Workshop on Coupled Mathematical Models for Physical and Biological Nanoscale Systems and Their Applications

Banff International Research Station,
The Banff Centre, Banff, Canada,
August 28th–September 2nd, 2016

Chaotic current self-oscillations in doped, weakly coupled semiconductor superlattices for true random number generation

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VOLUME 77, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1996

Synchronization and Chaos Induced by Resonant Tunneling in GaAs/AlAs Superlattices

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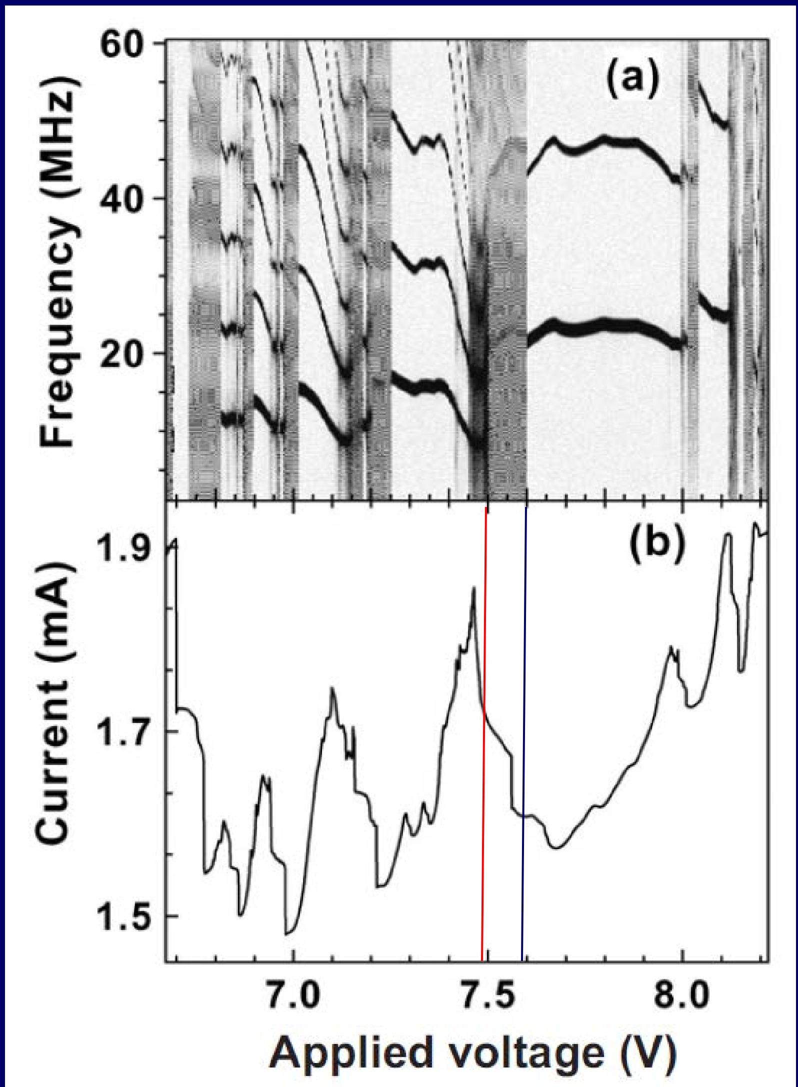
(Received 19 March 1996)



T **= 30 K: 9.0 nm GaAs**
4.0 nm AlAs
40 periods

(a) Frequency spectra of periodic and chaotic oscillations

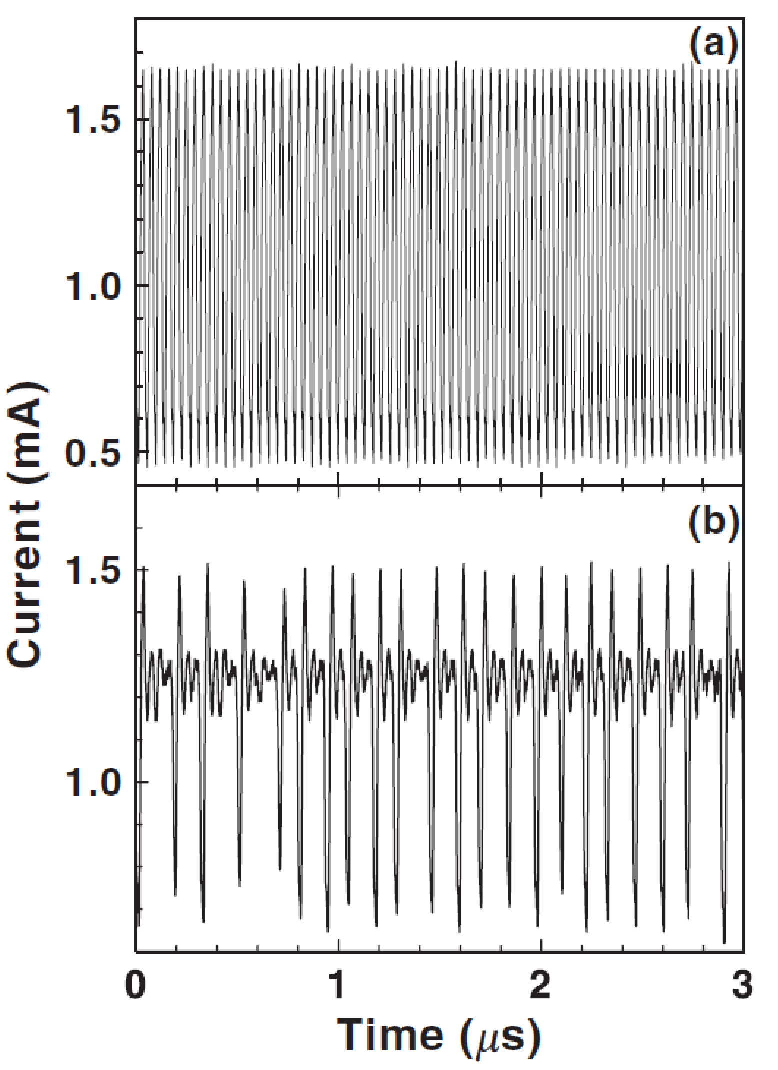
(b) Current-voltage characteristics

At *T* = 50 K, the chaotic windows become much narrower

Superlattices and Microstructures, Vol. 21, No. 4, 1997

Transition between synchronization and chaos in doped GaAs/AlAs superlattices

Yaohui Zhang, Robert Klann, Holger T. Grahn†, Klaus H. Ploog
Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, D-10117 Berlin, Germany



T = 30 K: 9.0 nm GaAs
4.0 nm AlAs
40 periods

(a) bias 7.6 V:
periodic oscillations

(b) bias 7.491 V:
chaotic oscillations

Letter

Chinese Science Bulletin

Semiconductor Technology

June 2012 Vol.57 No.17: 2070–2072
doi: 10.1007/s11434-012-5198-8

Experimental observation of spontaneous chaotic current oscillations in GaAs/$Al_{0.45}Ga_{0.55}As$ superlattices at room temperature

