Ferromagnetic integrated inductor/noise suppressor

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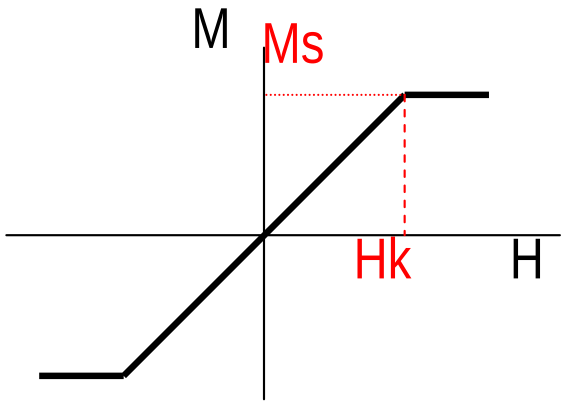
OUTLINE

1. Thin film permeameter for material evaluation
2. Slit works on thin film inductor
3. Thin film electromagnetic noise suppressor
4. Side channel attack protection
5. Summary

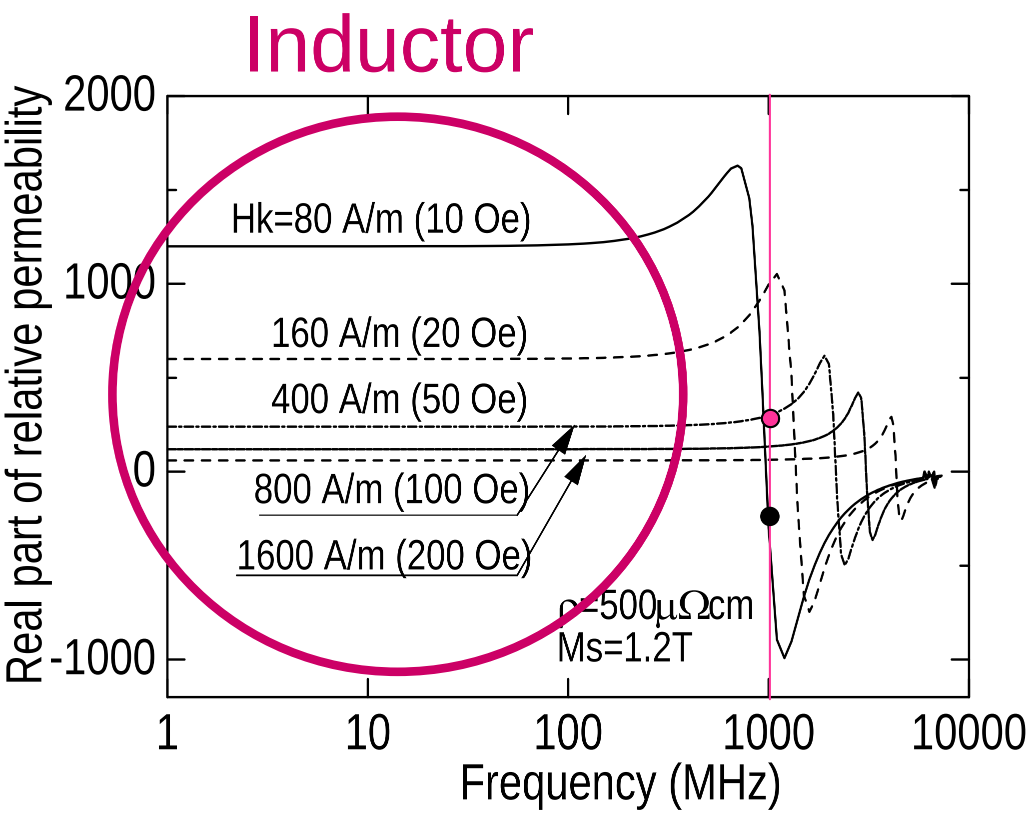
Permeability vs Ferromagnetic Resonance Freq.



