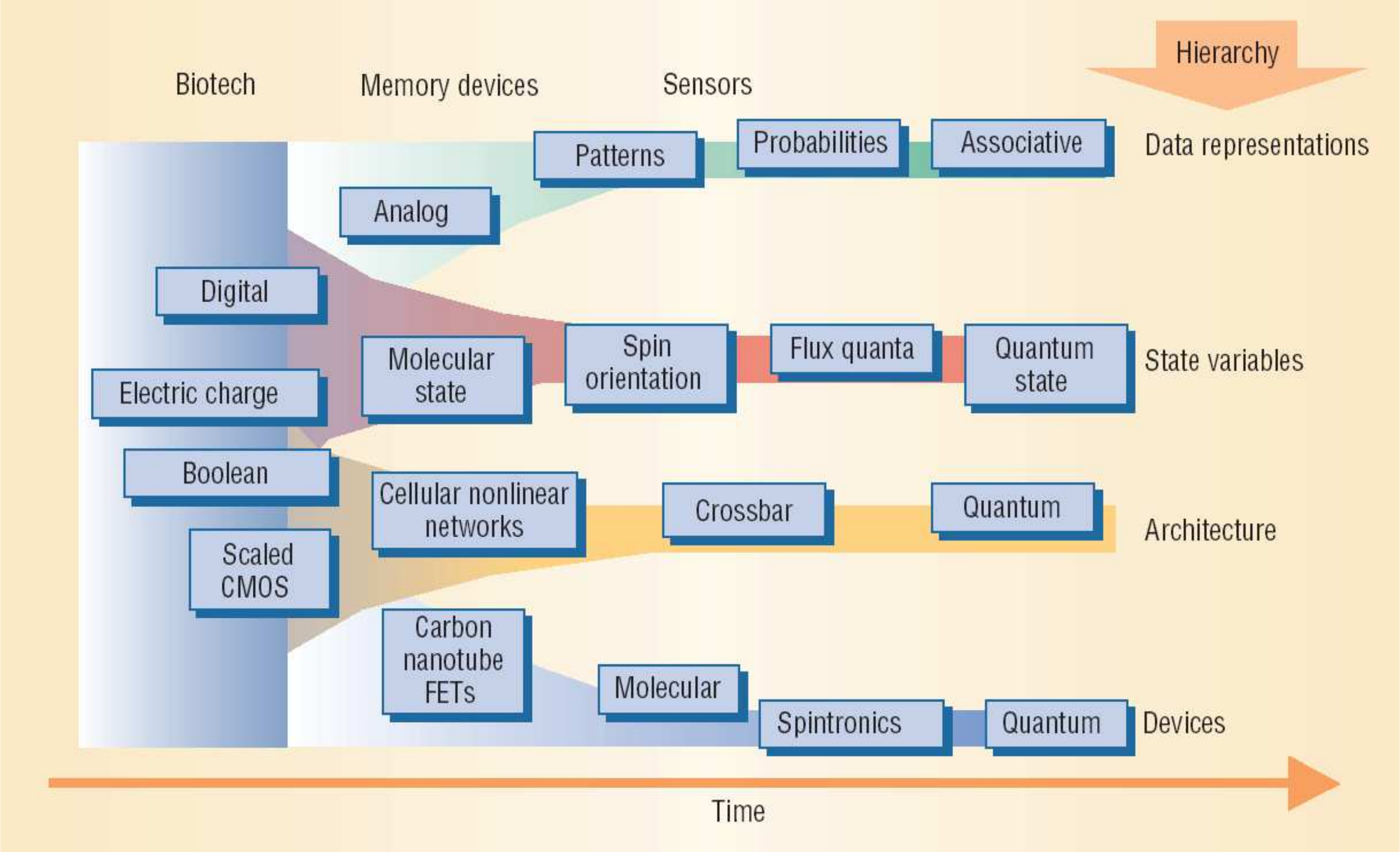
UNIVERSITY of VIRGINIA
SCHOOL OF ENGINEERING AND APPLIED SCIENCE

hplp
High-Performance Low-Power

Outline

- Motivation
- Spin Torque Oscillators (STOs)
- RF applications
- Coupled STO arrays
- Computing with STO arrays

(R)evolutionary trends



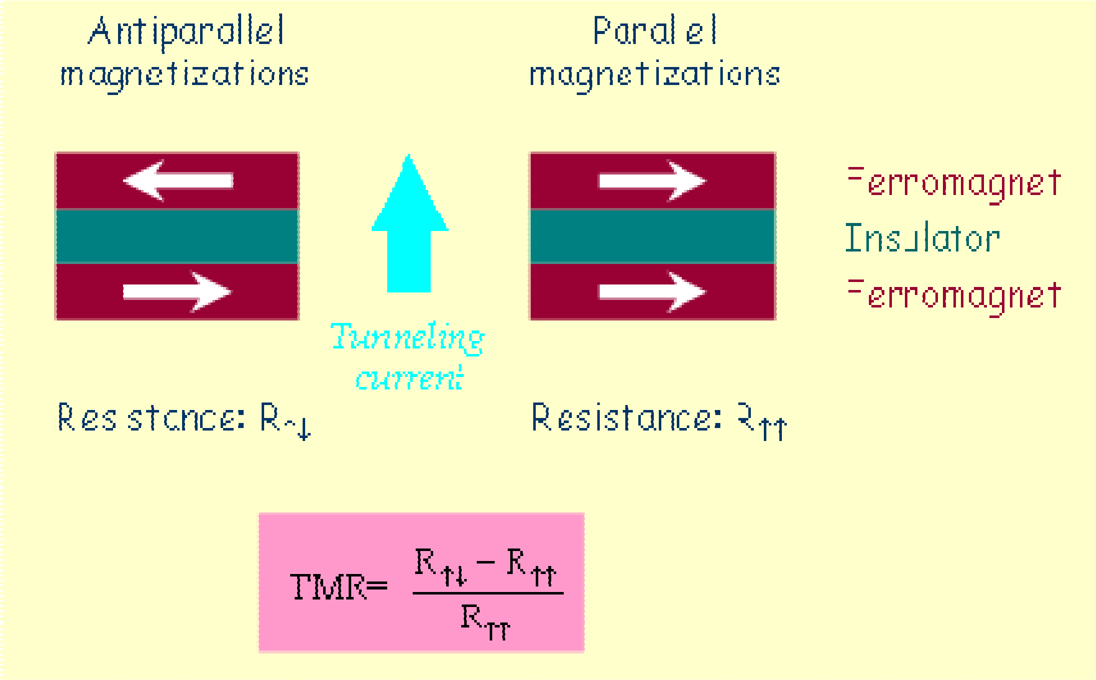
From G. Bourianoff et al.

Moving into the future

- Based on needs
  - Limits of current solutions
  - Unsustainable scaling trends
  - Emerging application requirements
- Based on opportunities
  - New materials discoveries
  - New device concepts
  - New technologies

Spin as a state variable - Spintronics

Memory, but also logic



Antiparallel magnetizations

Parallel magnetizations

Ferromagnet

Insulator

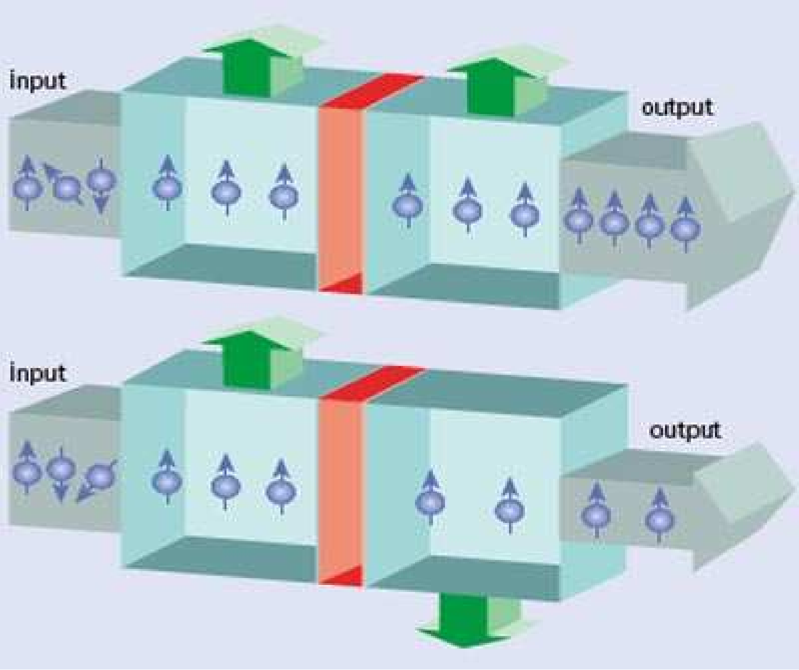
Ferromagnet

Tunneling current

Resistance: $R_{\uparrow\downarrow}$

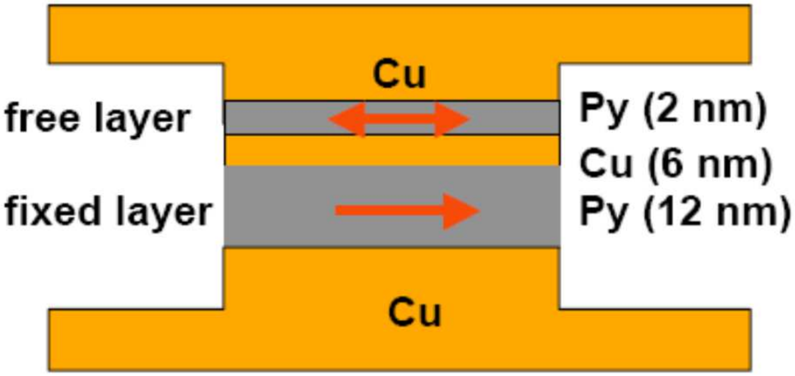
Resistance: $R_{\uparrow\uparrow}$

$$\mathrm{TMR} = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}}$$

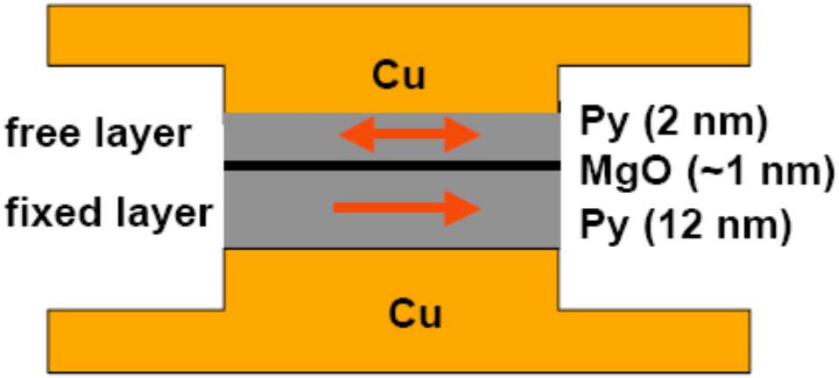


http://physicsworld.com/cws/article/print/32278/1/PWspi3_01-08

Spin Torque Transfer Technology



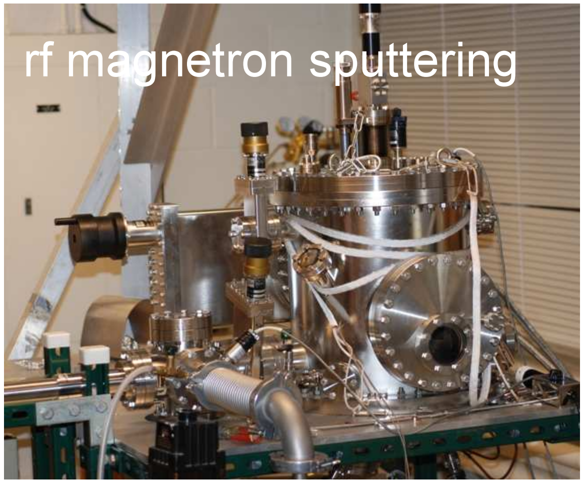
Nanopillar GMR
SPIN VALVE

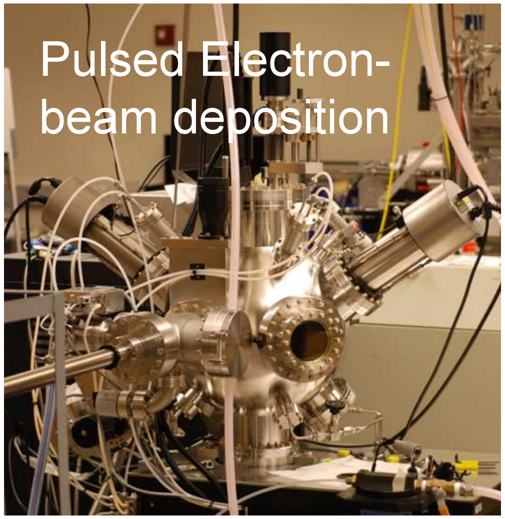


Nanopillar
MAGNETIC TUNNEL JUNCTION

From R. A. Buhrman, ***"Spin Torque Effects in Magnetic Nanostructures"*, Spintech IV, 2007**

Fabrication


rf magnetron sputtering


Pulsed Electron-beam deposition


Bias target ion beam deposition

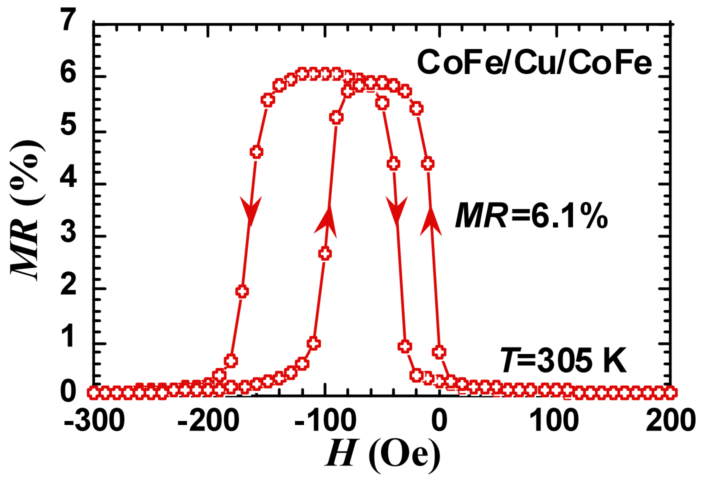

PPMS


Smart-lab™

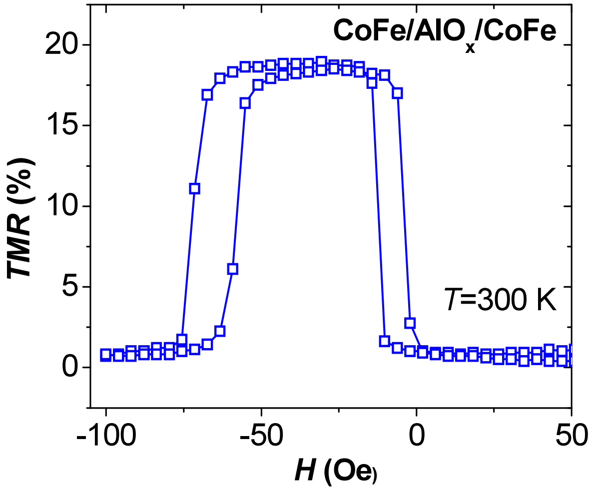
Experimental data

- Top and bottom pinned spin-valves with GMR~6% using BTIBD
- Prepared AlO*x*-barrier MTJs with TMR~20%
- Optical lithography and etching processes for spin-valves and MTJs
- Double AlO*x*-barrier MTJs for high TMR or low switching current for Spin Torque Transfer

Spin valve

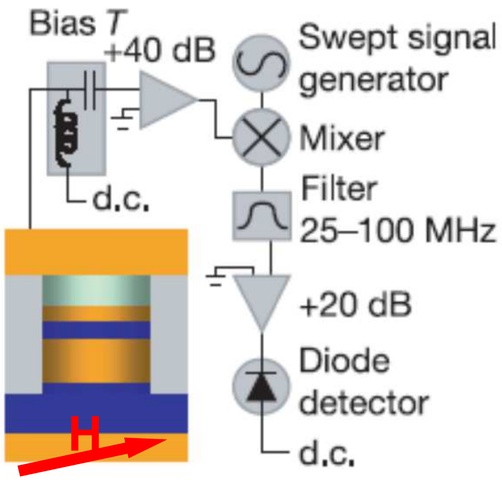


MTJ



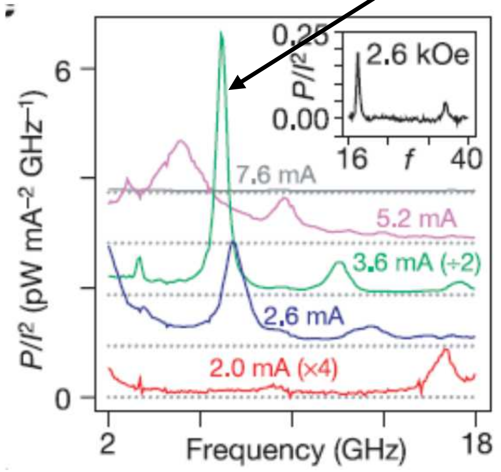
Spin Transfer Torque Nano-oscillator

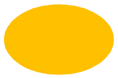
S. I. Kiselev, J. C. Sankey, I. N. Krivorotov, N. C. Emley, R. J. Schoelkopf, R. A. Buhrman and D. C. Ralph, "Microwave oscillations of a nanomagnet driven by a spin-polarized current", Nature, 425,380 (2003)."