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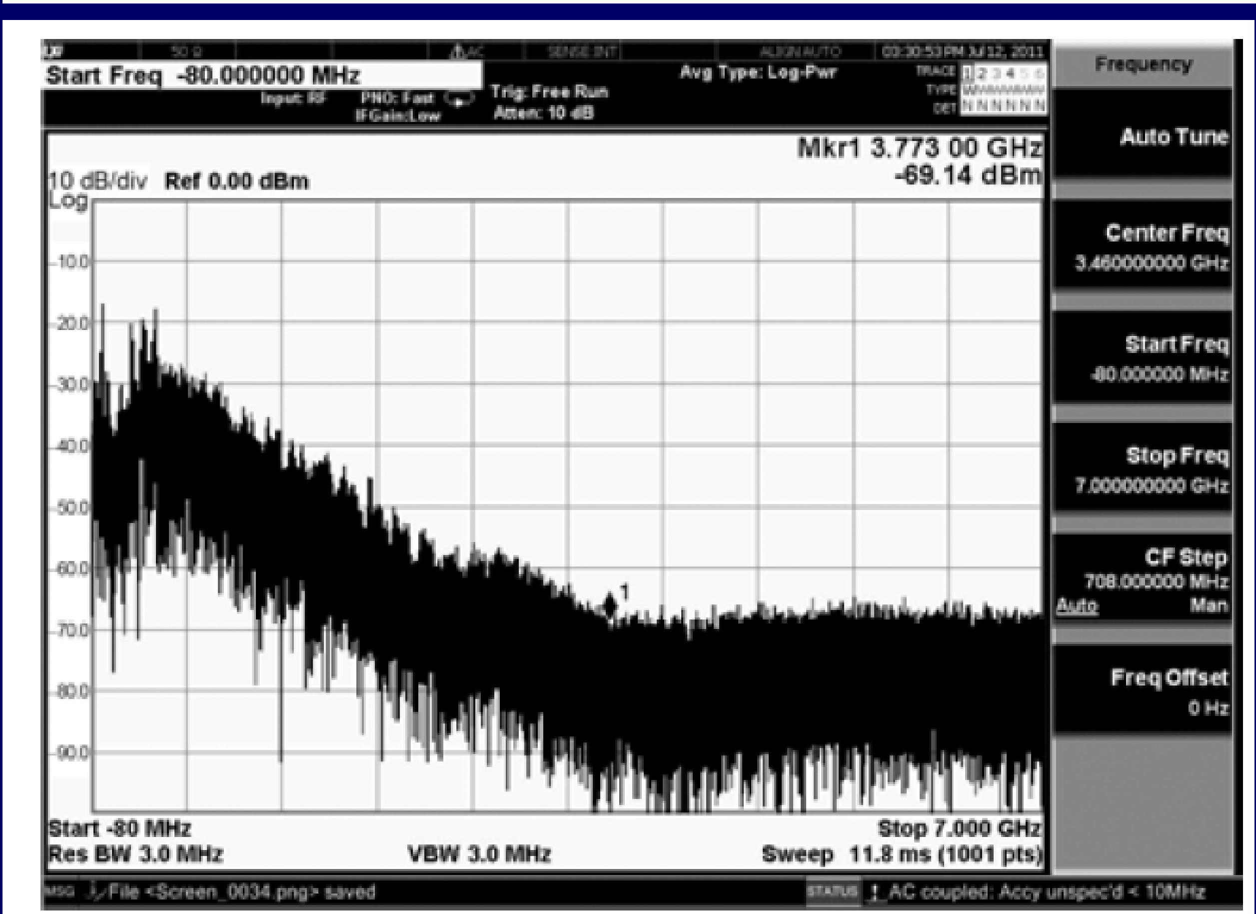

T = 300 K:
7.0 nm GaAs
4.0 nm $Al_{0.45}Ga_{0.55}As$
50 periods

Bias range:
6.21–6.8 V

Spectrum at 6.5 V
from 0 to 4 GHz

PRL **111,** 044102 (2013) PHYSICAL REVIEW LETTERS week ending 26 JULY 2013

Fast Physical Random-Number Generation Based on Room-Temperature Chaotic Oscillations in Weakly Coupled Superlattices

Wen Li,[1] Igor Reidler,[2] Yaara Aviad,[2] Yuyang Huang,[1] Helong Song,[1] Yaohui Zhang,[1] Michael Rosenbluh,[2] and Ido Kanter[2,*]

