EDA Challenges in Oscillator-based Boolean Computation

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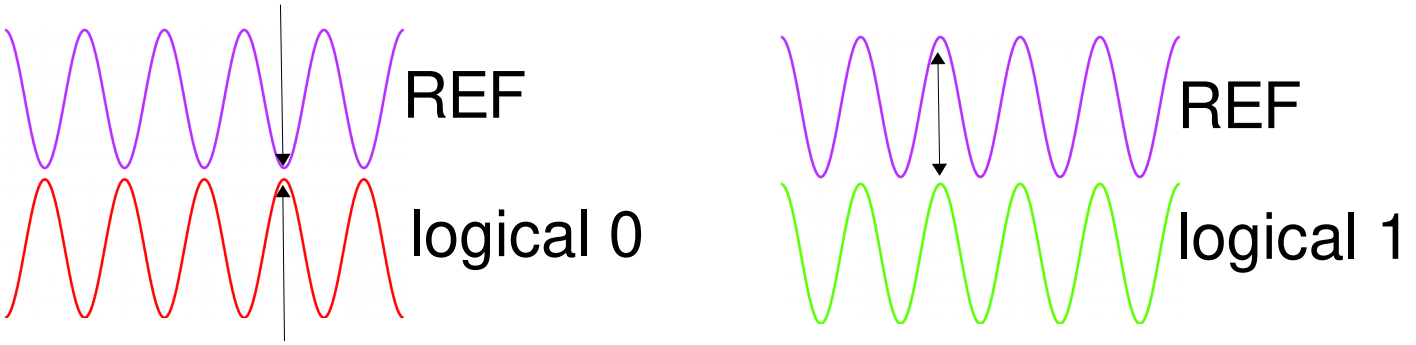
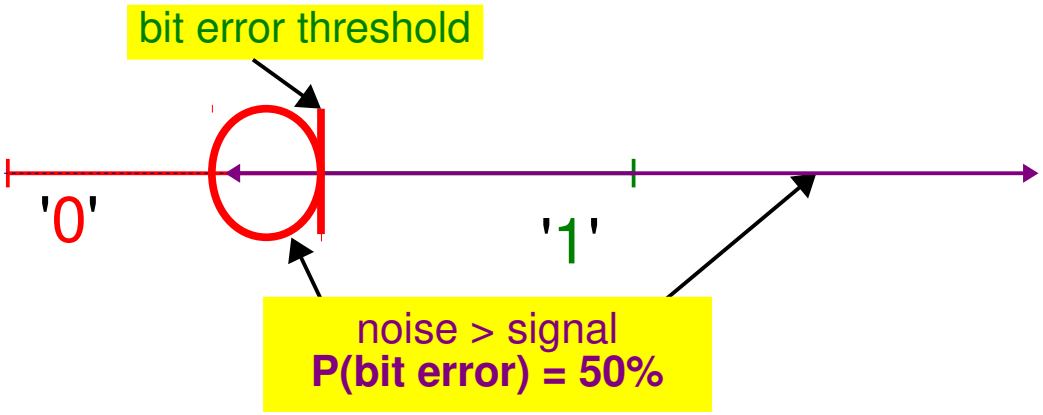
Encoding Bits Using Phase



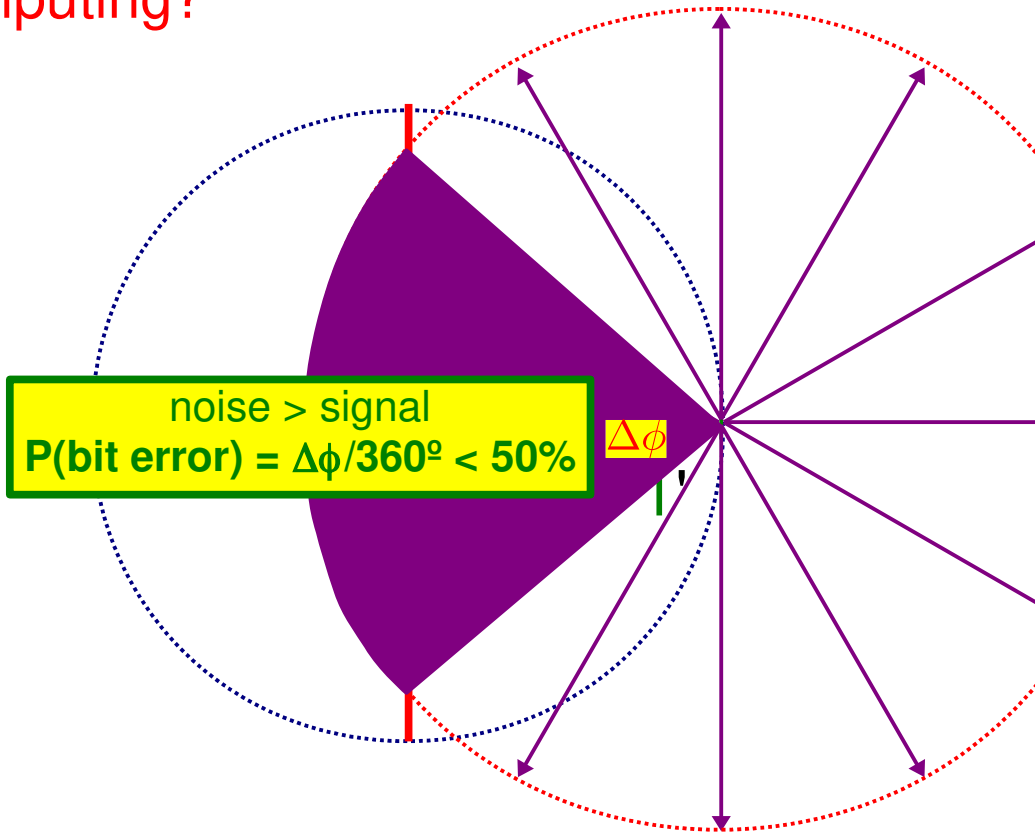
- Can you use this for computing?
- Even if you can: what is the advantage?

Superior Noise Immunity

- loose analogy: PM/FM vs AM in radio
- **Same reason why the BER of BPSK is superior to that of BASK**
- Can you use phase encoding for computing?



noise: level-based encoding



noise: phase-based encoding

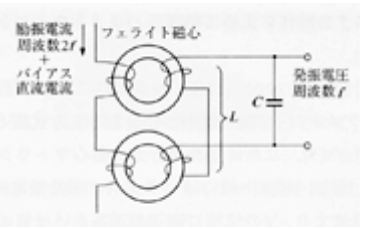
Phase Logic Computers

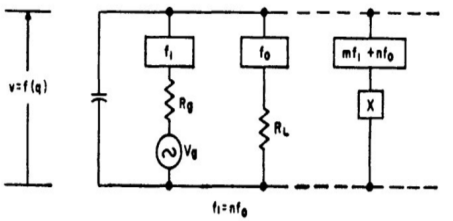
Eiichi Goto, John von Neumann, 1950s and 60s

- "cheap and reliable"
  - » "widely used in Japan"
- not easy to miniaturise
  - » inductors, iron cores
  - » transistors/ICs dominated
    - – level-based logic

Oi Electric
Parametron X-Ⅸ-01, 1964
Ferro-Electronic Calculator

Phase Based Logic:
underlying circuitry/components
have been **difficult to miniaturise**
or **impractical for integration**

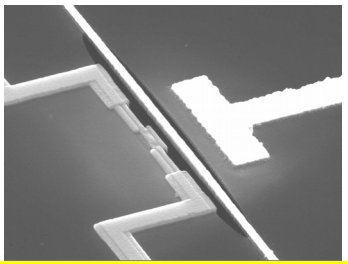




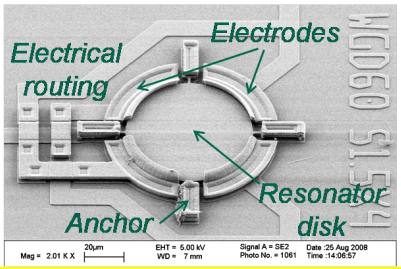
New Result: (almost) Any Oscillator will Do

details: Wang/Roychowdhury, "PHLOGON: Phase-based LOGic using Oscillatory Nano-systems". UCNC, 2014.
Roychowdhury, "Boolean Computation Using Self-Sustaining Nonlinear Oscillators". arXiv, 2014.

MEMS/NEMS

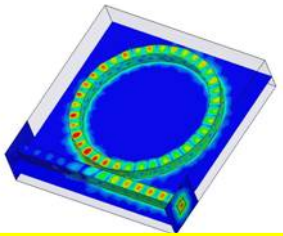


nanoswitch relaxation osc.



MEMS resonator osc.

