# Smart Magnon Spintronics

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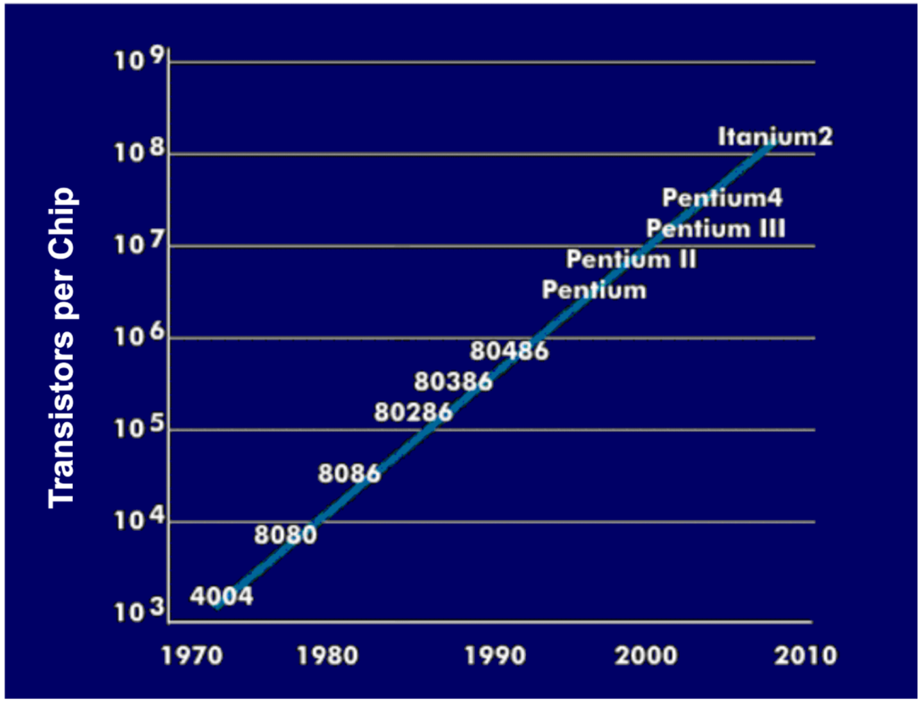
# Moore's law

**Moore's law:** the number of transistors on integrated circuits doubles every two years



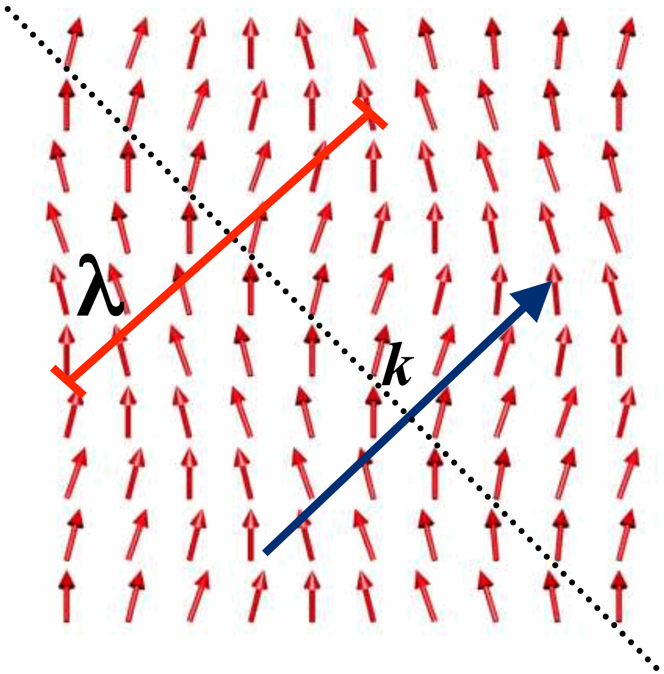

International Technology Roadmap for Semiconductors:

starting from the end of 2013, doubling only every three years!

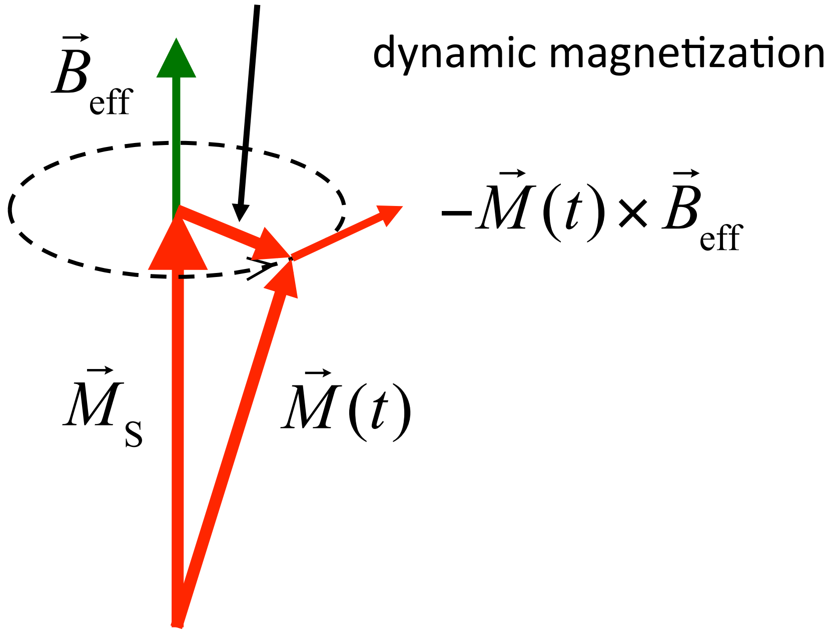
# Coherent dynamics: spin waves

**Landau-Lifshitz torque equation**

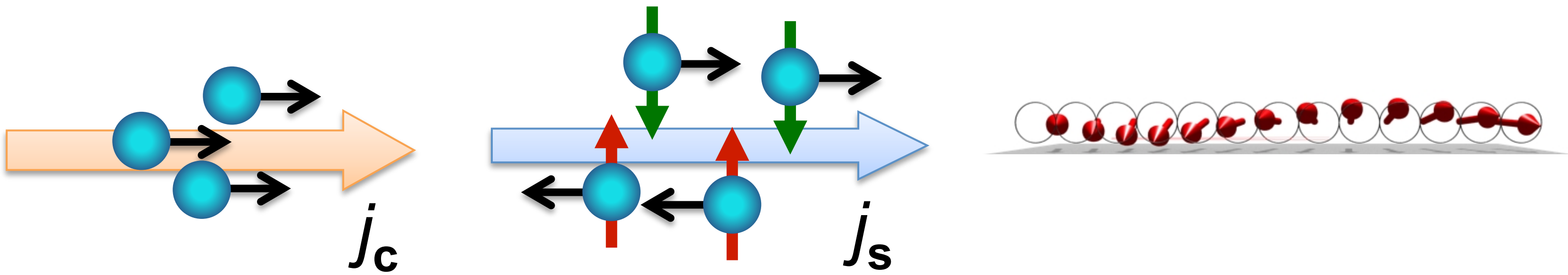
$$\frac{1}{|\gamma|}\frac{d\vec{M}(t)}{dt} = -\vec{M}(t)\times\vec{B}_{\text{eff}}(t)$$




$$\vec{m}(\vec{r},t) = \vec{m}_0(\vec{r})\times e^{i(\vec{k}\vec{r}-\omega t)}$$



# Electronics – Spintronics – Magnonics

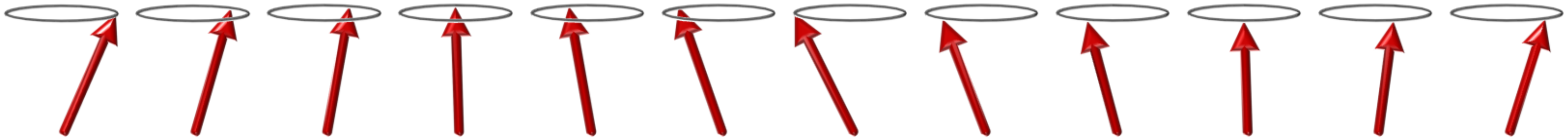



| Electronics | Spintronics | Magnonics |
|---|---|---|
| Carrier of information: **charge** of electron | Carrier of information: **spin** of electron | Carrier of information: **magnon** |

- GMR (Nobel Prize in 2007)
- TMR
- STT
- …

No flow of real particles!

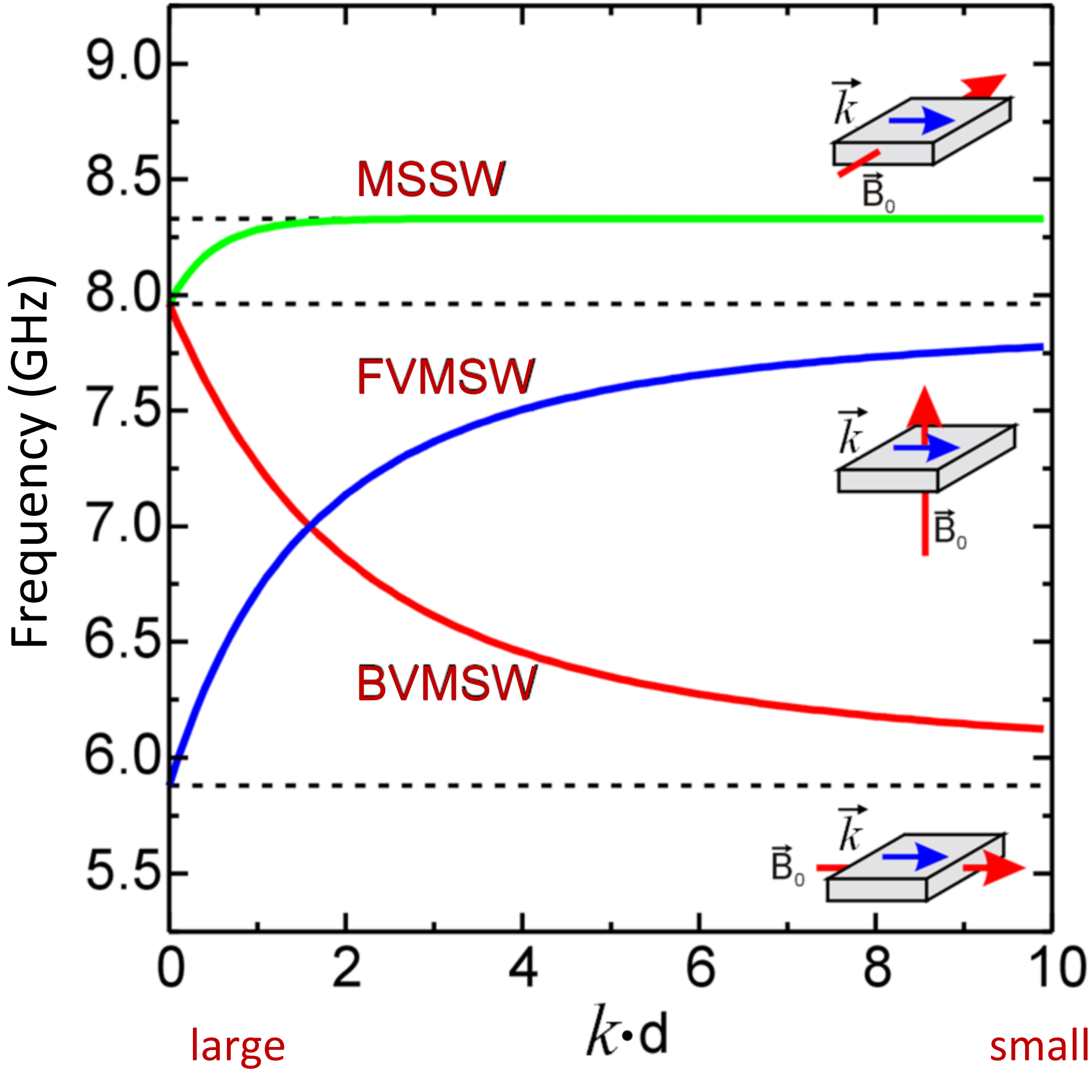
# Spin-wave fundamental limitations



| | |
|---|---|
| Wavelength: | down to nm (atomic scale) |
| Frequency: | from GHz to THz |
| Free-path: | up to cm |

→ magnonics has large potential for data processing

# Dipolar spin waves




Magnetostatic Surface Spin Waves

Forward Volume Magnetostatic Spin Waves

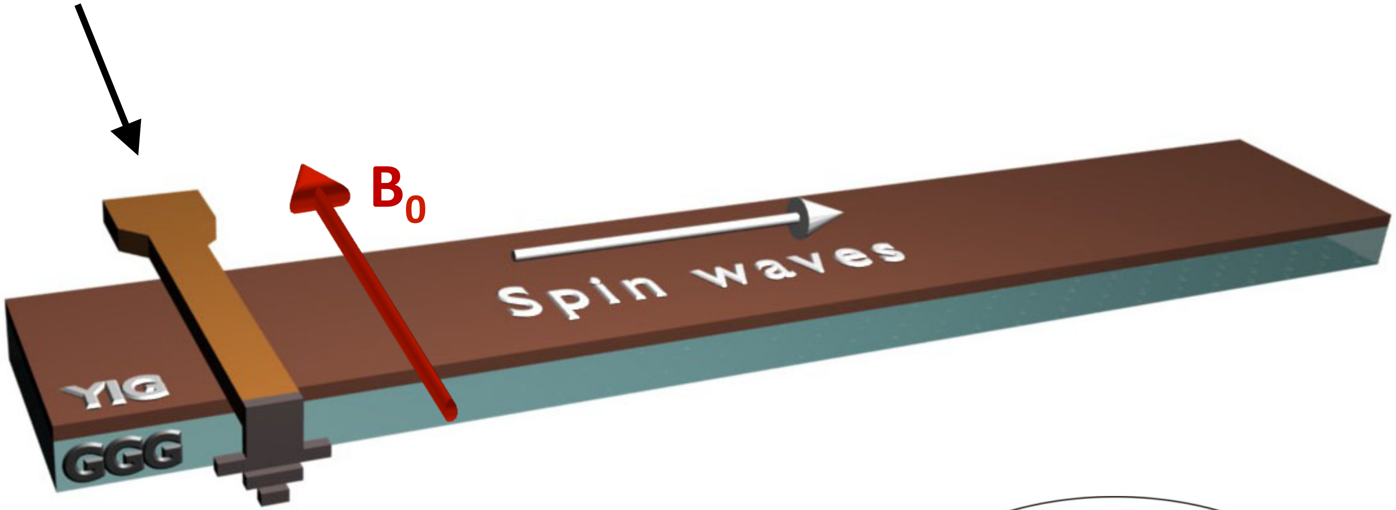
Backward Volume Magnetostatic Spin Waves

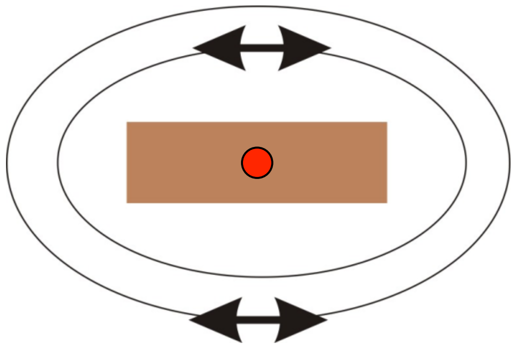
large wavelength

small wavelength

# Excitation of dipolar spin waves

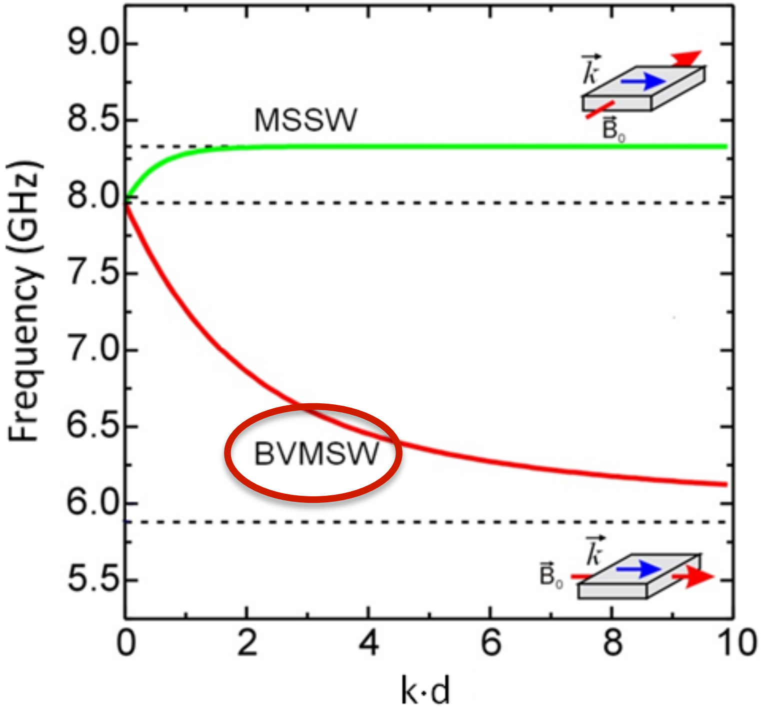
Input microwave signal



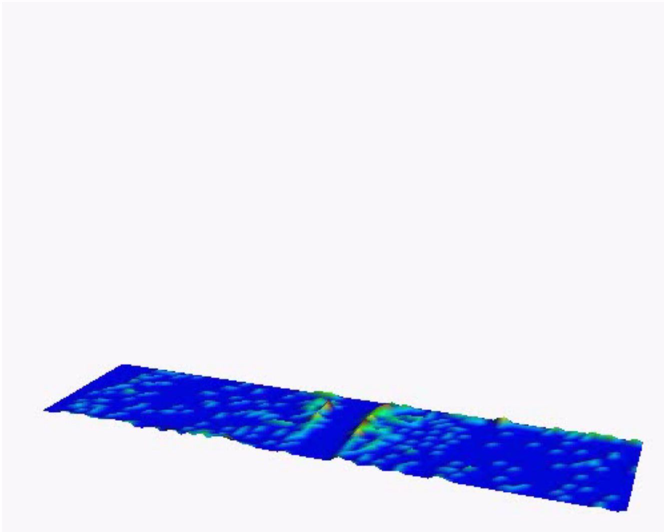



Alternating magnetic field

# Backward volume magnetostatic spin waves (BVMSW)

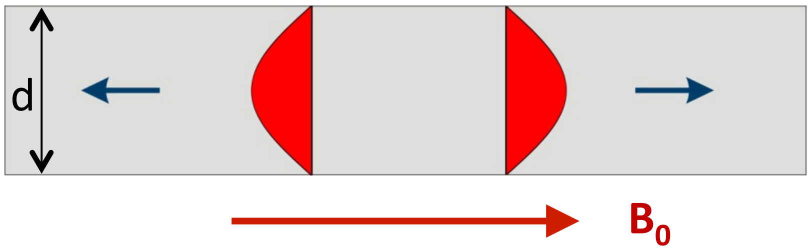



**Excitation of BVMSW**
measured with
Brillouin light scattering microscopy



**Dynamic magnetization profile**

$$m_x \sim \cos(kx)$$




# LPE Yttrium Iron Garnet $Y_3Fe_5O_{12}$ (YIG)

S. Geller, "Crystal Chemistry of the Garnets,"
*Z. Kristallogr., 125 (1967)*

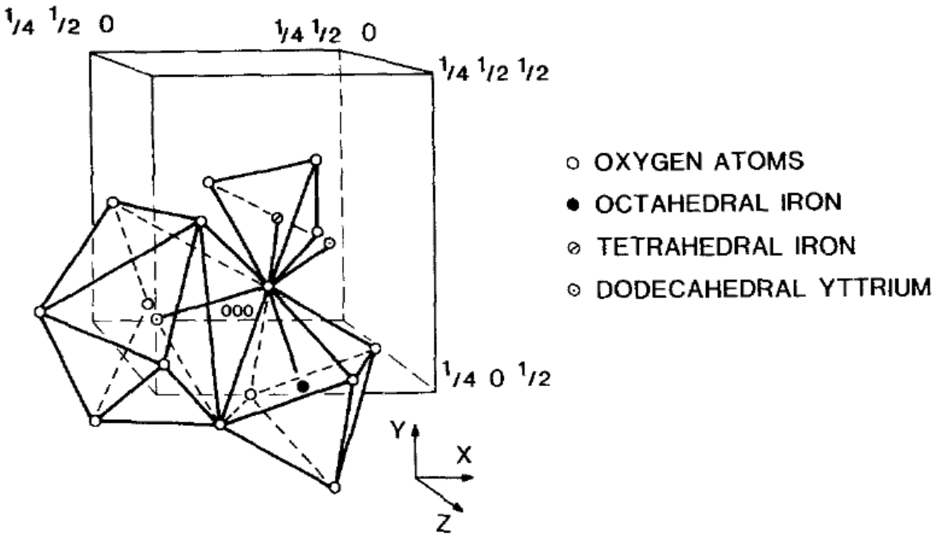
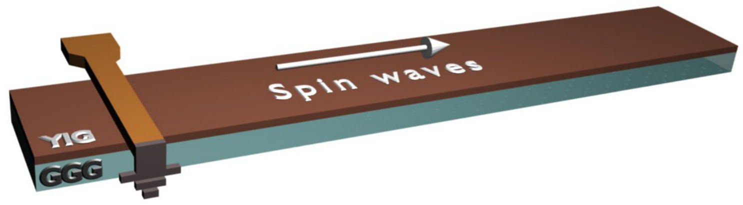