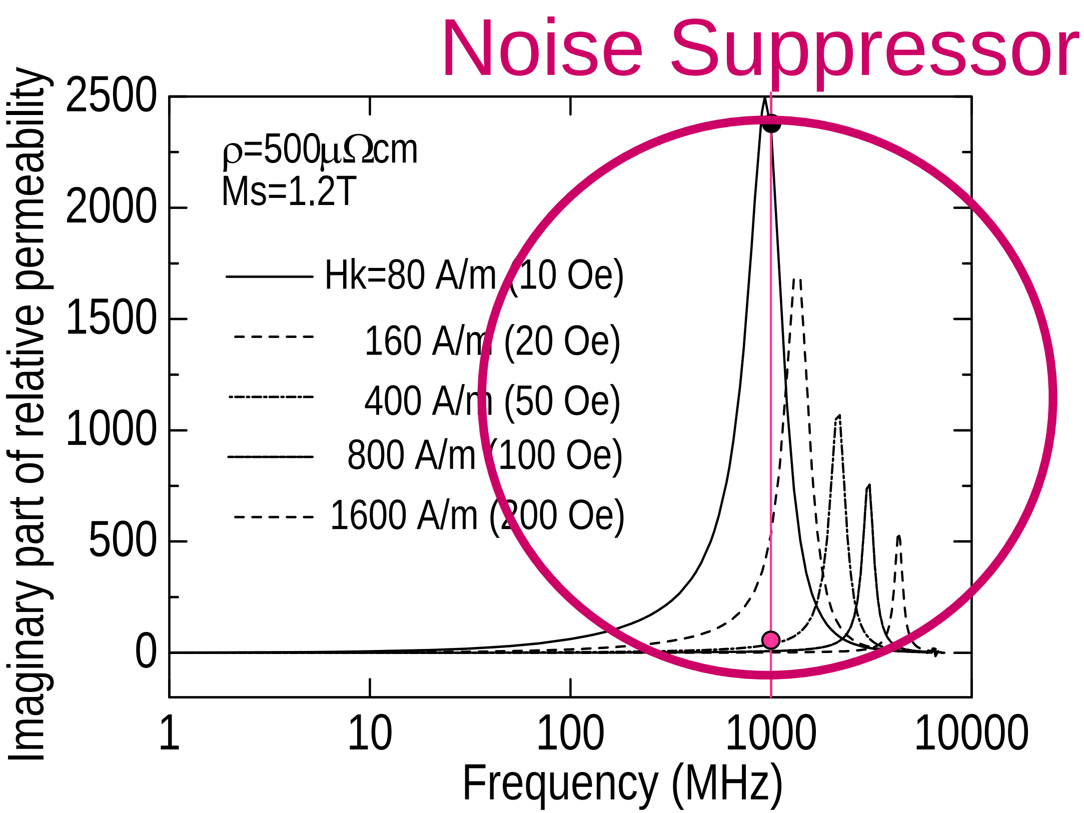
$$\mu = M_s / H_k$$

$$f_r = \frac{\gamma}{2\pi}\sqrt{M_s H_k / \mu_0}$$

$$\mu \cdot f_r^{\ 2} = const$$



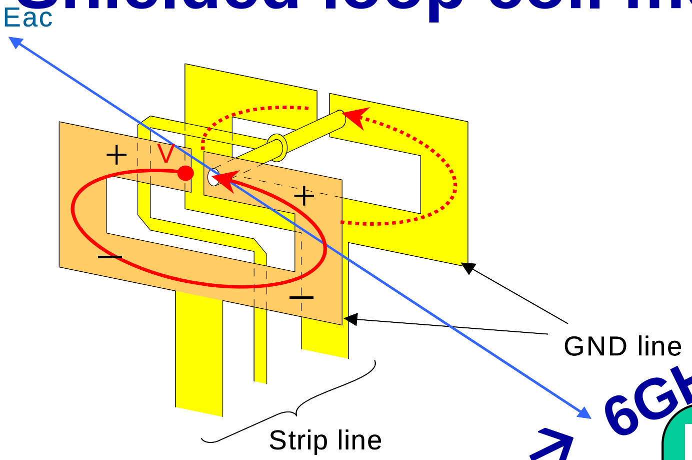
(a) Real part



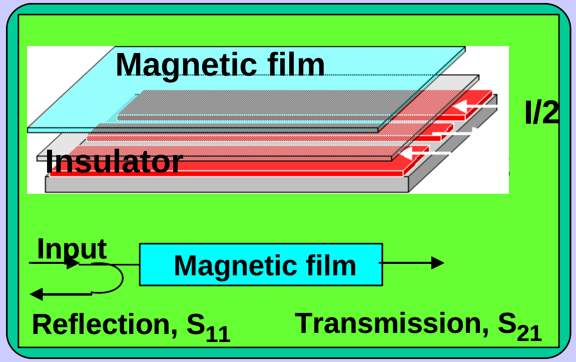
(b) Imaginary part