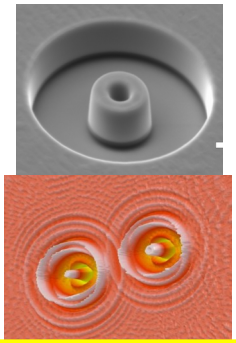
opto-electronic



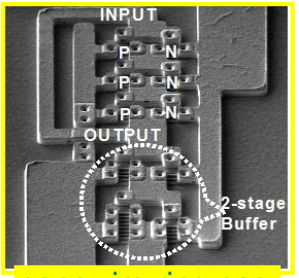
opto-resonator laser

VCSELs

novel nanodevices

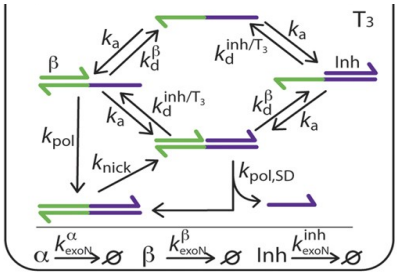


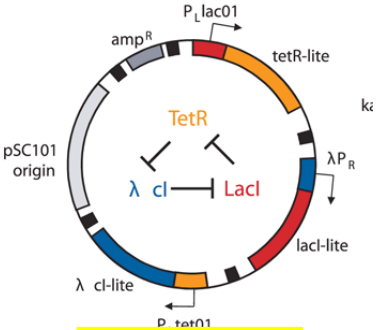
spin-torque



nanowire ring osc.

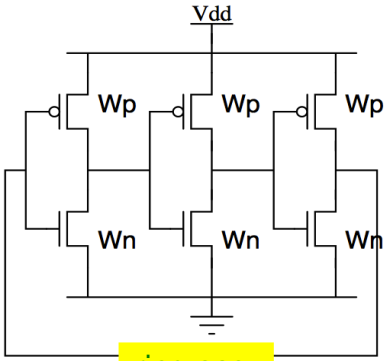
synth. bio. (DNA)