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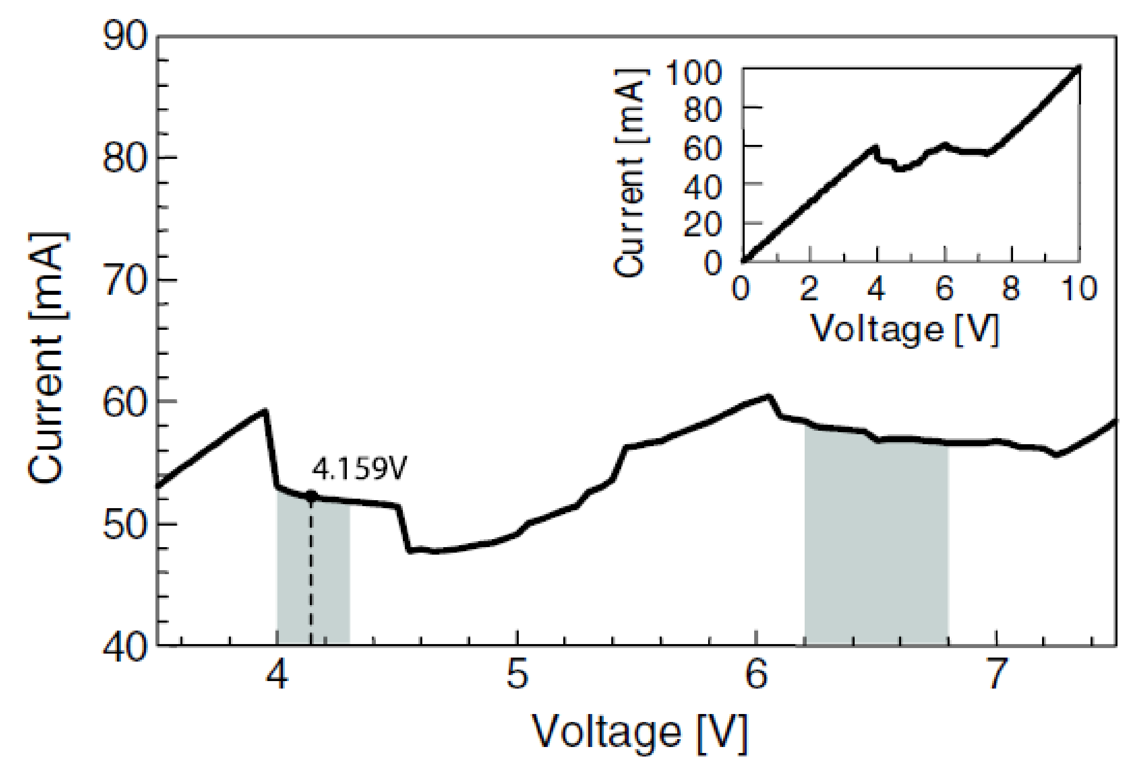
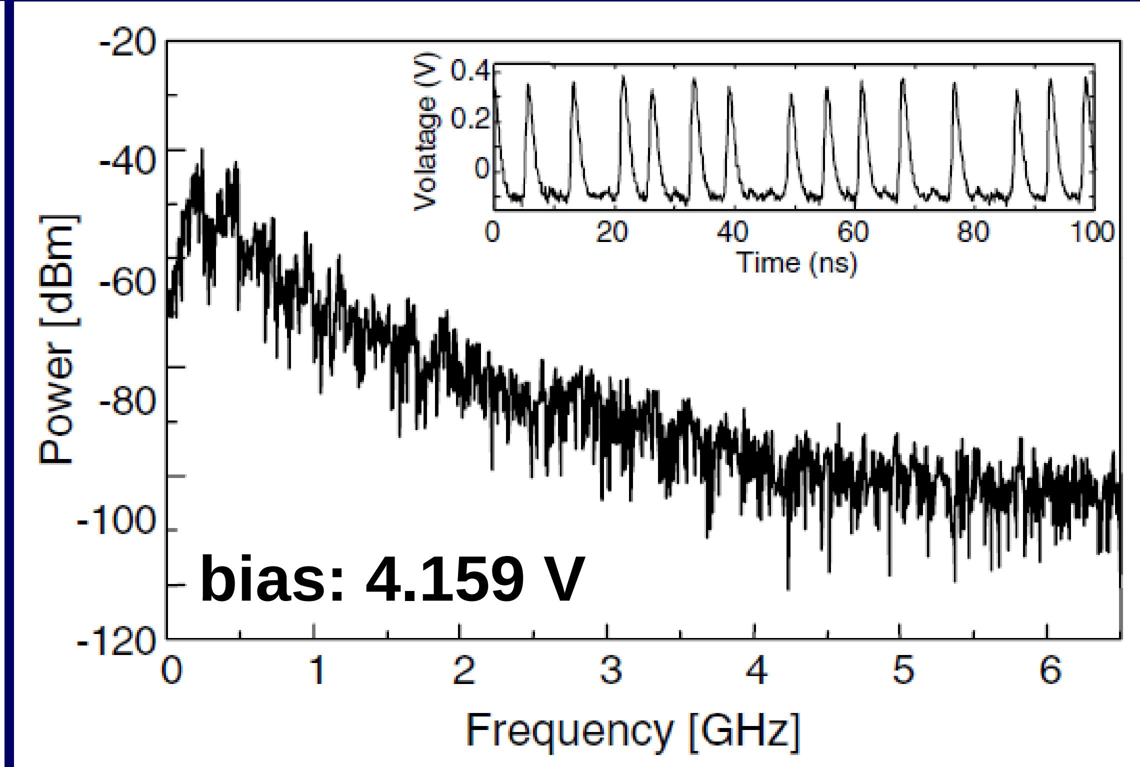
(Received 29 March 2013; revised manuscript received 28 May 2013; published 25 July 2013)

$T = 300$ K: 7.0 nm GaAs, 4.0 nm $Al_{0.45}Ga_{0.55}As$, 50 periods

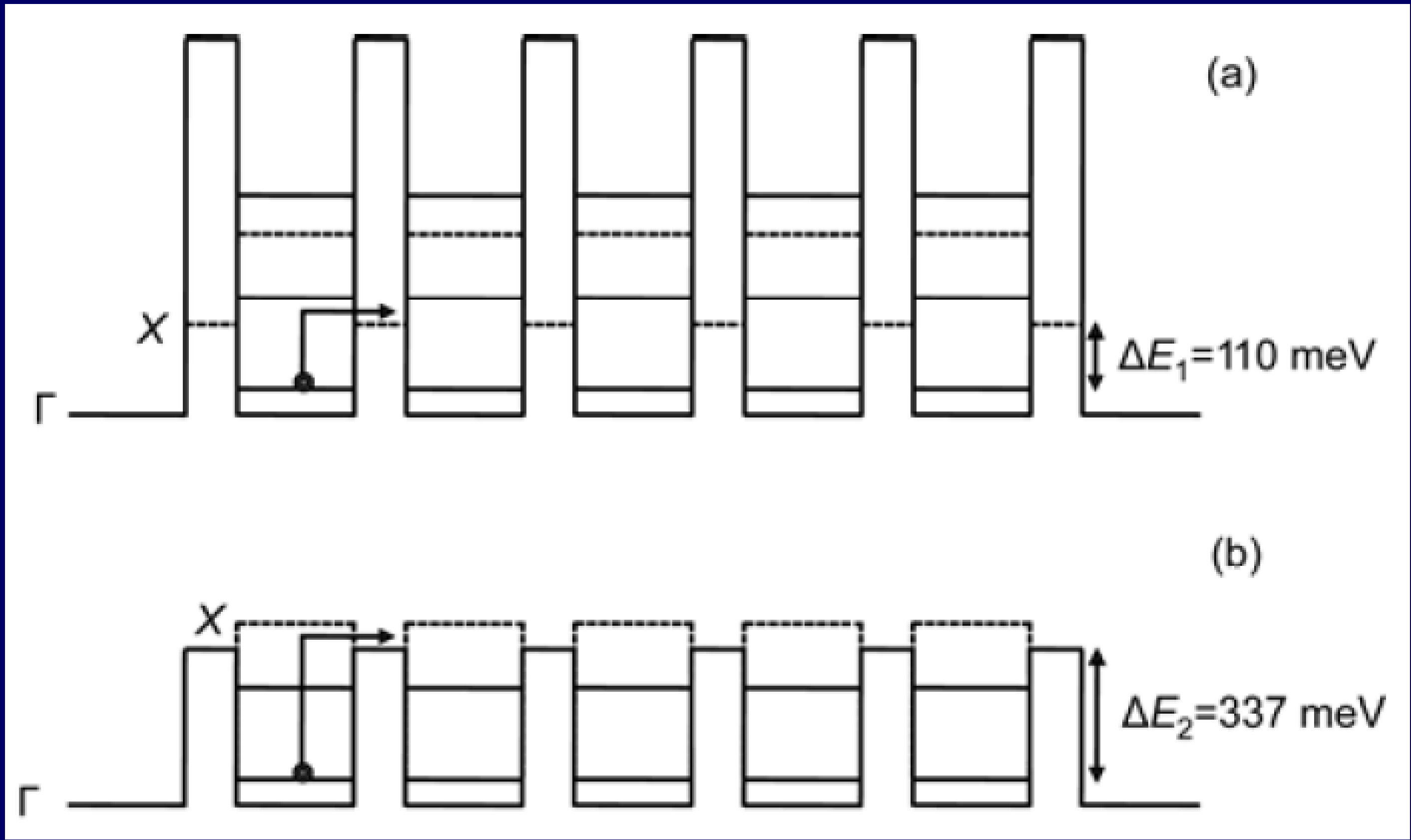




Outline

- Motivation
- Formation of electric-field domains in semiconductor superlattices
- True random number generator based on $GaAs/Al_{0.45}Ga_{0.55}As$ superlattices
- Chaos synchronization in networks of $GaAs/Al_{0.45}Ga_{0.55}As$ superlattices
- Conclusions