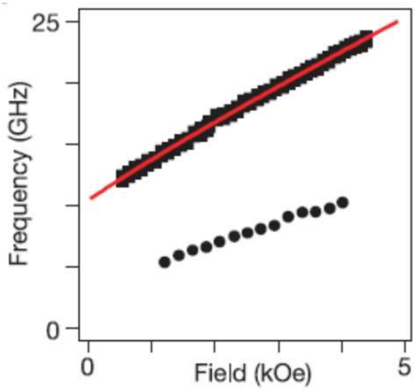
30 nmPt
2 nm Cu/
3 nm Co/
10 nm Cu/
40 nmCo/
80 nm Cu/

~ 0.1 nW measured



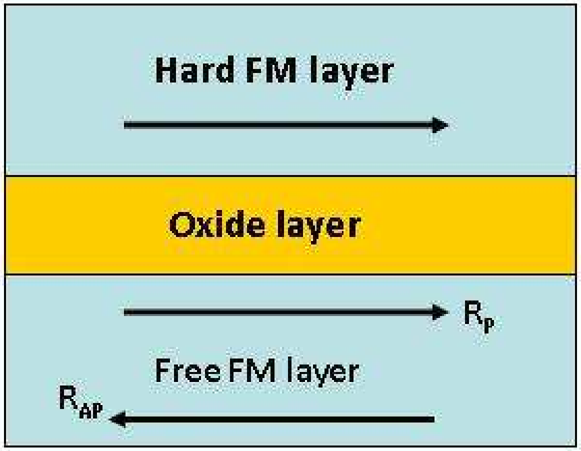


130 x 70 nm^2

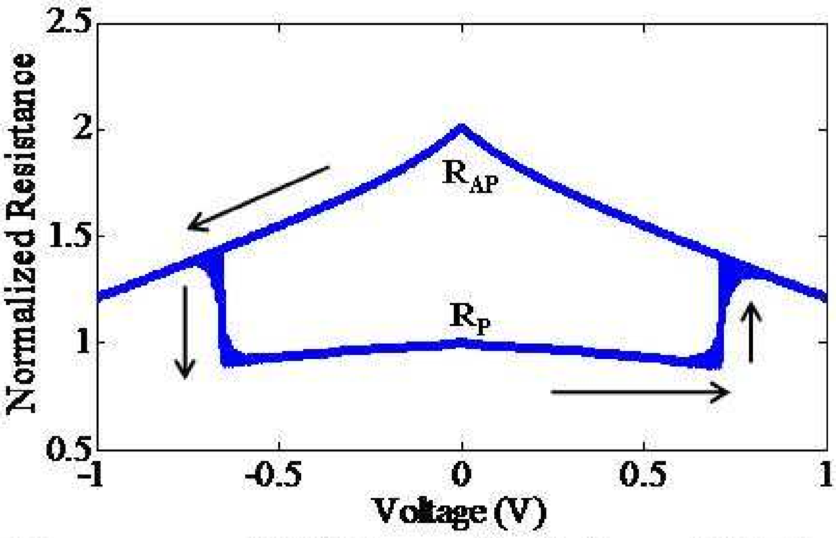


Circuit-level Device Model of Spin-Torque Oscillators

Magnetic Tunnel Junction: Overview



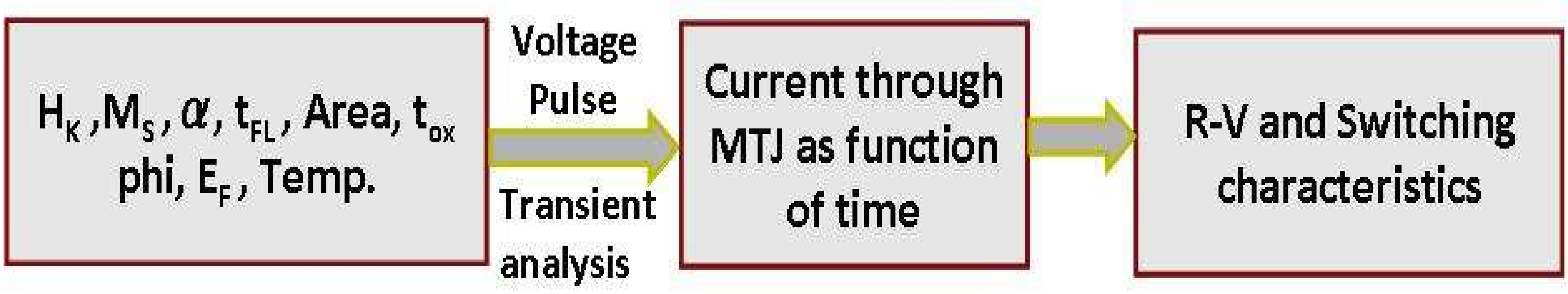
Magnetic Tunnel Junction (MTJ)



R-V Characteristics of MTJ

- Two States: Low Resistance (R_P) and High Resistance (R_{AP}).
- V>0 is applied to change from R_P to R_{AP}.
- V<0 is applied to change from R_{AP} to $R_{P.}$

MTJ SPICE Modeling



H_K, M_S, α, t_{FL}, Area, t_{ox}
phi, E_F, Temp.

Voltage Pulse

Transient analysis

Current through MTJ as function of time

R-V and Switching characteristics

Inputs in the model

Output of the model

MTJ characteristics

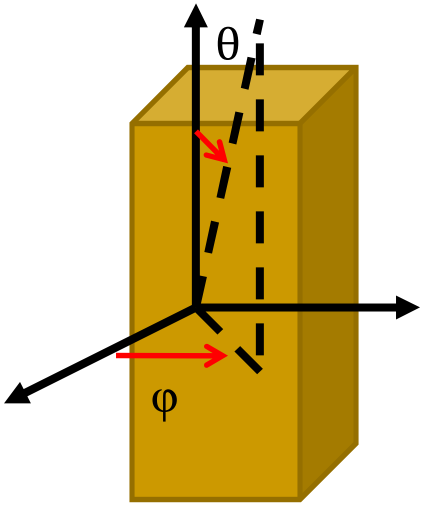
- Transport part is based on transmission of electrons through oxide barrier.
- Transient part solves the LLG equation in HSPICE.

1. A. Nigam, et al., In Proceedings of the International Semiconductor Conference, 2010.
2. A. Nigam, et al., Non-volatile Memories workshop, 2011.
3. A. Nigam, et al., International Symposium on Low Power Electronics and Design, 2011.

SPICE Circuit Model

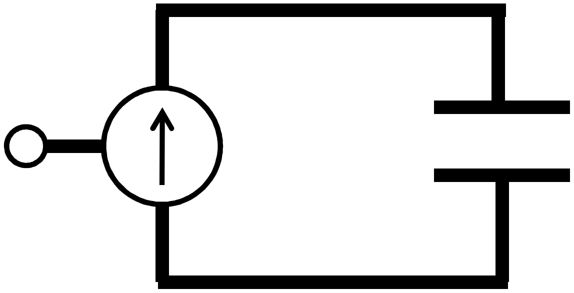
- Approach: Solve equations in terms of spherical angles.
- Map spherical angles as a voltage buildup on a capacitor.
- Map differential equation as a voltage-controlled current source.
- Allow SPICE to solve for the voltage capacitor ⇔ solving differential equation.

Magnetism to Electrical mapping	
Theta	Voltage
Phi	Voltage

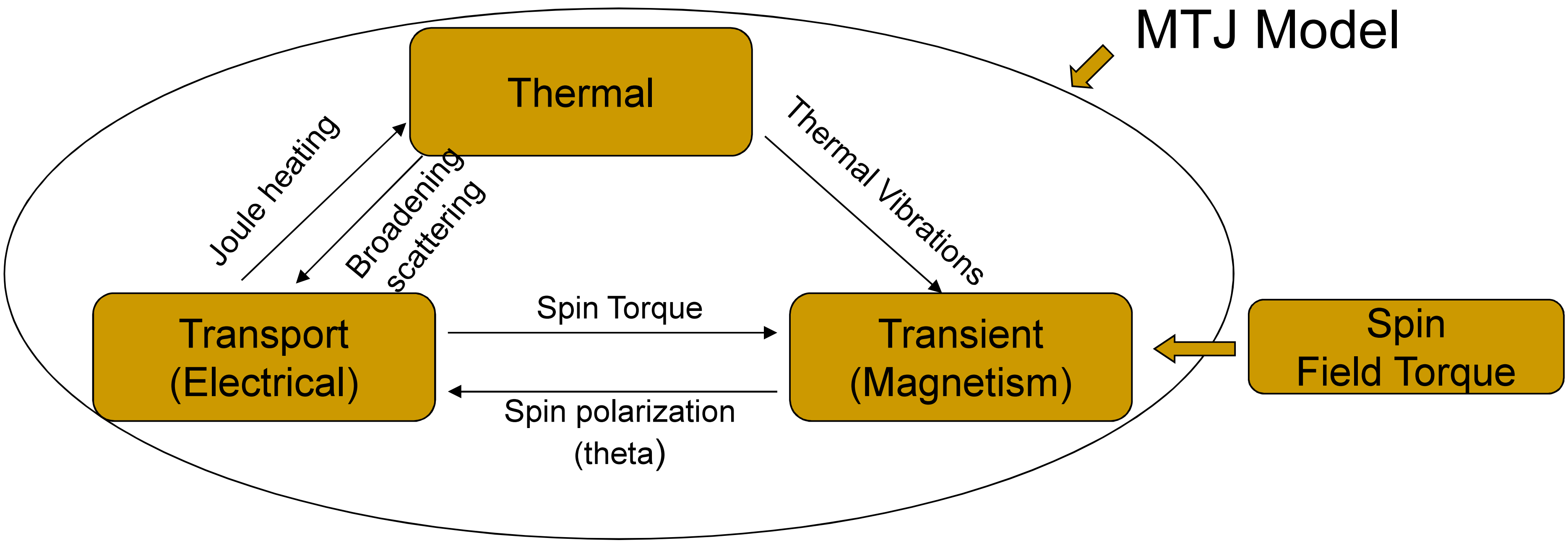


$$\frac{d\theta}{d\tau} = -\theta[\alpha(1+h) + h_p(\sin\varphi + \alpha\cos\varphi)\cos\varphi + \ \ldots$$

$$\frac{d\theta}{d\tau} = [\ \cdots\ ] \quad \Rightarrow \quad \frac{dV}{dt} = \frac{I}{C}$$



MTJ: Modeling



MTJ Model

Thermal

Joule heating

Broadening scattering

Thermal Vibrations

Transport (Electrical)

Spin Torque

Spin polarization (theta)

Transient (Magnetism)

Spin Field Torque

Torque acting on free layer (n_m) : $\Gamma = n_m \times H$

LLG equation solution after including field torque:

Model available for download at:

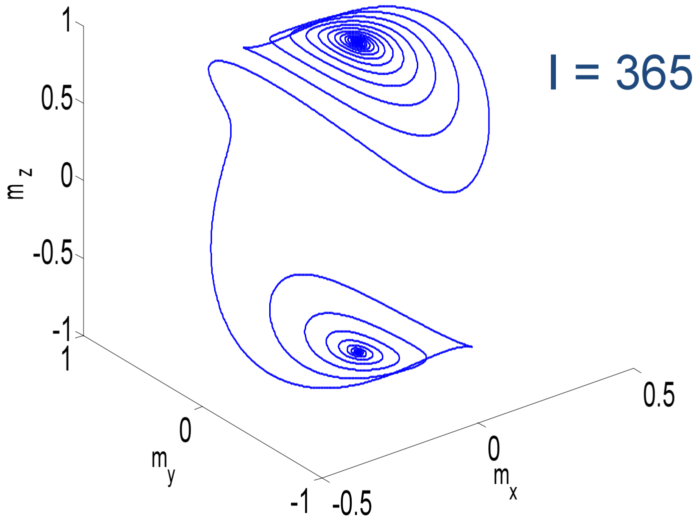
http://hplp.ece.virginia.edu

$$\frac{d\theta}{dt} = \alpha[H_z \sin\theta - H_x \cos\theta \cos\varphi - H_y \cos\theta \sin\varphi] + [H_y \cos\varphi - H_x \sin\varphi]$$

$$\frac{d\varphi}{dt} = [\alpha[H_x \sin\varphi - H_y \cos\varphi] + [H_z \sin\theta - H_x \cos\theta \cos\varphi - H_y \cos\theta \sin\varphi]]/\sin(\theta)$$

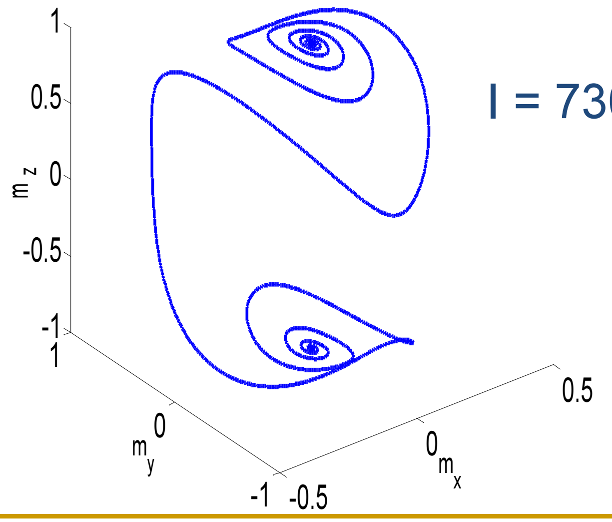
Precession: Free Layer Switching

- Torques acting on free layer magnetization
    - Uni-axial anisotropy, easy-plane anisotropy, spin torque