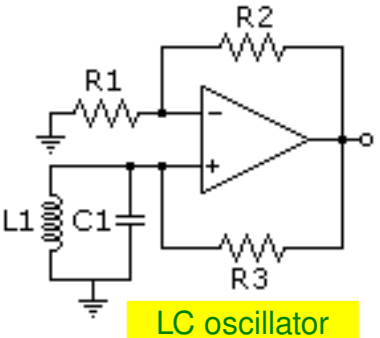




repressilator

CMOS/electronic

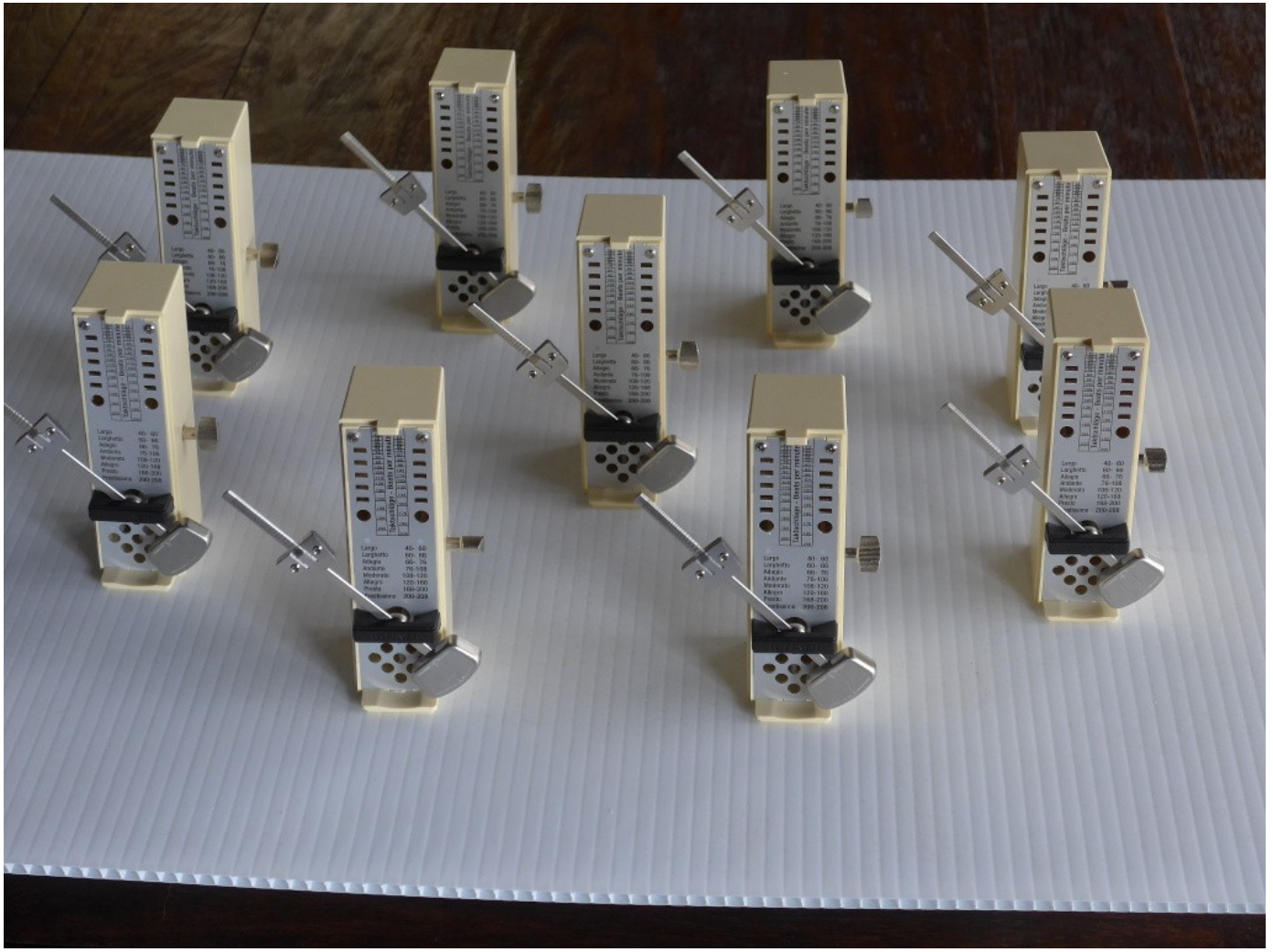




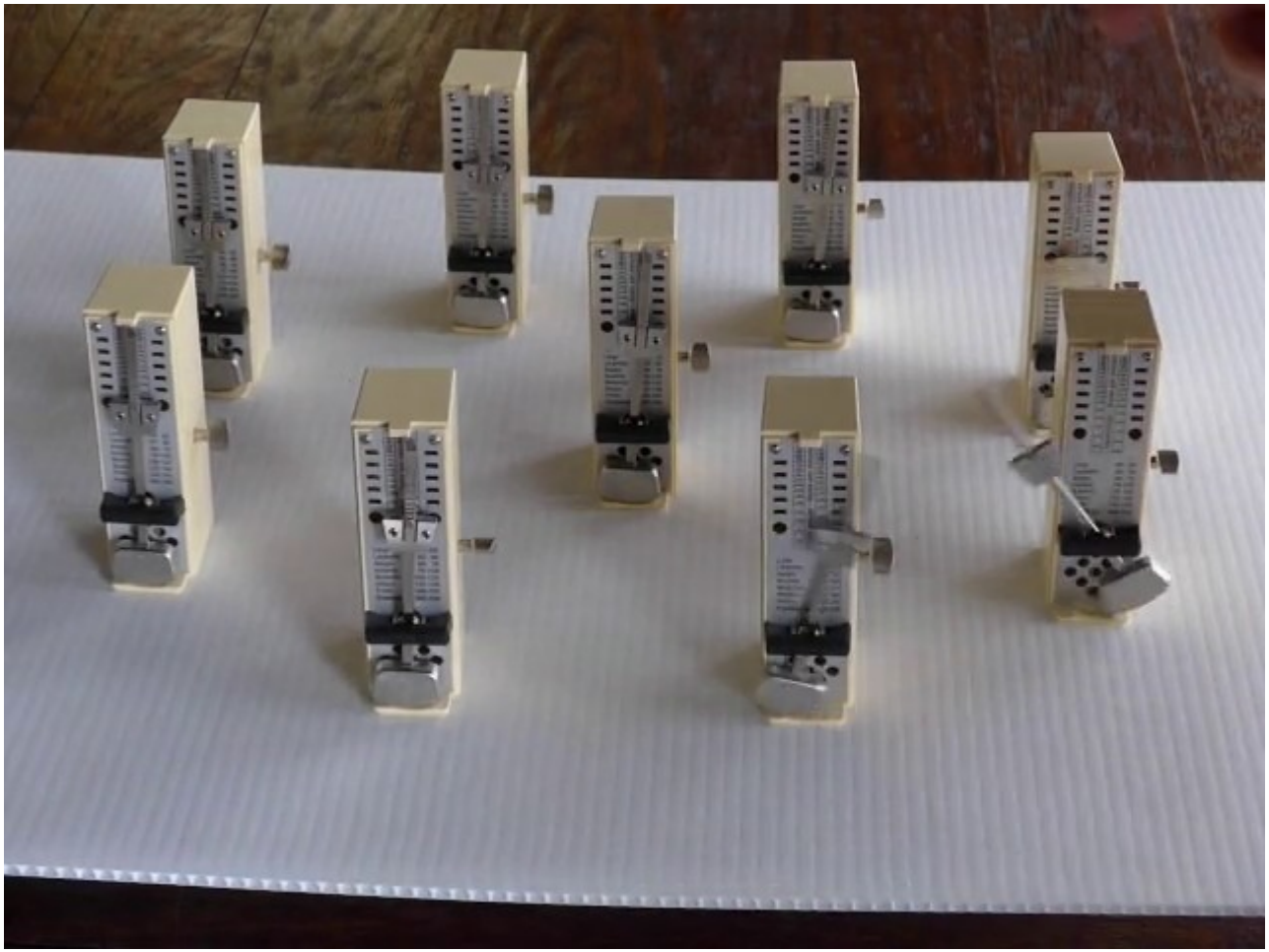
many are integrable and nano-scale

Underlying Mechanism: Injection Locking

- Oscillators can synchronize in phase/frequency

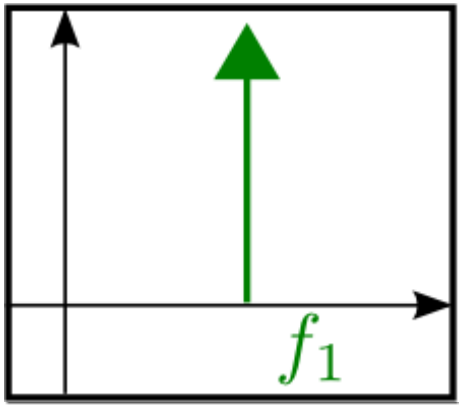


- **we use a variant: sub-harmonic injection locking**
  - **details**: Neogy/Roychowdhury, "Analysis and design of sub-harmonically injection locked oscillators", Proc. DATE, March 2012.

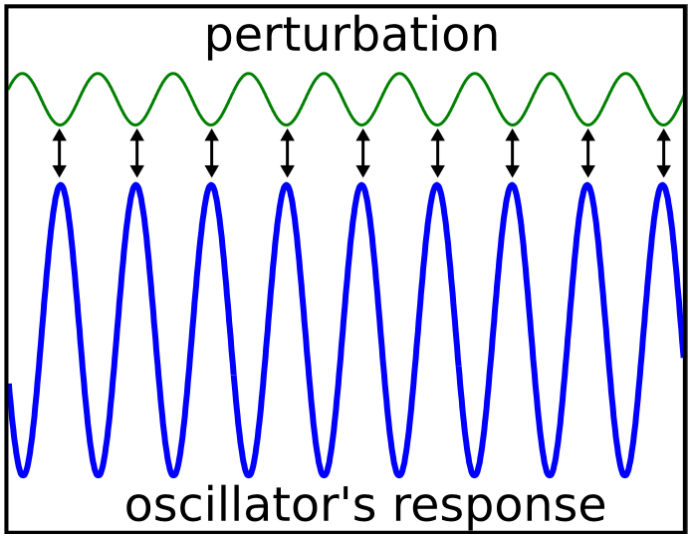


Underlying Mechanism: Injection Locking

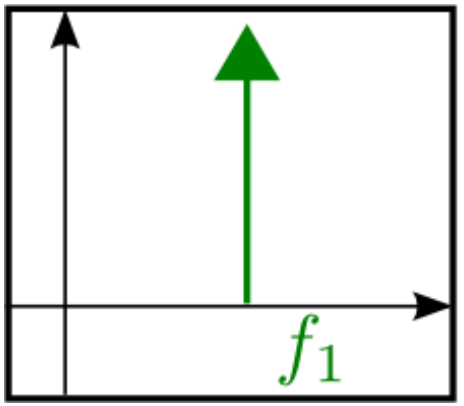
Injection Locking



phase lock



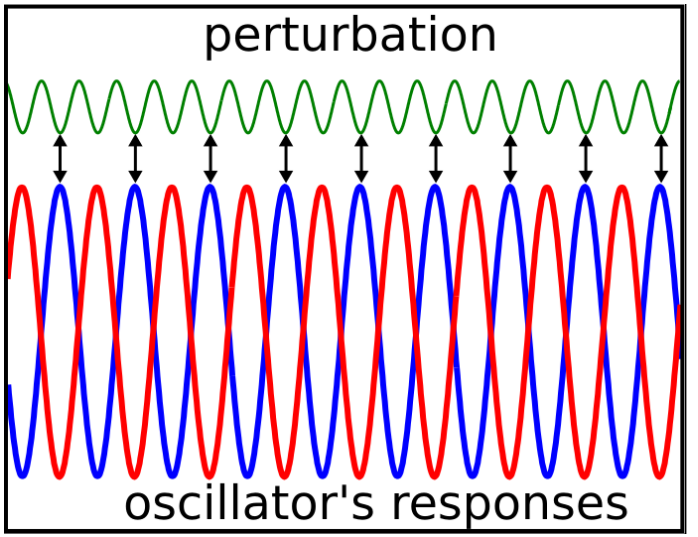
Sub-harmonic Injection Locking (SHIL)