Conduction band offset in GaAs/(Al,Ga)As SLs



(a) GaAs/AlAs:
Γ-X offset: 160 meV
Γ-Γ offset: 982 meV

(b) $GaAs/Al_{0.45}Ga_{0.55}As$:
Γ-X offset: 390 meV
Γ-Γ offset: 390 meV

In GaAs/AlAs SL at higher temperatures:
Γ-X transfer by thermionic emission

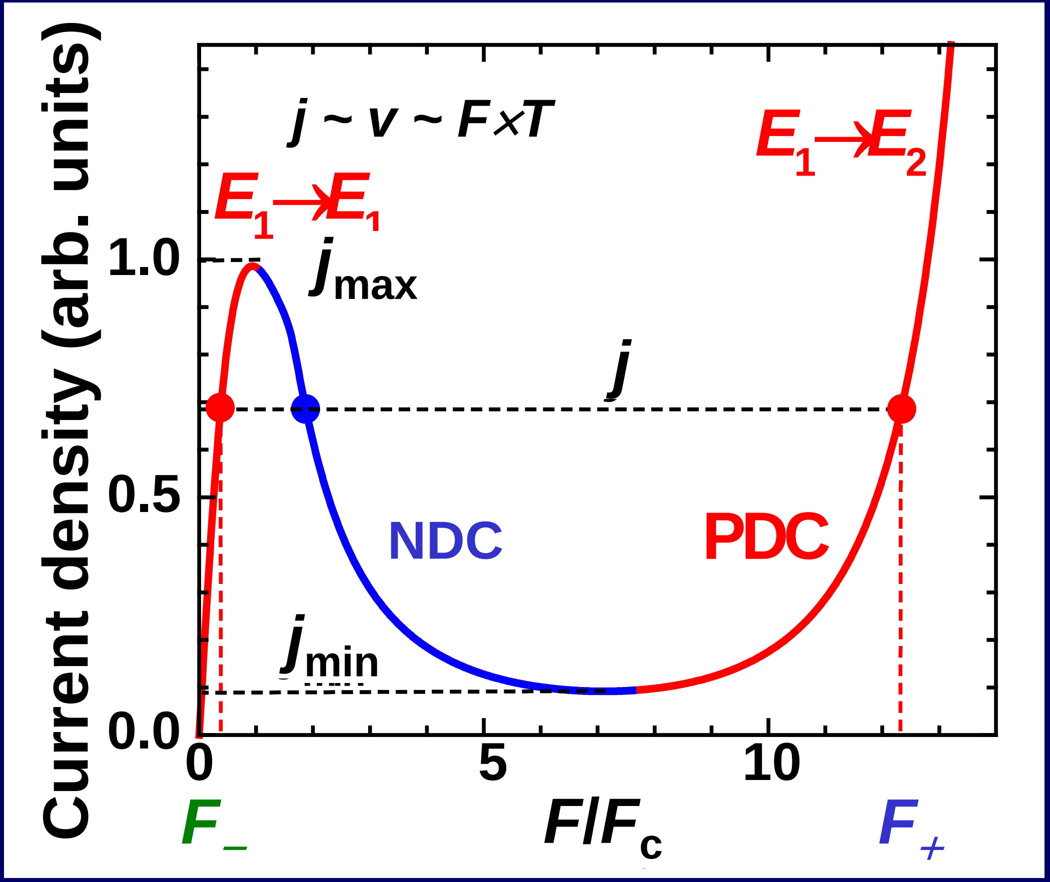
Y. Y. Huang, W. Li, W. Q. Ma, H. Qin, and Y. H. Zhang, Chin. Sci. Bull. 57, 2070 (2012).

Formation of electric-field domains

Large carrier densities

NDC: negative differential conductivity: unstable

PDC: positive differential conductivity: stable



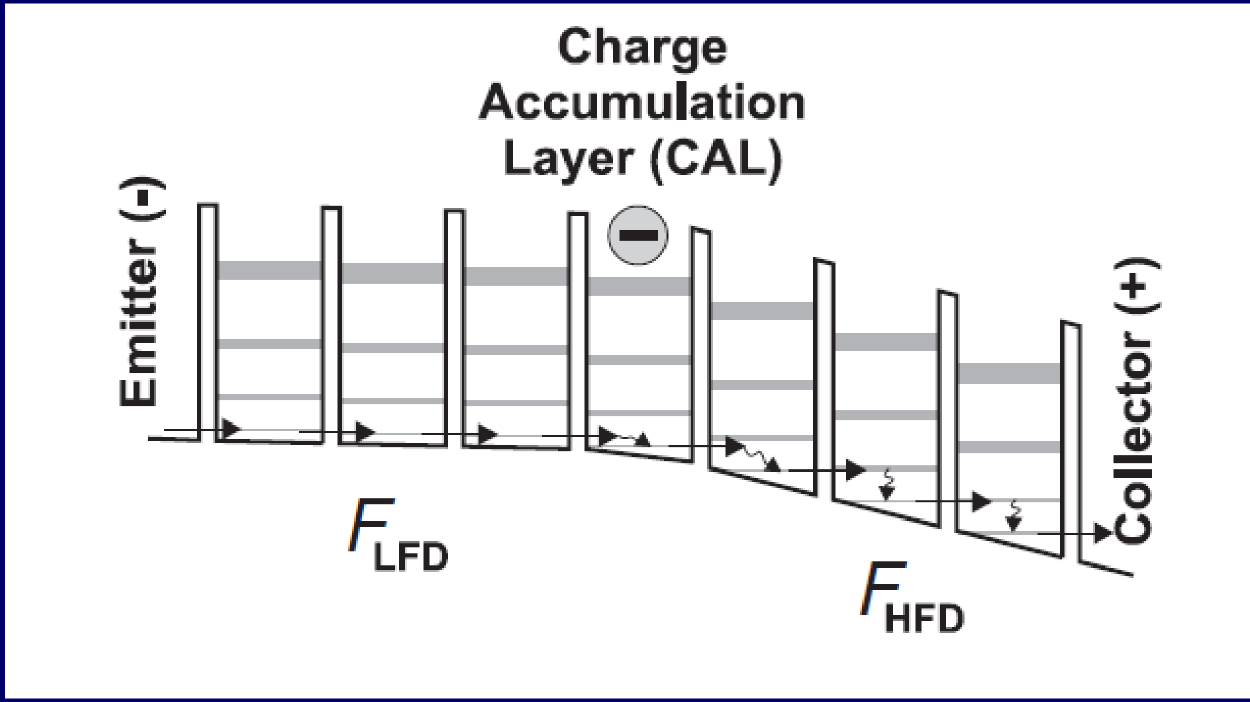
- Two domains with different field strength F_- and F_+ in PDC region
- Separated by accumulation layer with n_{accu}