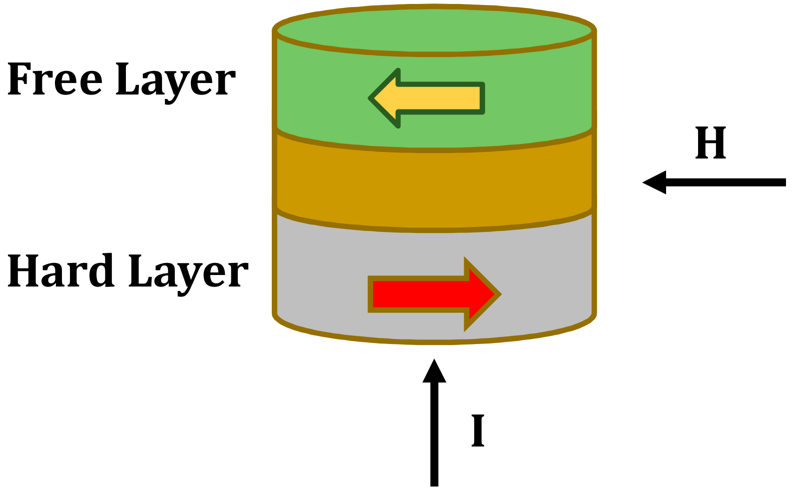
I = 365 uA

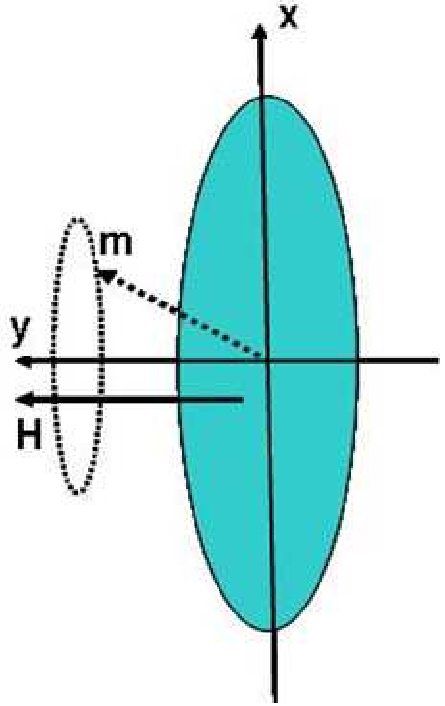
- Increase in spin current
    - Decreases no. of precessions
    - Decreases switching delay



I = 730 uA

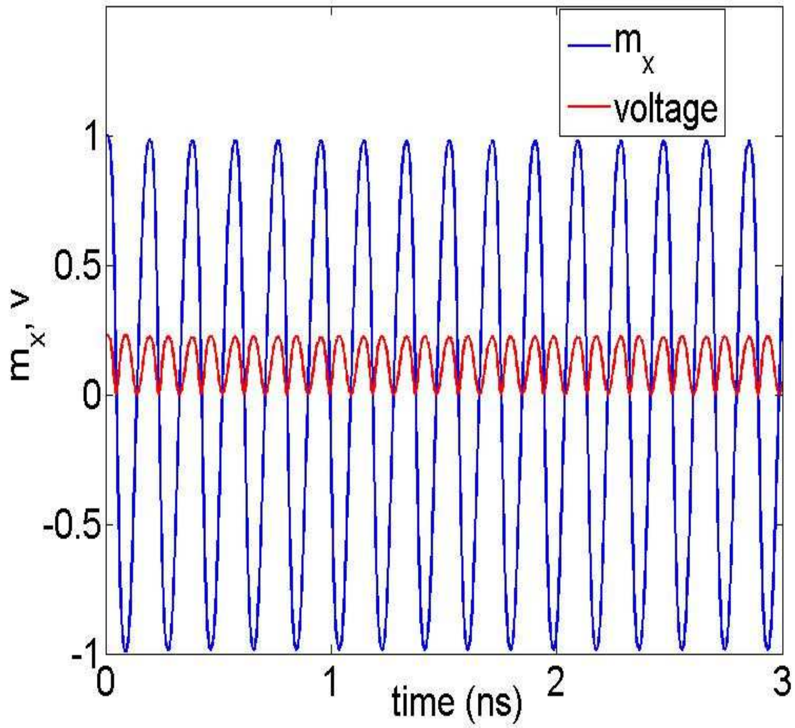
Spin Torque Oscillator: Schematic

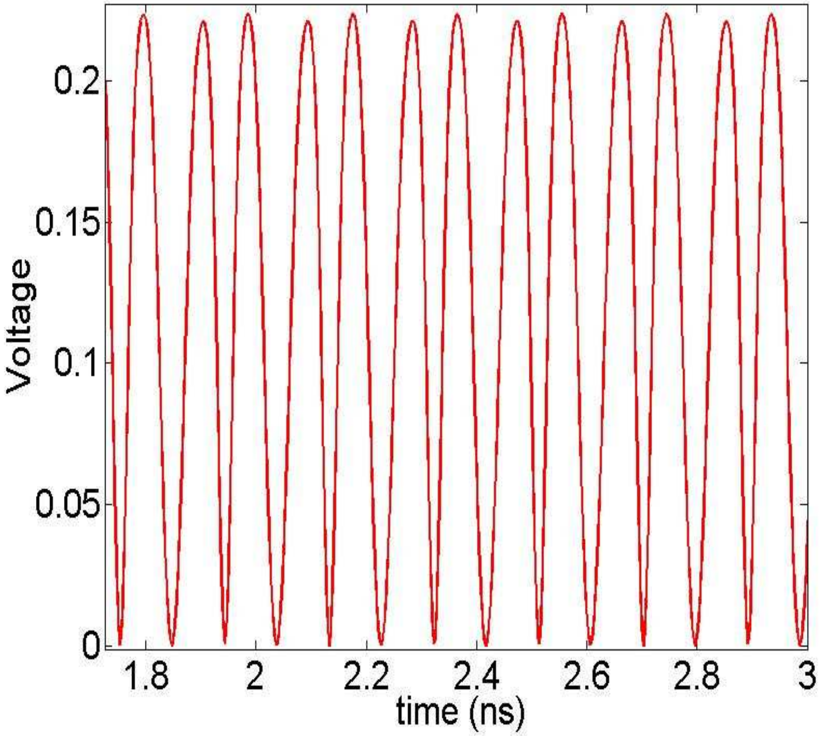




- H: Applied field along in the plane of free layer.
- m: Free layer magnetization vector.
- Free layer magnetization rotates around H.

Simulation Results: Oscillation Signal



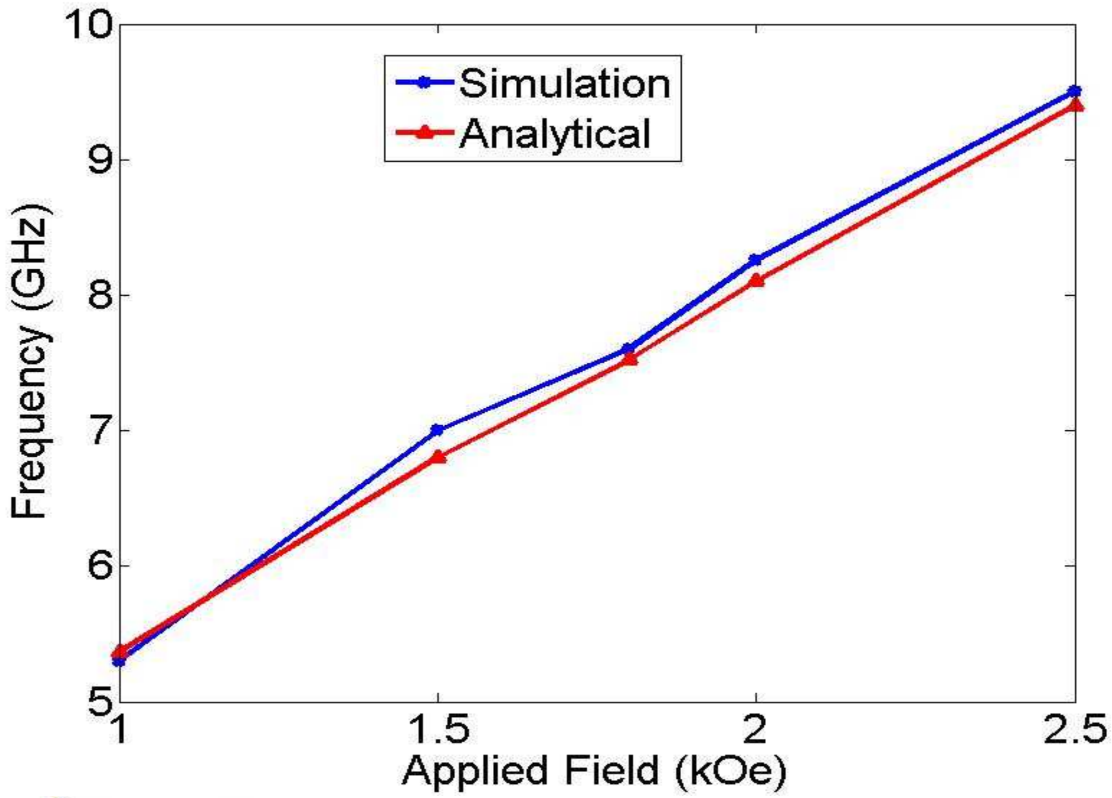


Parameters

α : 0.007
H_K : 900 Oe
M_S : 650 emu/cc
H : 900 Oe
I : 1.3 mA
t : 2 nm
A_r : 130 X 70 nm^2

- Voltage = 0.5*(1-m.p) [K. Kudo, et al., APL 2010]
- Magnetization f = 5.3 GHz
- Voltage f = 10 GHz

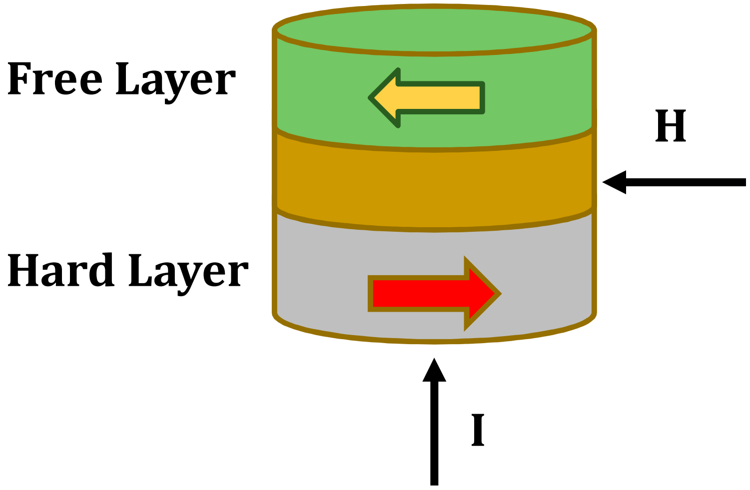
Oscillation Frequency vs. Applied Field

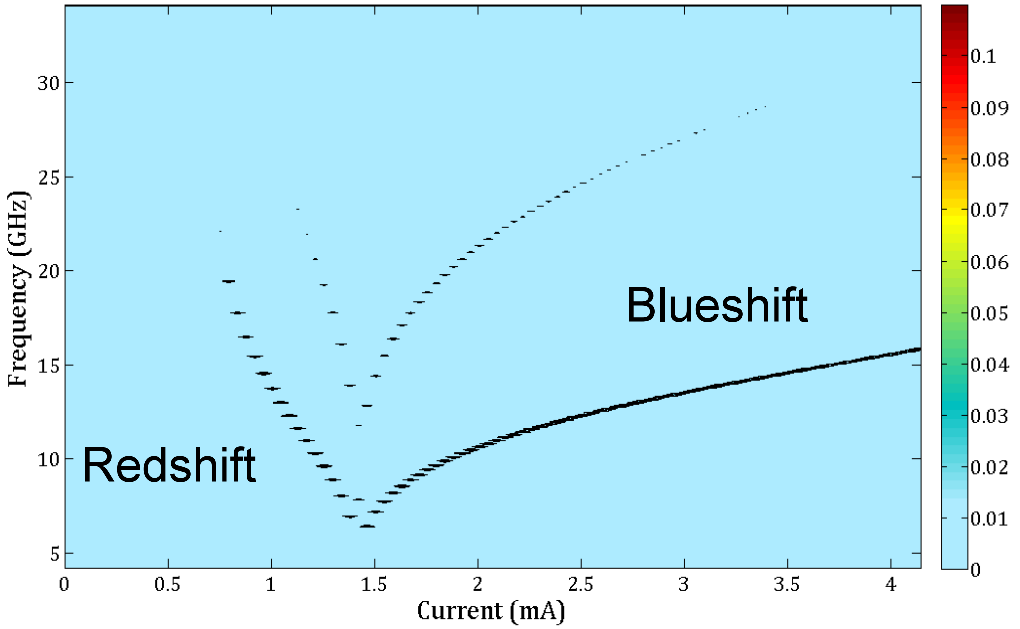


Analytical: $f = \frac{\gamma}{2\pi}(H + H_K)(H + H_K + 4\pi M_{eff})$ [W. H. Rippard, et al., PRL 2004]

Oscillation frequency varies linearly with applied field.

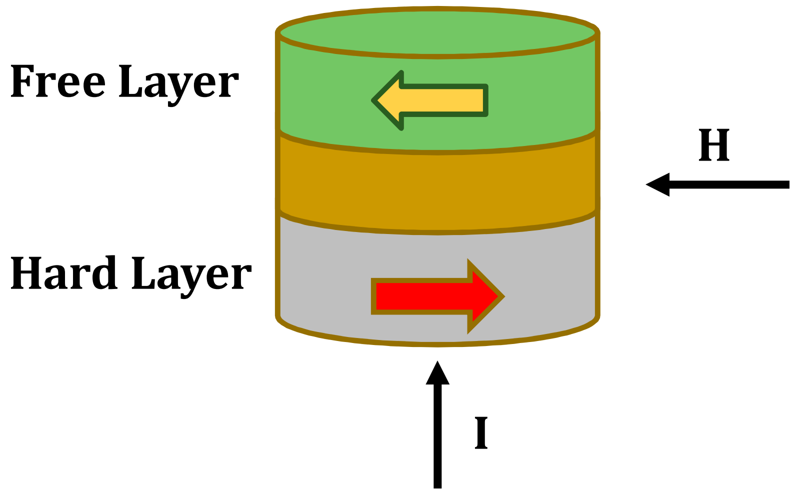
Spin Torque Oscillation: Frequency Dependence

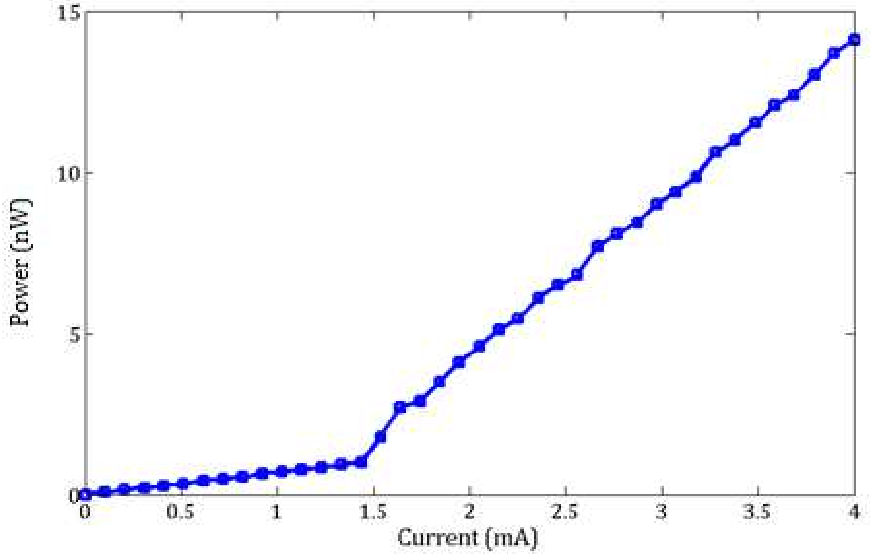




- Using SPICE model, capture the frequency dependence of oscillation as applied electric field is increased.
- Use in-plane magnetic field.
- Shows nonlinear frequency dependence. The redshift and blueshift regions signify different modes of oscillation.