lock 1

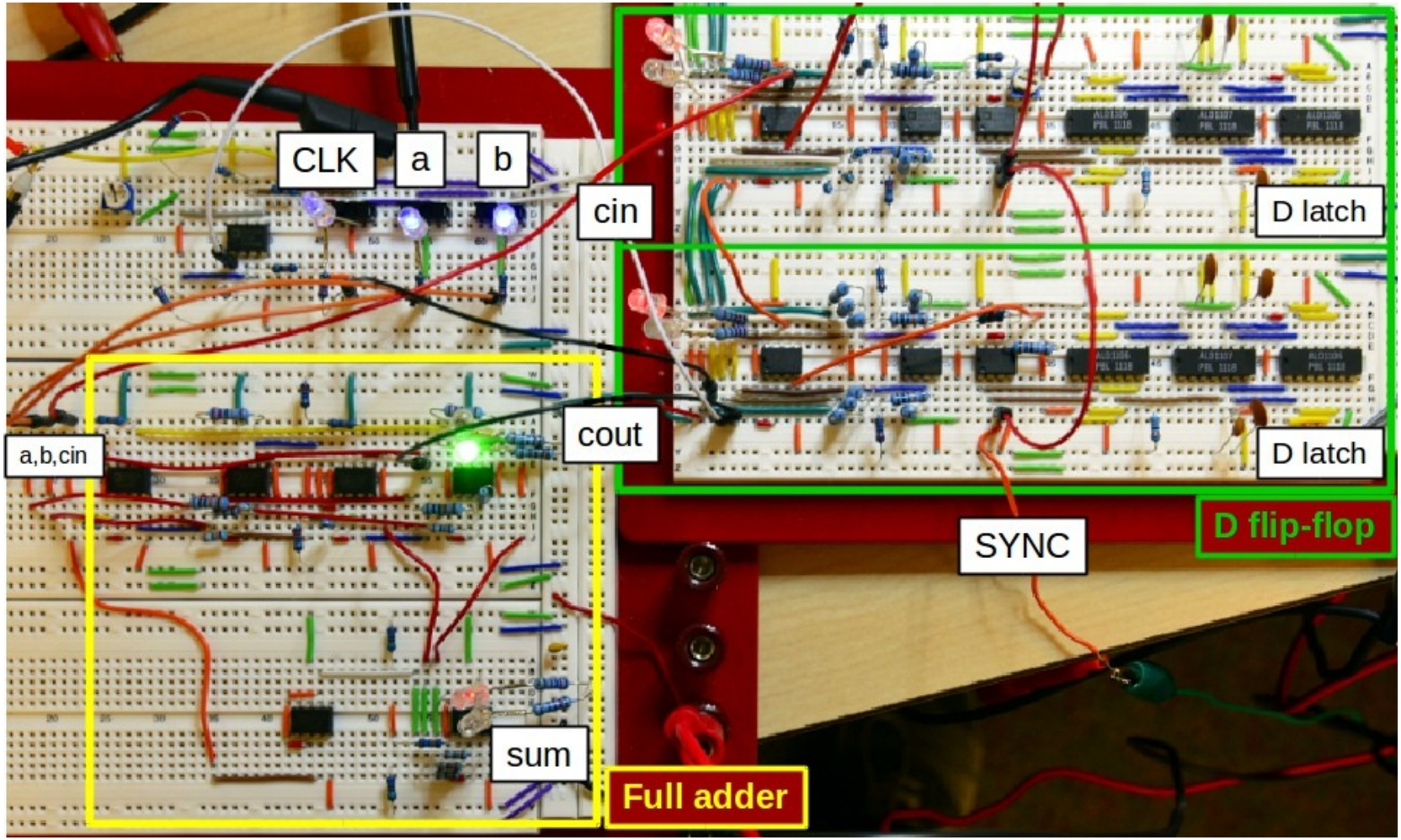
180° phase shift

lock 2

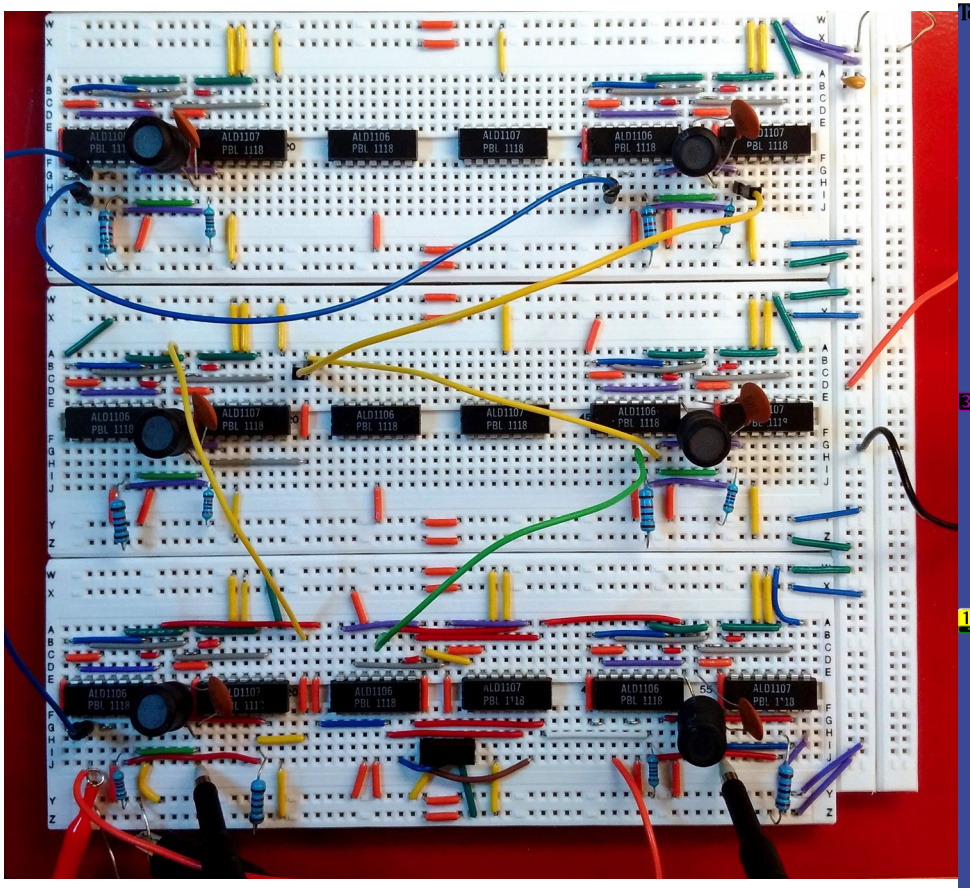


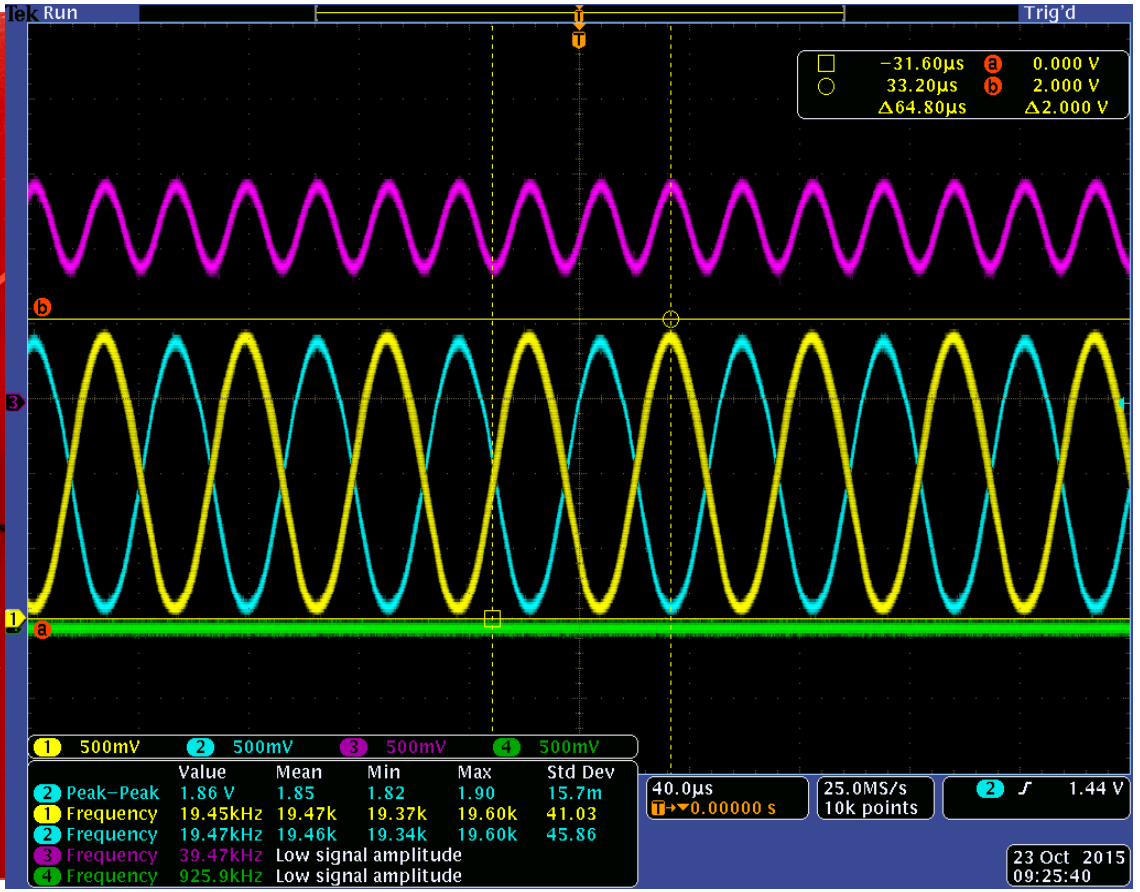
First Phase Logic FSM with Oscillators

- **PHLOGON: PHase LOGic using Oscillatory Nanosystems** using **CMOS ring oscillators**



Prototype with CMOS LC Oscillators





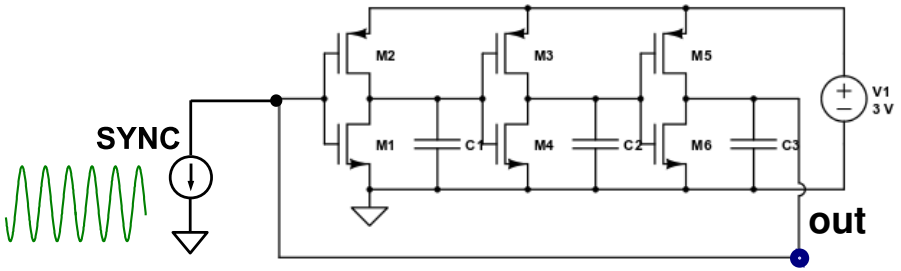
What Next?

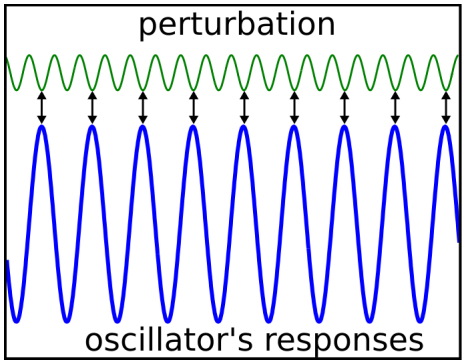
- **the idea** – oscillator-based Boolean computation
- **the mechanism** – SHIL
- **the motivation** – potential noise, energy advantages
- **the "proof-of-concept" prototypes**

- **novel "substrates" for computing**
- **physical design**

challenges in modelling & simulation

Simulating SHIL of Oscillators

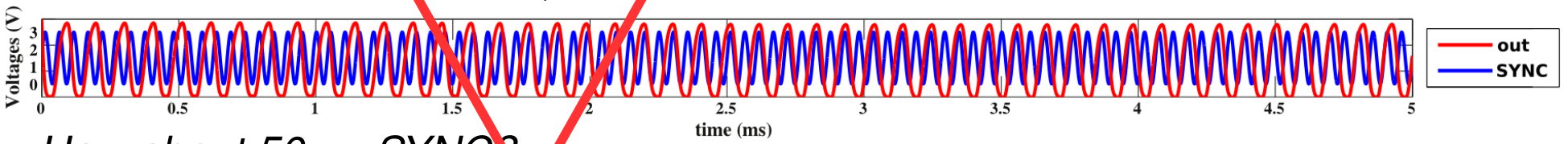




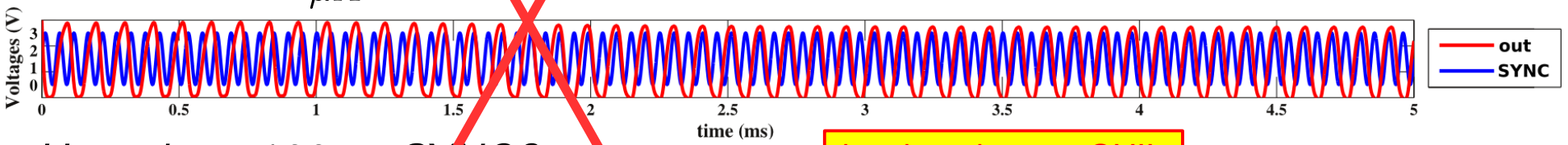
Sub-harmonic Injection Locking (SHIL)

Standard SPICE transient simulation

Is SHIL happening with 20 μA SYNC?