$$n_{\mathrm{accu}} = \varepsilon_0 \varepsilon \frac{F_+ - F_-}{e}$$

L. L. Bonilla and HTG, Rep. Prog. Phys. 68, 577–683 (2005)

Static electric-field domains

Large carrier densities



CAL: charge accumulation layer
LFD: low-field domain
HFD: high-field domain

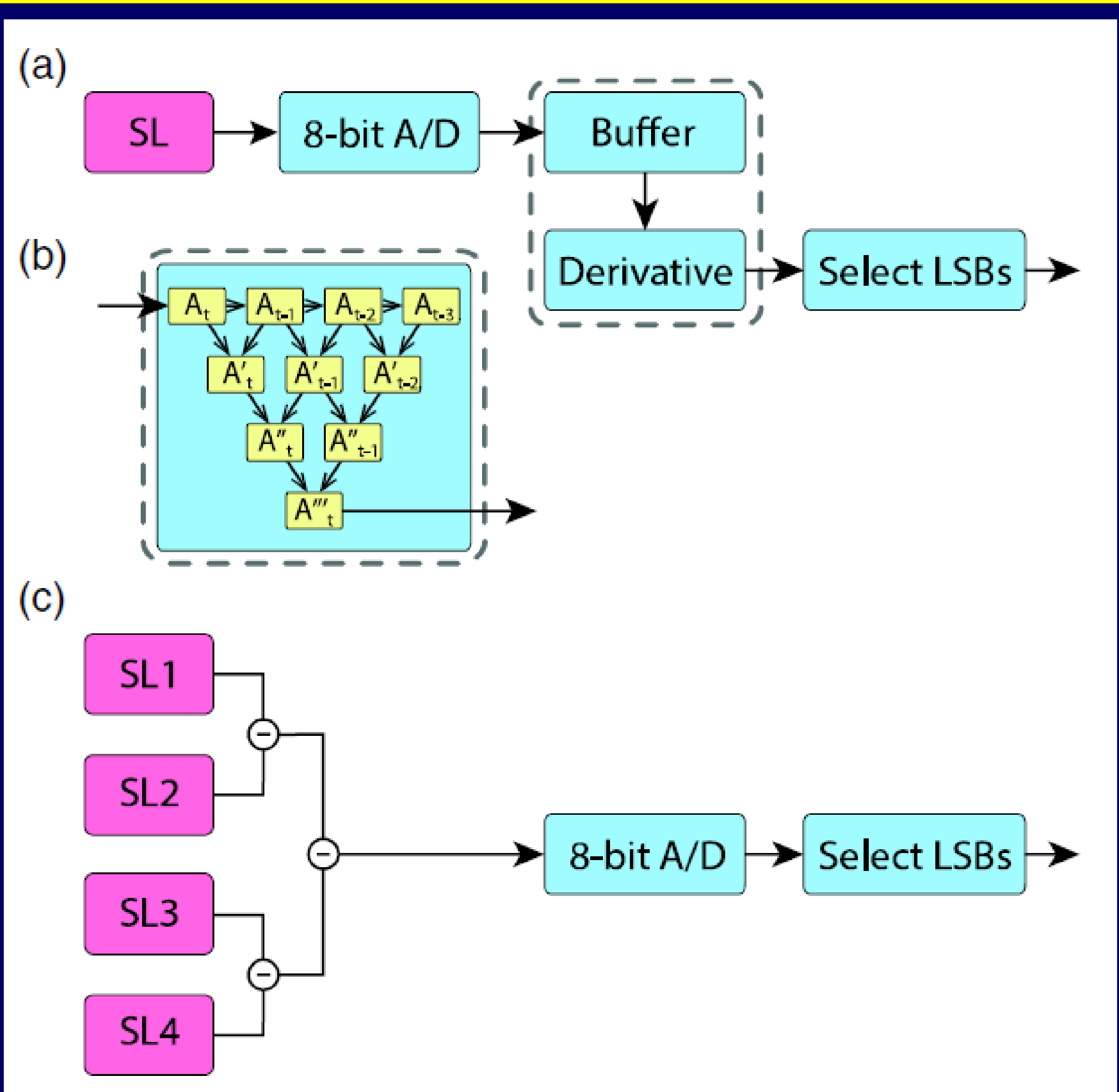
Dynamic electric-field domains

Intermediate carrier densities

Three types of
spontaneous current oscillations:

- Periodic: monopole and dipole oscillation modes
- Quasi-periodic: competition between dipole and monopole oscillation modes
- Chaotic: undriven (and also driven)