Spin Torque Oscillation: Power





- As current increases, the generated power also increases approximately linearly.

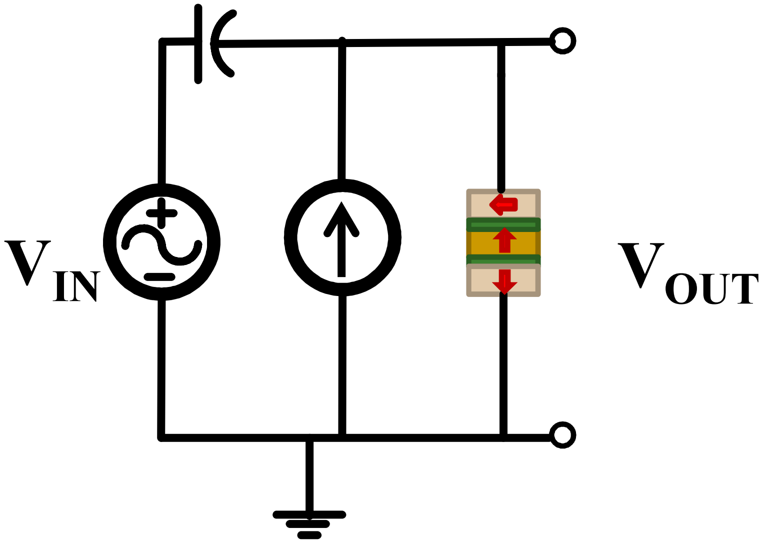
- In the redshift regime, the voltage that builds up across the magnetic tunnel junction is smaller than the voltage build up during the blueshift regime.

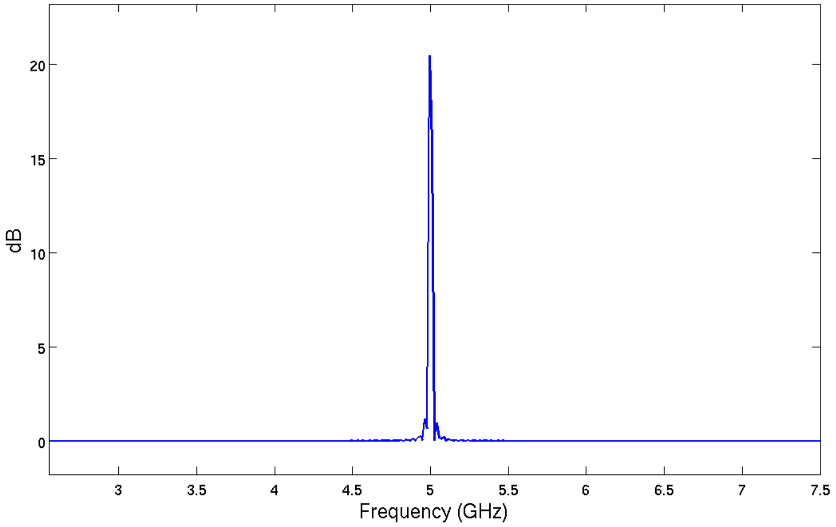
- As current increases, the effective resistance of junction increases since the free layer experiences larger oscillations.

- Weak output signal → Possible solution: Strengthen by synchronizing multiple STOs

Tunable RF Filters using STOs

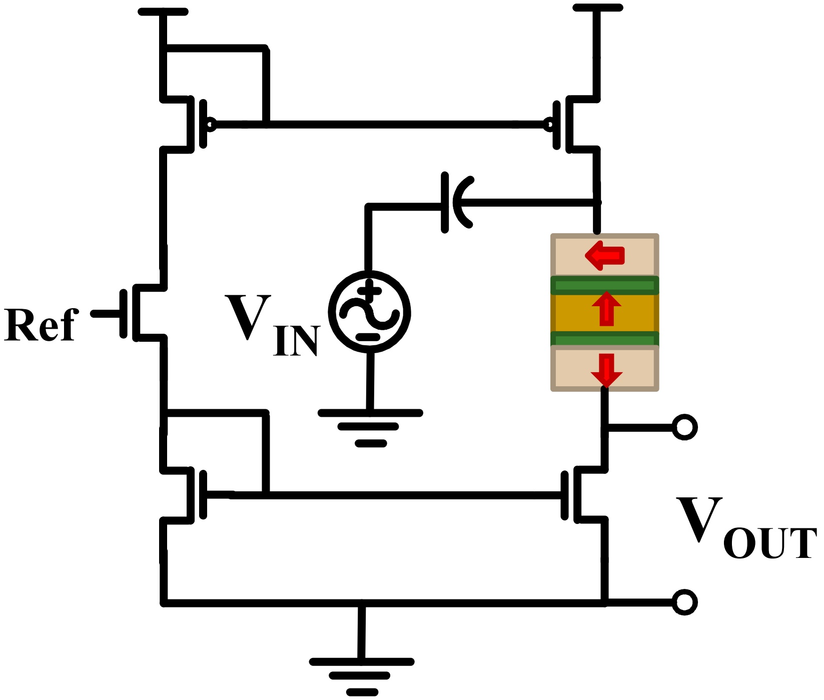
Narrow Band-pass Filter

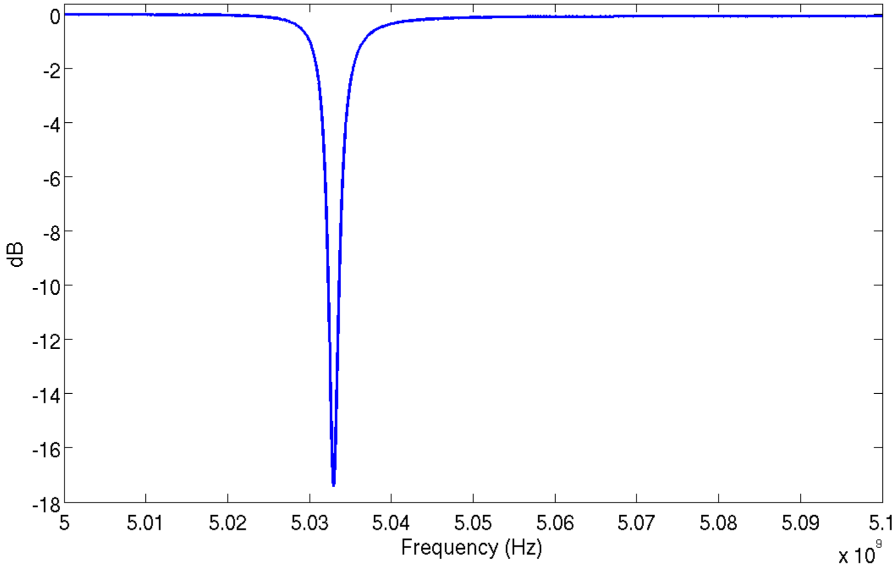




- The STO itself acts as a band-pass filter.
- The frequency of the filter is tuned by the current source which determines the operation frequency of the oscillator.
- An input AC voltage is fed into the STO and only frequencies very close to the operating frequencies of the STO are passed, while others are blocked.

Narrow Notch Filter





- Similarly, a notch filter can be implemented using STO. The filter frequency is tuned using the **REF** voltage to adjust the cascode current mirror.
- An input AC voltage is fed into the STO. For the operating frequency, the STO acts as an open circuit creating a notch filter.

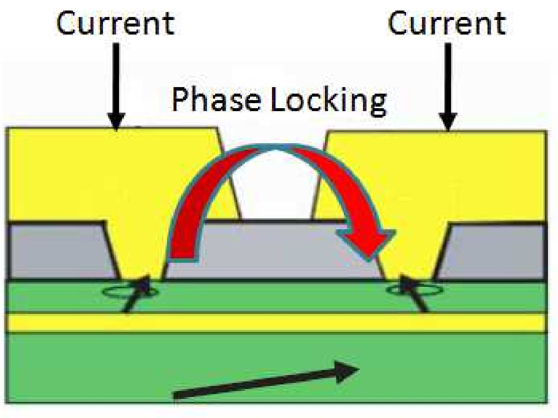
STO Arrays

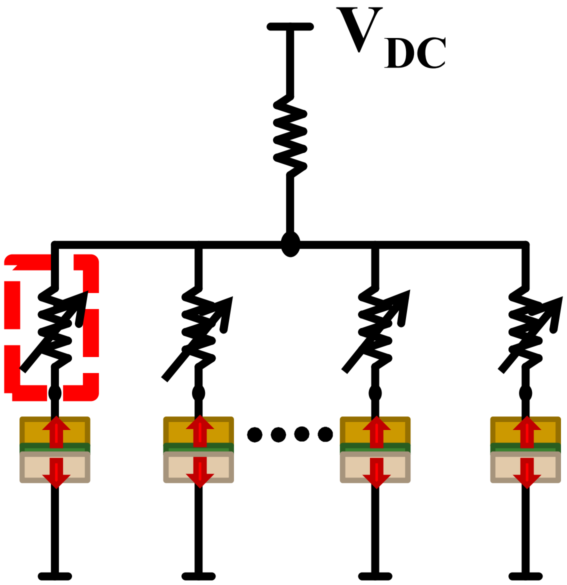
Interacting Spin Torque Oscillators

- Two modes of synchronization
  - Spinwave interaction
  - Electrically-coupled

- Spinwave coupling connects two STOs with a shared free layer.*
  - Injected current creates spinwaves in free layer which communicate with each other.

- Another approach uses a electrically coupled STOs which communicate via current changes in each branch of the parallel connection.





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* S. Kaka *et. al.*, *Nature* **437**,389 (2005)

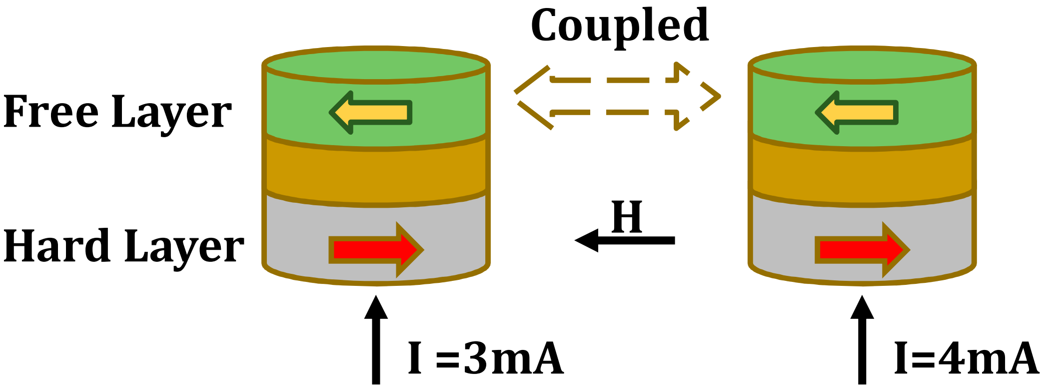
STO Arrays

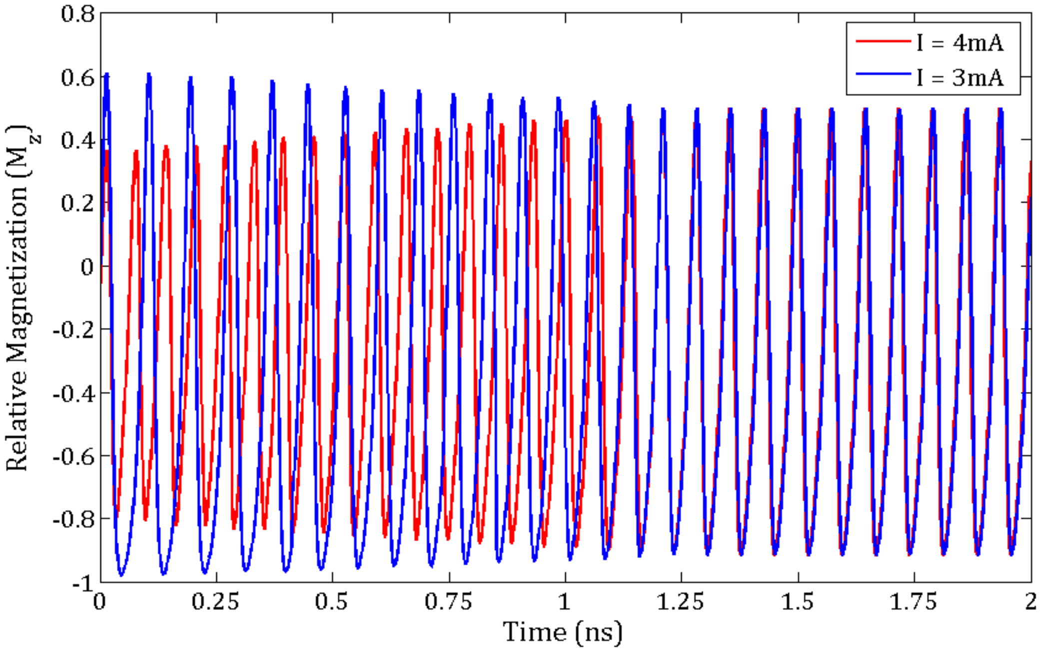
- STO geometry: in-plane vs. perpendicular
- STO physical design: patterned vs. unpatterned
- Metrics: power/energy, amplitude, delay to sync
- Spin wave coupling
- Electrical coupling

Spin Torque Oscillation: Coherence

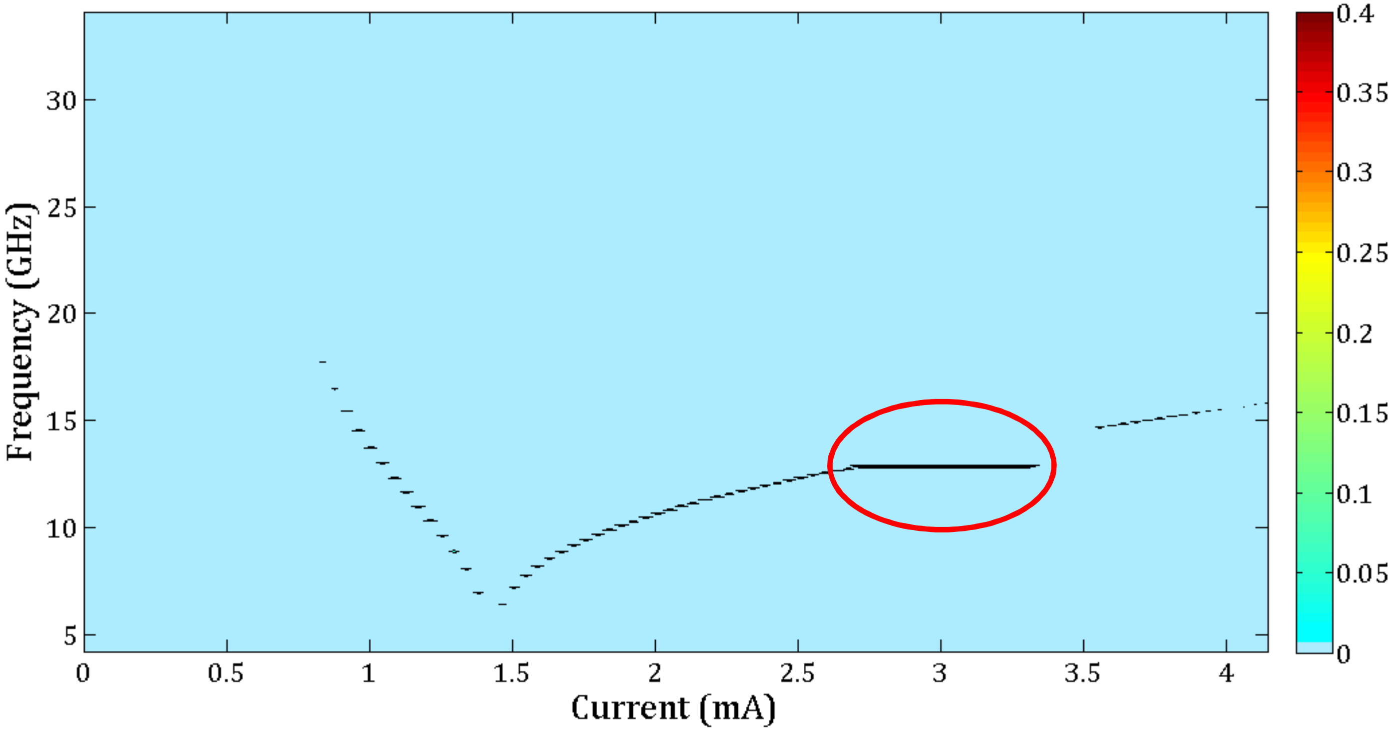
- Using the same coupling mechanism, we apply to two STOs driven at different frequencies.