**Figure 1.** The structure of YIG (after [6]).




YIG thickness: 2.1 μm

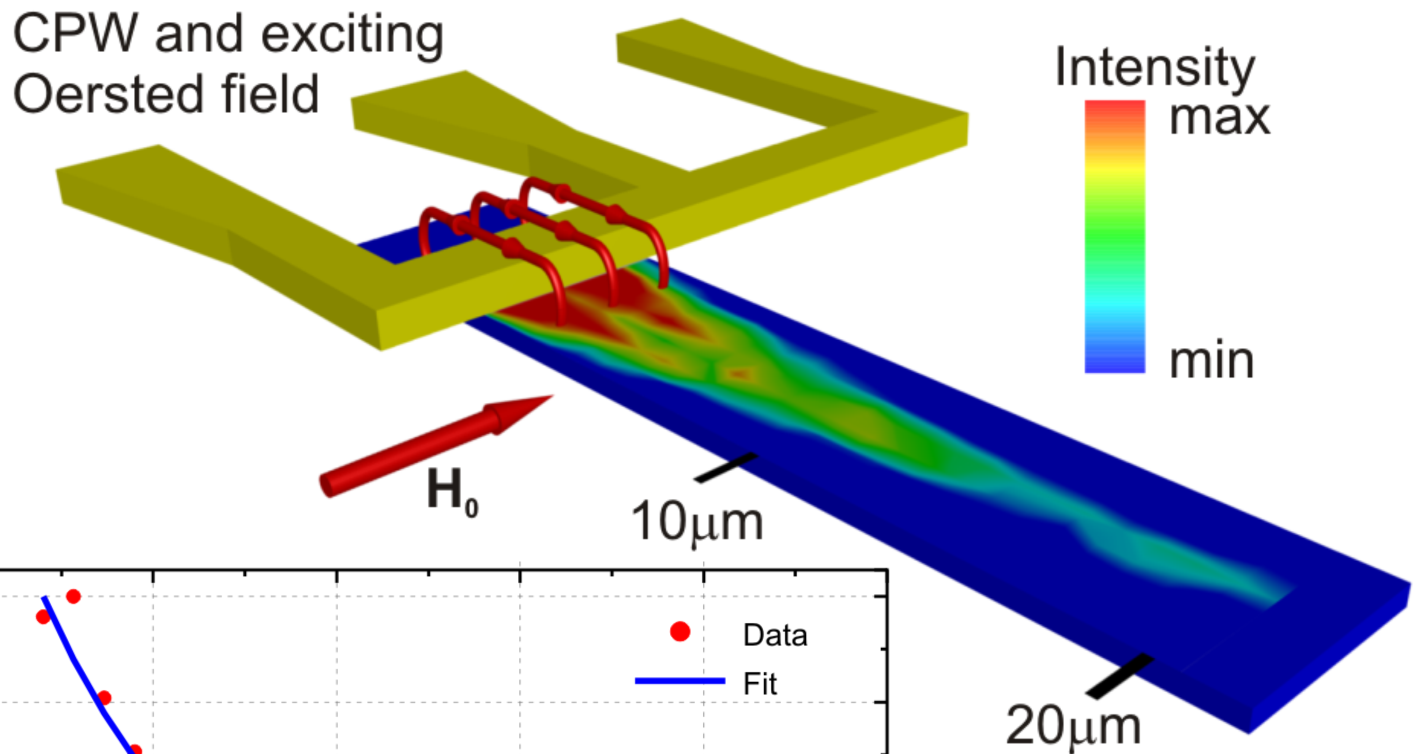
Waveguide sizes: 1.5*20 $mm^2$

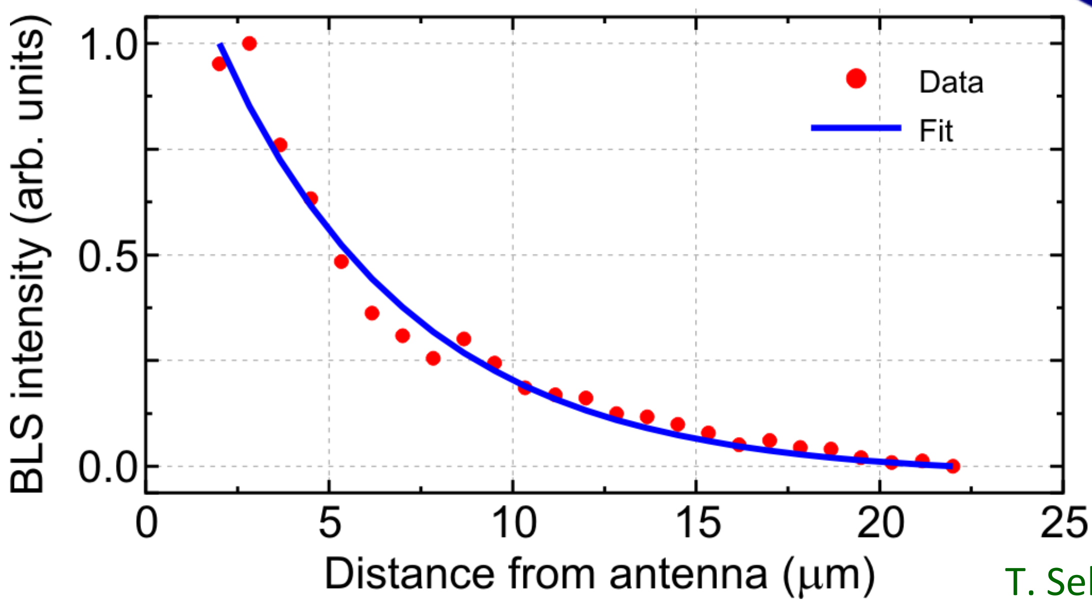
Magnetic field: 170 mT

- YIG has smallest known magnetic loss
- YIG is magnetic insulator

Serga, Chumak, Hillebrands, *YIG Magnonics*, *J. Phys. D* **43**, 264002 (2010).

# Spin-wave propagation in $Co_2Fe_{0.4}Mn_{0.6}Si$ Heusler waveguides




$Co_2Fe_{0.4}Mn_{0.6}Si$
Thickness 30 nm
Stripe width 4 μm
External field: 40 mT
Frequency: 6.2 GHz

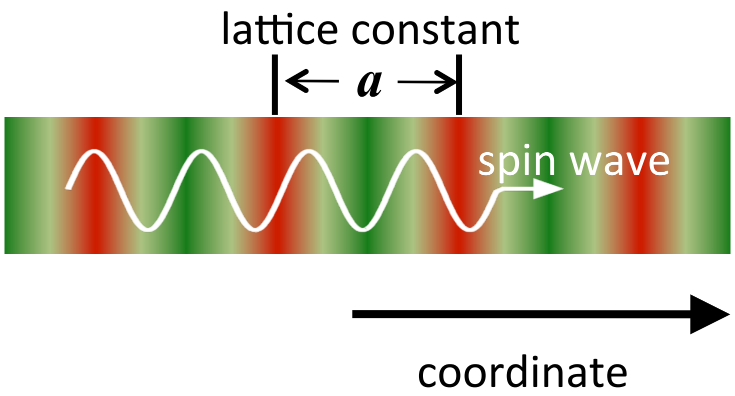
T. Sebastian, Y. Ando et al., APL**100**, 112402 (2012)

# What is a “magnonic crystal”?

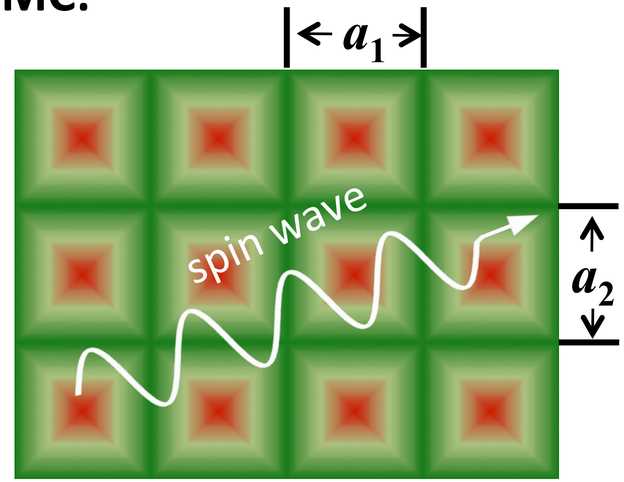
## Magnonic crystal (MC):

- artificial medium with periodic lateral variation in magnetic properties

### 1D MC:




### 2D MC:




- analogous to photonic and sonic crystals but operates with spin waves in the microwave frequency range

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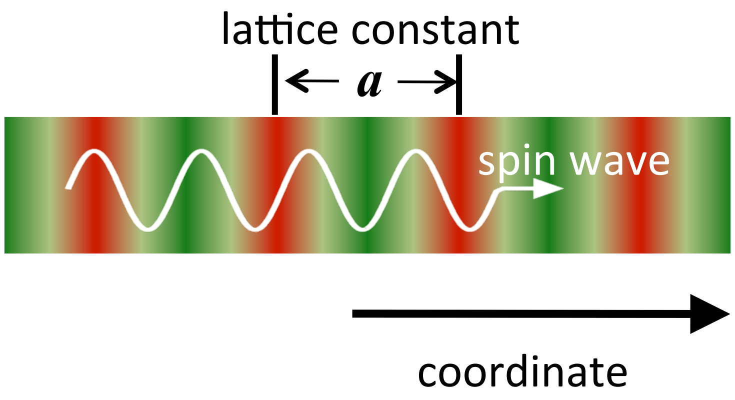
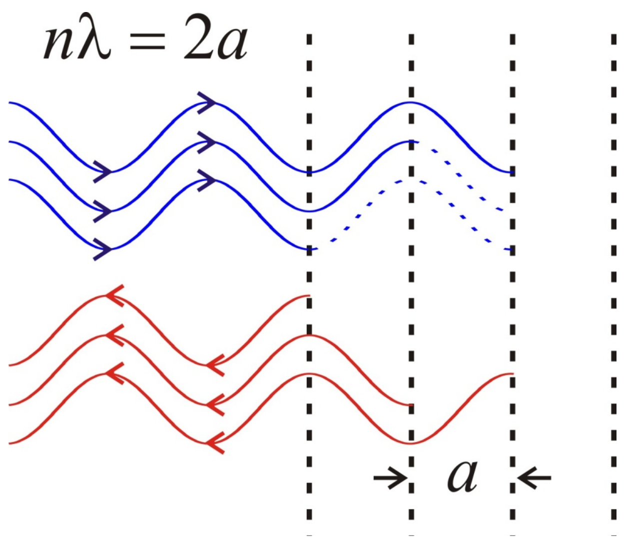


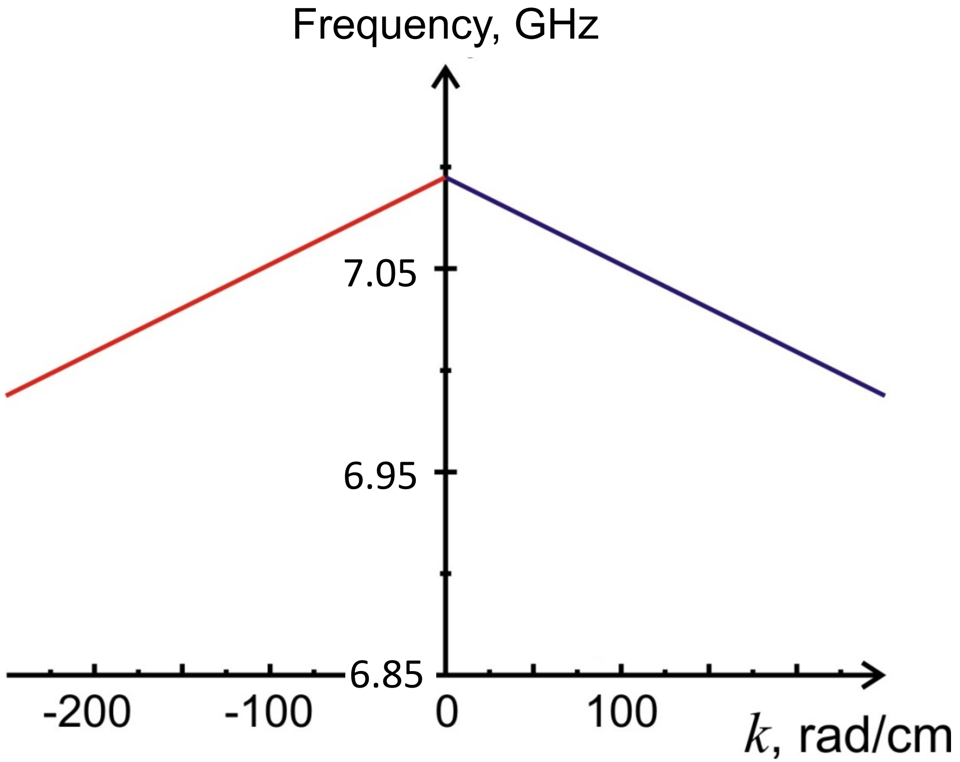

Bragg scattering (formation of band gaps)

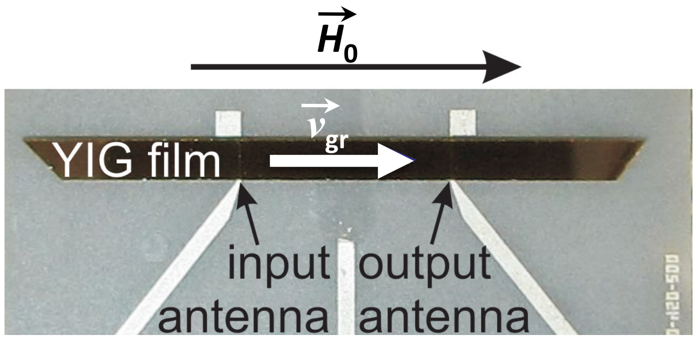



- analogous to photonic and sonic crystals but operates with spin waves in the microwave frequency range

# Spin wave in plane waveguide

## Backward Volume Magnetostatic Waves (BVMSW)



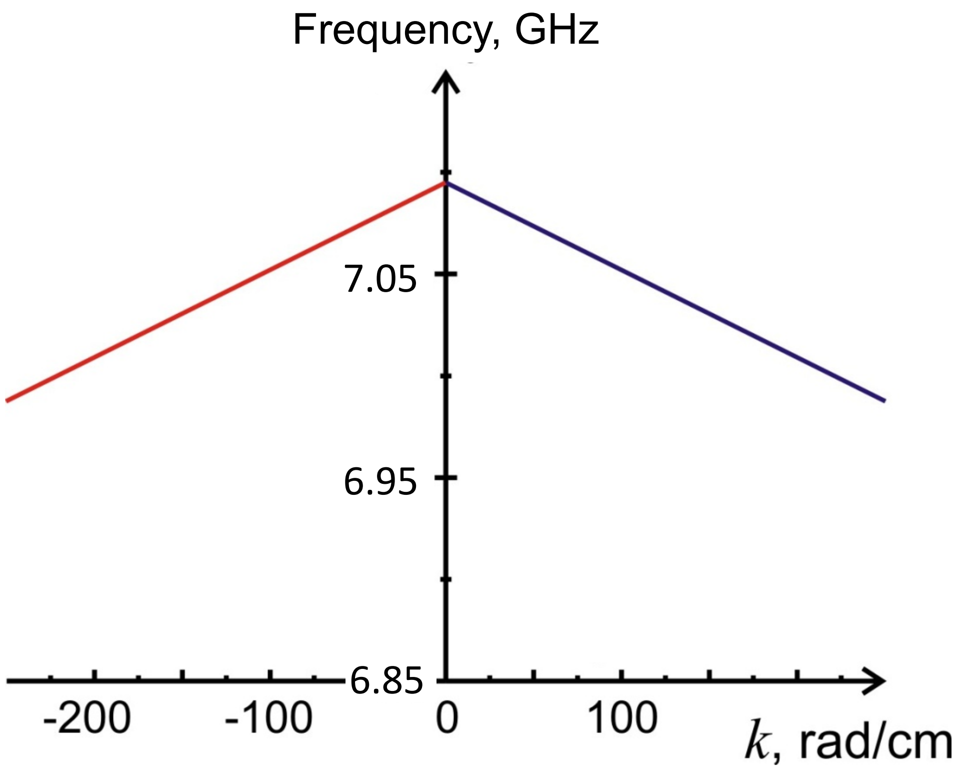



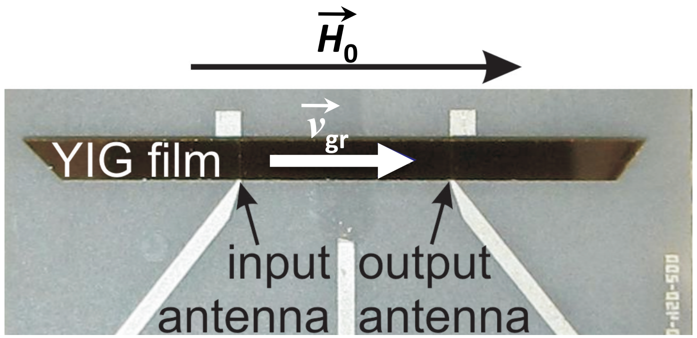

**BVMSW - reciprocal wave**

Schneider *et al.*, PRB **77**, 214411 (2008)

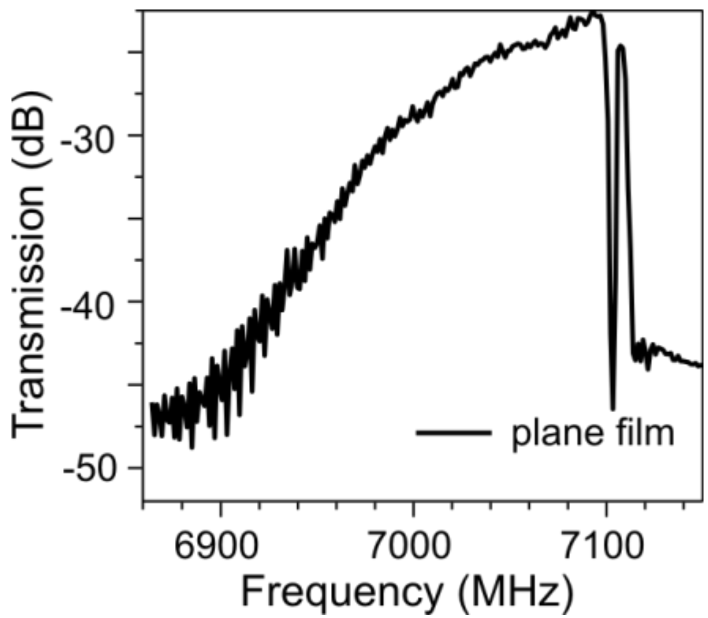
# Spin wave in plane waveguide

**Backward Volume Magnetostatic Waves (BVMSW)**



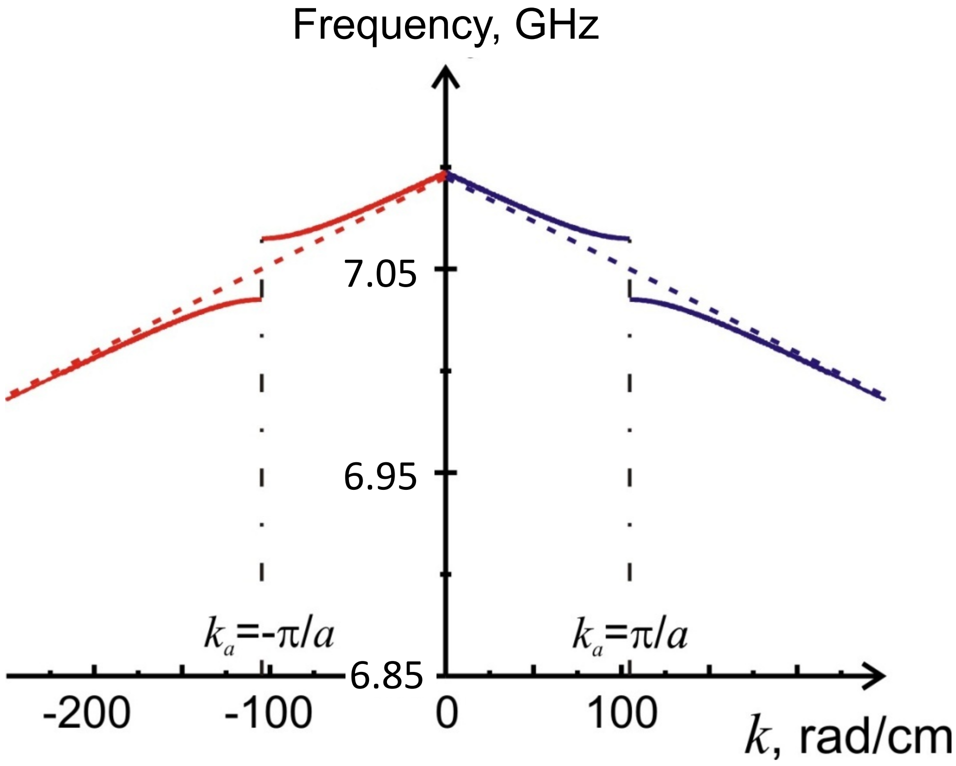



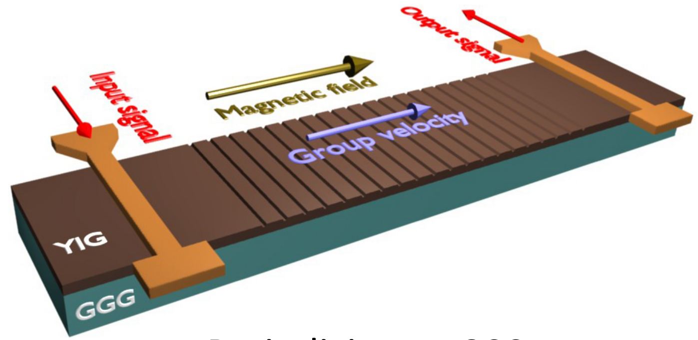

Magnetic field $H_0 = 1.8$ kOe
Magnetization $4\pi M_0 = 1750$ G
YIG film thickness $d_0 = 5.5$ μm



# Magnonic crystal

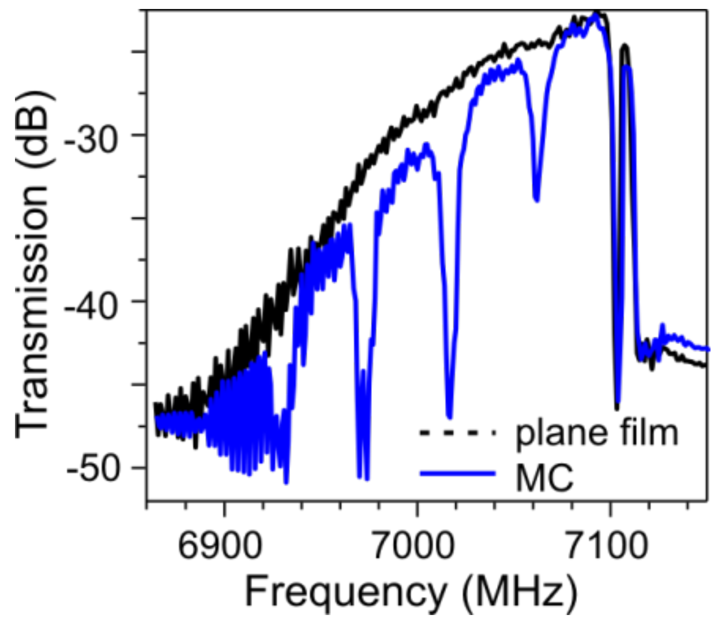
**Backward Volume Magnetostatic Waves (BVMSW)**




Periodicity $a$ = 300 μm

**Number of grooves $N_g$ = 20**




Chumak, *et al.*, APL **93**, 022508 (2008)

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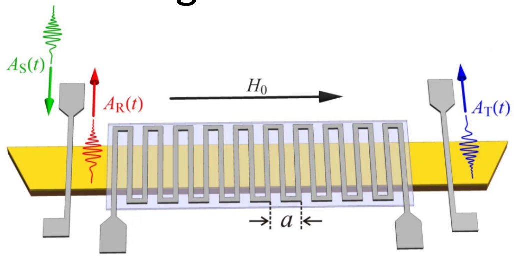
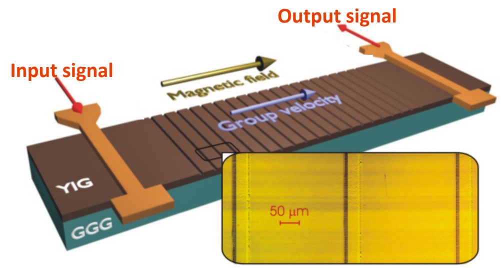
# Which magnetic property do we modulate?