Methods for generating random sequence

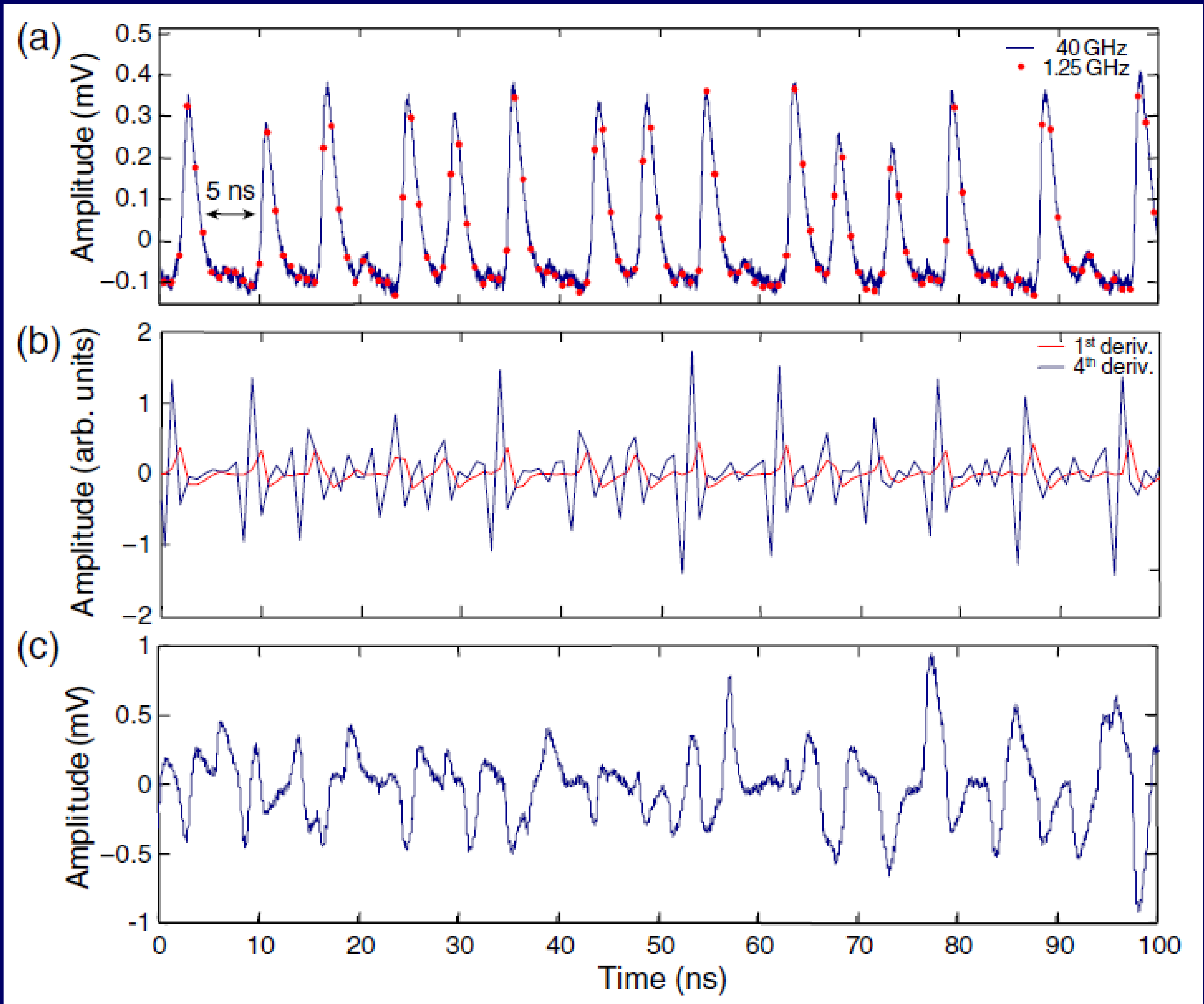


Method 1: a dynamical buffer of the last $n + 1$ successively digitized current values is used to calculate the n^{th} discrete derivative as exemplified for $n = 3$ in (b). Then, the m least significant bits (LSBs) of the resulting n^{th} derivative are appended as shown in (a).

Method 2: linear combination of the analog chaotic current oscillations of several uncorrelated SLs

W. Li, I. Reidler, Y. Aviad, Y. Y. Huang, H. L. Song, Y. H. Zhang, M. Rosenbluh, and I. Kanter, Phys. Rev. Lett. 111, 044102 (2013).

True random number generator (TRNG)



(a) Sampling frequency:
blue line: 40 GHz
red dots: 1.25 GHz

(b) <u>Method 1:</u>
Discrete derivative:
red line: 1st order
blue line: 4th order
for 1.25 GHz sampling

(c) <u>Method 2:</u>
Linear combination of 4 recorded SL oscillation traces digitized at 40 GHz

W. Li, I. Reidler, Y. Aviad, Y. Y. Huang, H. L. Song, Y. H. Zhang, M. Rosenbluh, and I. Kanter, Phys. Rev. Lett. 111, 044102 (2013).

True random number generator (TRNG)

LSB: least significant bit, RBG: random bit generator, Results based on NIST and TestU01 statistical test suites

Number of combined SL devices	1	2	4	6
Derivative	4	3	⋯	⋯
Max sampling rate (GHz)	1.25	5	10	20
Retained LSBs	5	4	4	4
RBG rate (Gbit/s)	6.25	20	40	80

Typical rates of bit transfer:

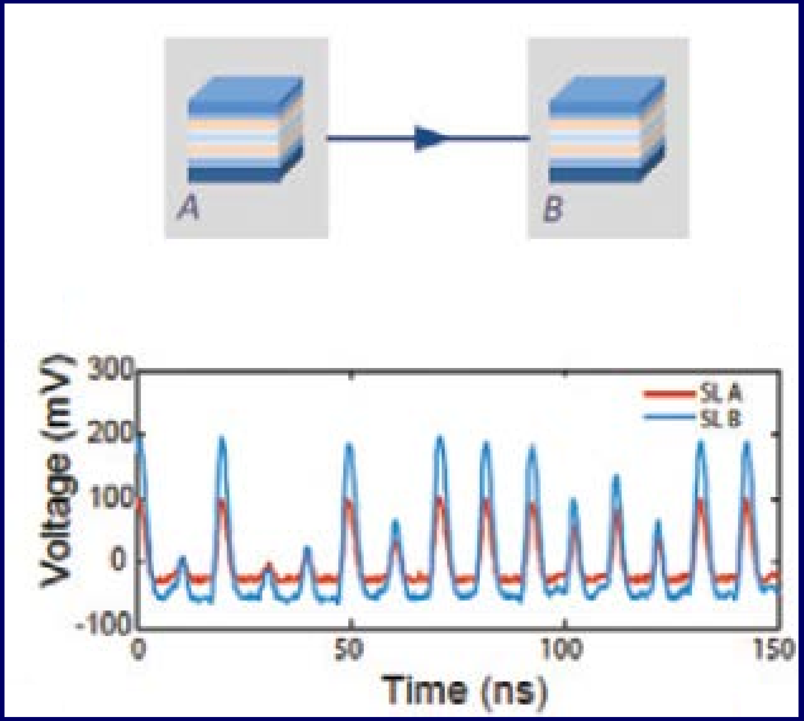
Currently available TRNGs: up to 1–2 Gbit/s

Superlattice TRNG: up to 80 Gbit/s

W. Li, I. Reidler, Y. Aviad, Y. Y. Huang, H. L. Song, Y. H. Zhang, M. Rosenbluh, and I. Kanter, Phys. Rev. Lett. 111, 044102 (2013).

Synchronization: leader-laggard configuration

Unidirectional coupling with 16 m cable by using an amplifier from SL A to SL B. Chaotic SL A drives nonchaotic SL B.



Highly synchronized waveform with delay of 65 ns originating from the 16 m cable

W. Li, Y. Aviad, I. Reidler, H. L. Song, Y. Y. Huang, K. Biermann, M. Rosenbluh, Y. H. Zhang, <u>HTG</u>, and I. Kanter, Europhys. Lett. 112, 30007 (2015).