- The coupling mechanism causes the oscillators to synchronize with each other by slowing down or speeding up as necessary.





Spin Torque Oscillation: Coherence

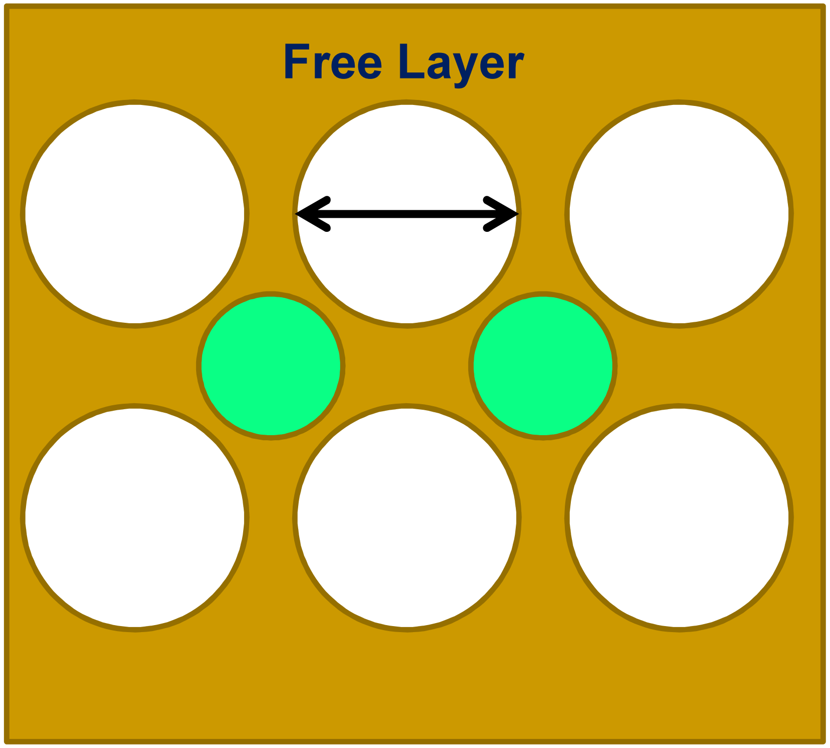


- When the current is strong enough to create a large coupling energy, the cells cohere.

- The resonant frequency remains constant in the coupled regime. At higher currents, the driven frequency is too large for coherence.

Spinwave Interaction in Patterned Free Layers

Spinwaves in Patterned Free Layer



Hole Pattern

Simulation Parameters:

Fixed layer diameter: 40nm

Contact-Contact distance: 105nm

Hole diameter: 40nm – 100nm

Hole-Hole distance: 105nm

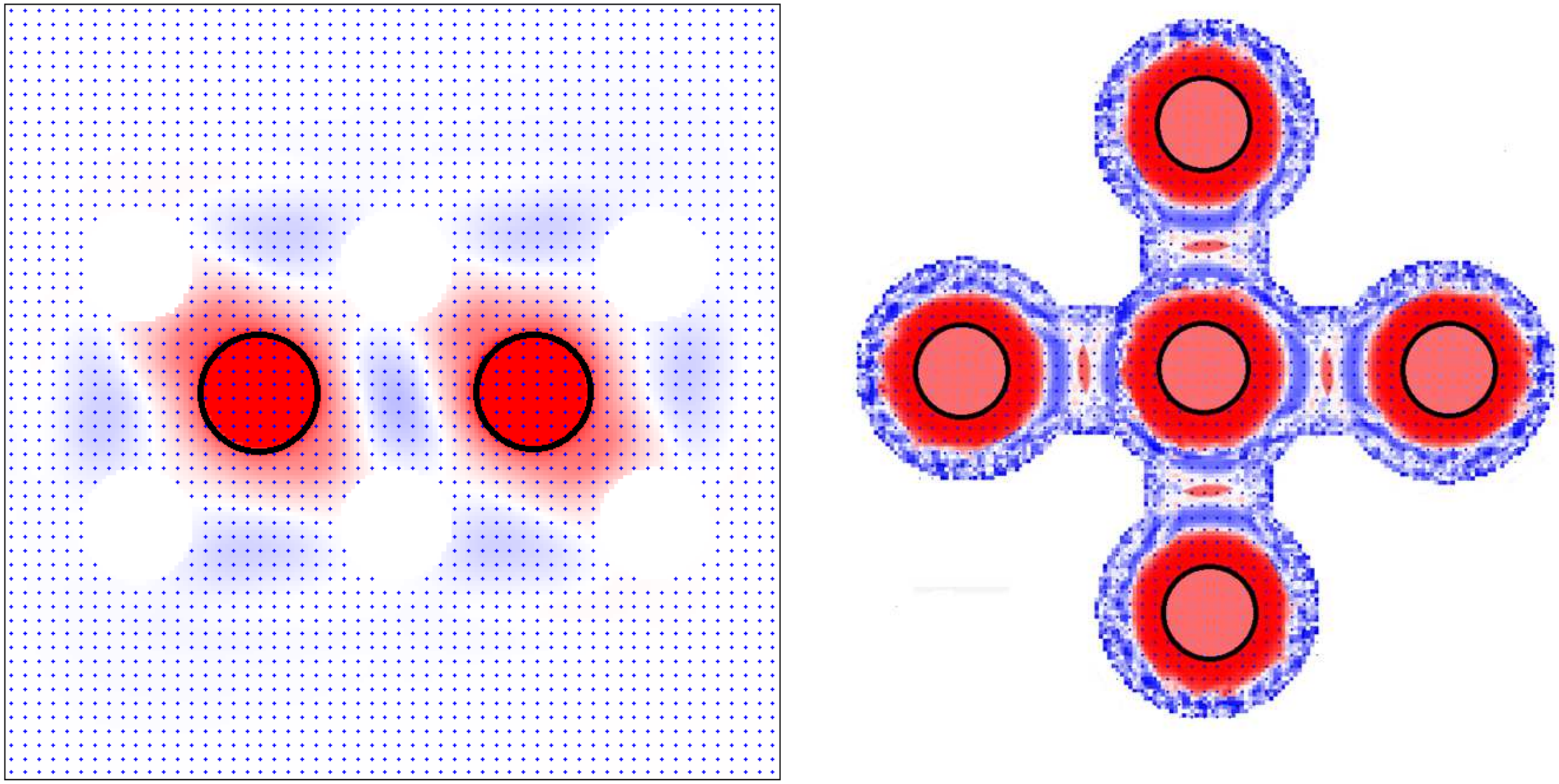
$Ms = 7x10^5$ A/m

Exchange constant = $2x10^{-12}$

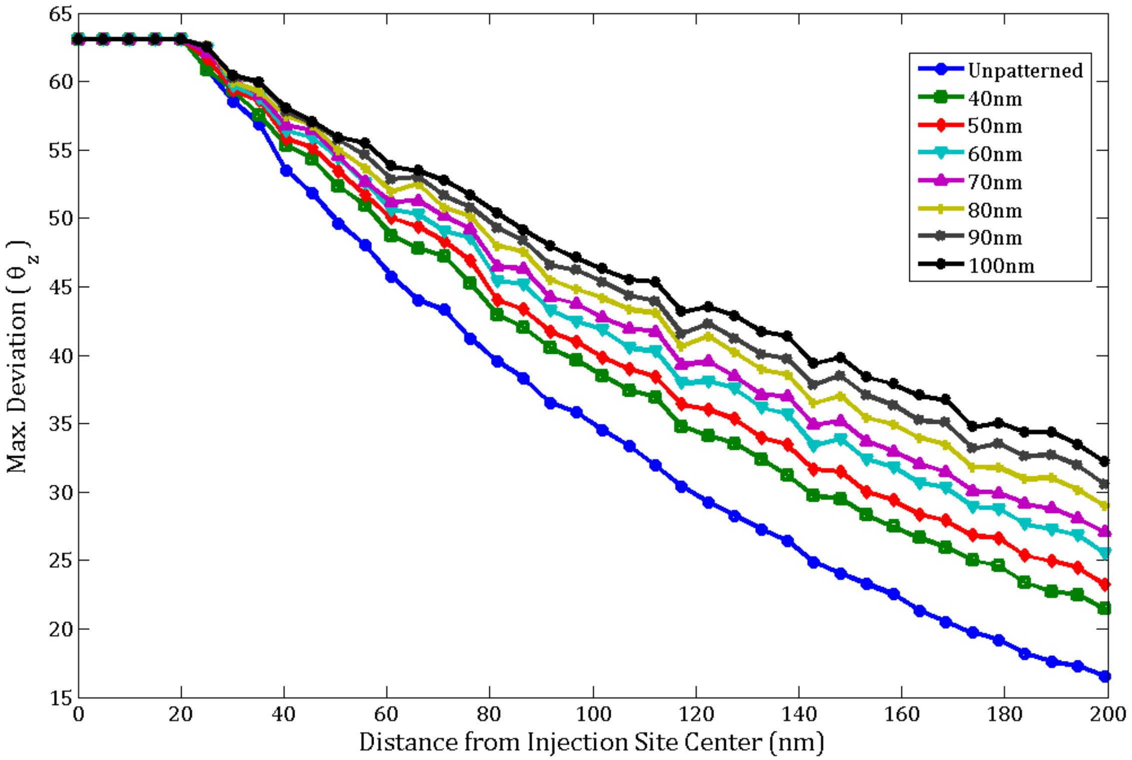
$K1 = 2x10^6$ J/m^3

$\alpha = 0.03$

OOMMF Simulations



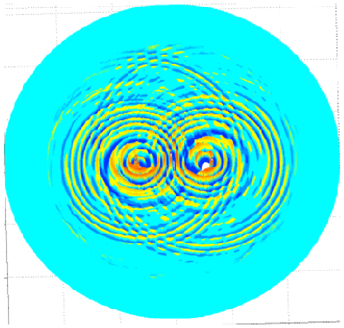
Wave Decay in Patterned Layer



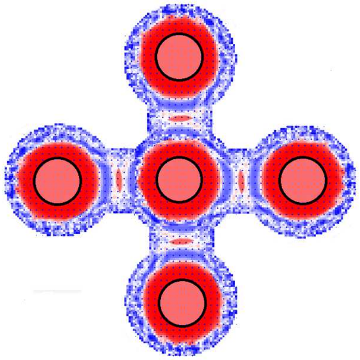
- When the free layer is patterned, the spinwaves decay slower.
- As the pattern sizes get bigger the slower the rate of decay of the spinwaves.
- The patterns prevent the spinwave from dispersing and “guide” the wave towards the neighboring STO

Spinwave Coupling of STO

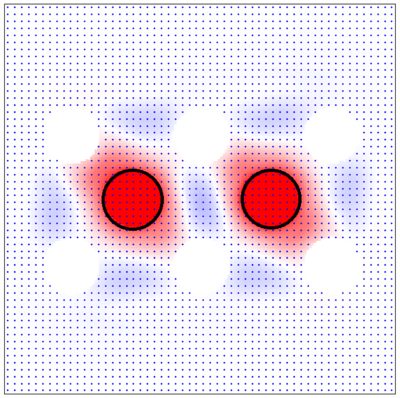
- Two STO can be coupled by spinwave interactions, but connecting multiple STOs remains a challenge.
- Decay of spinwave can also limit the types of topologies which can be implemented using magnetically coupled STOs.
- Patterning a shared free layer could possibly aid in maintaining spinwave for longer range interaction and implementation of topologies.



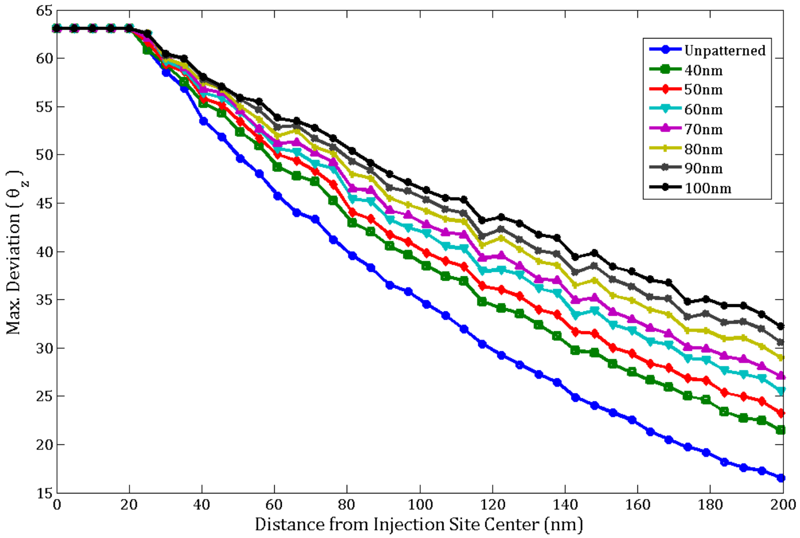
Two STO coupled through spinwaves.*



Bridge structure.



Holes structure.