## Bias magnetic field




Fetisov *et al.*, JAP **79**, 5730 (1996)
Chumak *et al.*, J. Phys. D **42**, 205005 (2009)

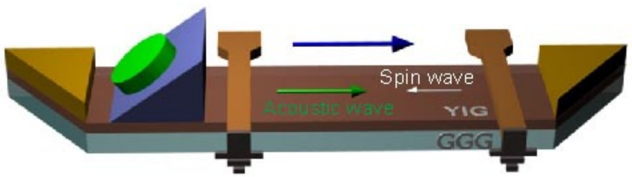
## Waveguide thickness




Sykes *et al.*, APL **29**, 388 (1976)
Chumak *et al.*, APL **93**, (2008)

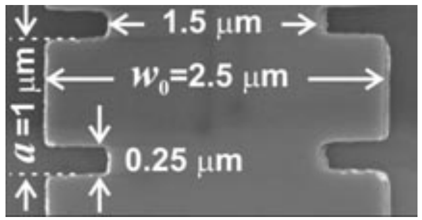
$$f(k) = \gamma \sqrt{H_0 \left( H_0 + 4\pi M_0 \frac{1 - \exp\left\{-\sqrt{(\pi/w)^2 + k^2}\, d\right\}}{\sqrt{(\pi/w)^2 + k^2}\, d} \right)}$$

## Effective saturation magnetization




Wang *et al.*, APL **94**, 083112 (2009)
Chumak *et al.*, PRB, **81**, 140404 (2010)
Obry *et al.*, APL **102**, 202403 (2013)

## Waveguide width

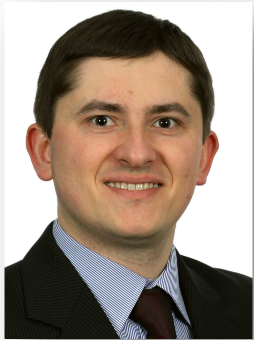



Lee *et al.*, PRL **102**, 127202 (2009)
Chumak *et al.*, APL **95**, (2009)

# Collaborators

## Technische Universität Kaiserslautern

A. Chumak



V. Vasyuchka

A. Serga

B. Hillebrands

## University of Western Australia

M. Kostylev

## University of Oxford UK

A. Karenowska

## Oakland University USA

A. Slavin

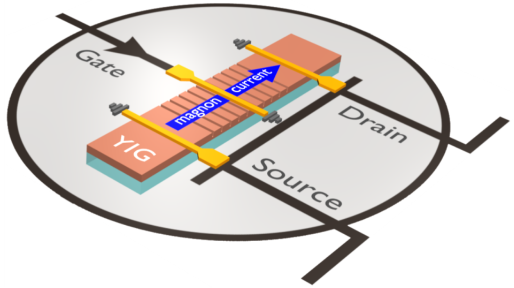
V. Tiberkevich

# AG Magnetismus

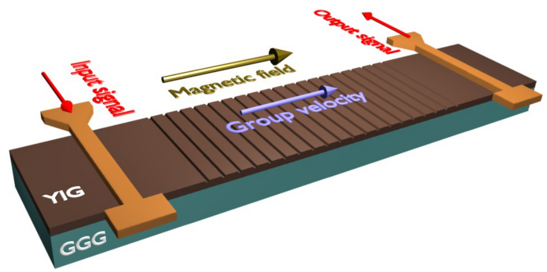
Philipp Pirro, Thomas Brächer, Milan Agrawal, Frank Heussner, Ana Ruiz Calaforra, Benjamin Jungfleisch,
Dr. Evangelos Papaioannou, Jochen Greser, Dr. Vitaliy Vasyuchka, Dr. Tomohiro Koyama, Björn Obry,
Philipp Fuhrmann, Thomas Langner, Viktor Lauer, Dr. Andrés Conca Parra, Dr. Alexander Serga,
Dr. Andrii Chumak, Peter Clausen, Thomas Sebastian, Katrin Vogt,
Prof. Burkard Hillebrands, Thomas Meyer

# Magnonic crystal based data processing

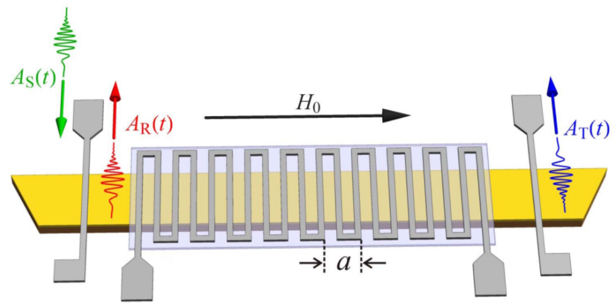
I. Magnon control magnon
Magnon transistor




II. Parametrically driven crystal
Data buffering




III. Dynamic magnonic crystal
All-linear time reversal



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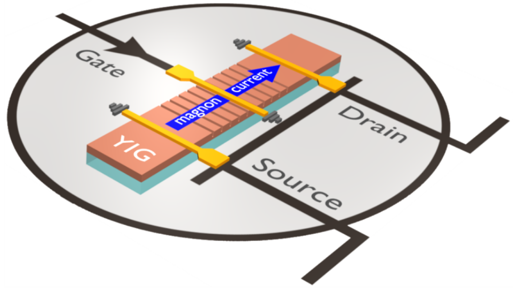


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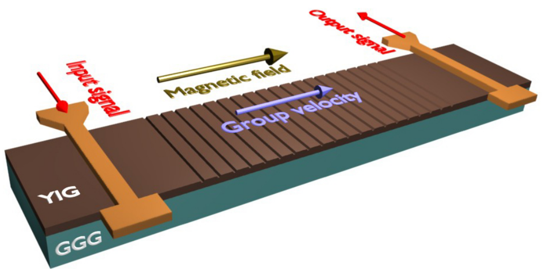


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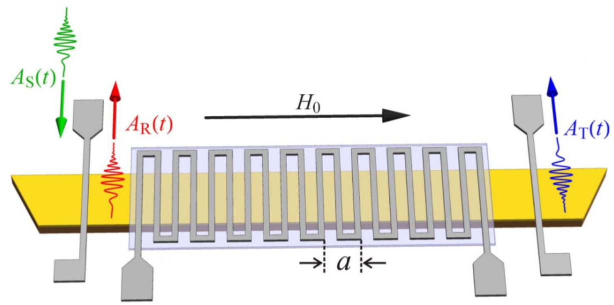
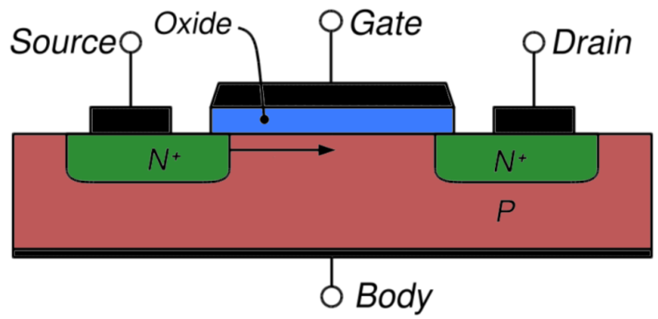


# Electronics and field effect transistor

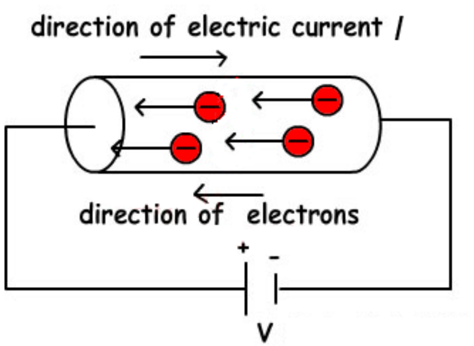
Electronics - involves the flow of electrons

CMOS Field effect transistor:




Most major problem:

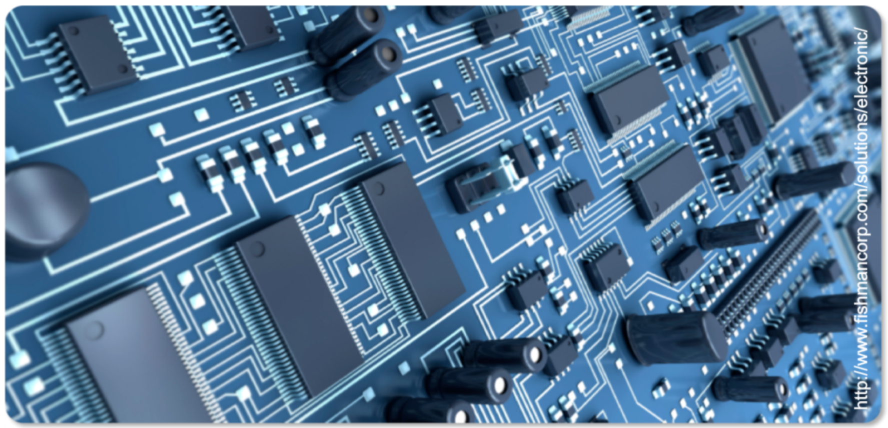
Joule heating (1841):



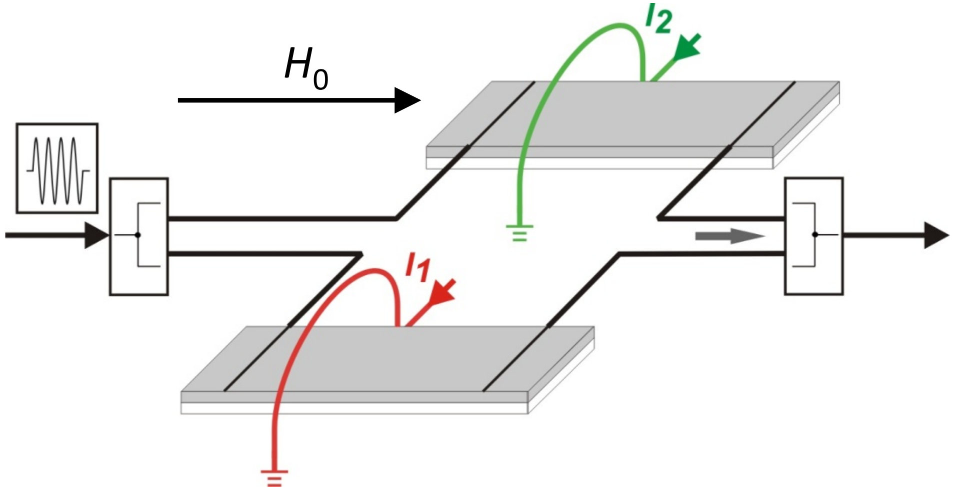

Heat loss power:

$P = I*V = R*I^2$,

*I – electric current,*
*V – applied voltage,*
*R - resistance*

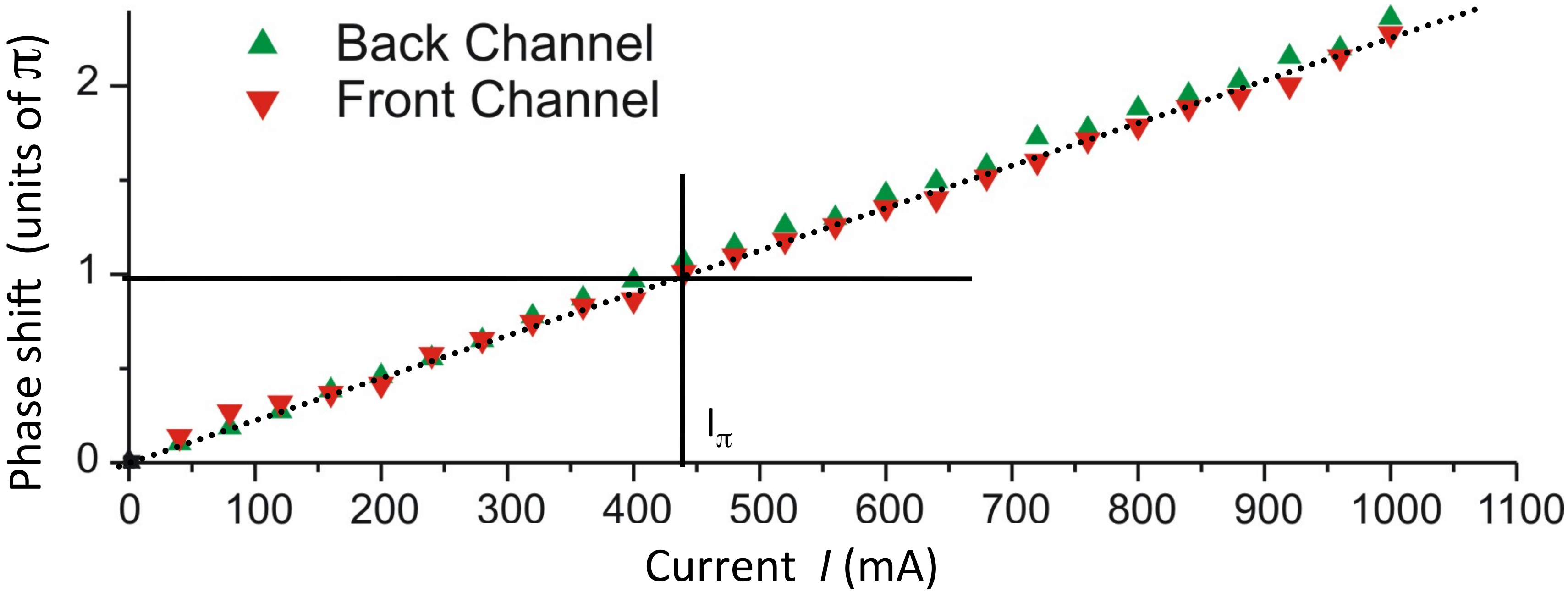


# Mach-Zehnder interferometer based spin-wave logic gate




Kostylev et al., **APL 87**, 153501 (2005)

Schneider et al., **APL 92**, 022505 (2008)



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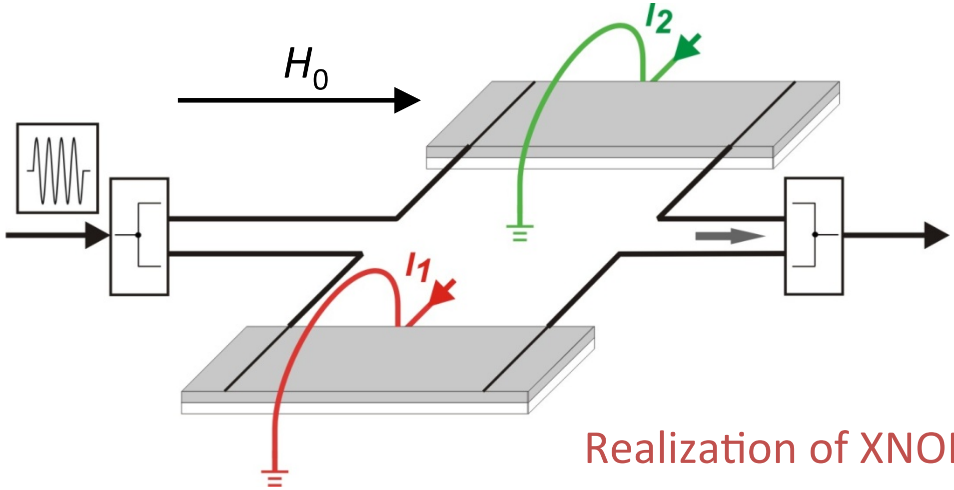
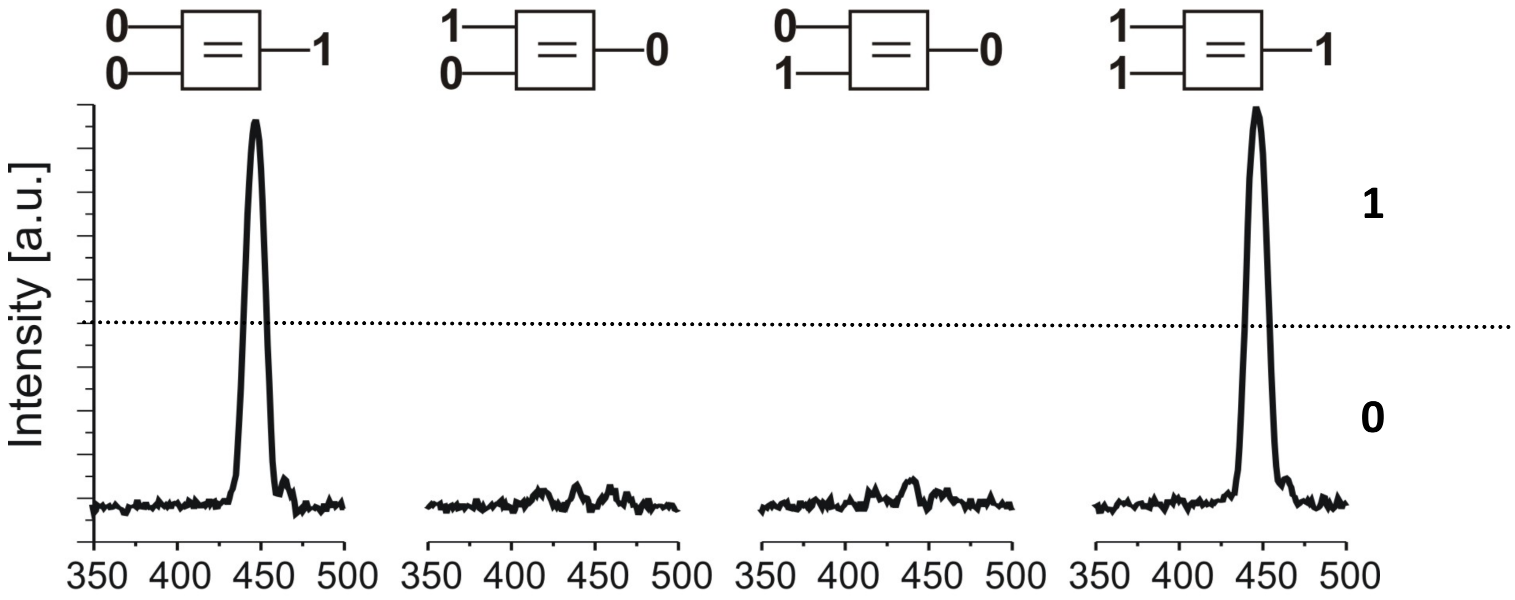



| Inputs | | Output |
|---|---|---|
| A ($I_1$) | B ($I_2$) | |
| 0 (0) | 0 (0) | 1 |
| 0 (0) | 1 ($I_\pi$) | 0 |
| 1 ($I_\pi$) | 0 (0) | 0 |
| 1 ($I_\pi$) | 1 ($I_\pi$) | 1 |

Realization of XNOR gate




Schneider et al., **APL 92**, 022505 (2008)

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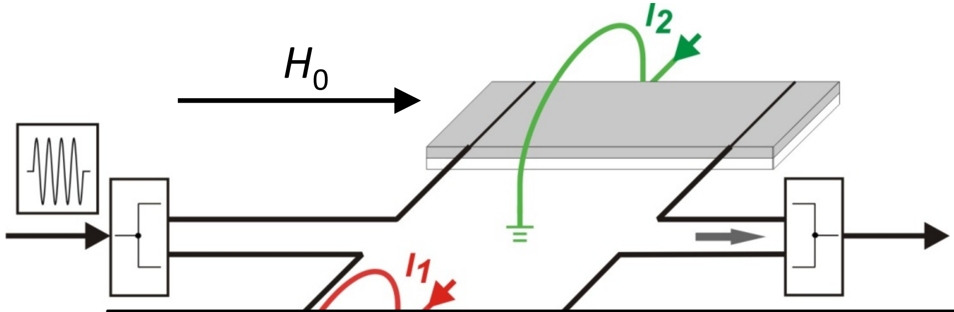
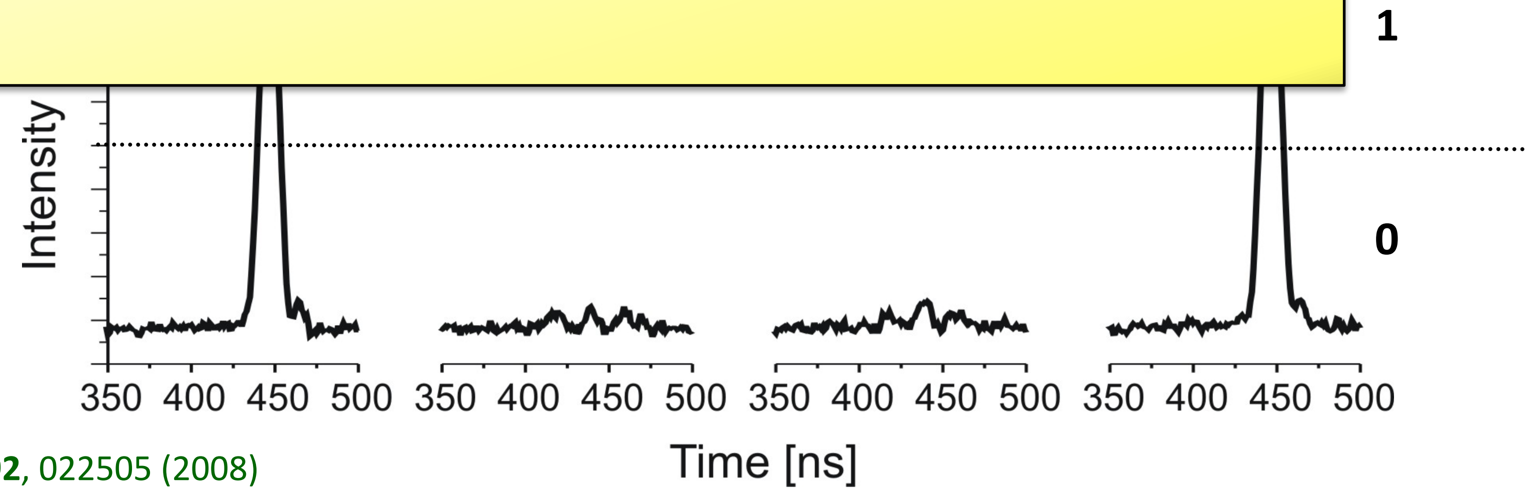



| Inputs | | Output |
|---|---|---|
| A ($I_1$) | B ($I_2$) | |
| 0 (0) | 0 (0) | 1 |
| 0 (0) | 1 ($I_\pi$) | 0 |
| | | 0 |
| | | 1 |