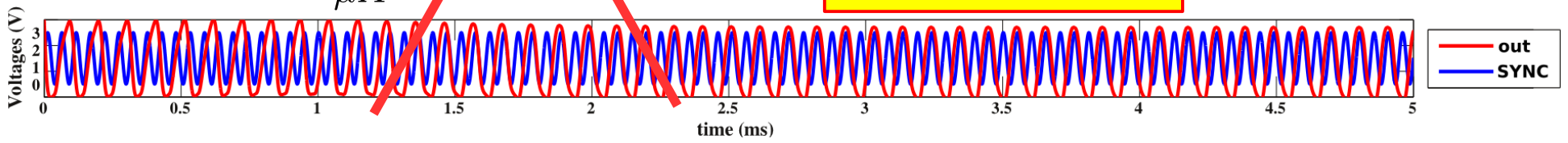


How about 50 μA SYNC?



hard to observe SHIL

How about 100 μA SYNC?



inefficient

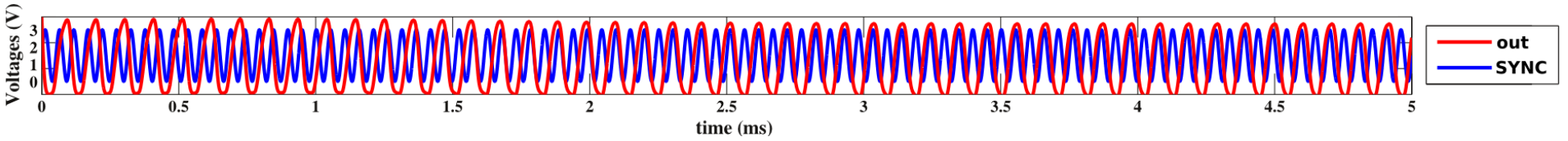
unbounded error in phase

not much insight into design

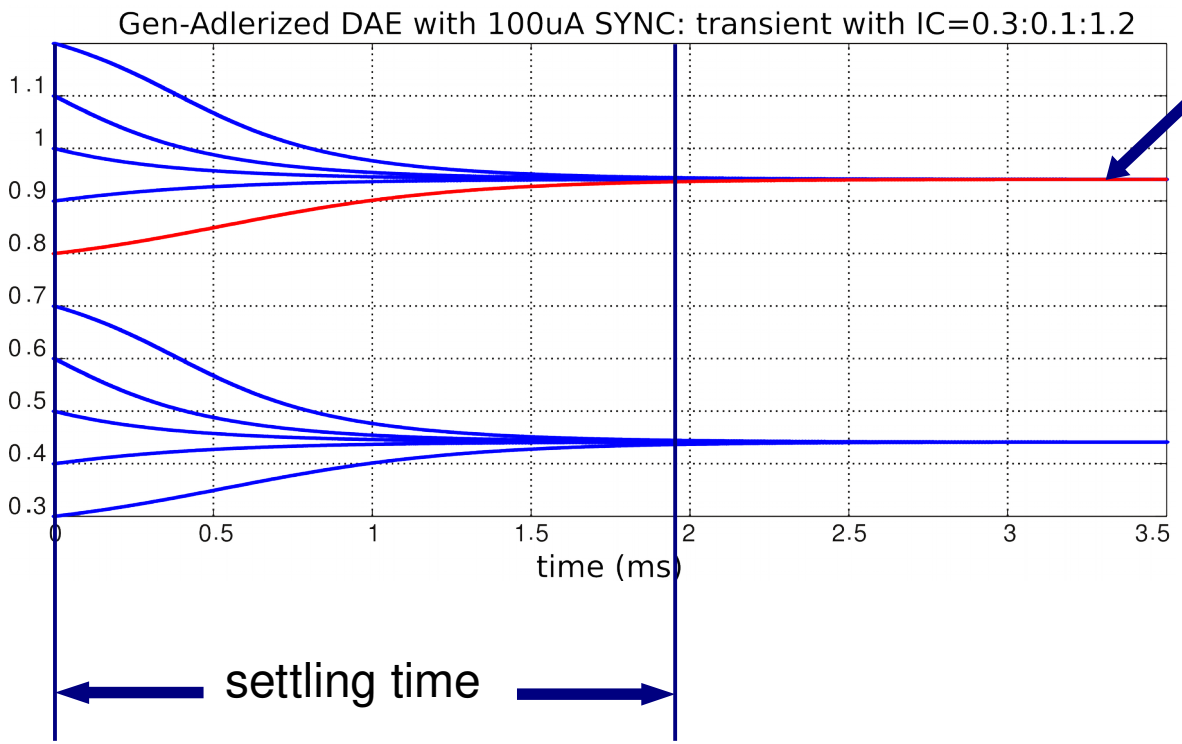
Design tools with phase macromodel analyses

Phase-macromodel-based Analyses

Standard SPICE transient simulation



Phase-based simulation



SHIL occurs: curve "flattens"

"locked phase error"

$\Delta\phi$

Generalized Adler's Equation

$$\frac{d}{dt}\Delta\phi(t) = f_0 - f_1 + f_0 \cdot g(\Delta\phi(t))$$

$$g(\Delta\phi(t)) = \int_0^{1} \vec{v}_1^T(\tau + \Delta\phi(t)) \cdot \vec{b}_1(\tau) d\tau$$

Perturbation Projection Vector (PPV)

details: Bhansali/Roychowdhury, "Gen-Adler: the Generalized Adler's equation for injection locking analysis in oscillators". Proc. ASPDAC, 2009.

Phase-macromodel-based Analyses

Model osc. in MAPP

osc. DAE

Simulate PSS: shooting or HB

C, G matrices

Extract PPVs

Gen-Adler Analysis

$$\frac{d}{dt}\Delta\phi(t) = f_0 - f_1 + f_0 \cdot g(\Delta\phi(t))$$

phase DAE

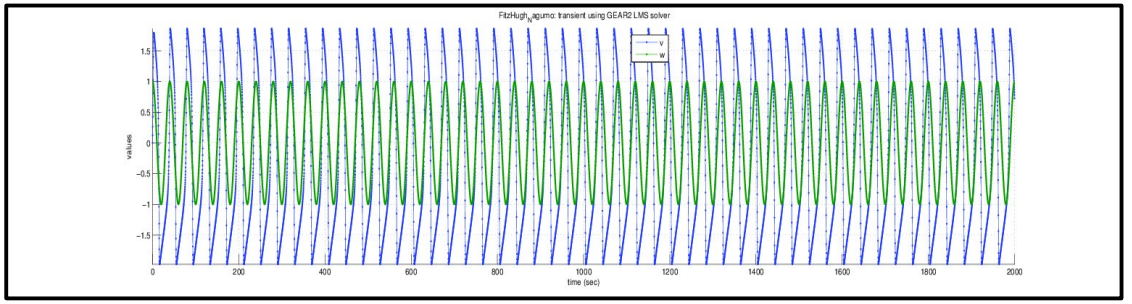
DAEAPI
CircuitPKG
Verilog-A?

DC — **locking range**

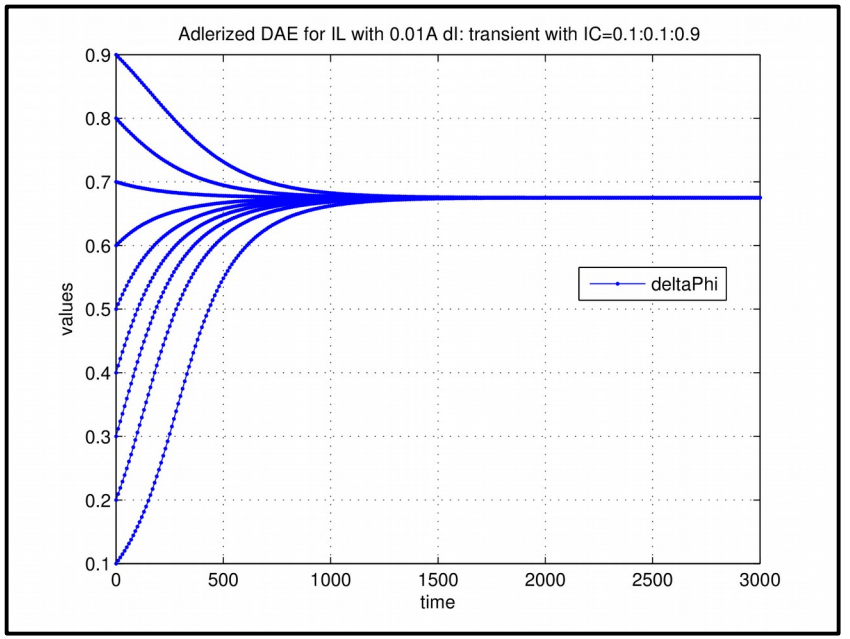
TRAN — **phase dynamics**

Observe Injection Locking properties

Standard TRAN simulation:



Phase-based TRAN:



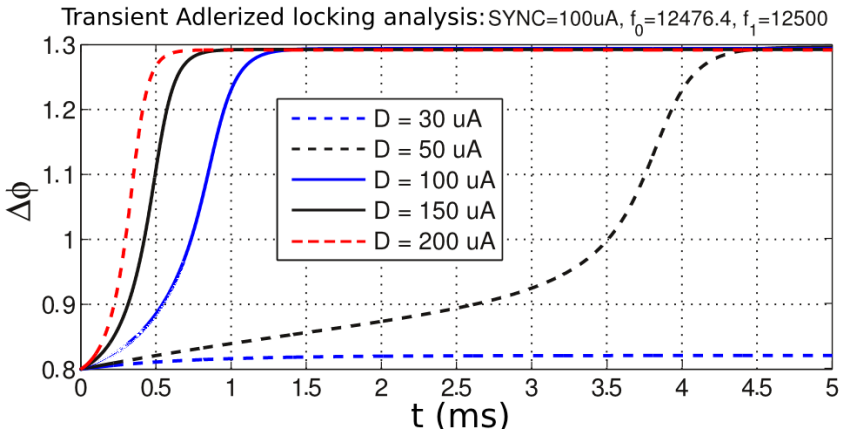
$\Delta\phi(t)$ captures phase response nicely

details: Bhansali/Roychowdhury, "Gen-Adler: the Generalized Adler's equation for injection locking analysis in oscillators". Proc. ASPDAC, 2009.

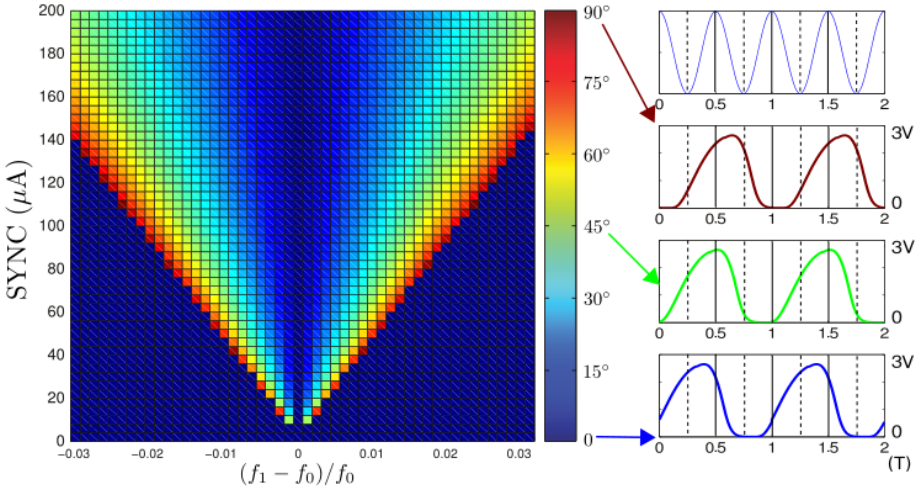
More Capabilities of the Design Tools

details: Wang/Roychowdhury, “Design Tools for Oscillator-based Computing Systems”, DAC, 2015.

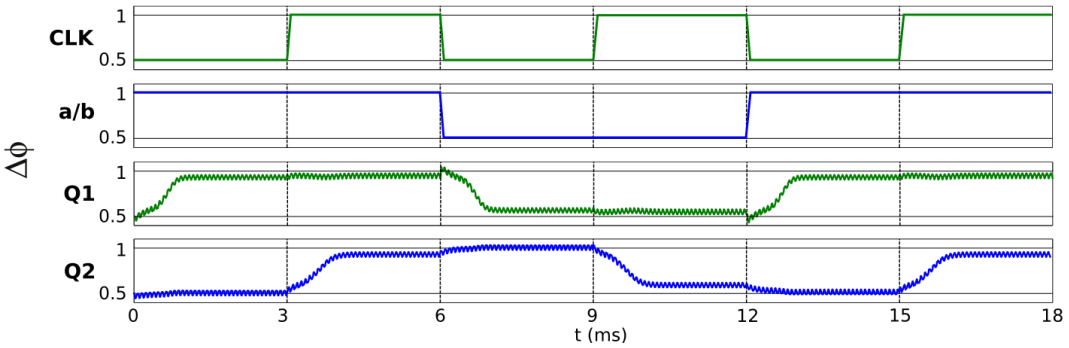
Timing of phase-based D latch



Locked phase error vs. variations in oscillator natural frequency



Full system transient in phase domain



open-source release: **PHLOGON.eecs.berkeley.edu**

Novel "Substrates" for Computing

- **What does it take to explore them?**
  - » in simulation at least

MEMS/NEMS | opto-electronic | novel nanodevices | synth. bio. (DNA) | CMOS/electronic

Toy example:

nanoswitch relaxation osc. | opto-resonator laser | oligator | ring osc.

MEMS resonator osc. | VCSELs | nanowire ring osc. | repressilator | LC oscillator

Can we make a metronome SHIL
(to store a phase-based bit)?

Modelling a Metronome

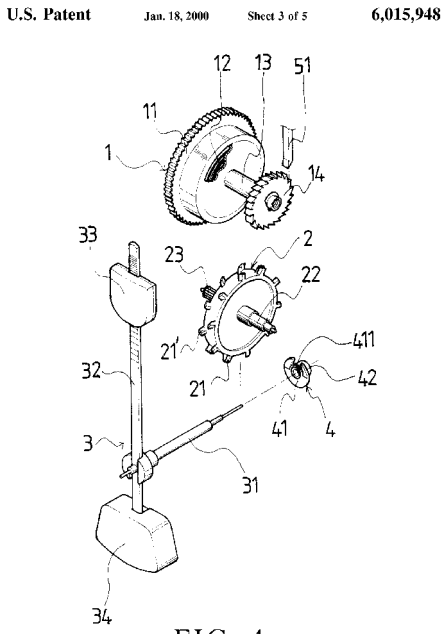
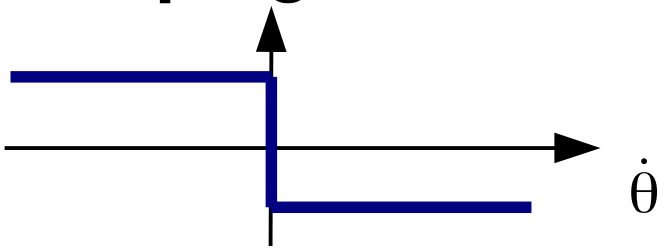