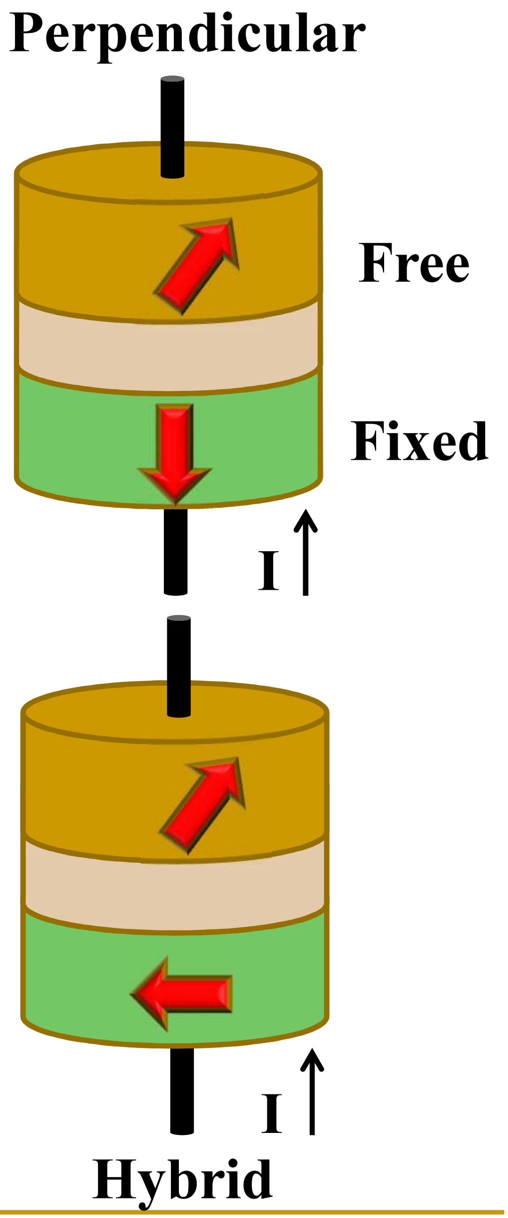


* G. Csaba & W. Porod

Electrically Coupled STOs

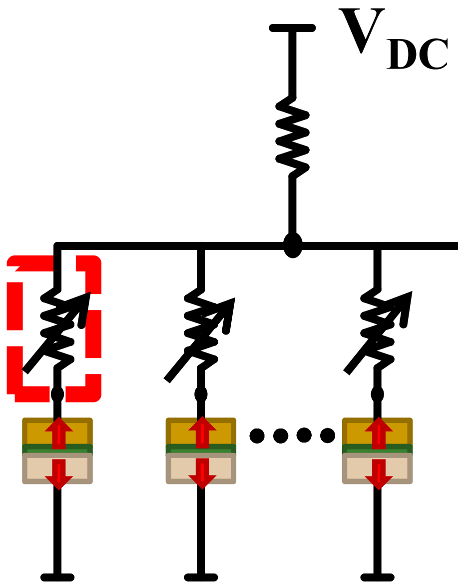
STO Geometries

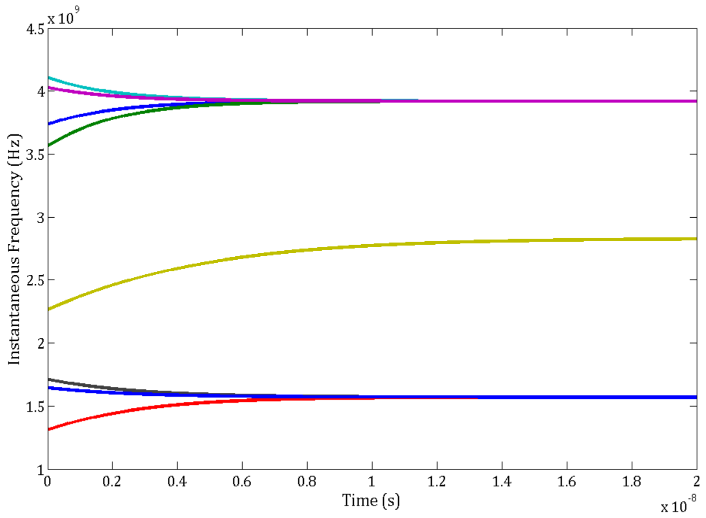
- Many different configuration of STOs yield various results depending on metrics.
- Two different structures were examined: Perpendicular and Hybrid.
- Perpendicular uses two out-of-plane magnetic layers for the fixed and free layer.
- Hybrid uses an in-plane fixed layer and out-of-plane free layer.
- Metrics considered for effective pattern recognition application:
  - Quick convergence time.
  - Strength of output signal from each STO in associative array.

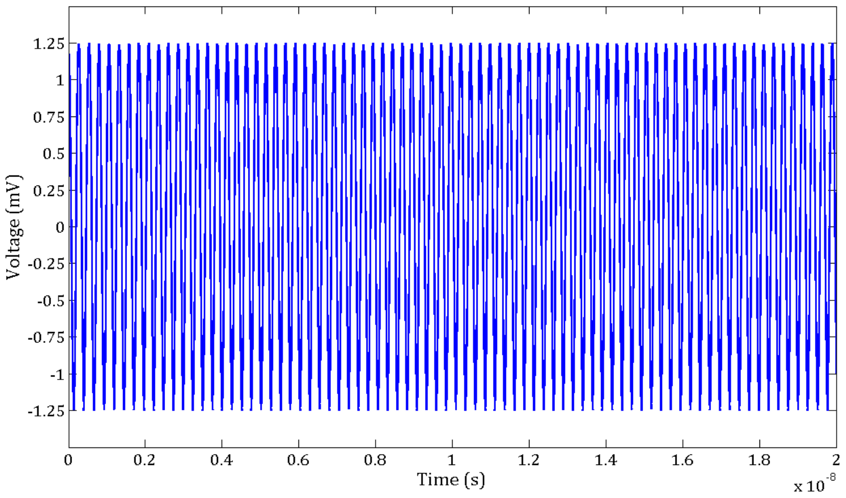


Coherence using Perpendicular STOs

- Using perpendicular fixed and free layers leads to harmonic oscillation
- Coherence shown previously.
- Problem: The magnitude of oscillation of voltage is small (~1.25mV).

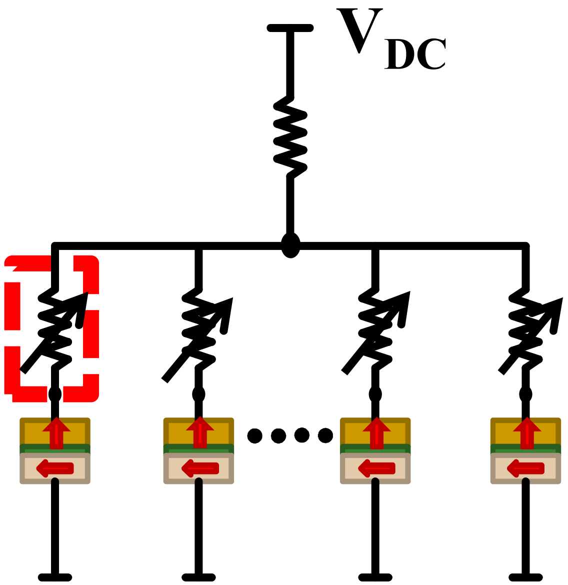


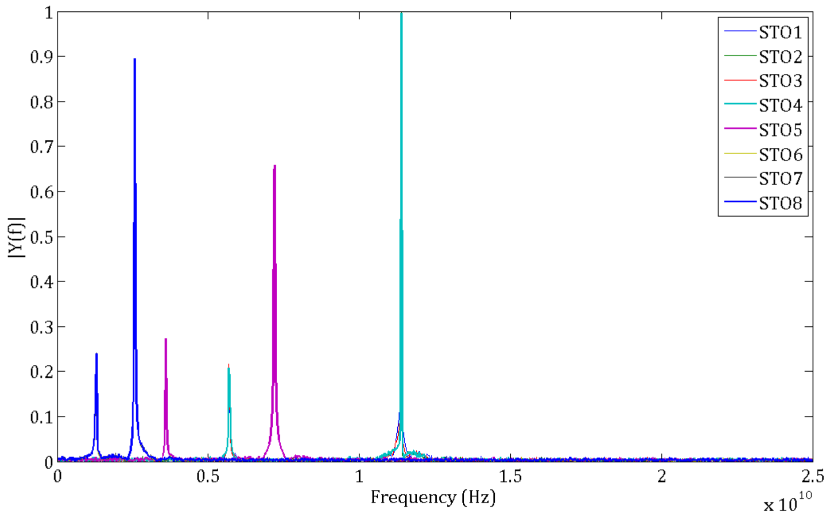


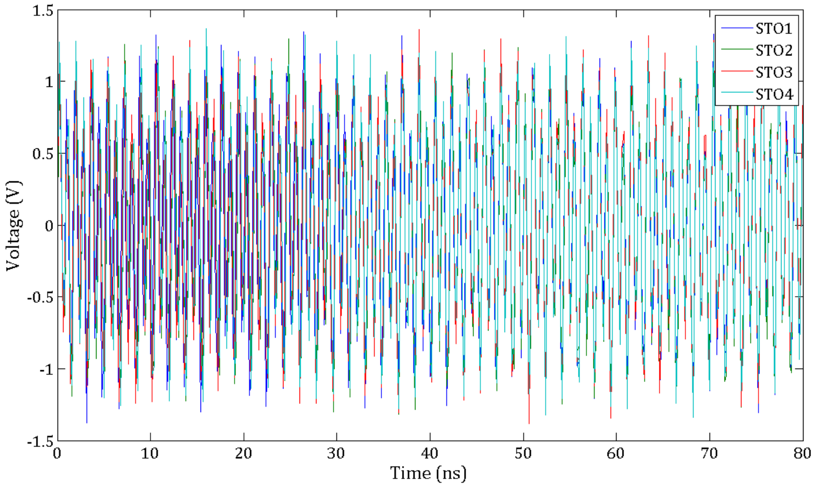


Coherence using Hybrid STOs

- Using in-plane fixed and perpendicular free layers leads to a more complicated harmonic oscillation.
- Coherence occurs but in bunching of frequencies happens for smaller range of frequencies (~0.2GHz).
- Time to cohere is also longer (~20-30ns) compared to perpendicular only (~5-8ns).

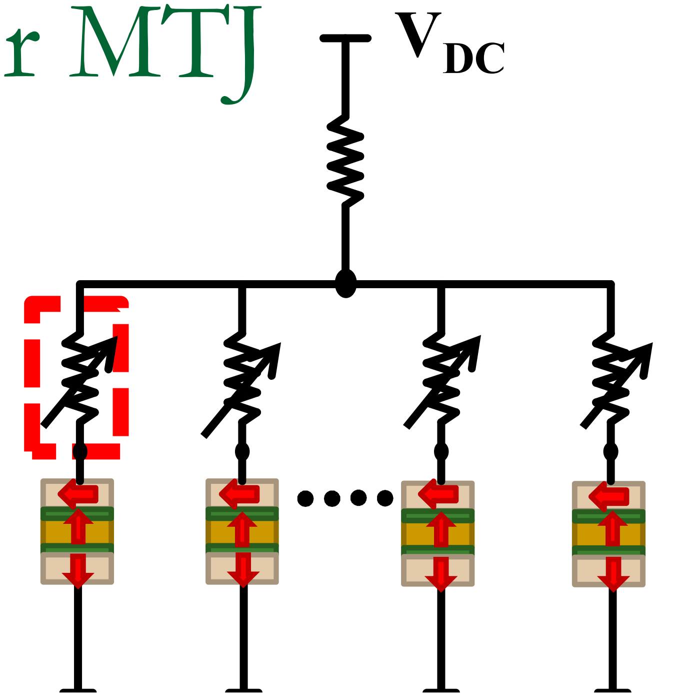


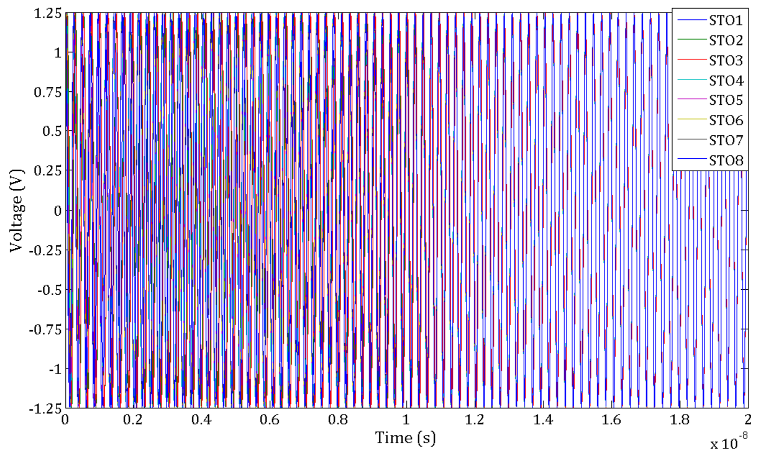




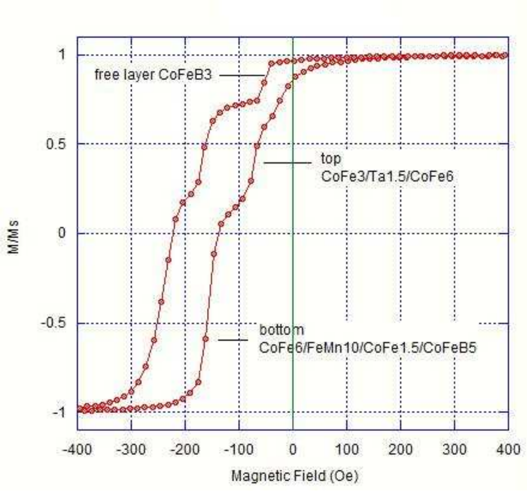
Novel idea: Dual Barrier MTJ

- Using a Dual MTJ structure allows us to take advantage of both cases.
- The free layer and driving fixed layer are both perpendicular giving harmonic oscillation.
- The reading fixed layer is in-plane allowing for higher magnitude voltage signal.

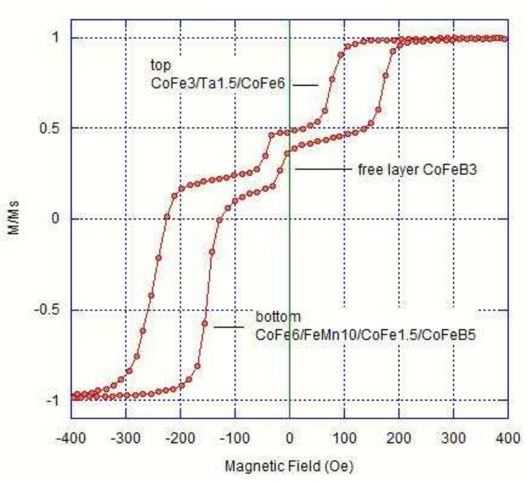




Dual Barrier MTJs: Experimental Results



DBMTJ (**P**)

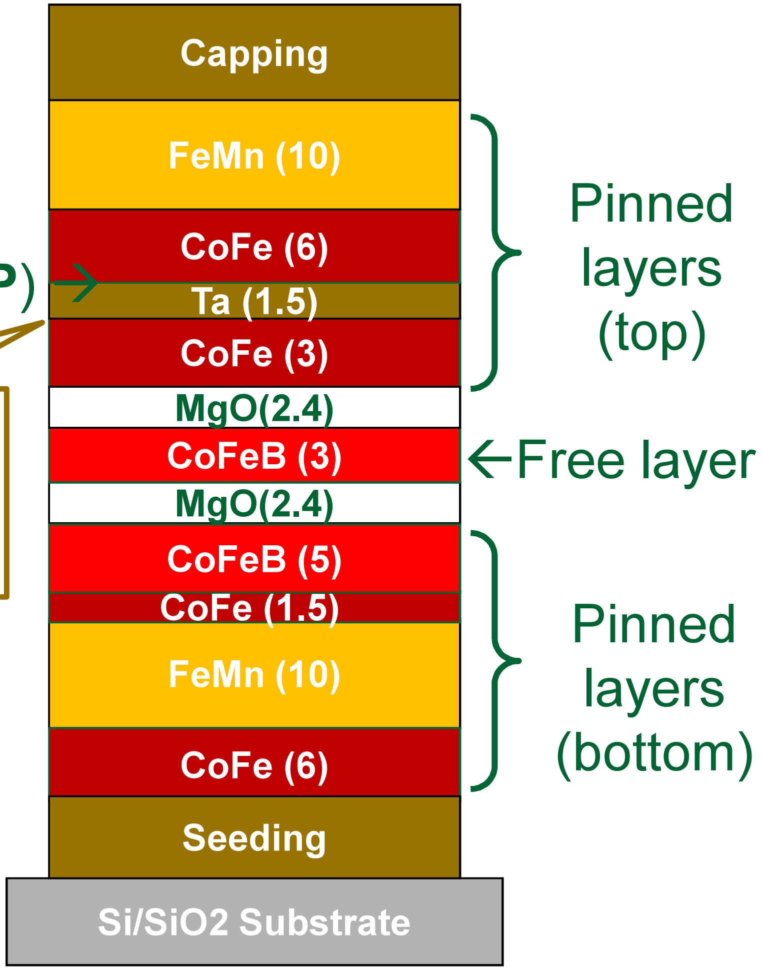


DBMTJ (**AP**)