Development of thin-film permeameter

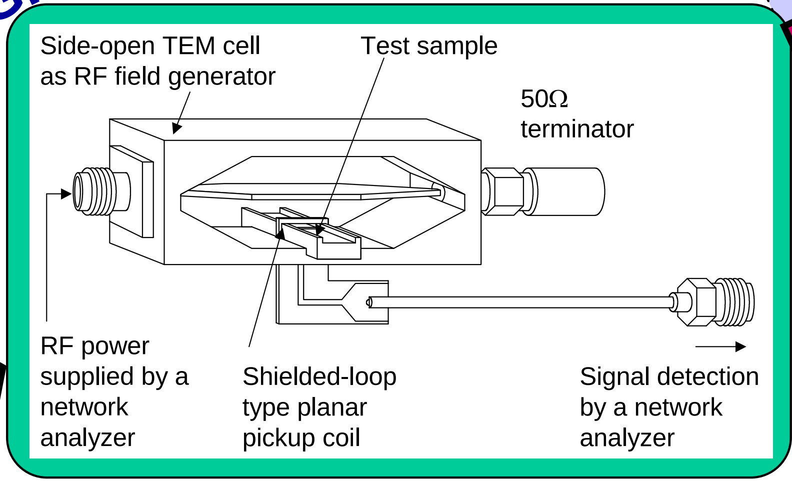
Shielded loop coil method

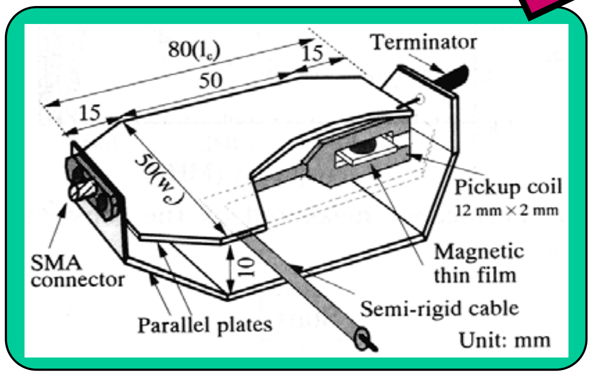


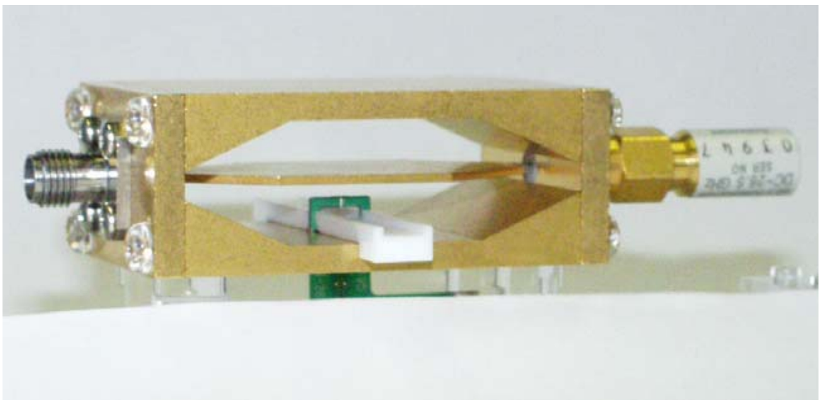
3GHz → 6GHz → 9GHz → → → 20GHz



Coplanar line method (coming)