FIG. 4

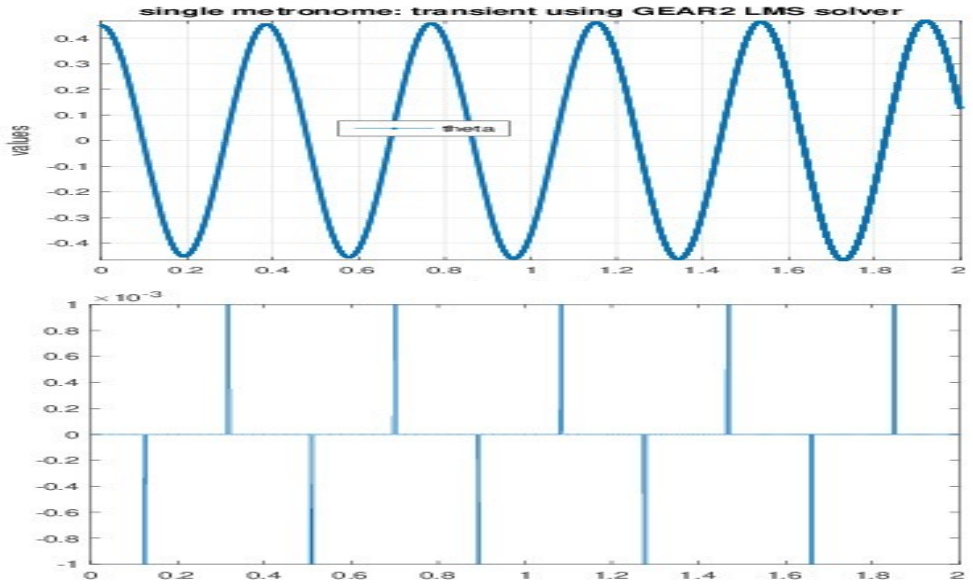
$\theta \quad \dot{\theta}$

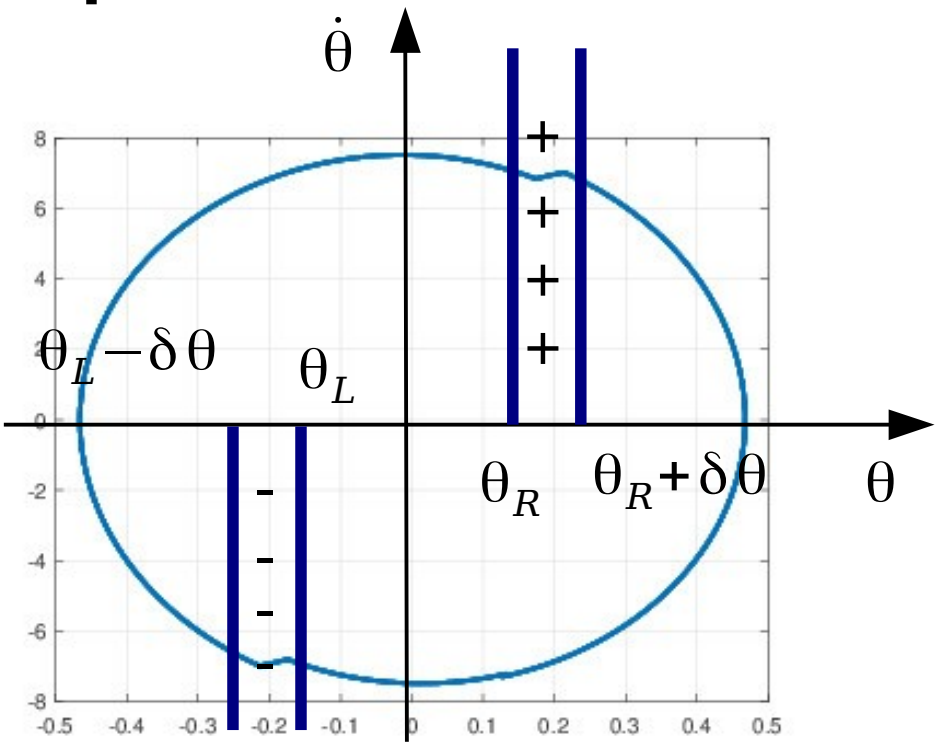
double-weighted pendulum

friction damping

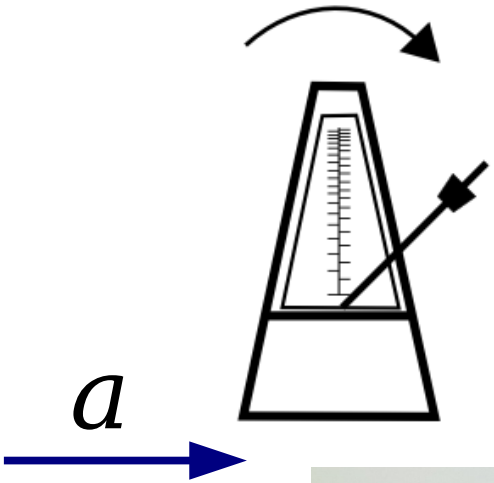


escapement mechanism





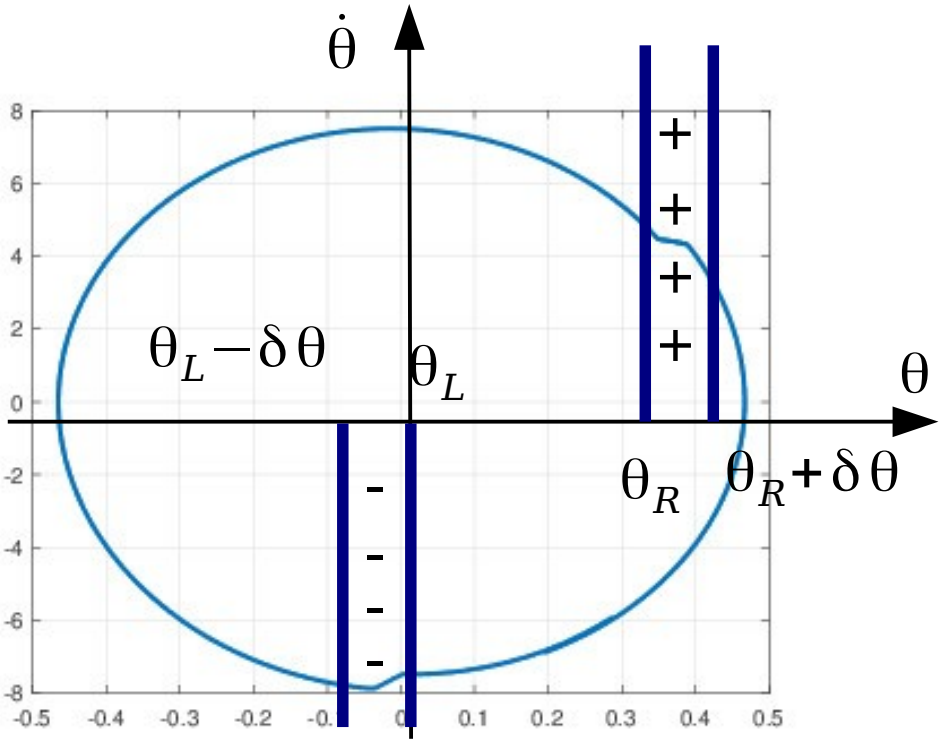
Tweaking a Metronome



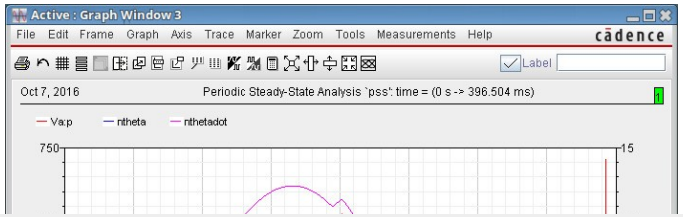
It doesn't SHIL...