Break vacuum (**AP**)

Insertion of Ta (1.5 nm)

- promote top pinning
- block of Mn diffusion



Capping

FeMn (10)

CoFe (6)

Ta (1.5)

CoFe (3)

MgO(2.4)

CoFeB (3)

MgO(2.4)

CoFeB (5)

CoFe (1.5)

FeMn (10)

CoFe (6)

Seeding

Si/SiO2 Substrate

Pinned layers (top)

←Free layer

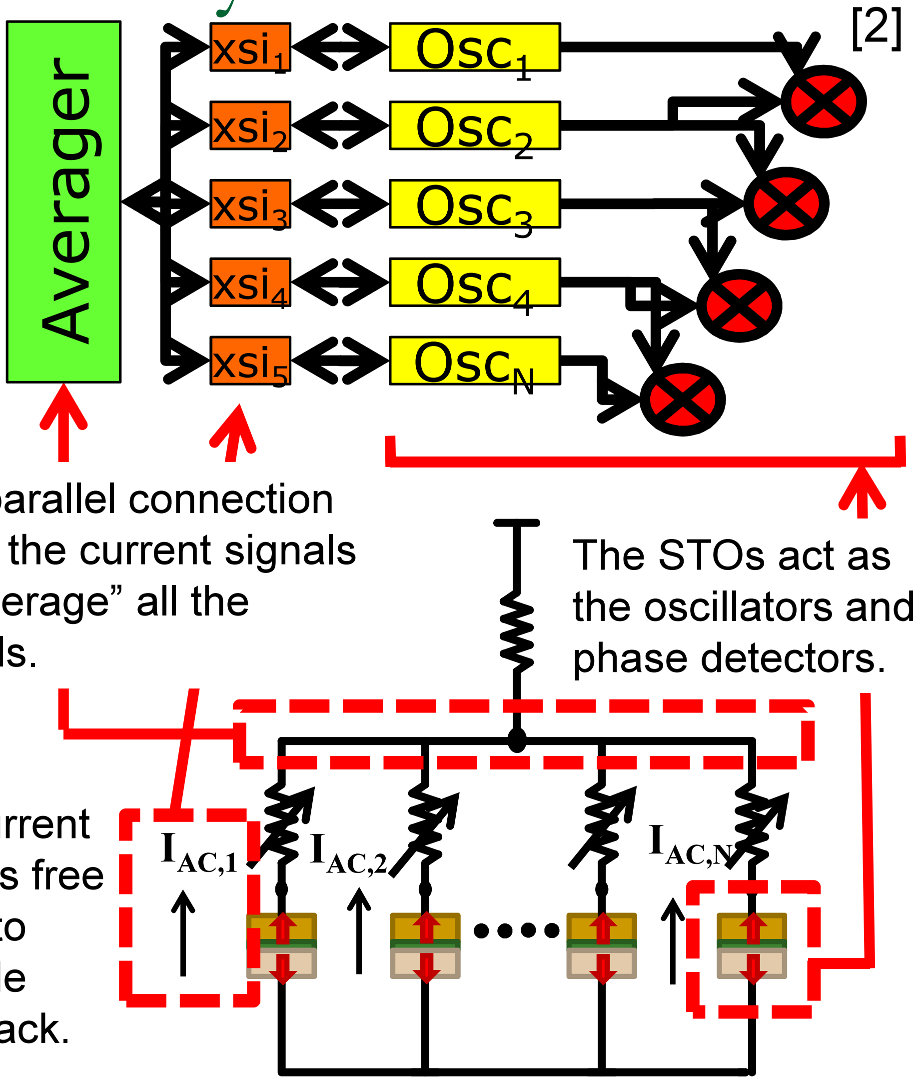
Pinned layers (bottom)

* G. Feng *et. al.* J. Appl. Phys. 105, 033916 (2009)

Computing with STO arrays

Electrically Coupled Array of STO

- Electrically coupling STOs could simplify creation of networks.
- The parallel coupled STOs act as an oscillatory neural network proposed by Hoppensteadt *et al.* [1]
- Can be arranged in many topologies and requires only N-connections.
- This neural network requires three components: oscillators, a common medium (e.g. averager), and periodic signal which creates feedback and couples the oscillators.



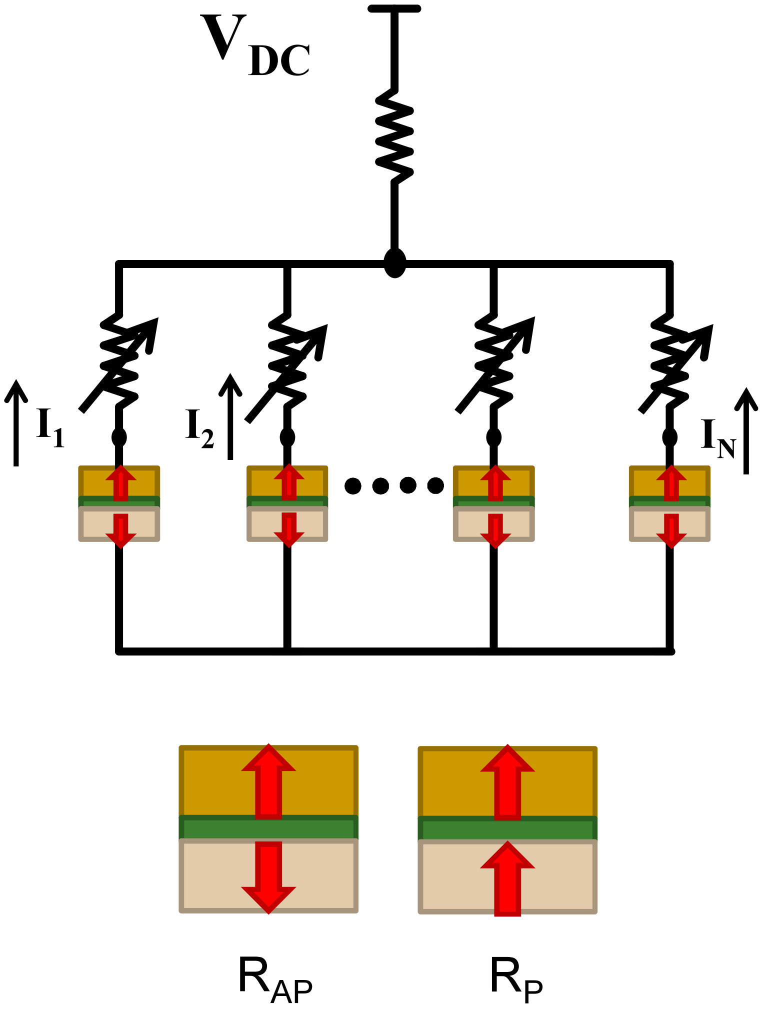
The parallel connection sums the current signals to “average” all the signals.

The STOs act as the oscillators and phase detectors.

AC current excites free layer to provide feedback.

[1] F. C. Hoppensteadt and E. M. Izhikevich. *Phys. Rev. Lett.*, vol. 82 (14), 1999
[2] D. Nikonov & G. Bourianoff

Parallel Coupled Array: Dynamics



1. Each STO is driven by a current which is made up of DC and AC components:

$$I_i = I_{ac,i} + I_{dc,i}$$

2. The two components are related as* :

$$I_{ac,i} \approx \Lambda_{TMR} I_{dc} \mathbf{m_i(t)} \cdot \mathbf{m_F}$$

$$\Lambda_{TMR} = \frac{R_{AP} - R_P}{R_{AP} + R_P}$$

3. By Kirchoff's current law: $I_{ac} = \sum_i I_{ac,i}$

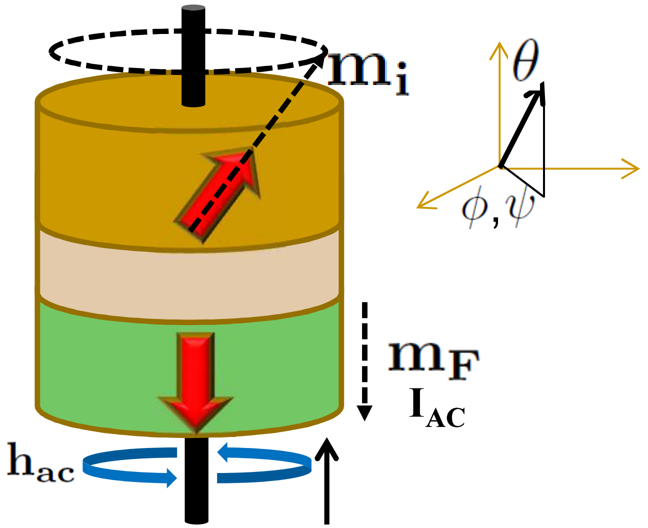
4. The total AC current distributes the energy of the system, injecting energy into some branches while extracting from others.

---

* P. Tabor, V. Tiberkevich, et al., *Phys. Rev. B* 82, 020407 (2010).

Parallel Coupled Array: Dynamics II

5 This occurs because the AC field generates a magnetic field in the free layer of the STO: $\mathbf{H_{ac}} = \xi I_{ac} \mathbf{h_{ac}}$ where ξ is material dependent property.



6 Therefore, the energy injected/extracted is given by:

$$E_i = -\mu_0 M_s V_0 \oint \mathbf{H_{ac}} \cdot d\mathbf{m_i}$$

$$= -\sum_j \vartheta_j |\mathbf{m_i}| \sin\theta_{ac} \cos(\phi_i - \phi_j - \psi_{ac})$$

7 This energy changes the frequency as: $\delta f_i = (\frac{\partial f_i}{\partial E_i}) E_i$

8 This yields Kuramoto's relationship for synchronization where Δ_{ij} is the coupling constant*:

$$\boxed{\frac{1}{2\pi}\dot{\phi}_i = f_i - \sum_j \Delta_{ij} \sin(\phi_i - \phi_j + \psi_{tot})}$$

$$\mathbf{m_i} = (r_{x,i}\cos\phi_i, r_{y,i}\sin\phi_i, r_{z,i})$$

$$\mathbf{h_{ac}} = (\sin\theta_{ac}\cos\psi_{ac}, \sin\theta_{ac}\sin\psi_{ac}, \cos\theta_{ac})$$

$$\vartheta_j = \pi\mu_0 M_s V_0 \xi \Lambda_{TMR} I_{dc,j} \sin\theta_f$$

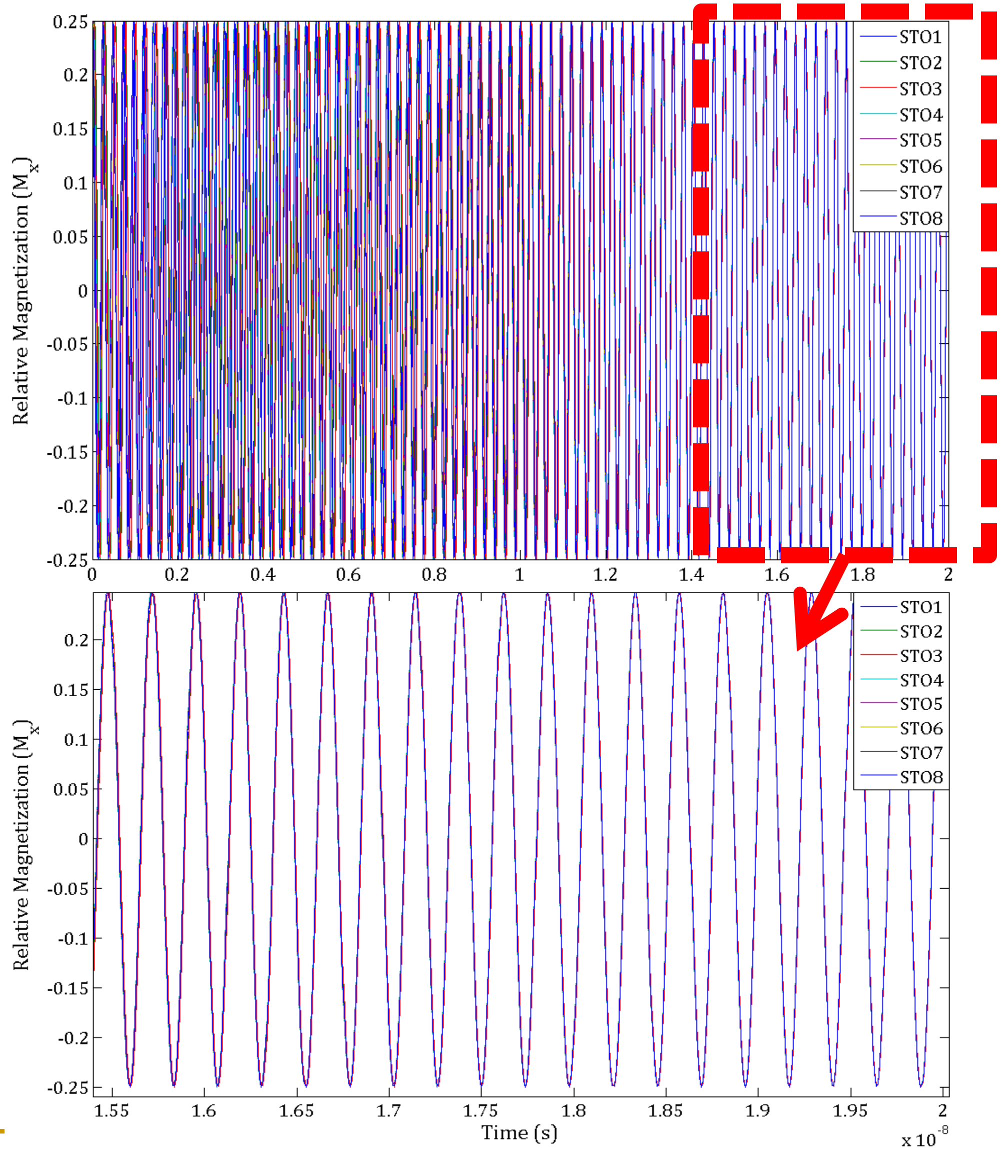
$$\Delta_{ij} = -(\frac{\partial f_i}{\partial E_i})\vartheta_j |\mathbf{m_i}| \sin\theta_{ac}$$

---

* Y. Kuramoto, *Chemical Oscillations, Waves, and Turbulence* (Springer-Verlag, New York, 1984).