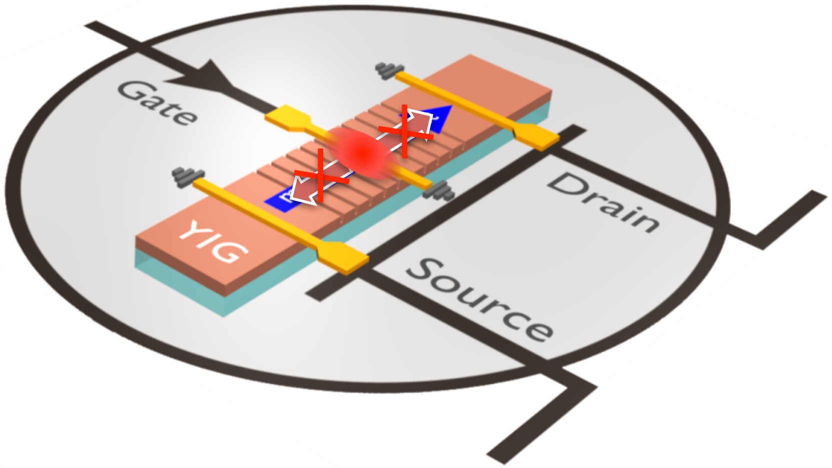
Input: DC pulses
Output: magnon packets

**How to control one magnon by another?**

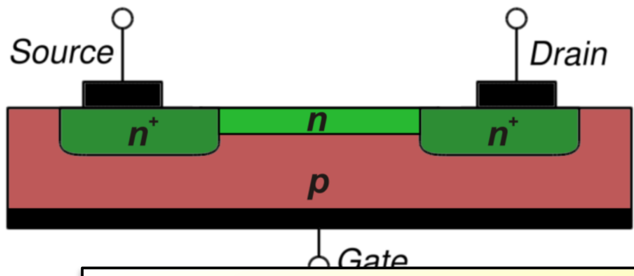



Schneider et al., **APL 92**, 022505 (2008)

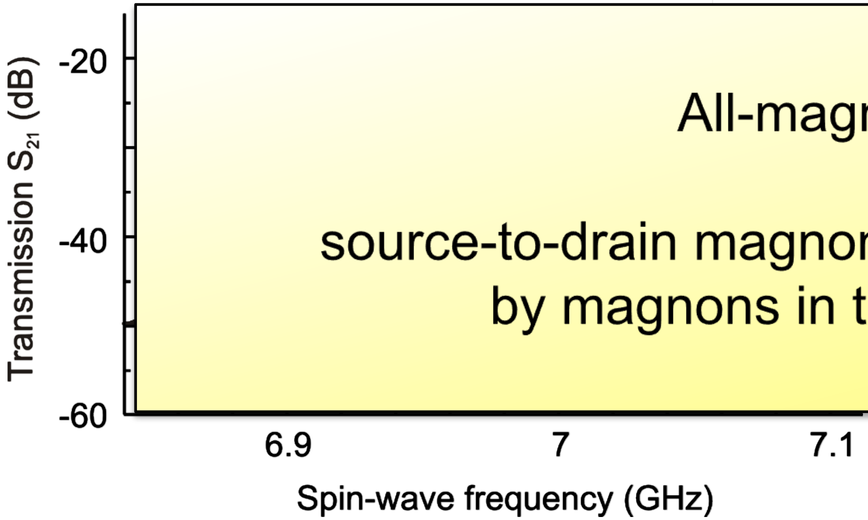
# Magnon transistor




Semiconductor field-effect transistor:




Magnonic crystal acts as an enhancer of non-linear effects




All-magnon device:

source-to-drain magnon flow should be controlled by magnons in the transistor's gate

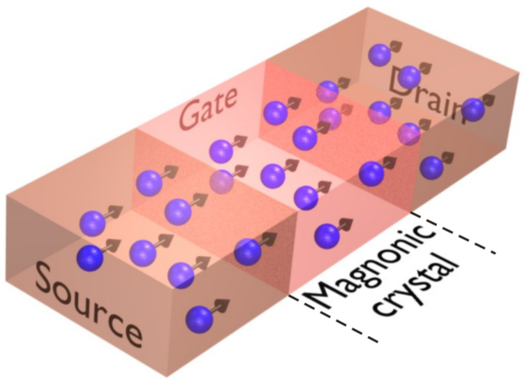
Technische Universität Kaiserslautern

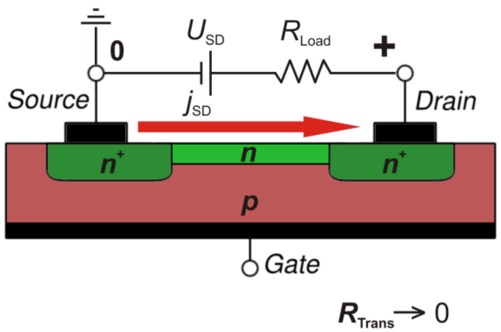
# Magnon transistor

**Opened:** $R \rightarrow 0$

Gate magnon density

$n_G = 0$

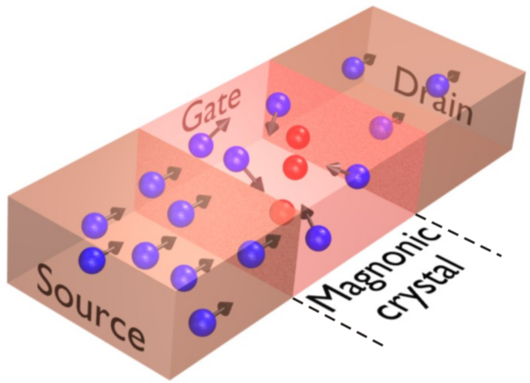


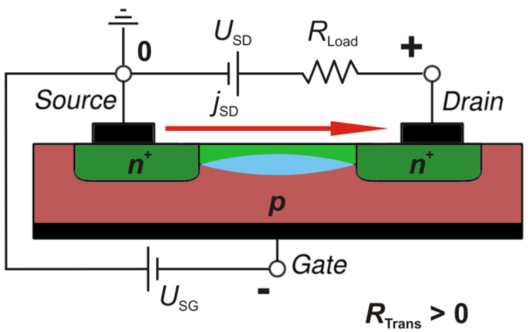




**Semi-closed:** $R > 0$

Gate magnon density

$n_G > 0$

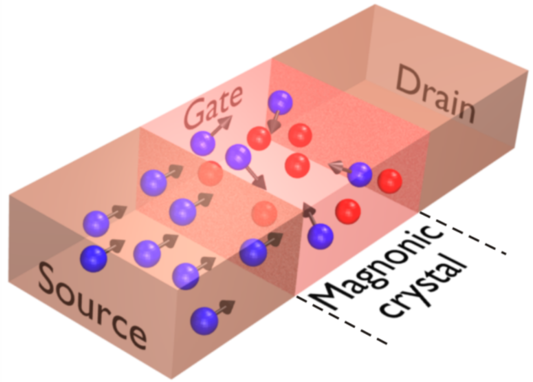


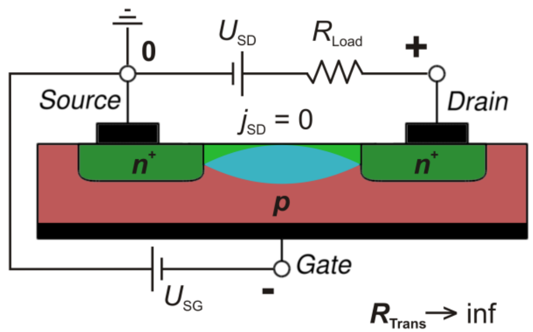




**Closed:** $R \rightarrow \infty$

Gate magnon density

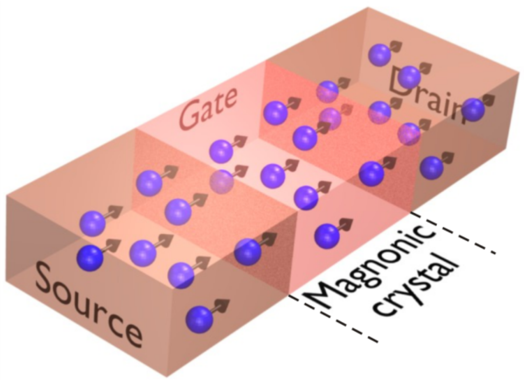
$n_G >> 0$

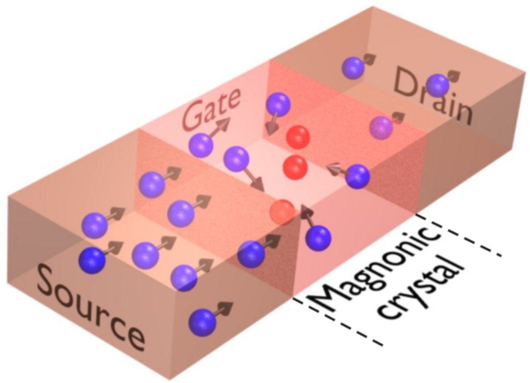


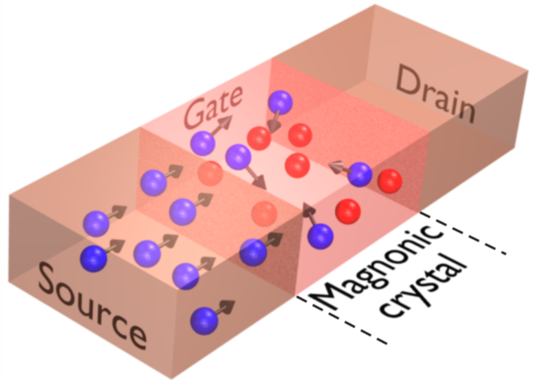



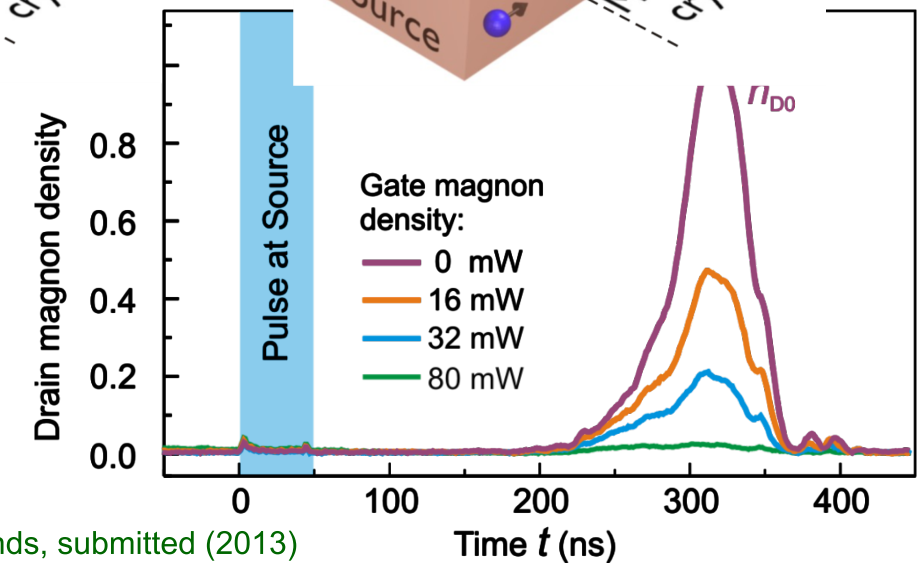
# Magnon transistor

| **Opened:** $R \rightarrow 0$ | **Semi-closed:** $R > 0$ | **Closed:** $R \rightarrow \infty$ |
|---|---|---|
| Gate magnon density | Gate magnon density | Gate magnon density |
| $n_G = 0$ | $n_G > 0$ | $n_G >> 0$ |



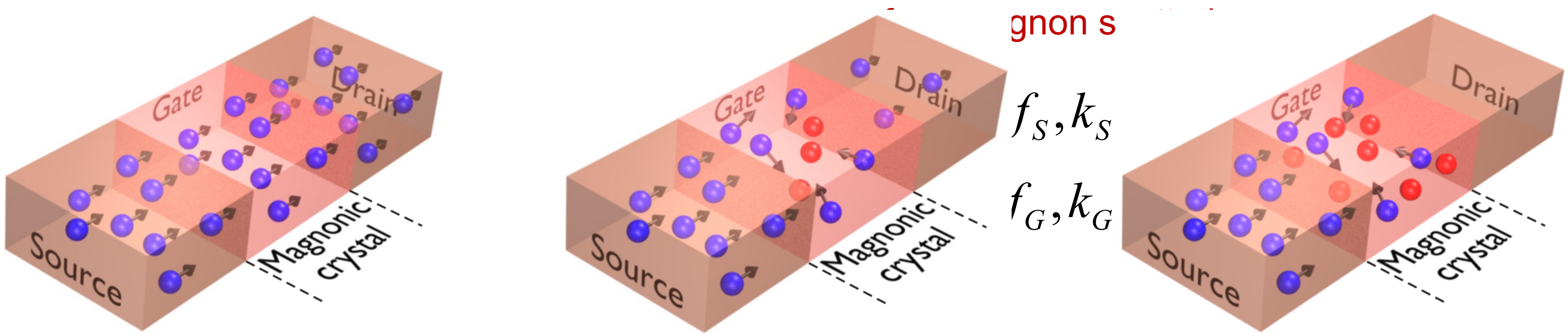



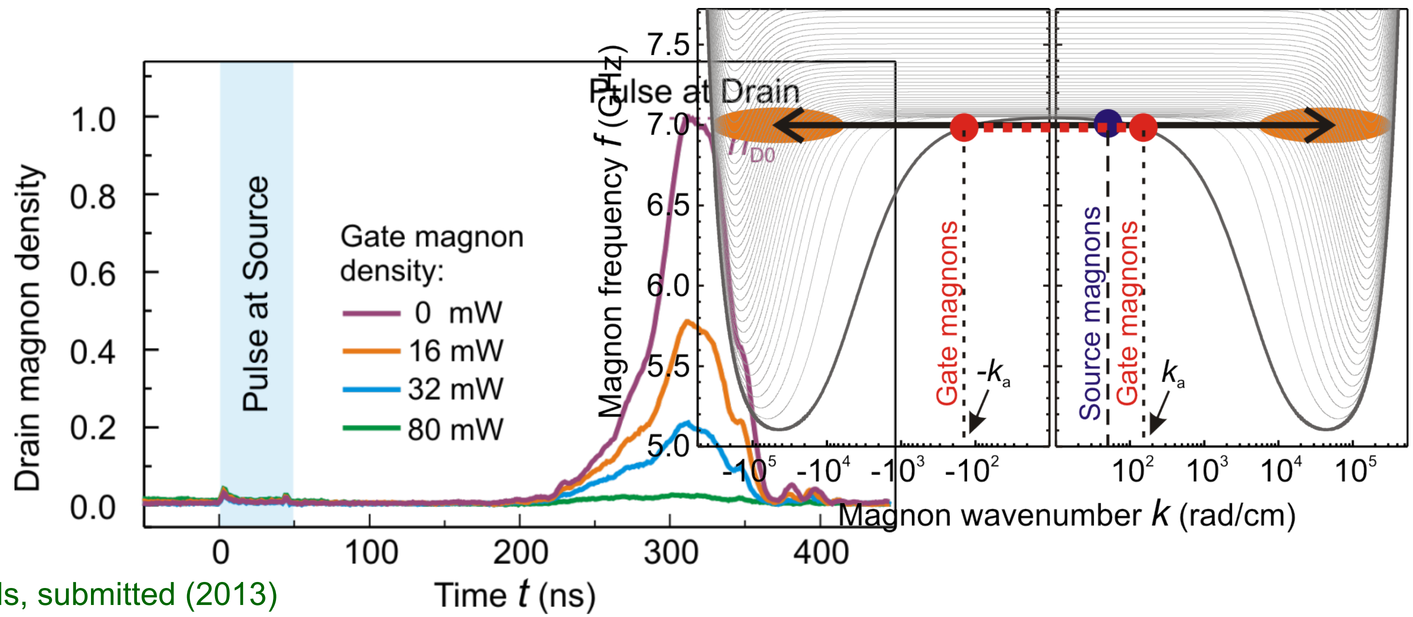




Chumak, Serga, Hillebrands, submitted (2013)

# Magnon transistor

**Opened:** *R* → 0 | **Semi-closed:** R > 0 | **Closed:** R → ∞

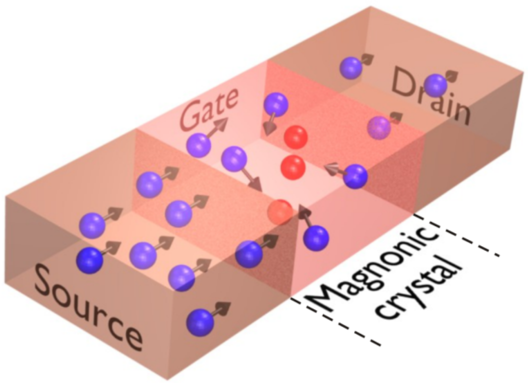


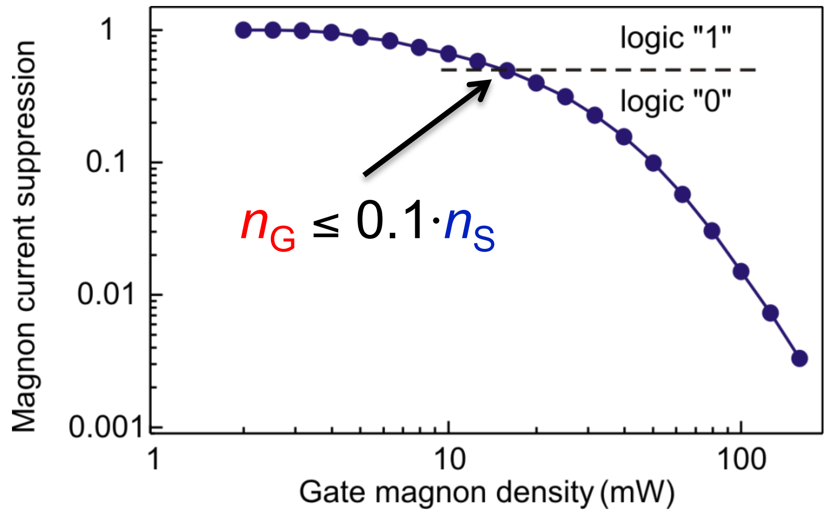



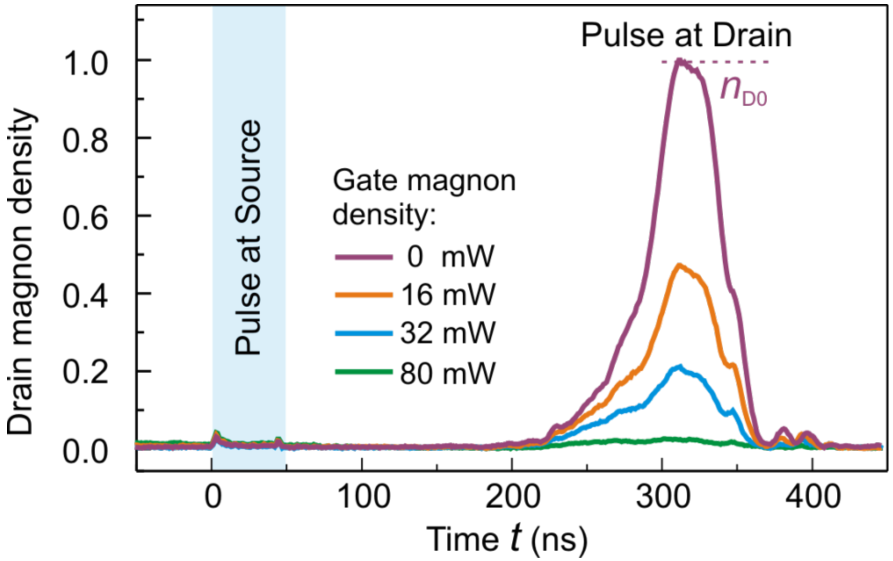

Chumak, Serga, Hillebrands, submitted (2013)

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

# Magnon transistor




“magnon control magnon“ principle was realized:

data can be processed on the same magnetic chip

# Device parameters

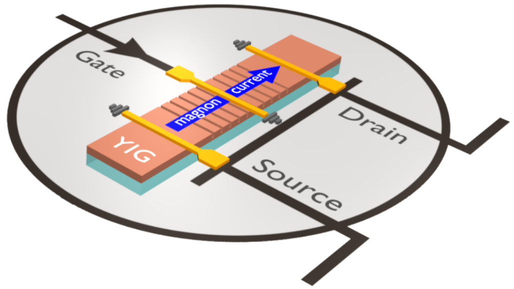
**This is just a proof of concept!**

(example: CMOS uses $3 \times 10^{-18}$J switching energy, we used $3 \times 10^{-9}$J)

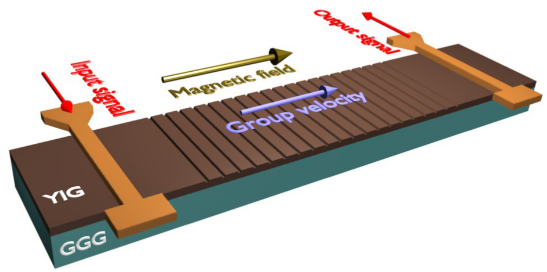
- Classical Computing
  - Scalar variable
  - Boolean logic
- Wave Computing
  - Vector variable
  - Special task data processing
- Quantum Computing
  - Vector state variable
  - Entanglement