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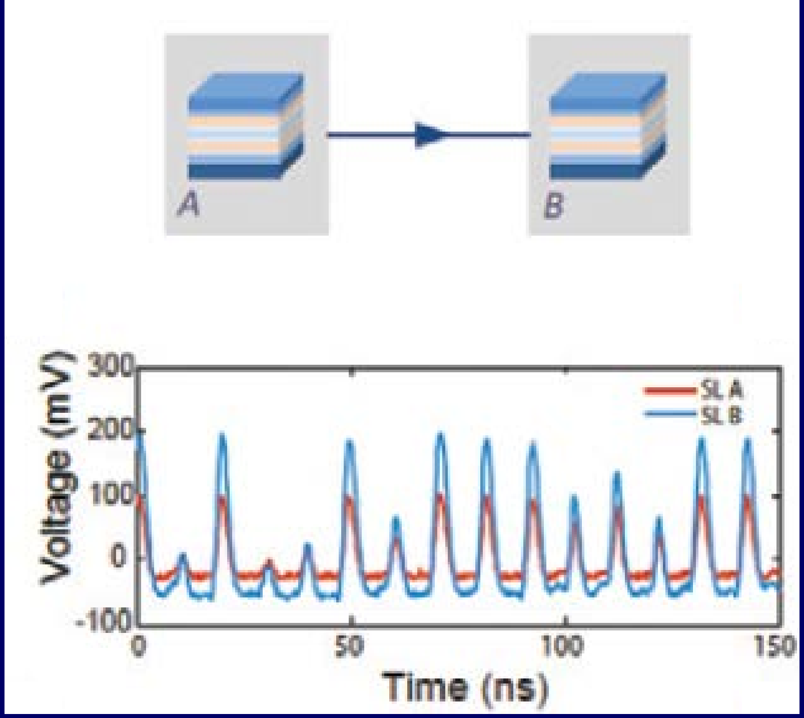
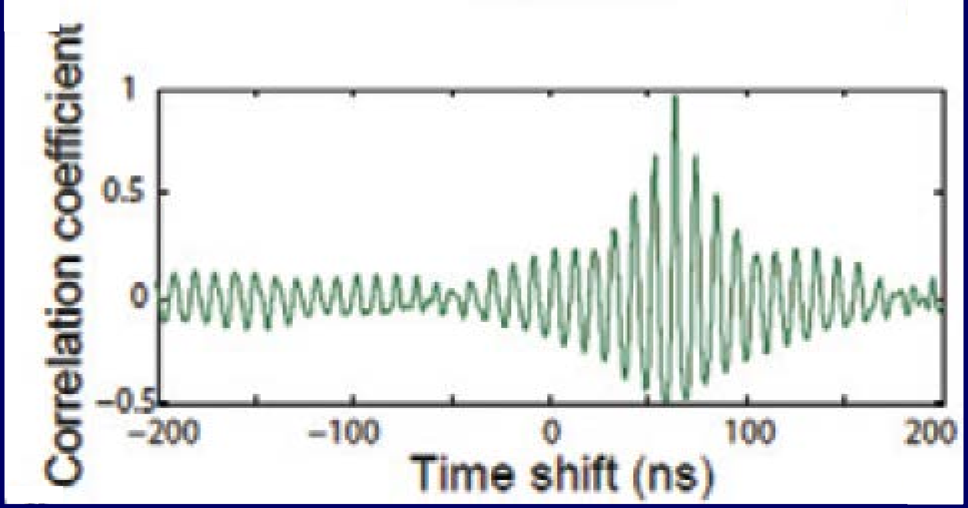


Highly synchronized waveform with delay of 65 ns originating from the 16 m cable

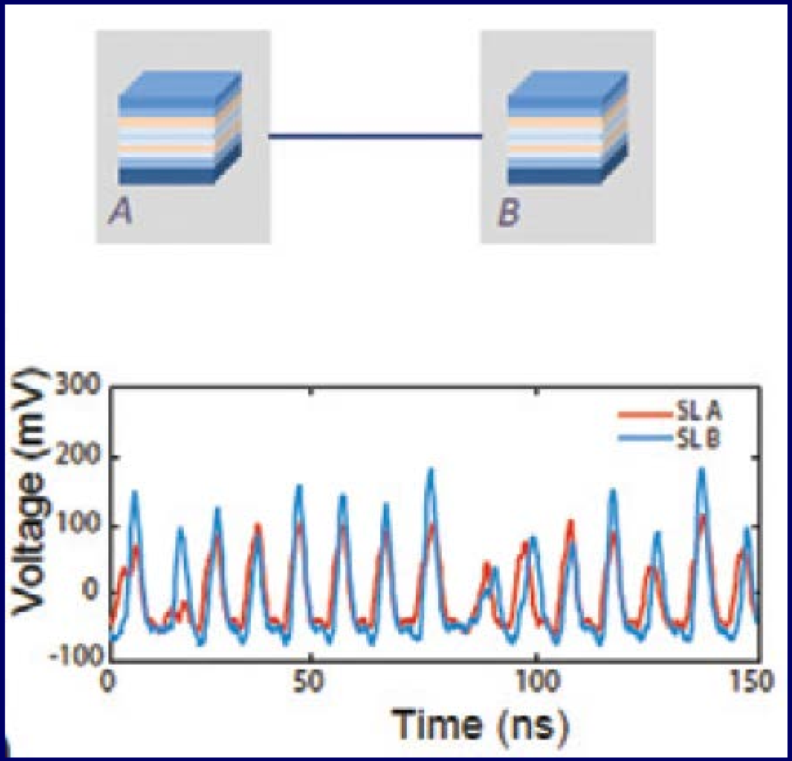
Cross correlation of SLs A and B with a value of one at 65 ns



W. Li, Y. Aviad, I. Reidler, H. L. Song, Y. Y. Huang, K. Biermann, M. Rosenbluh, Y. H. Zhang, <u>HTG</u>, and I. Kanter, Europhys. Lett. 112, 30007 (2015).

Synchronization: face-to-face configuration

Bidirectional coupling with 16 m cable without any amplifier.
Chaotic SL A coupled to chaotic SL B.



Synchronized waveform with delay of 65 ns originating from the 16 m cable

W. Li, Y. Aviad, I. Reidler, H. L. Song, Y. Y. Huang, K. Biermann, M. Rosenbluh, Y. H. Zhang, HTG, and I. Kanter, Europhys. Lett. 112, 30007 (2015).

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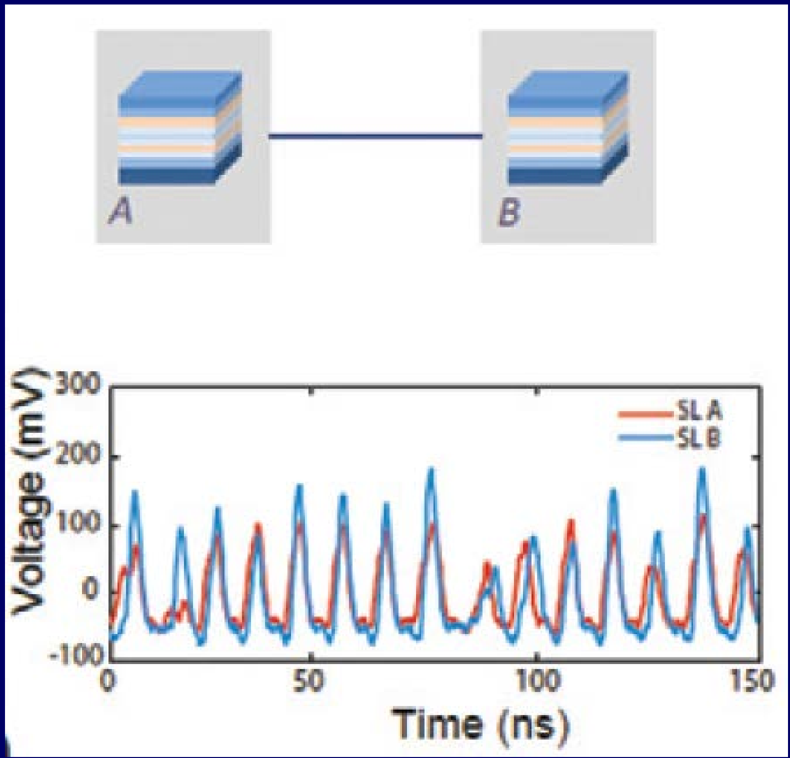
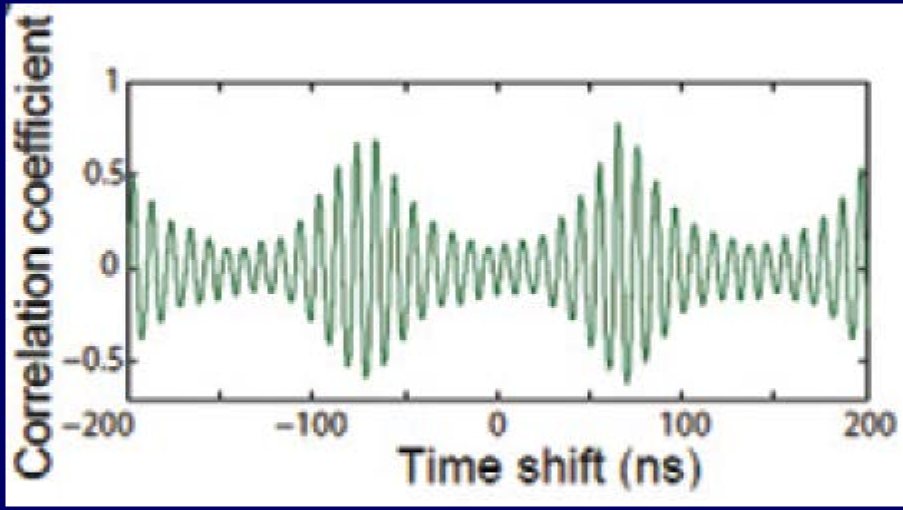