Synchronization of STOs

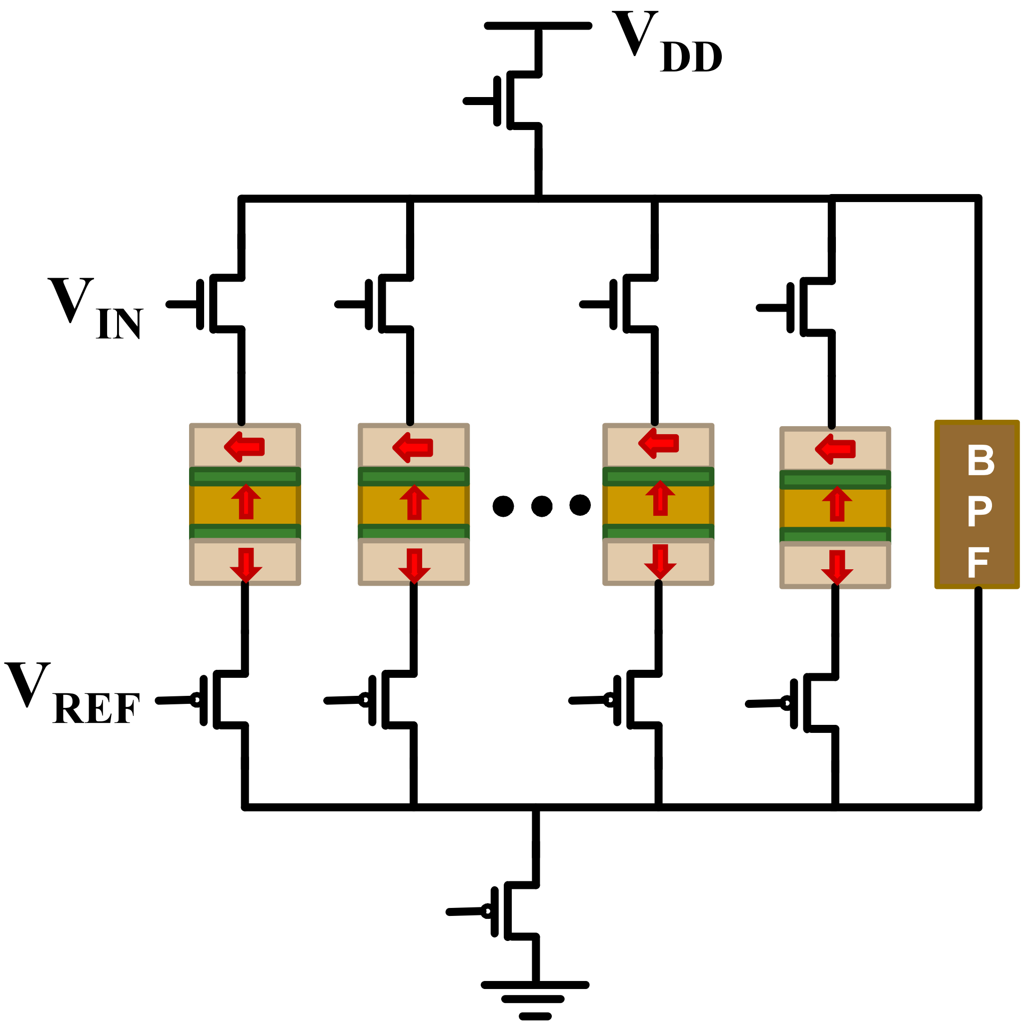
- Eight different STOs are connected in parallel to each other.
- First Case: All 8 STOs have high degree of matches → Low resistances.
- $R_{1..8}$ = 10-15Ω
- All STOs synchronize and phase-lock.
- Coherence time: ~10ns.



Associative memory using STO arrays

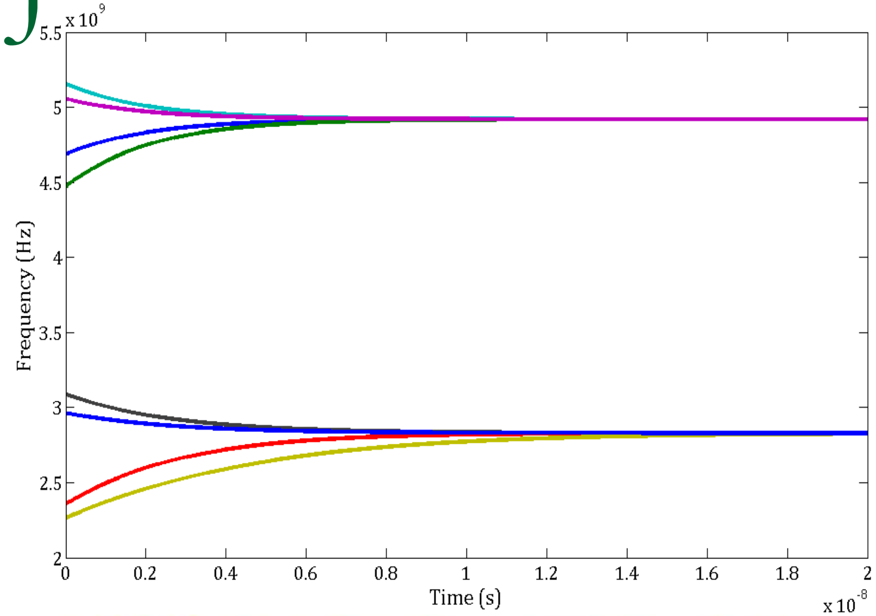
Analog Pattern Recognition using DMTJ STOs

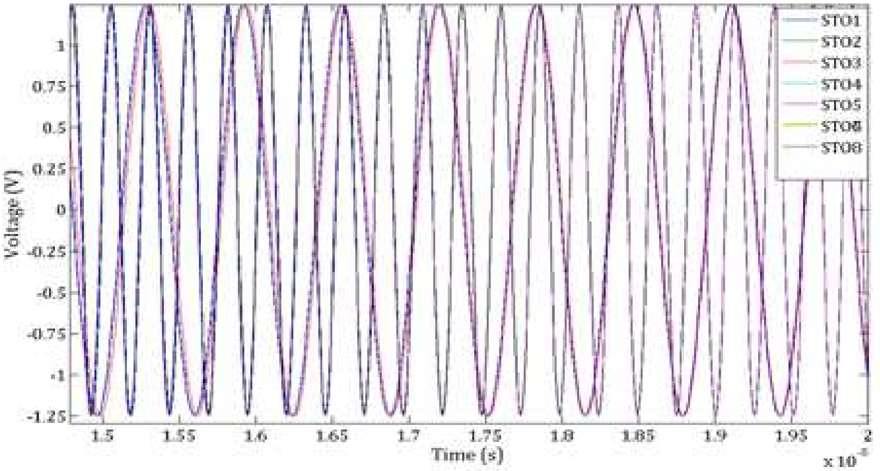
- For analog vectors, the variable resistor can be modeled using two source followers.
- This structure keeps the voltage across DMTJ the same as long as the offset between input and reference remains the same.
- Bandpass filter (RLC-network) keeps only the frequencies relating to high matches.



Coherence in DMTJ

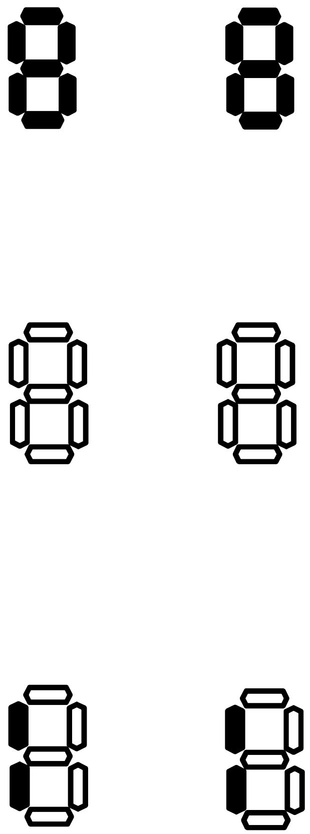
- The DMTJ STOs have the a large range of voltages which can cohere together
- Coherence time is small compared to just hybrid structures (5-10ns).
- The structure has a high magnitude voltage oscillation similar to hybrid structure.
- Phases lock when synchronized.



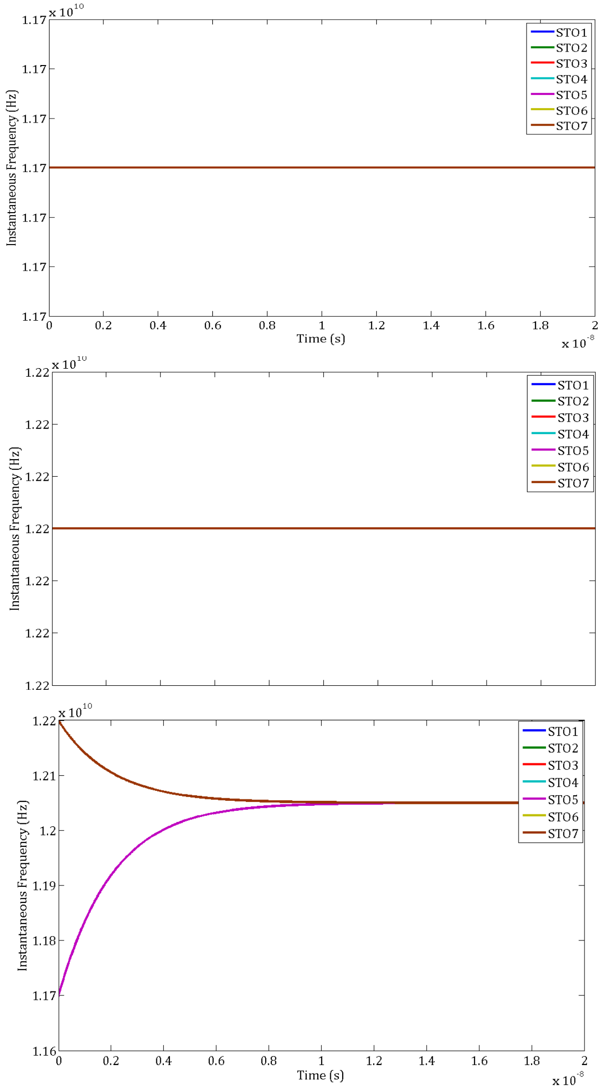


Pattern Recognition

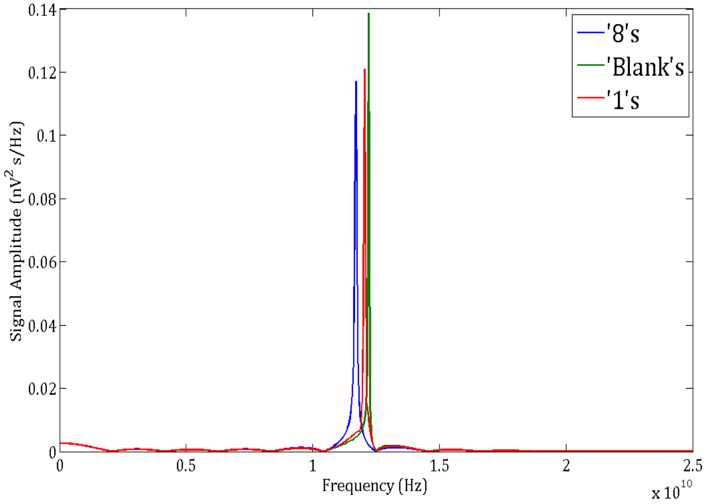
Reference **Input**



Coherence Time



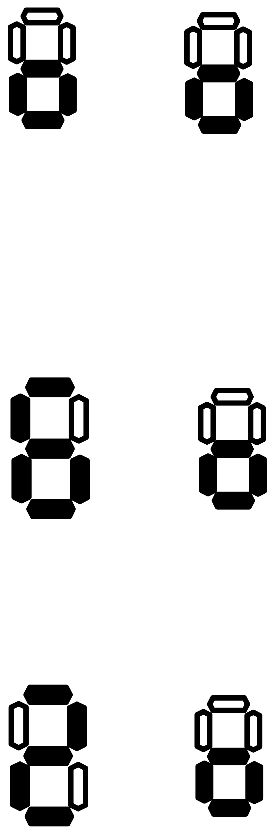
Signal Amplitude



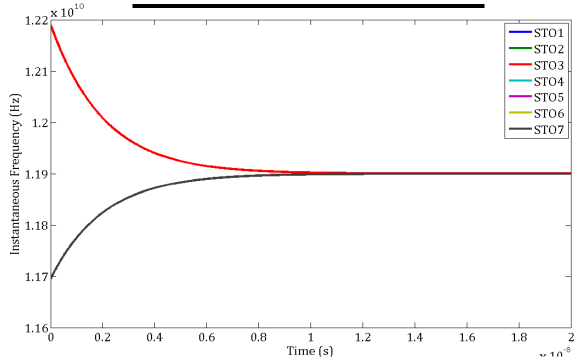
For exact matches with different patterns, the frequency and the output power of the total signal are nearly the same.

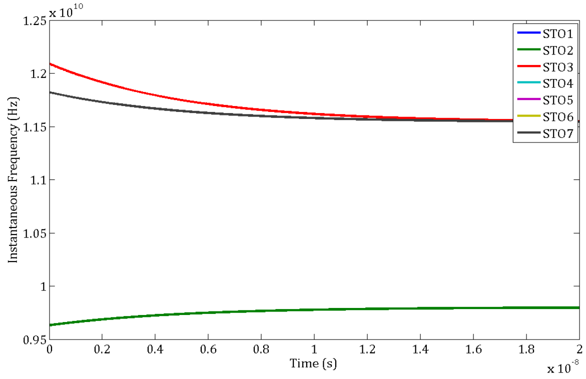
Pattern Recognition

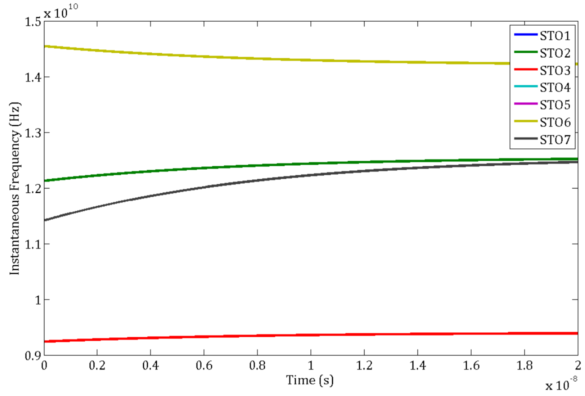
Reference Input



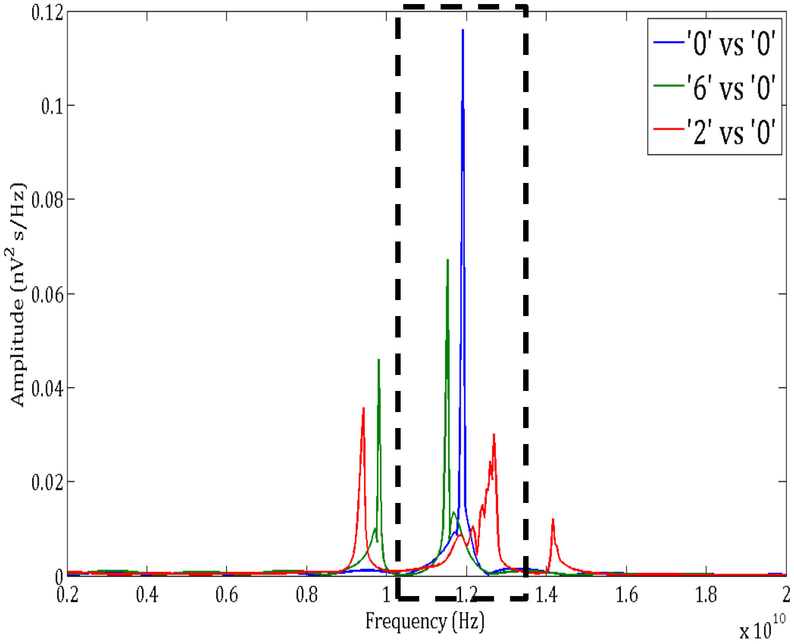
Coherence Time







Signal Amplitude



Frequencies of best match are shown in dashed box. These can be filtered using BPF.

Amplitude shows ‘6’ is a better match than ‘2’.

Conclusions and future work

- STOs and STO arrays
- SPICE model: http://hplp.ece.virginia.edu
- RF applications
- Associative memory computation
- Fabrication of hybrid CMOS/STOs
- Higher level complex applications

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