# Magnonic crystal based data processing

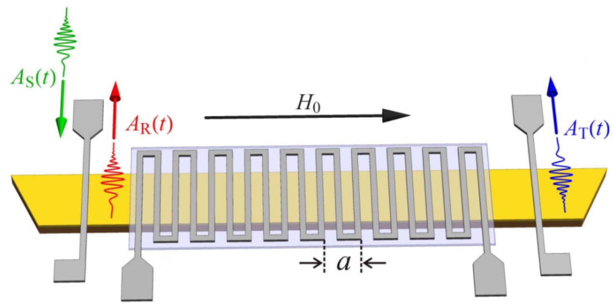
I. Magnon control magnon
Magnon transistor




II. Parametrically driven crystal
Data buffering



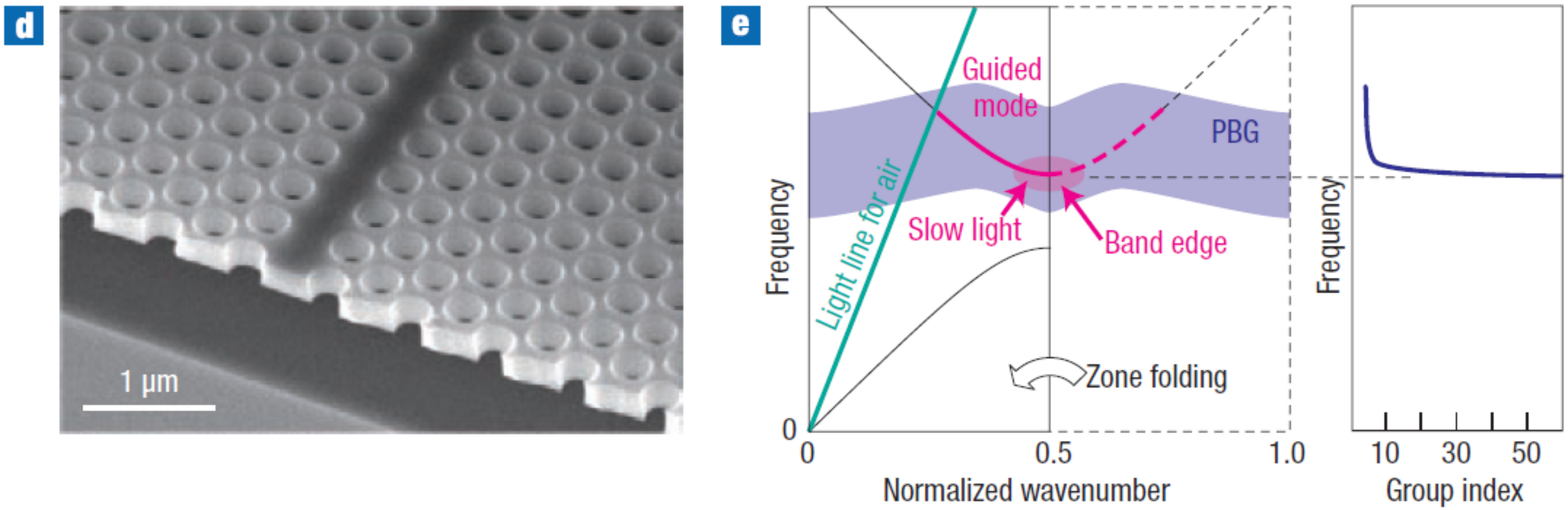

III. Dynamic magnonic crystal
All-linear time reversal



# Slowing or even stop of light

REVIEW ARTICLE | FOCUS

## Slow light in photonic crystals

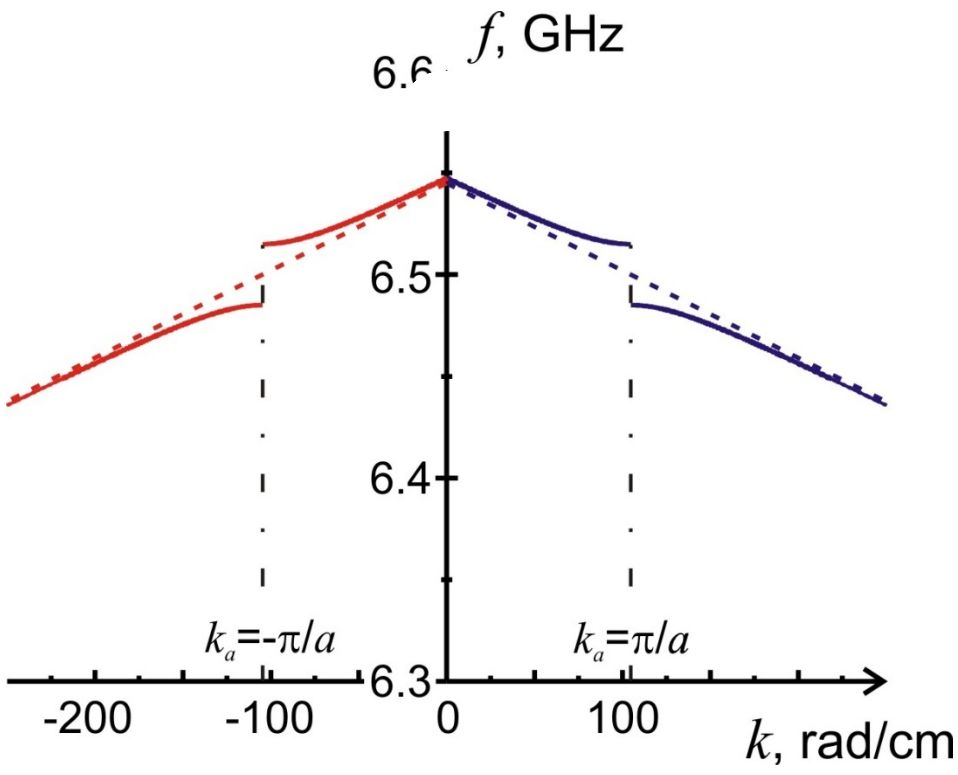


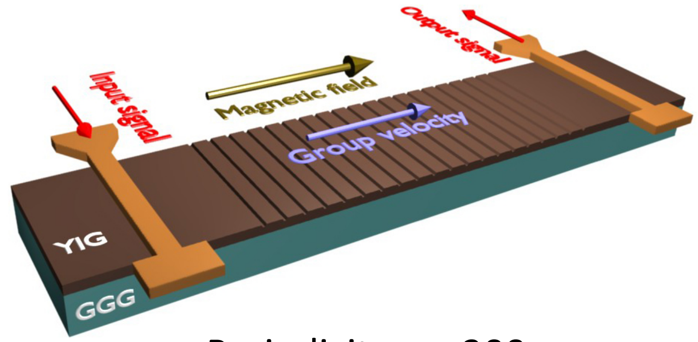

Slow light with a group velocity hundreds of times lower than *c*
is attainable with present photonic crystal-based technology

T. Baba, Nature Photonics, **2** 465 (2008)

# Spin-wave group velocity in magnonic crystal

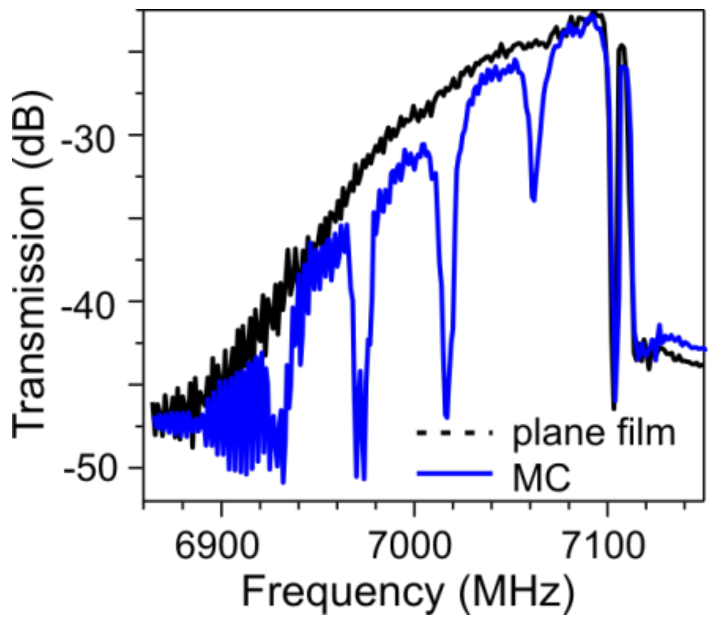
Backward Volume Magnetostatic Waves (BVMSW)




Periodicity $a$ = 300 μm

**Number of grooves $N_g$ = 10**

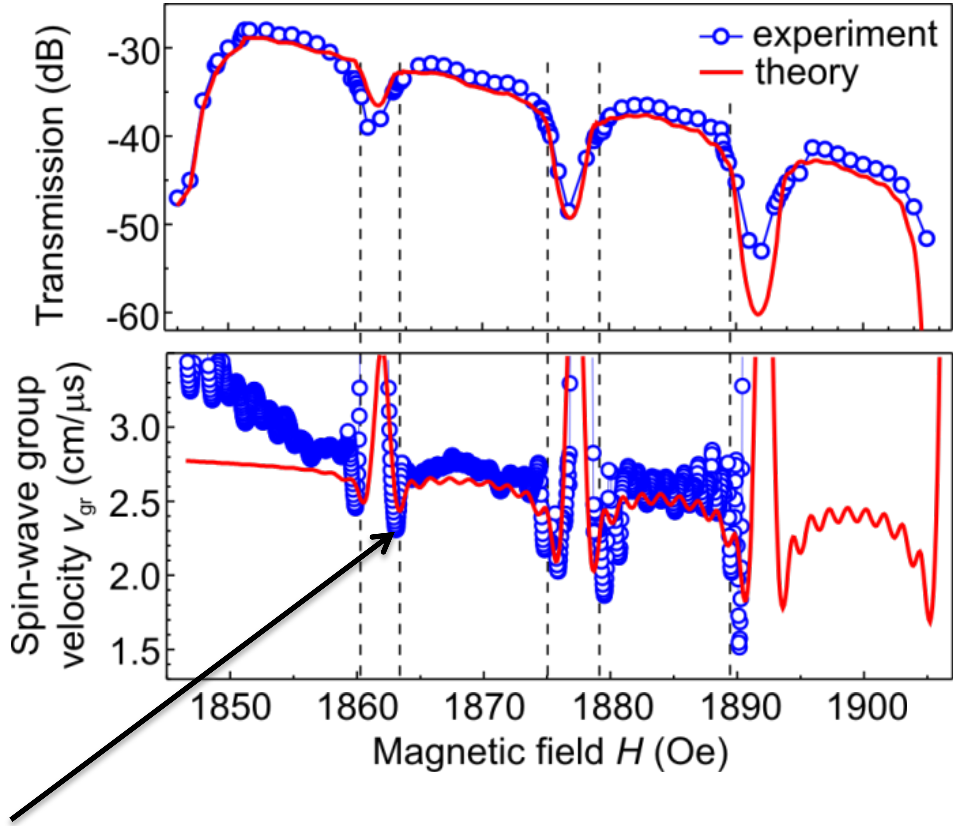



Chumak, *et al.*, APL **93**, 022508 (2008)

# Spin-wave group velocity in magnonic crystal

Theory: transfer matrix approach

Chumak *et al.*, JAP **105**, 083906 (2009)



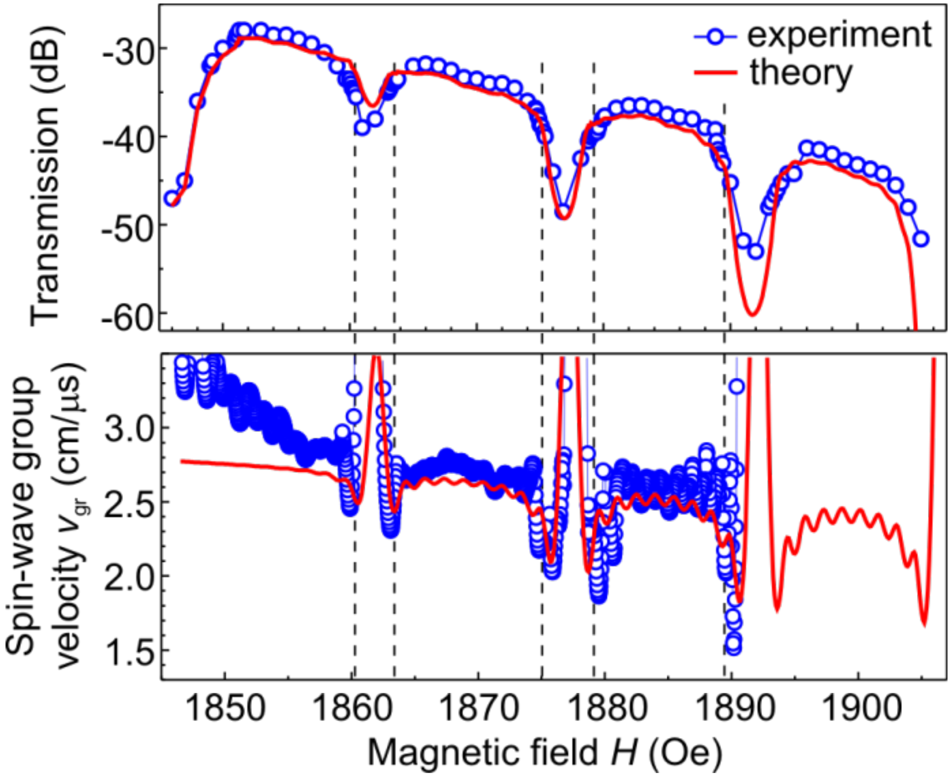

No wave deceleration and storage is possible ?

Group velocity decreases 20% maximum !

# Spin-wave group velocity in magnonic crystal

Theory: transfer matrix approach

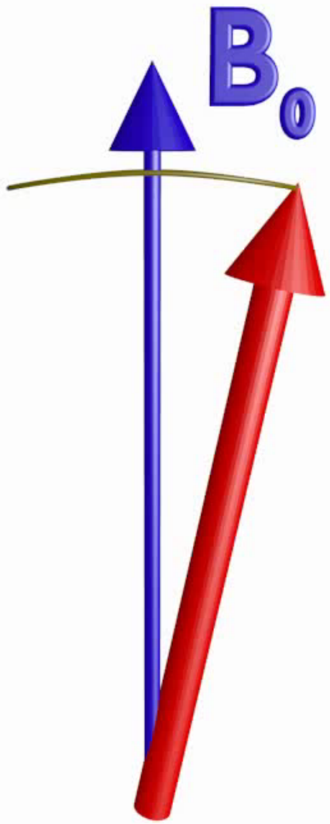
Chumak *et al.*, JAP **105**, 083906 (2009)




No wave deceleration and storage is possible ?

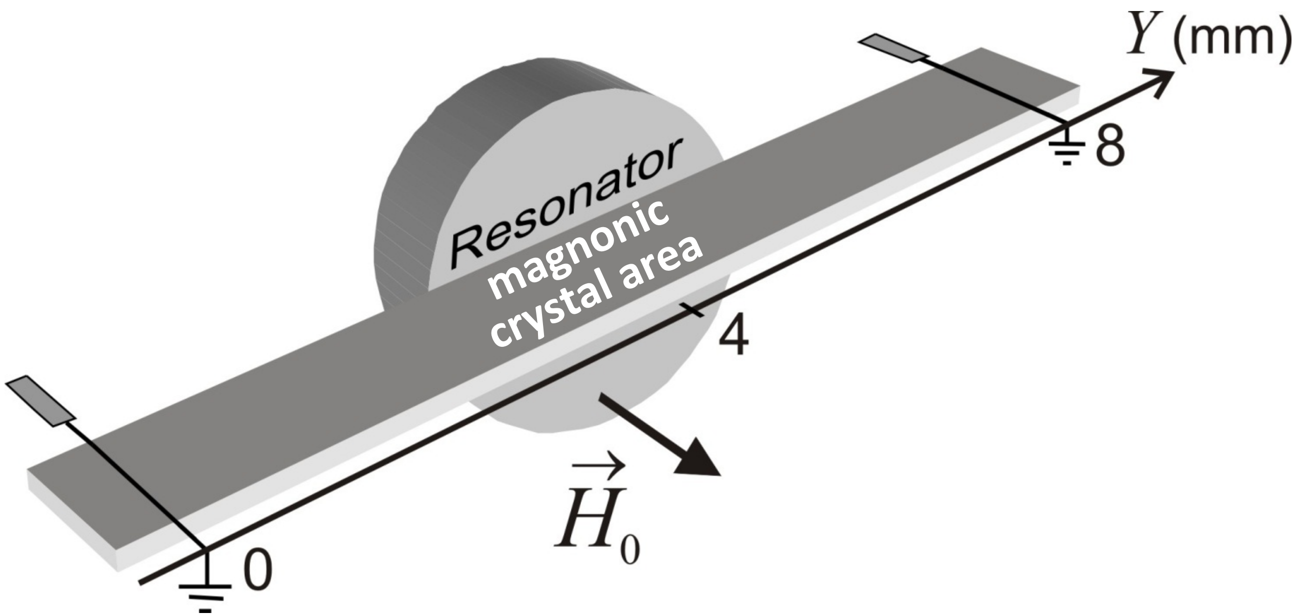
Let us use parametrical amplification after spin-wave left the crystal area

# Parametric amplification of spin waves



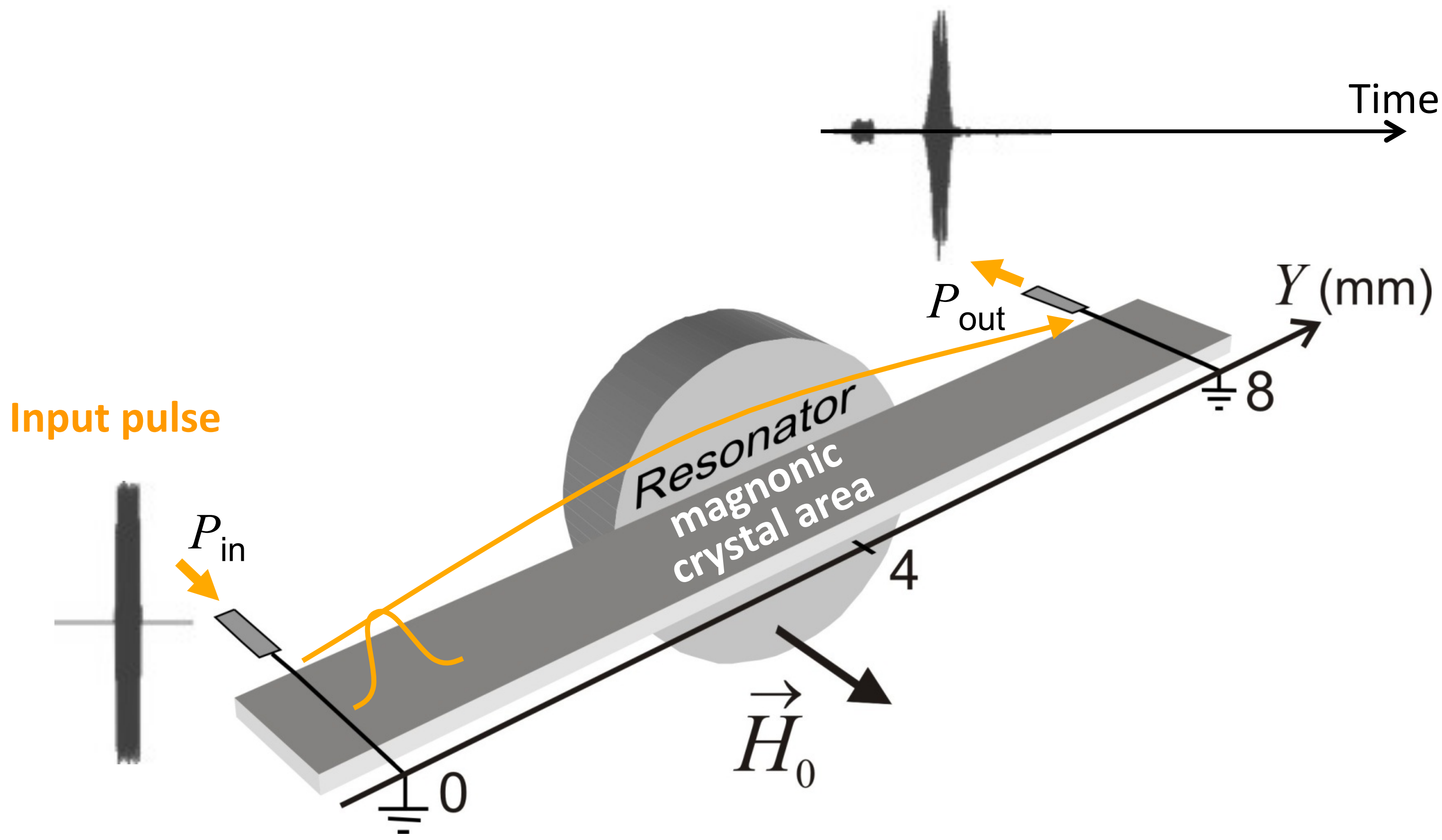

A swing:

# Parametric recovery of spin-wave pulse



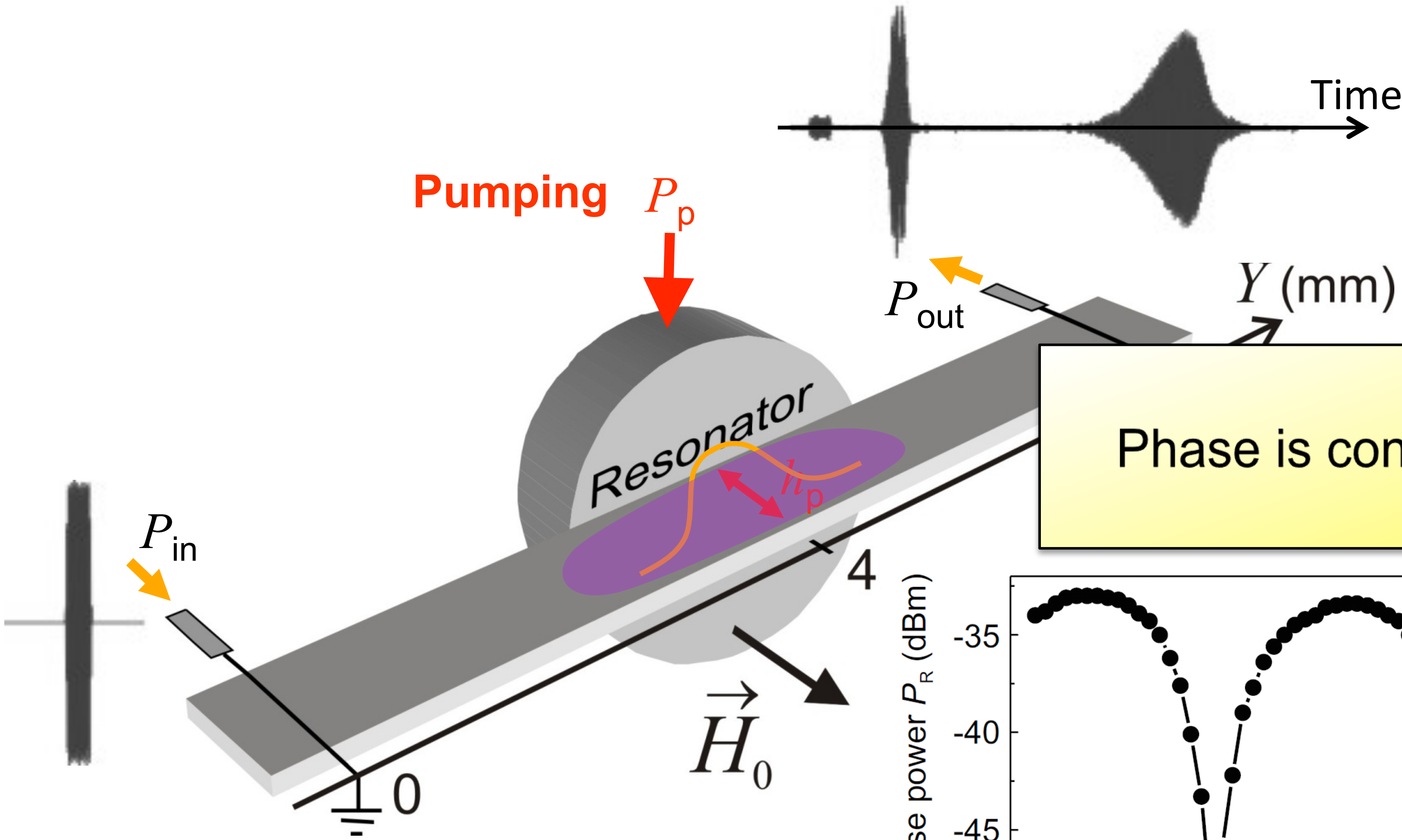

Chumak, *et al.*, PRL **108**, 257207 (2012)

# Parametric recovery of spin-wave pulse

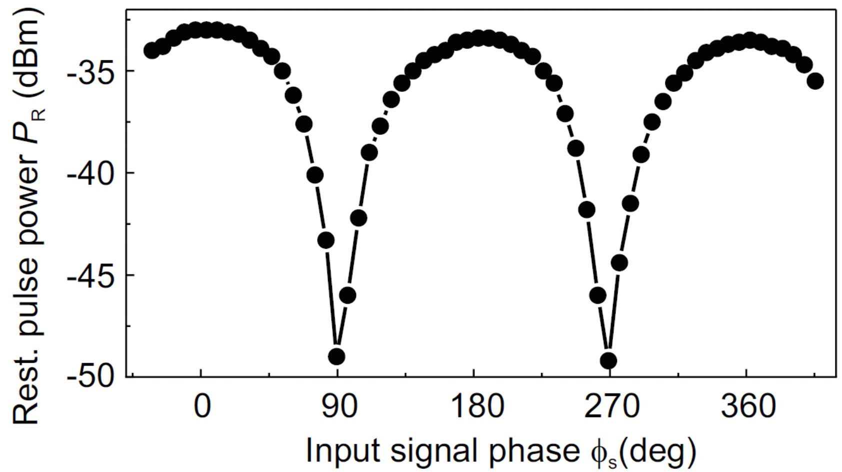



Chumak, *et al.*, PRL **108**, 257207 (2012)

# Parametric recovery of spin-wave pulse




Phase is conserved!

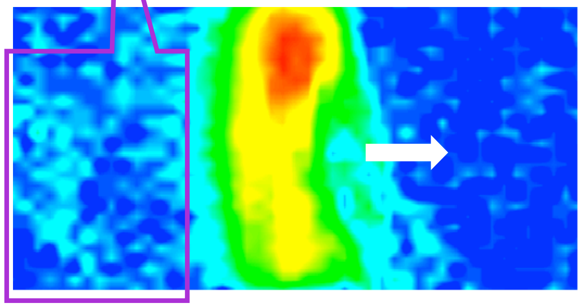


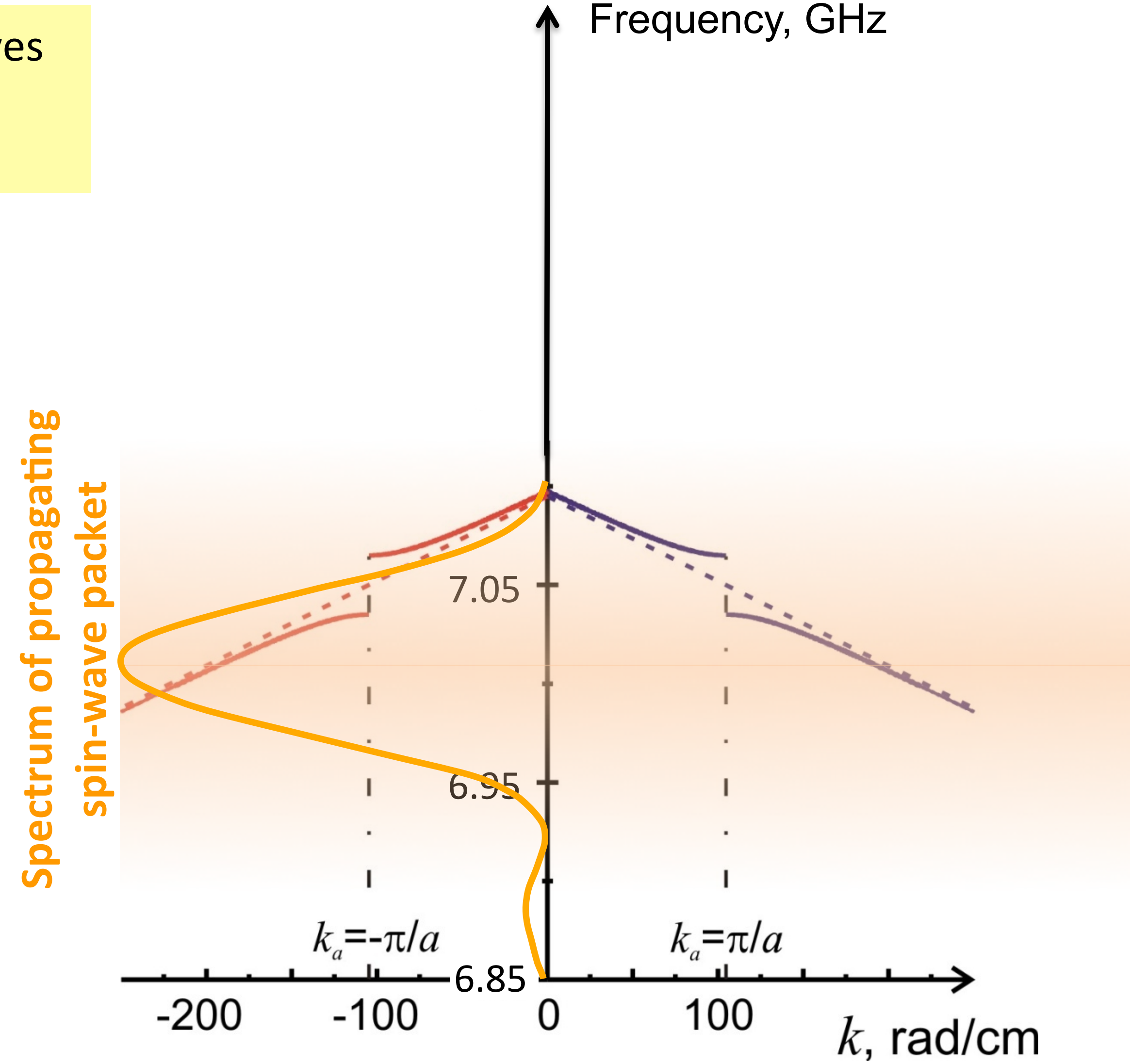

Chumak, *et al*., PRL **108**, 257207 (2012)

Serga et al. PRL **99**, 227202 (2007); Chumak, et al. PRB **79**, 014405 (2009)

# Signal storage and restoration

Propagating spin-wave packet leaves a “ship wake” formed from **secondary** spin waves

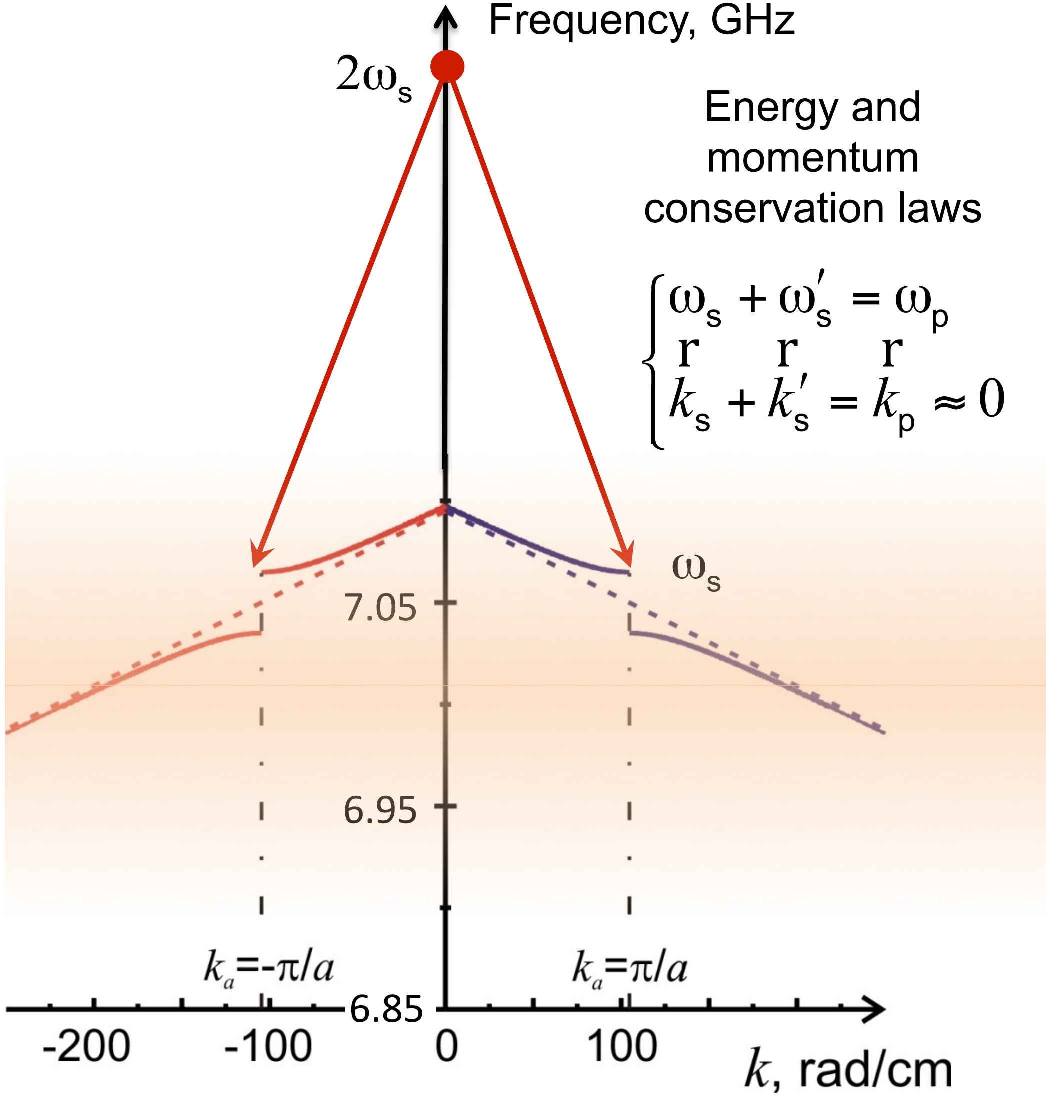




# Signal storage and restoration

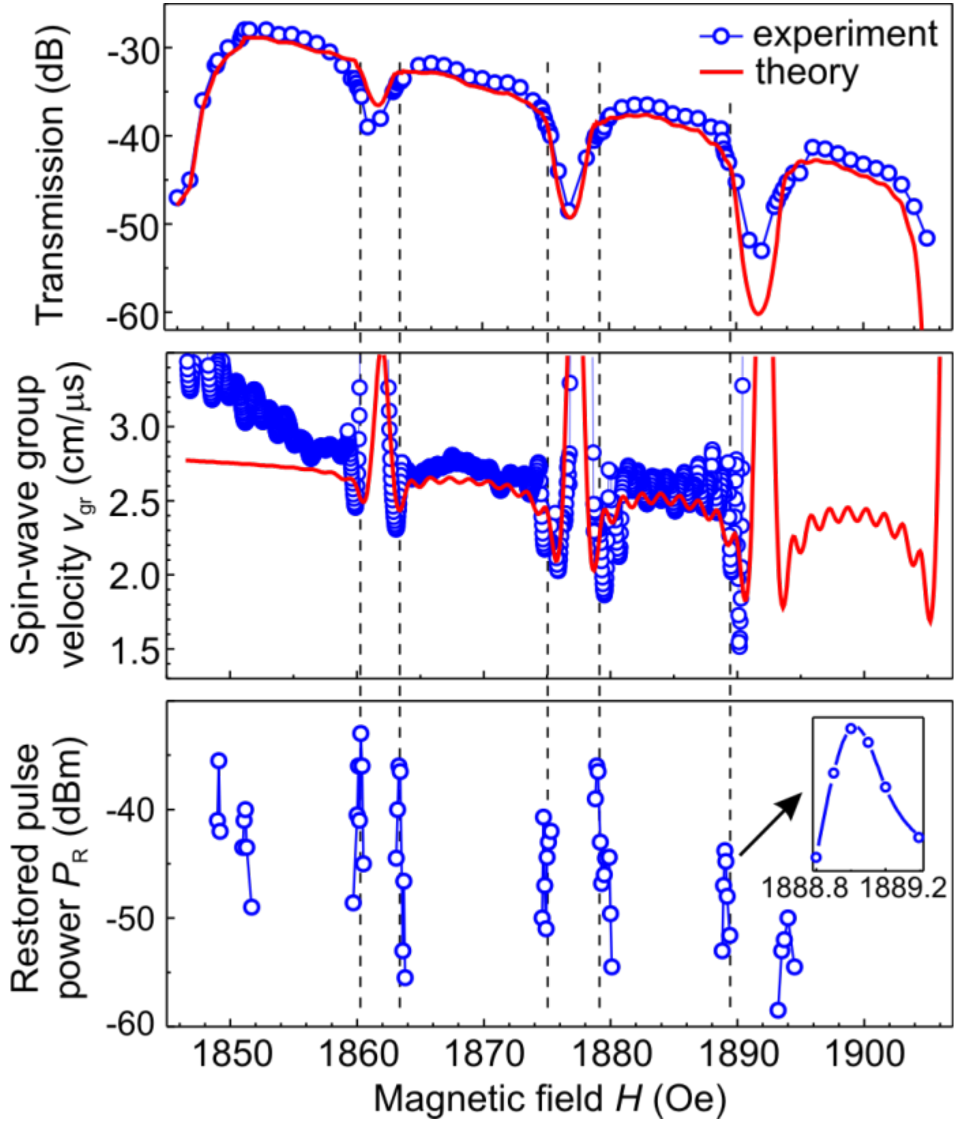
Propagating spin-wave packet leaves a “ship wake” formed from **secondary** spin waves

**Parallel parametric pumping**
energy transfer from photon field in two contra-propagating spin waves



# Spin-wave group velocity in magnonic crystal

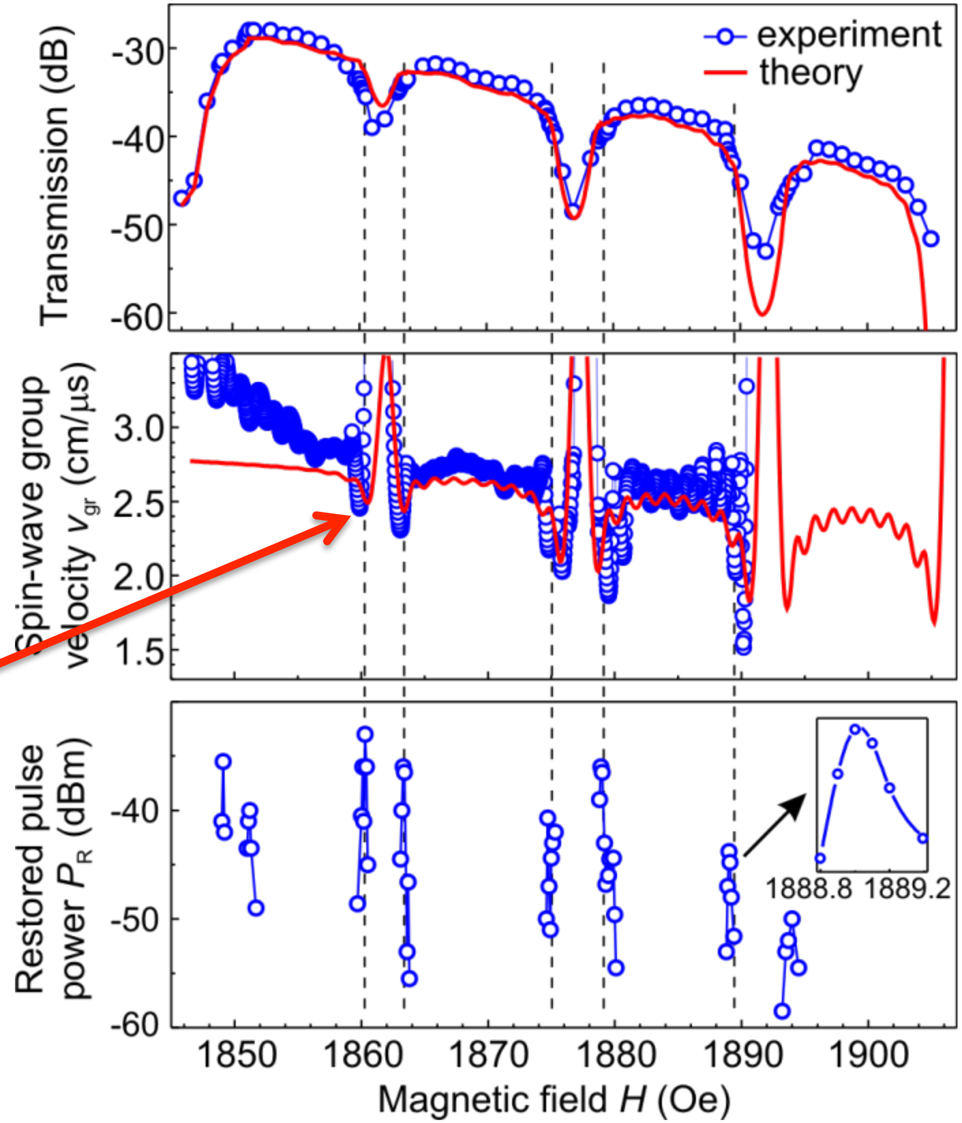
No wave deceleration and storage is possible ?