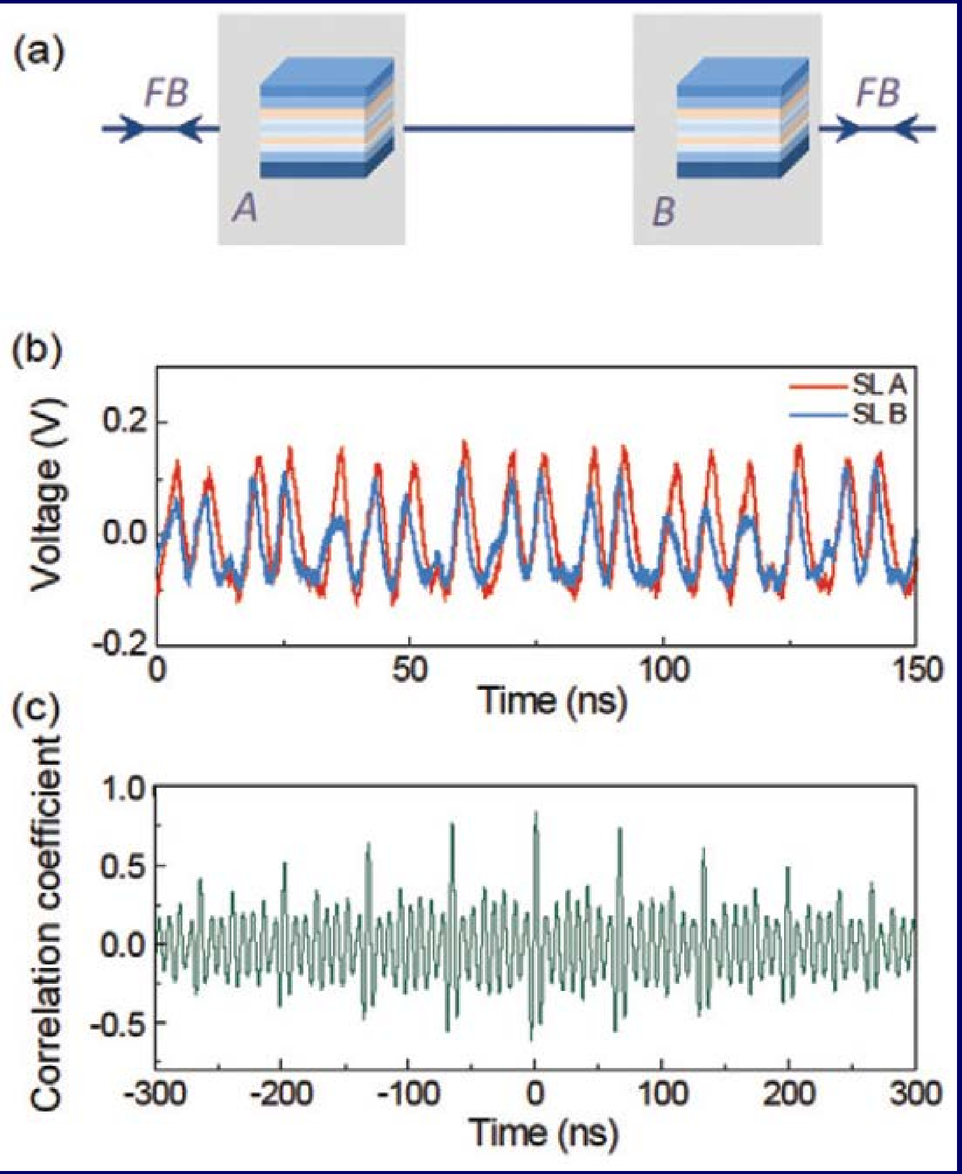
Synchronized waveform with delay of 65 ns originating from the 16 m cable

Symmetric cross correlation of SLs A and B with fading revivals at ±(2*n*+1)×65 ns, but maximum < 1



W. Li, Y. Aviad, I. Reidler, H. L. Song, Y. Y. Huang, K. Biermann, M. Rosenbluh, Y. H. Zhang, HTG, and I. Kanter, Europhys. Lett. 112, 30007 (2015).

Zero-lag synchronization (ZLS)



(a) Two mutually coupled SLs with a 16 m cable with an additional self-feedback (FB) coupling of 8 m for each SL.

(b) Synchronized waveform with zero delay

(c) dominant peak of cross correlation with a value of 0.84 at zero time shift and fading revivals at $\pm n \times 65$ ns

W. Li, Y. Aviad, I. Reidler, H. L. Song, Y. Y. Huang, K. Biermann, M. Rosenbluh, Y. H. Zhang, HTG, and I. Kanter, Europhys. Lett. 112, 30007 (2015).

Conclusions

- Spontaneous chaotic current oscillations at room temperature have been observed in weakly coupled GaAs/$Al_{0.45}Ga_{0.55}As$ superlattices
- All-electronic true random number generator with bit rates up to 80 Gbit/s has been demonstrated using chaotic oscillations in GaAs/$Al_{0.45}Ga_{0.55}As$ superlattices at room temperature
- Leader-laggard, face-to-face, and zero-lag synchronization have been demonstrated at room temperature using mutually coupled chaotic GaAs/$Al_{0.45}Ga_{0.55}As$ superlattices

Outlook

- **Improvement of the performance by using weakly coupled GaAs/Al$_x$Ga$_{1-x}$As superlattices with larger values of *x*, e.g. 0.5 to 0.7**
- **Origin of the spontaneous chaotic current oscillations**
- **Synchronization of much larger scale networks and development of reliable as well as advanced secure communication protocols**

Thank you very much for your attention

THE END