M. Yamaguchi et al.
T. Mag. Soc. Jpn.,
3 (2003) 137-140

Also
Ryowa Electronics Co.
Model PMM-9G1

9GHz measurement jig

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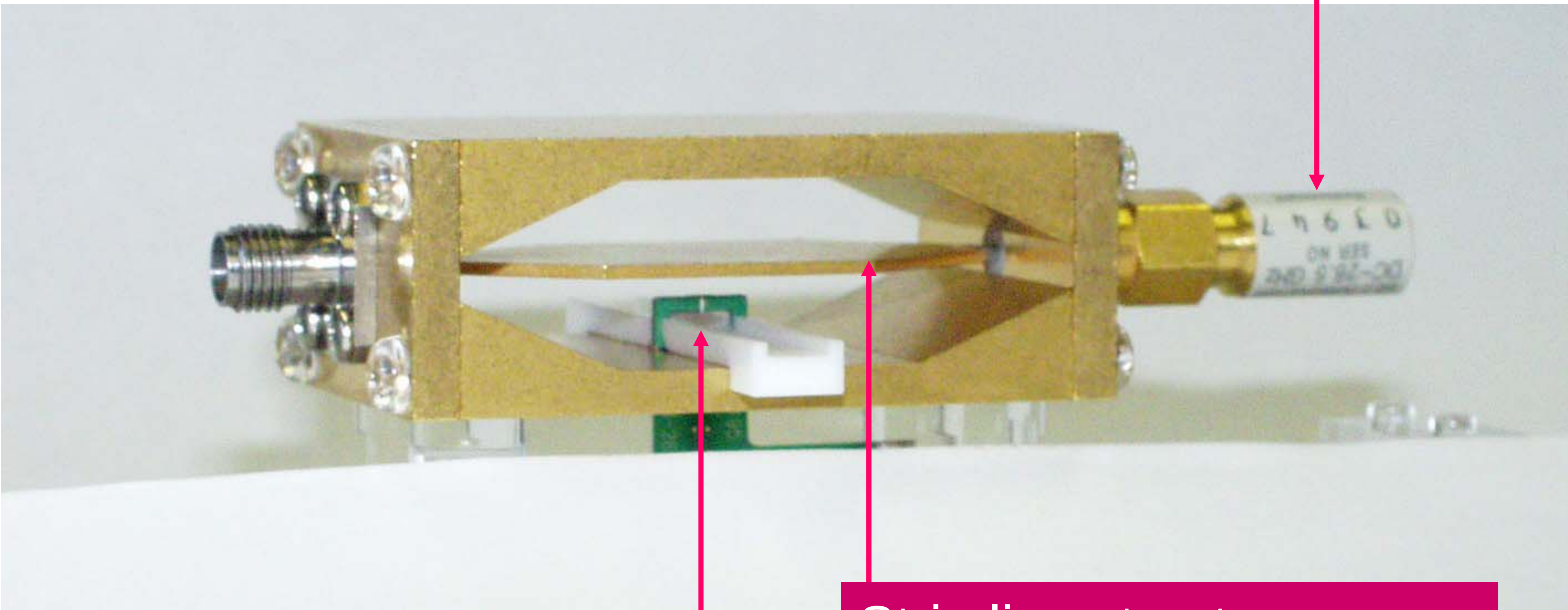
Loaded end:

Yielding **TRAVELING** EM field



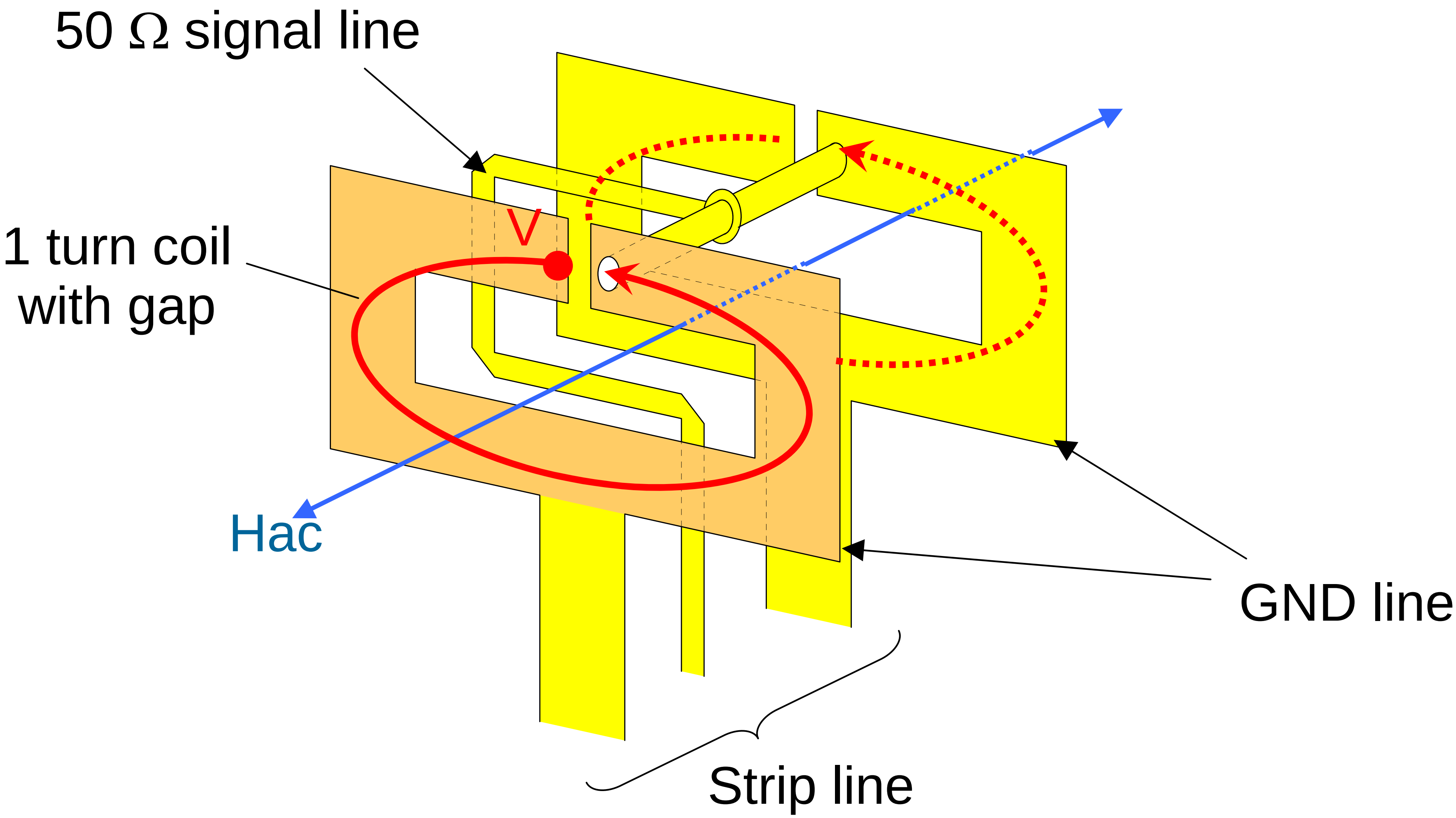
Centered pick-up coil arrangement

Improved EM uniformity at the coil window