**Storage at band gap edges**

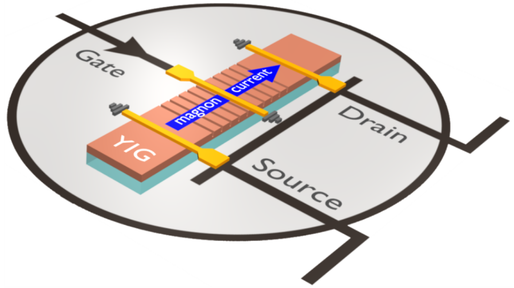
# Spin-wave group velocity in magnonic crystal

- new eigen-excitations exist in magnonic crystal
- they are quasi-normal modes (have standing character but interact with propagating waves)

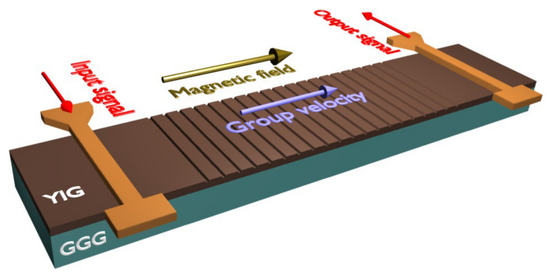


# Magnonic crystal based data processing

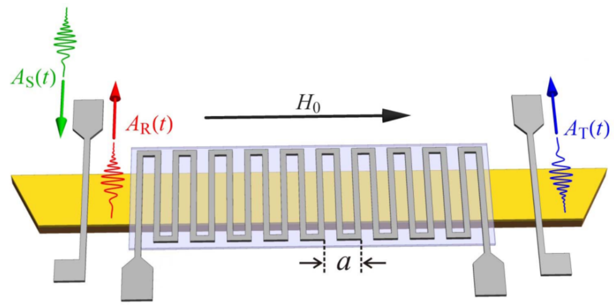
I. Magnon control magnon
Magnon transistor




II. Parametrically driven crystal
Data buffering




III. Dynamic magnonic crystal
All-linear time reversal

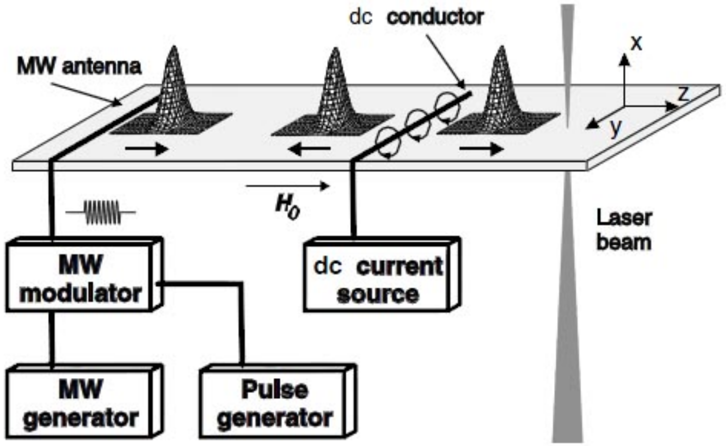


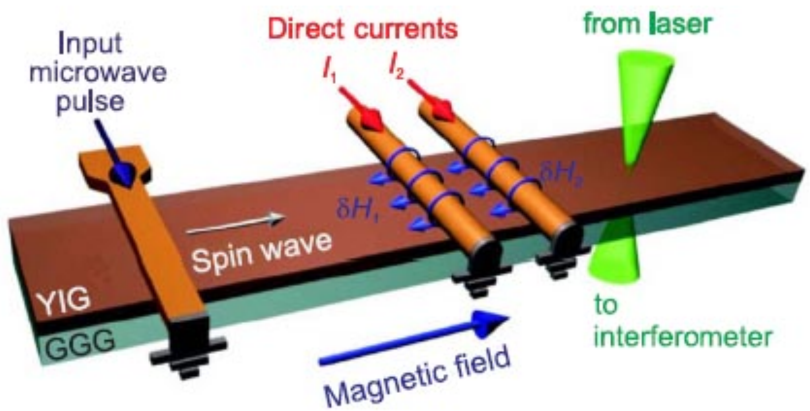
# Dynamic magnonic crystal: Preliminary studies

Preliminary studies

Static regime with a single and double wire

Dynamic regime with two wires



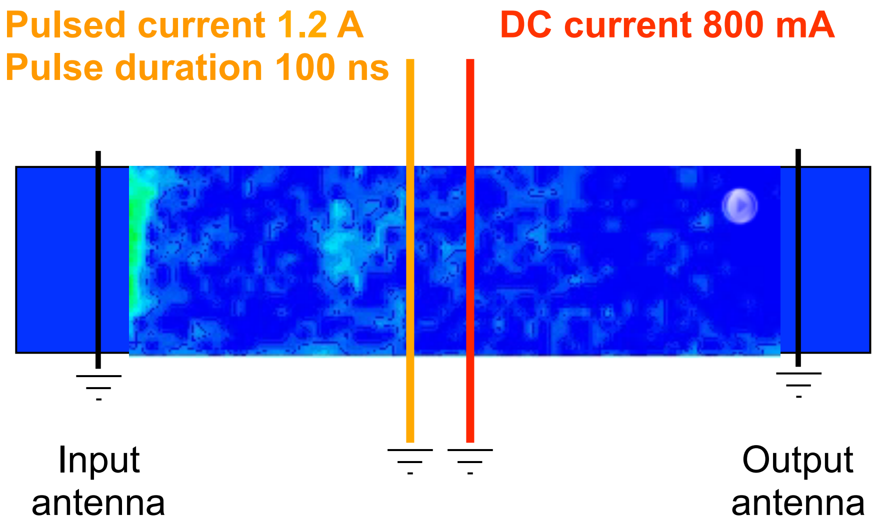




Demokritov *et al.*, PRL 93, 047201 (2004)
Kostylev *et al.*, PRB 76, 184419 (2007)
Hansen *et al.*, PRL. 99, 127204 (2007)

Serga *et al.*, APL 94, 112501 (2009)

# Spin wave reflection from magnetic barriers

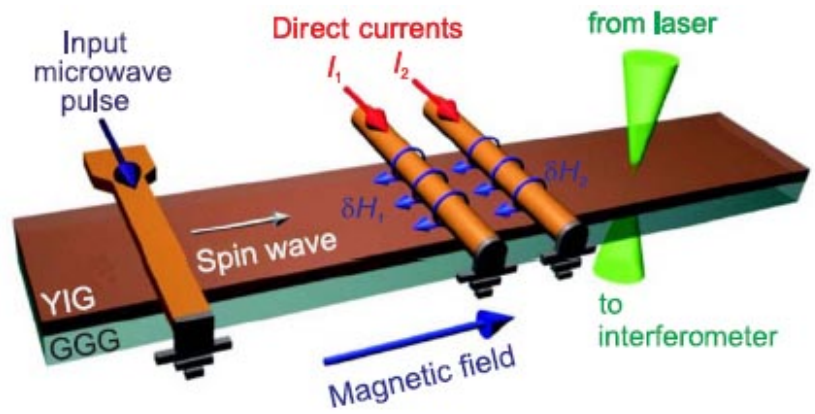
## Short SW pulse 18 ns




Distance between the current wires 0.8 mm
Antenna's diameter 25 μm
YIG: 6 mm × 1.8 mm × 5.7 μm

| | |
|---|---|
| FMR frequency | 7.199 GHz |
| Carrier frequency | 7.125 GHz |
| Bias magnetic field | 1836 Oe |
| Carrier wave number | 112 rad/cm |
| Measured group velocity | 3 cm/mks |

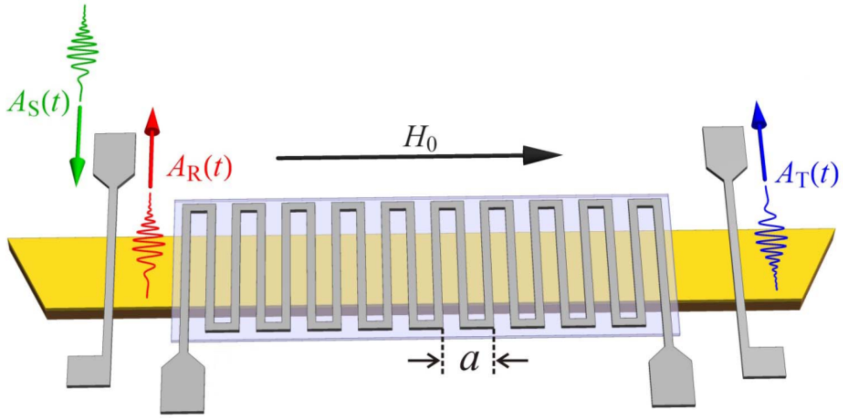
Dynamic regime
with two wires

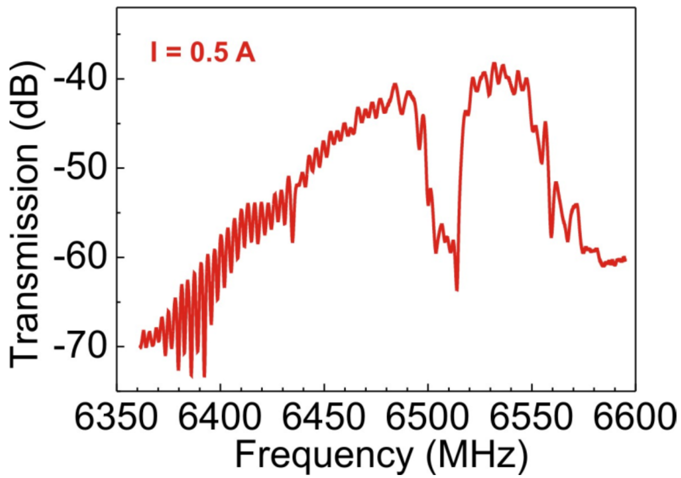


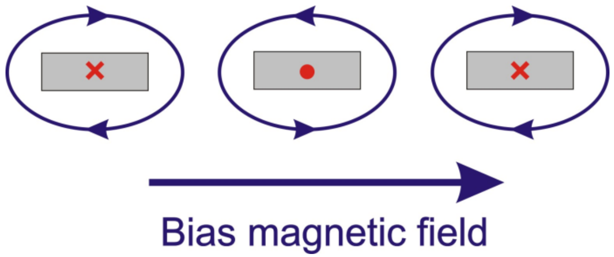

Serga *et al.*, APL 94, 112501 (2009)

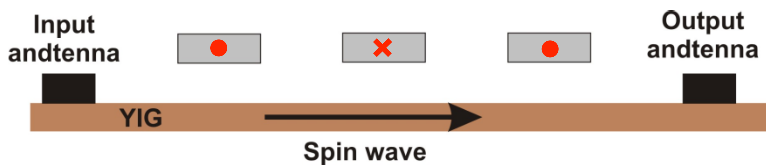
# Dynamic magnonic crystal

Periodic modulation of the bias magnetic field by current-carrying wires



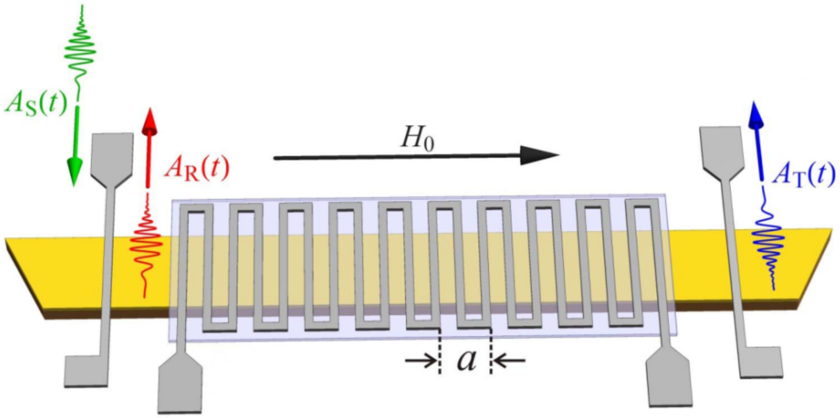

Lattice constant: $a$ = 300 μm

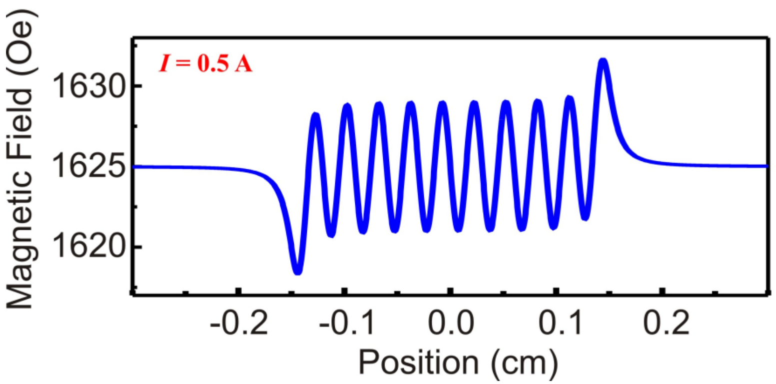
Number of periods: $N_g$ = 20

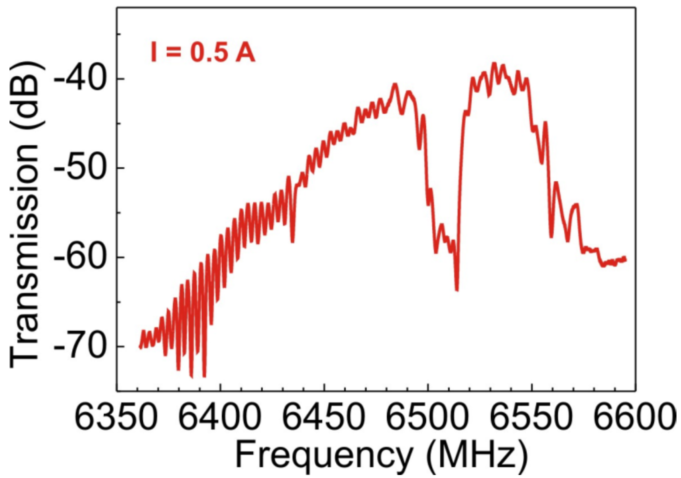
Chumak *et al.*, J. Phys. D 42, 205005 (2009)

# Dynamic magnonic crystal

Periodic modulation of the bias magnetic field by current-carrying wires




Lattice constant: $a$ = 300 μm

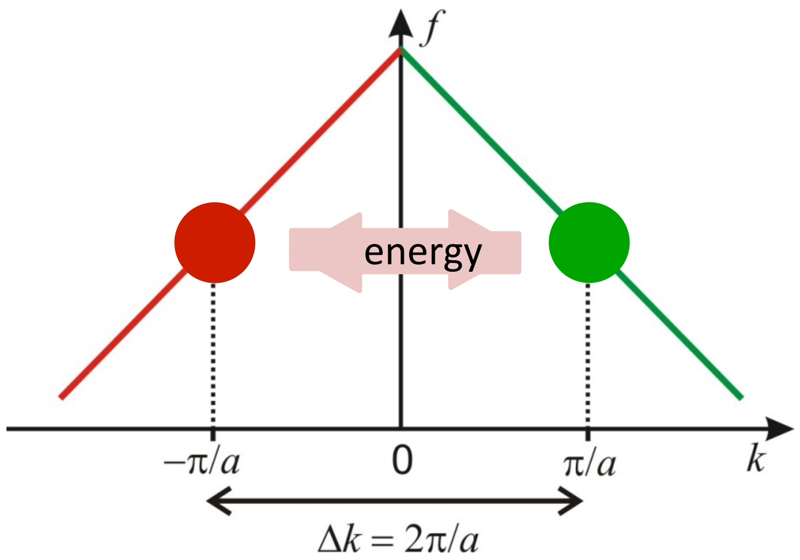
Number of periods: $N_g$ = 20

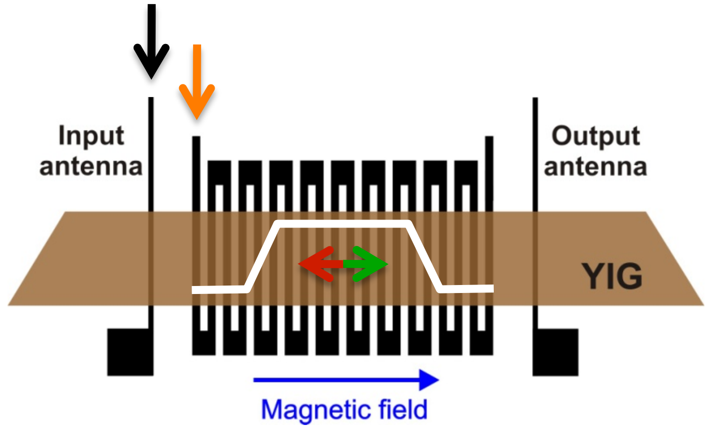
Chumak *et al.*, J. Phys. D 42, 205005 (2009)

DMC can be switched ON/OFF in ~10 ns

~30 times faster than relaxation and propagation times

# Spin-wave mode coupling by DMC

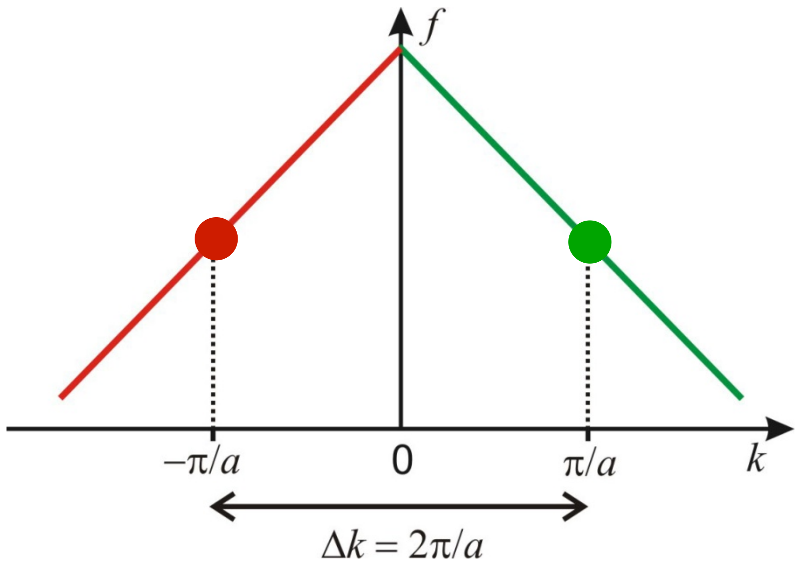


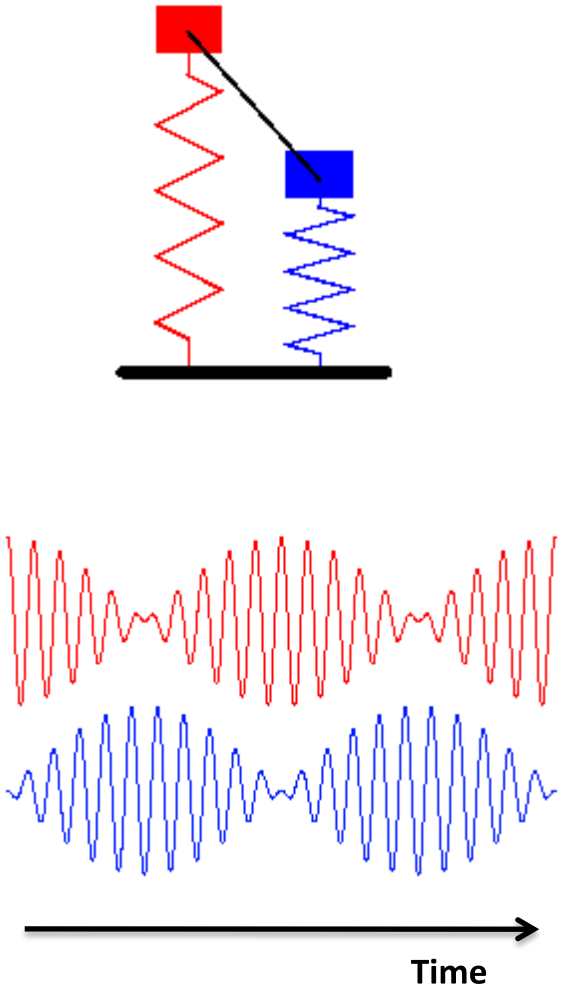




Two modes with $k = \pi/a$ and $k = -\pi/a$ are coupled by periodic variation of field

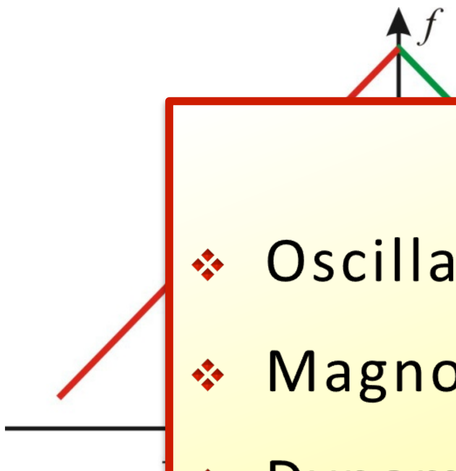
Coupling provides a mechanism for energy transfer

# Coupled oscillators – classical example

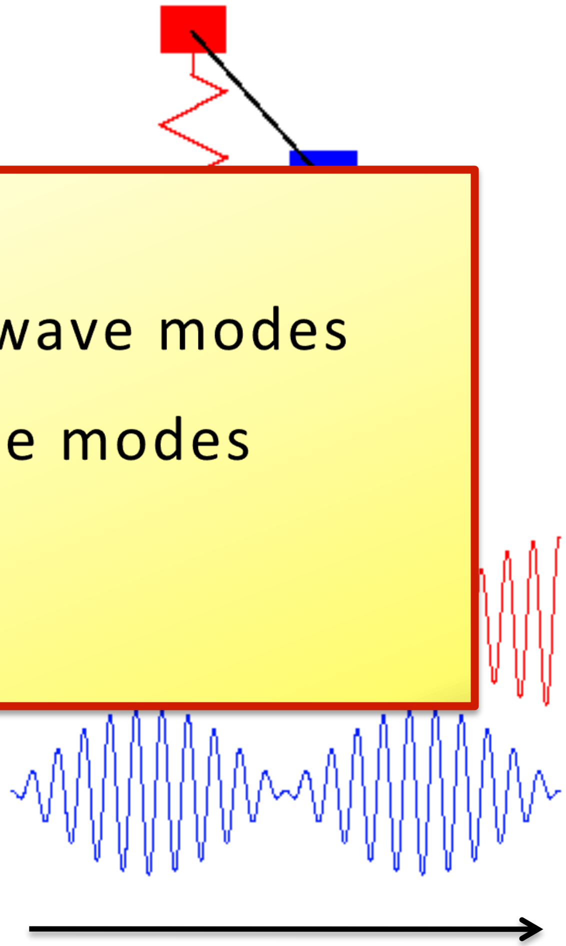


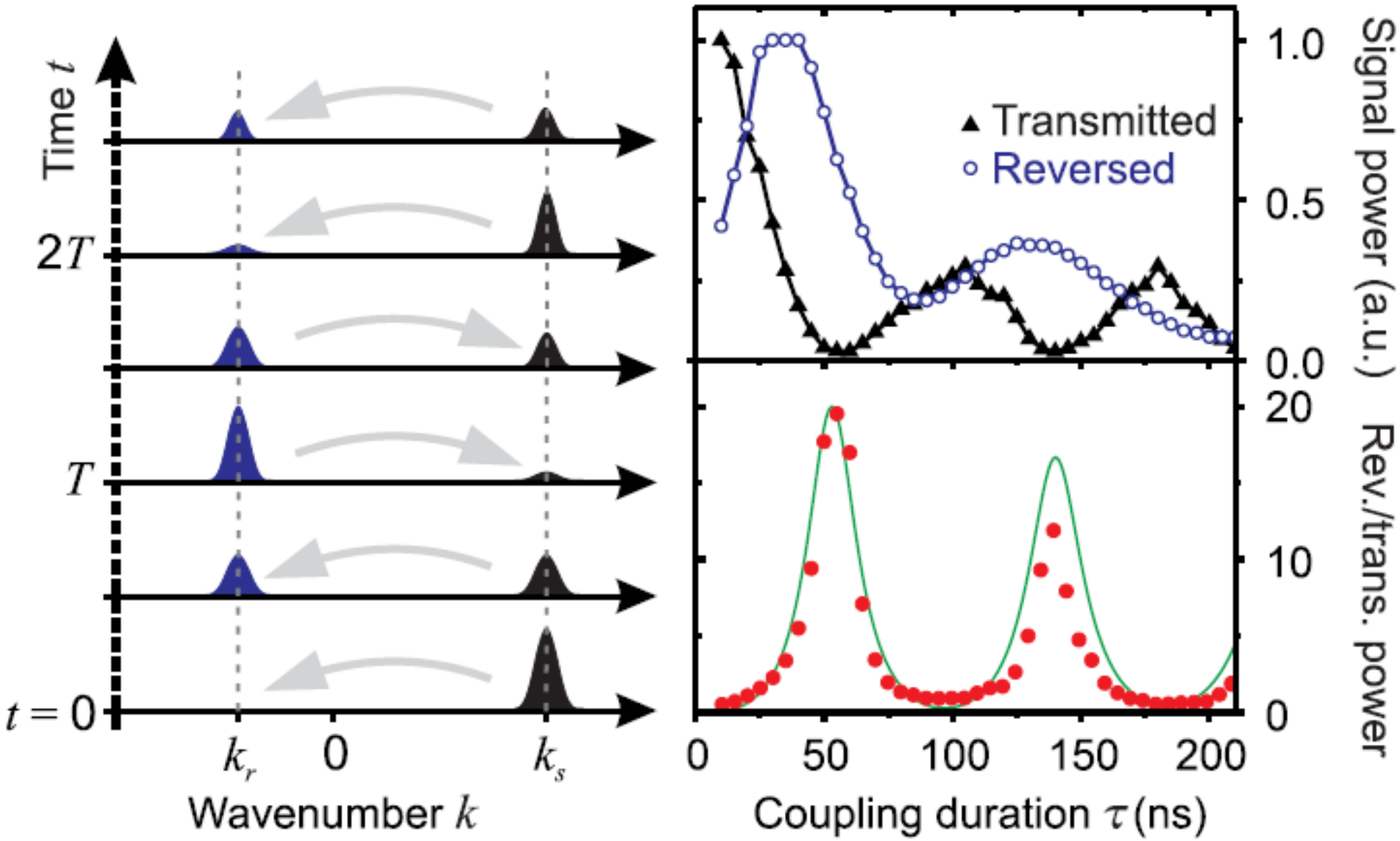
# Coupled oscillators – classical example