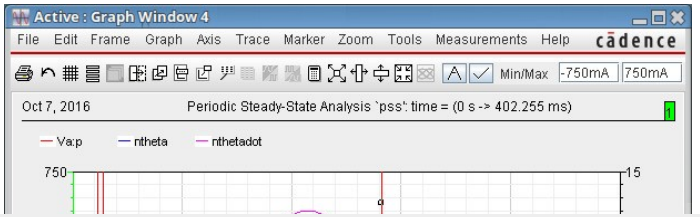
no second-harmonic in PPV

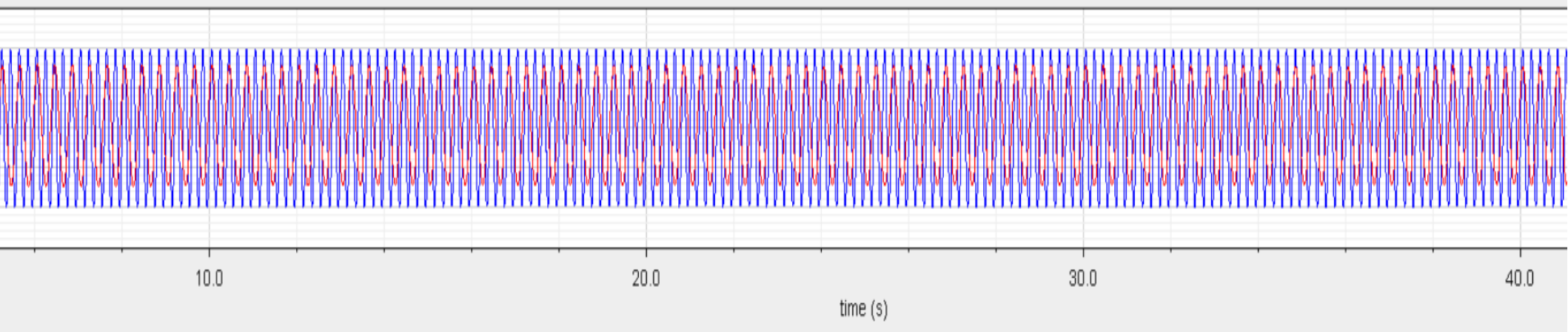
tweak escapement angles

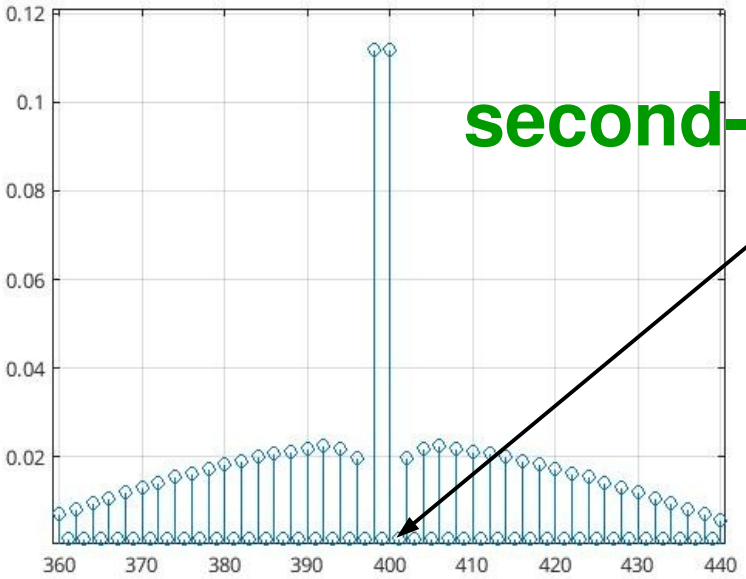


Tweaking a Metronome

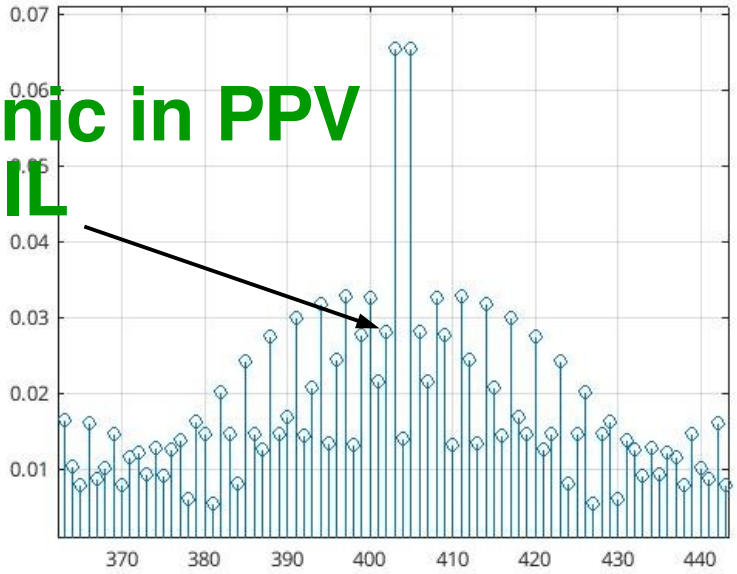




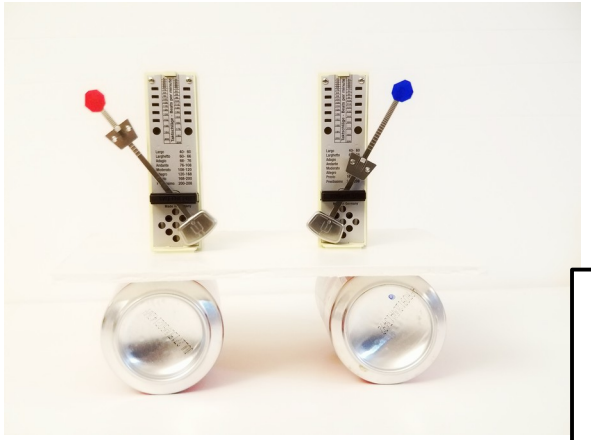


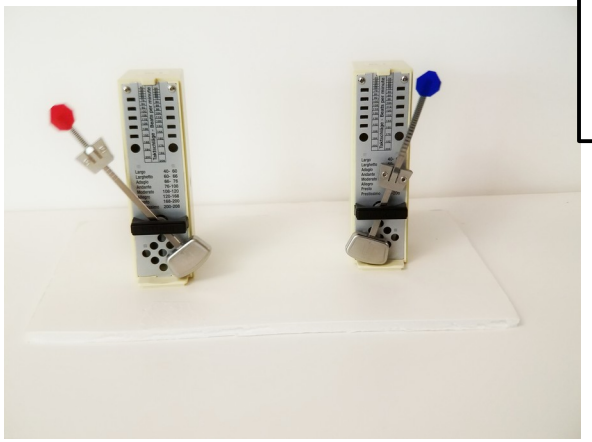


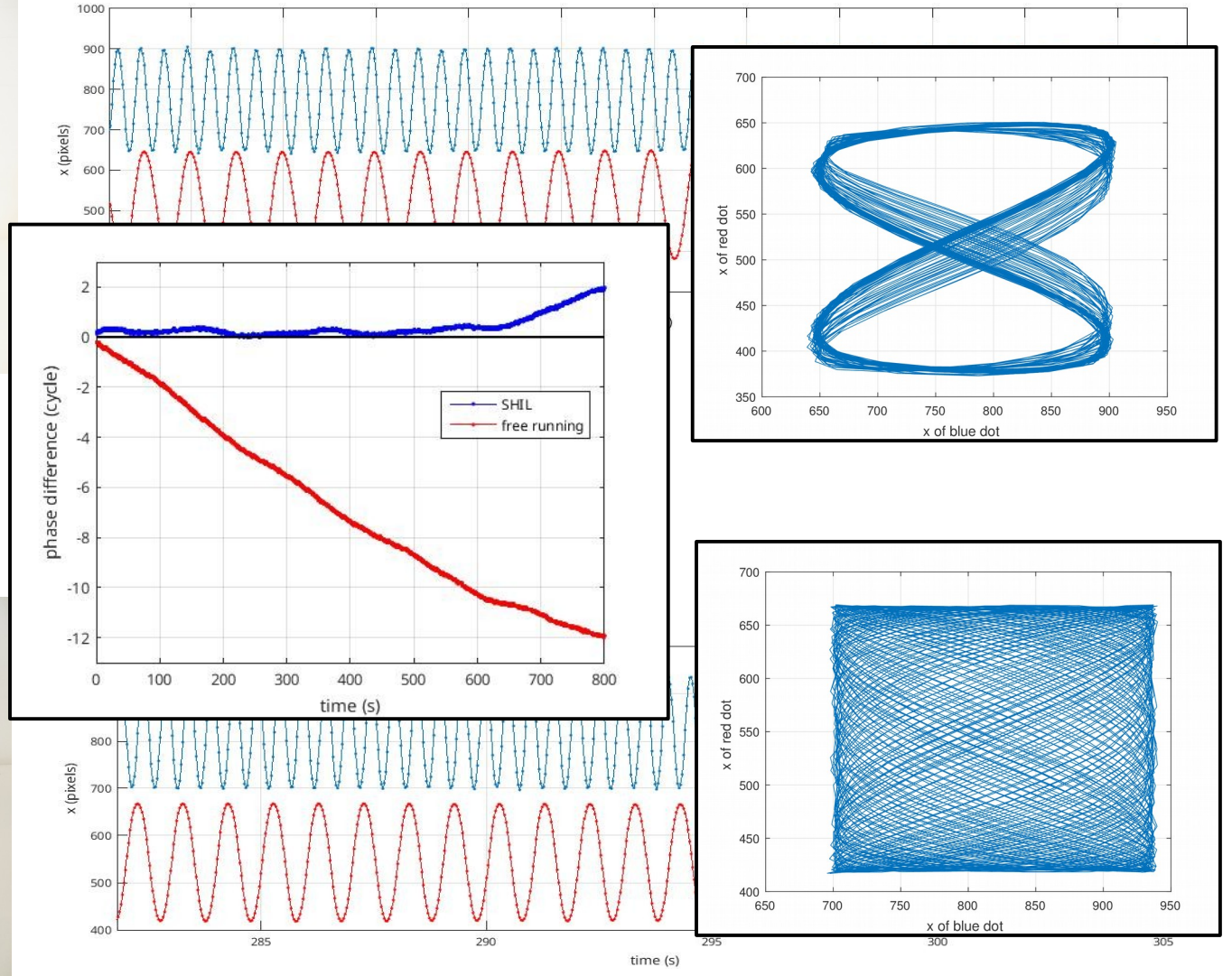
second-harmonic in PPV for SHIL



SHIL in Metronome





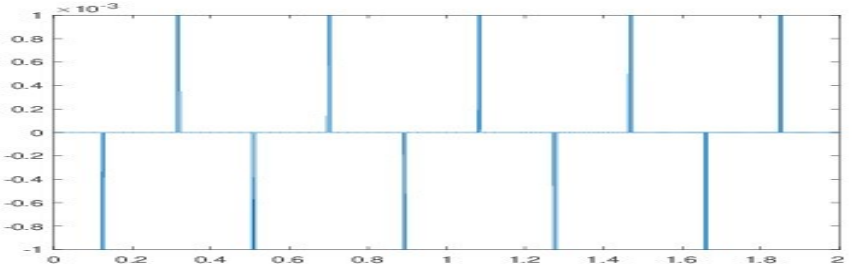


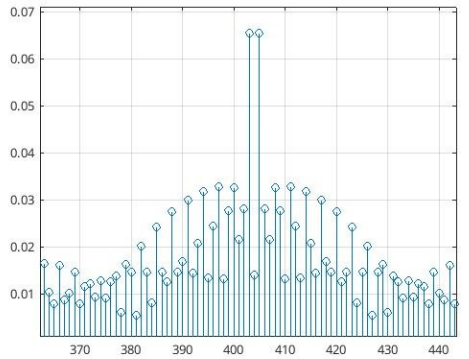
Tianshi Wang , UC Berkeley

Novel “Substrates” for Computing

- **What does it take to explore them?**
  - » in simulation at least

- **metronome toy example**
  - » modelling the nonlinearity
  - » “simulation-ready”
    - –smooth, continuous, well-posed
  - » tweak the nonlinearity
    - –guided by phase-macromodels
  - » system design
    - –coupling, flipping the bit (?)





Novel “Substrates” for Computing

- **CMOS oscillators**
  - » not novel, but much to be done
- **MEMS oscillators/resonators**
  - » Mahboob & Yamaguchi 2011
  - » resonate body transistor
- **Spin Torque Nano-oscillators**
- **PCM/RRAM/NCFET relaxation osc.**
- **Optical oscillators/resonators**
- **Biological oscillators**
  - » metabolism network, gene regulation, neural network