- Oscillators are replaced by wave modes
- Magnonic crystal couples the modes
- Dynamic MC is required

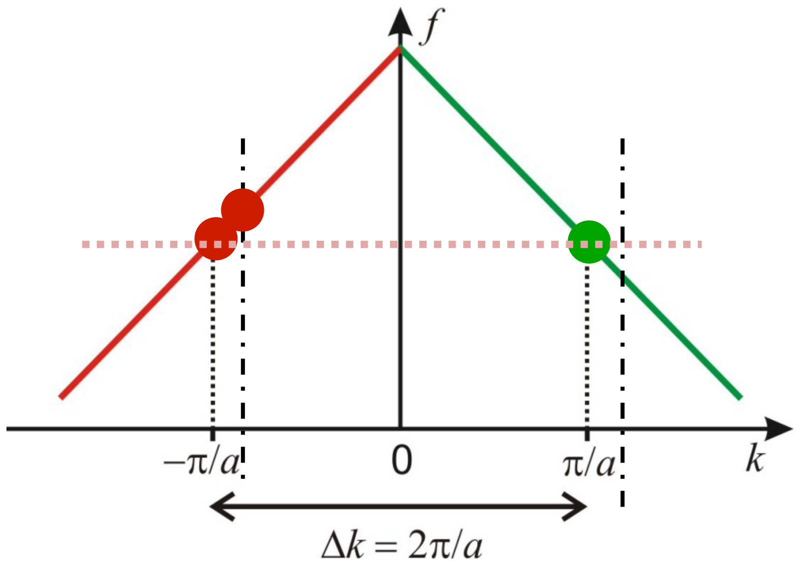


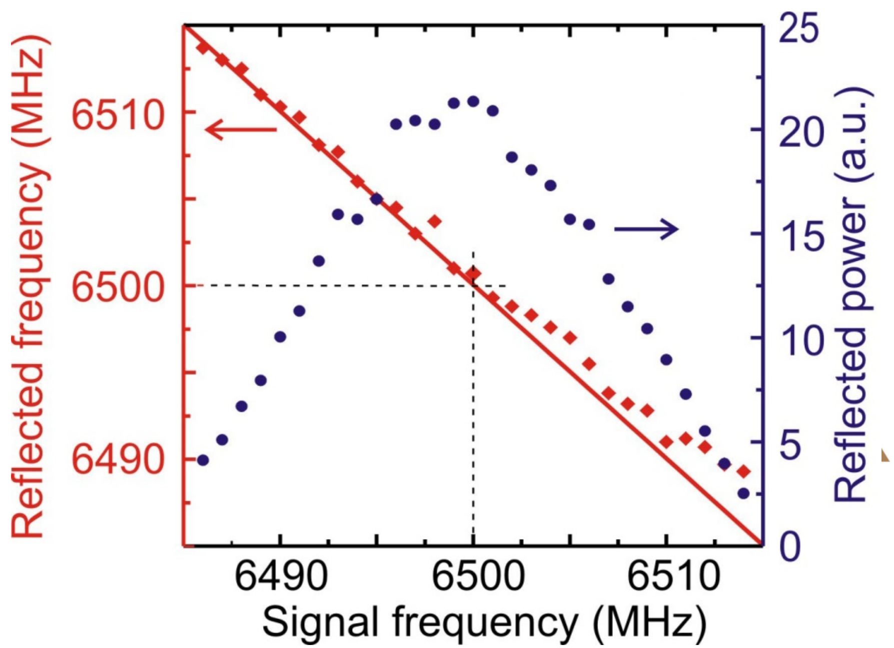
# Spin-wave mode coupling by DMC




Karenowska *et al.*, Phys. Rev. Lett. 108, 015505 (2012)

# Frequency shift by DMC

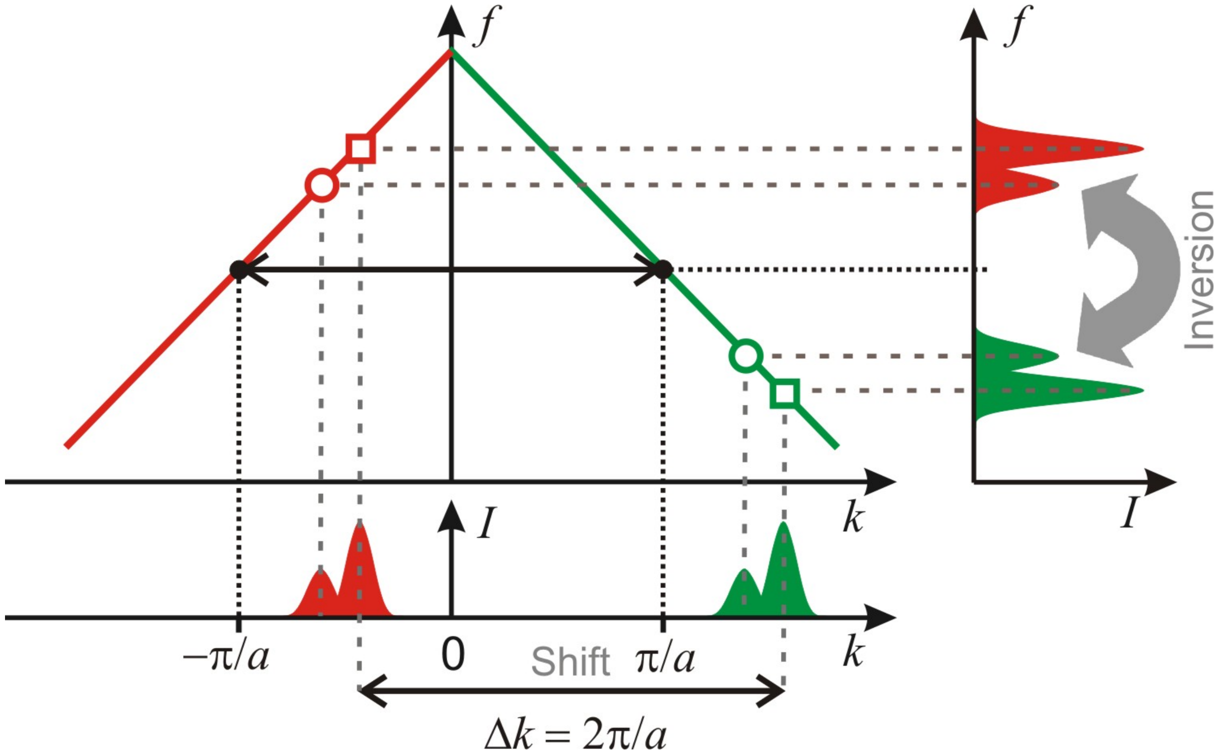



Shift in wavenumber $\Delta k = 2\pi/a$ takes place -> results in frequency shift

Chumak *et al.*, Nat. Commun. 1:141 (2010)

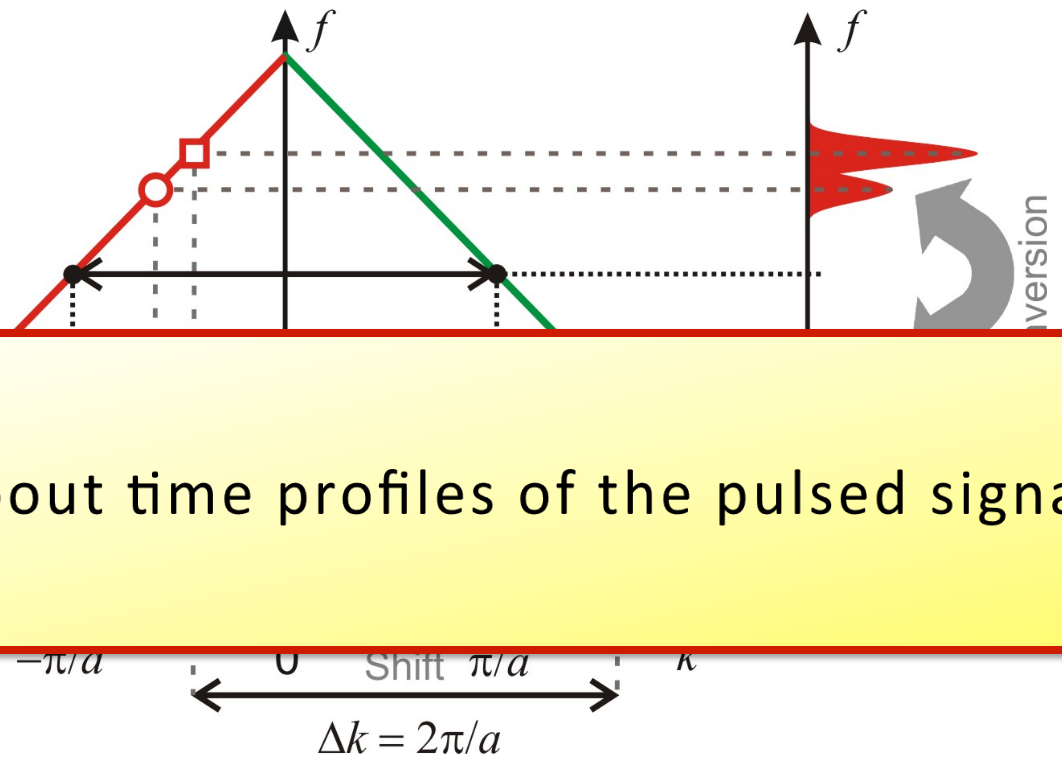
# Frequency inversion by DMC




Shift in wavenumber $\Delta k = 2\pi/a$ takes place -> results in frequency shift

The effect is to invert the frequency spectrum of the wavepacket

# Frequency inversion by DMC




How about time profiles of the pulsed signals?

Shift in wavenumber $\Delta k = 2\pi/a$ takes place -> results in frequency shift

The effect is to invert the frequency spectrum of the wavepacket

# All-linear time reversal by DMC

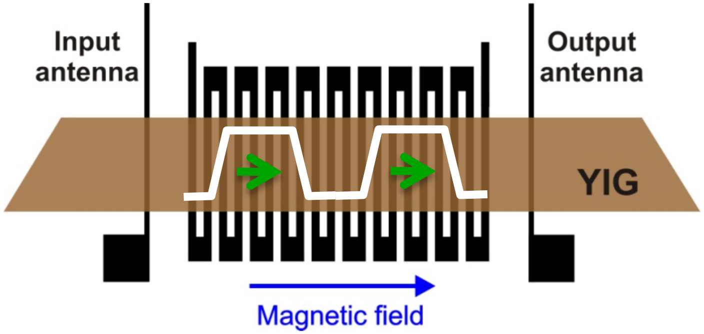
**Input signal:**

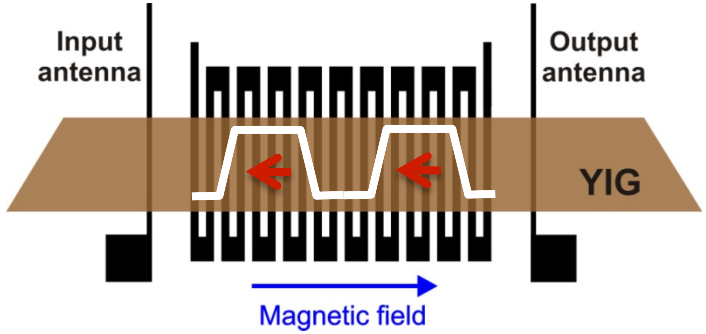
$$A_S(t) \sim \sum_{\Delta f} \exp(-i\,2\pi\,\Delta f\;t)$$

$\Delta f$ is a frequency shift from the Bragg frequency

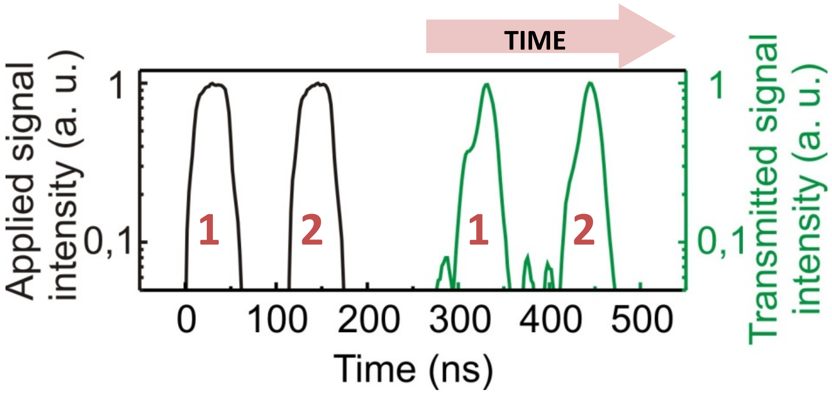
**Reflected signal:**

$$A_R(t) \sim \sum_{\Delta f} \exp(i\,2\pi\,\Delta f\;t) \sim A_S(-t)$$

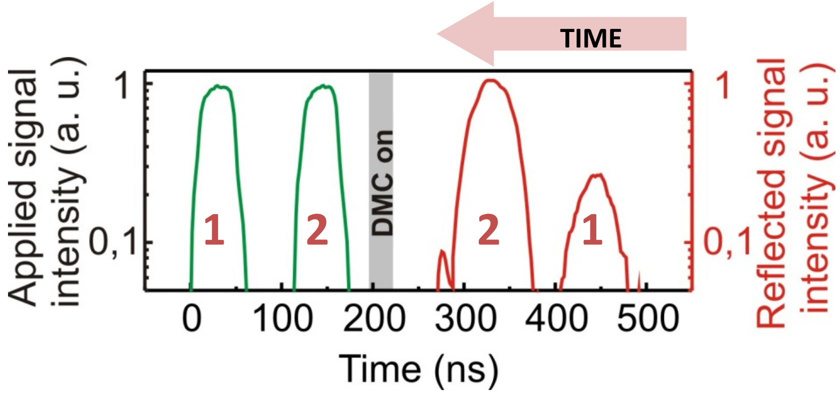



**Transmission:**

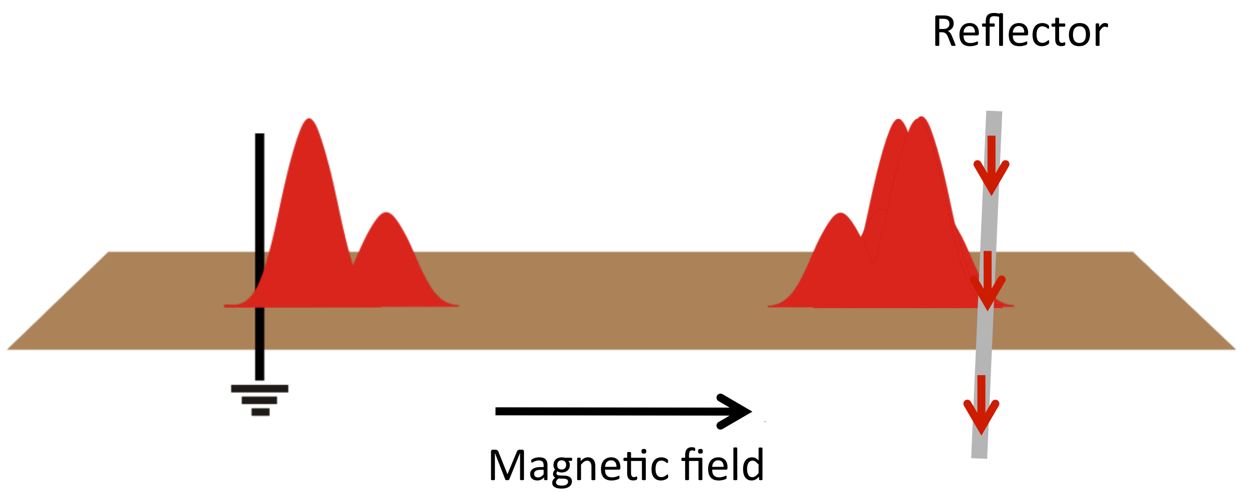


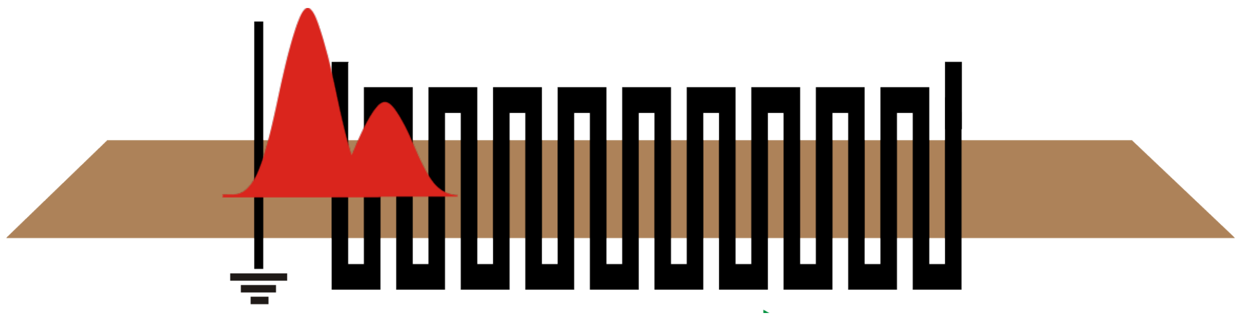

**Reflection:**




Chumak et al., **Nat. Commun. 1:141** doi: 10.1038/ncomms1142 (2010)

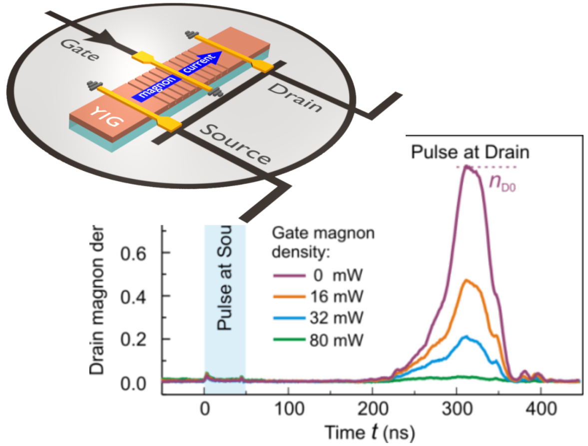
# Classical reflection from mirror

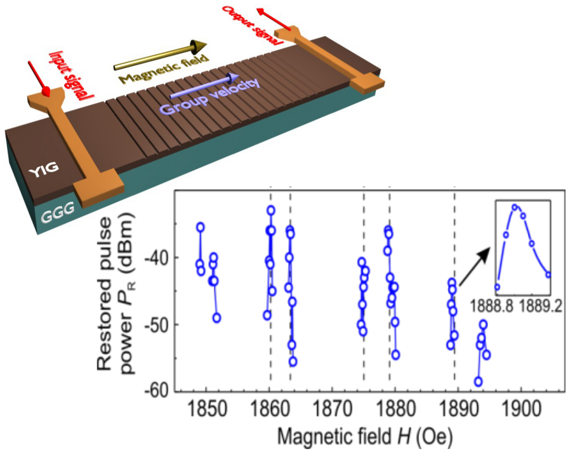


# Conclusions

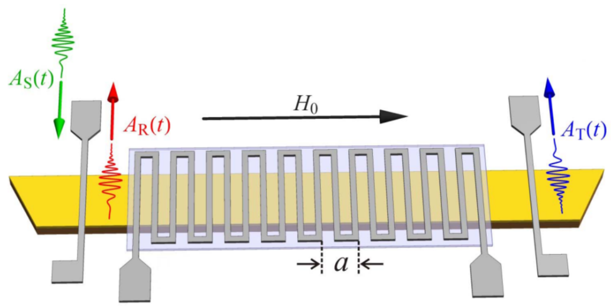
- Magnons propose an alternative to electrons for data processing



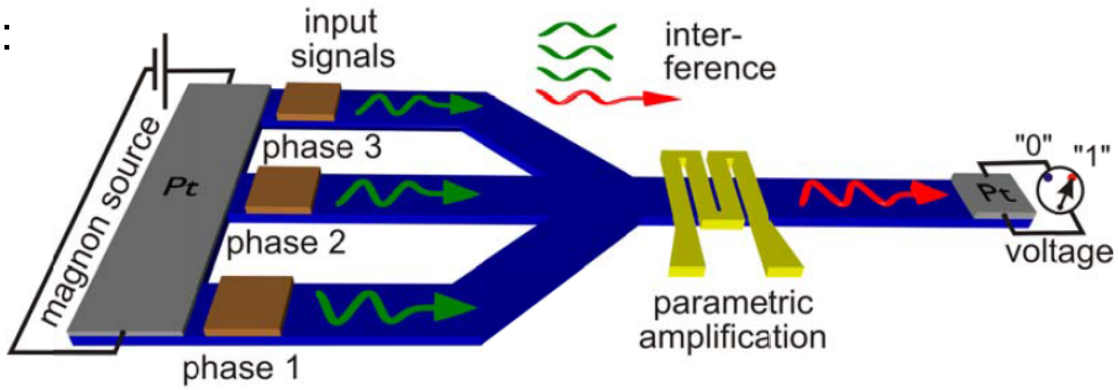

- Magnon-based data buffering can be realized using quasi-normal modes of the crystal (delay 10μs)

- All-linear time reversal is demonstrated



# Outlook

Magnonic majority gate:




The most urgent problems:

- Spin-orbit torque
  Can we detect spin waves electrically?
- Dzyaloshinskii-Moriya interaction
  Can we manipulate spin waves by electric field?
- Damping manipulation
  Can we switch off some of the damping mechanisms?
- Algorithms for wave-based data processing
  Some tasks can be solved faster without digital data processing