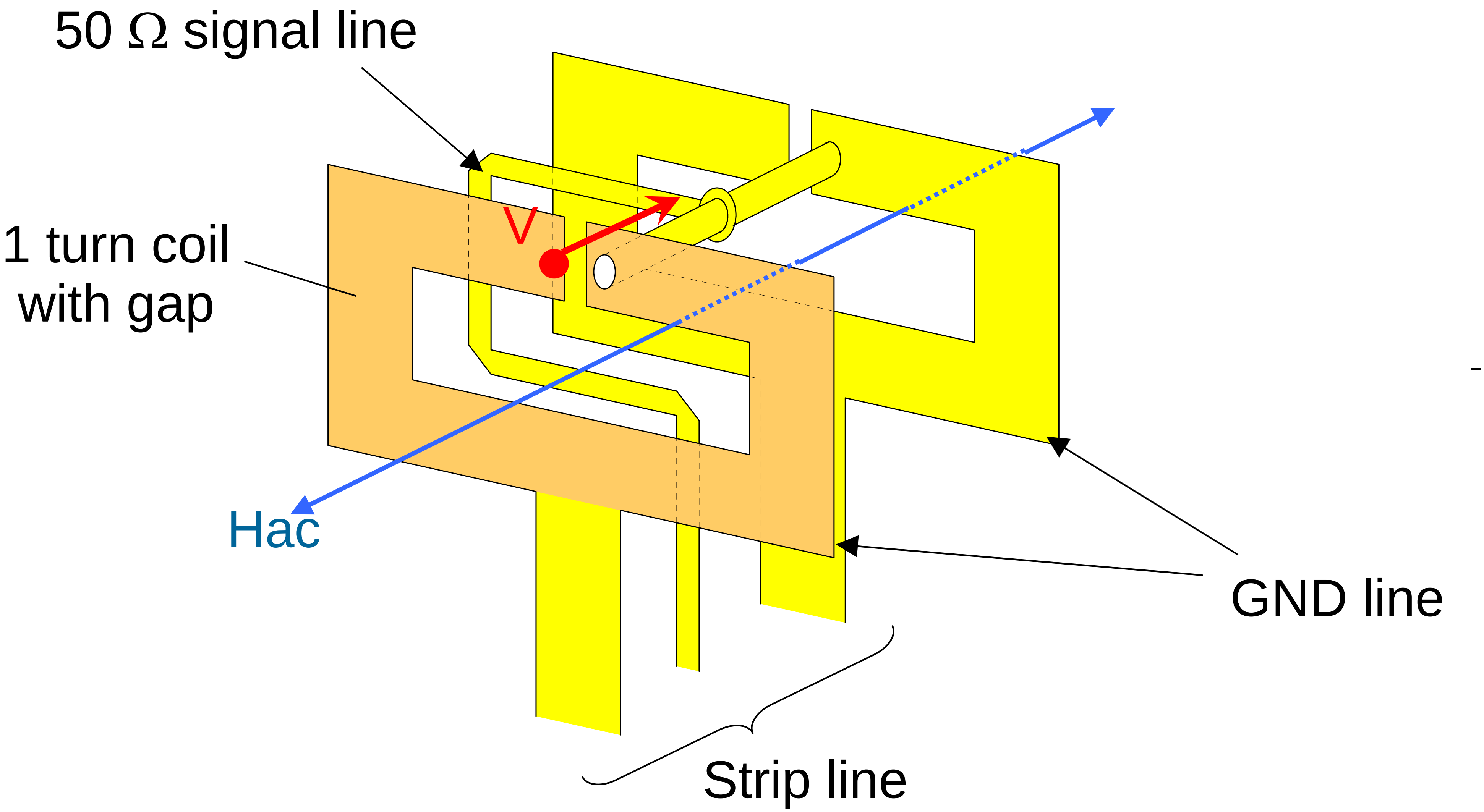
Strip line structure (Side-open TEM cell)

Improved EM uniformity throughout the jig

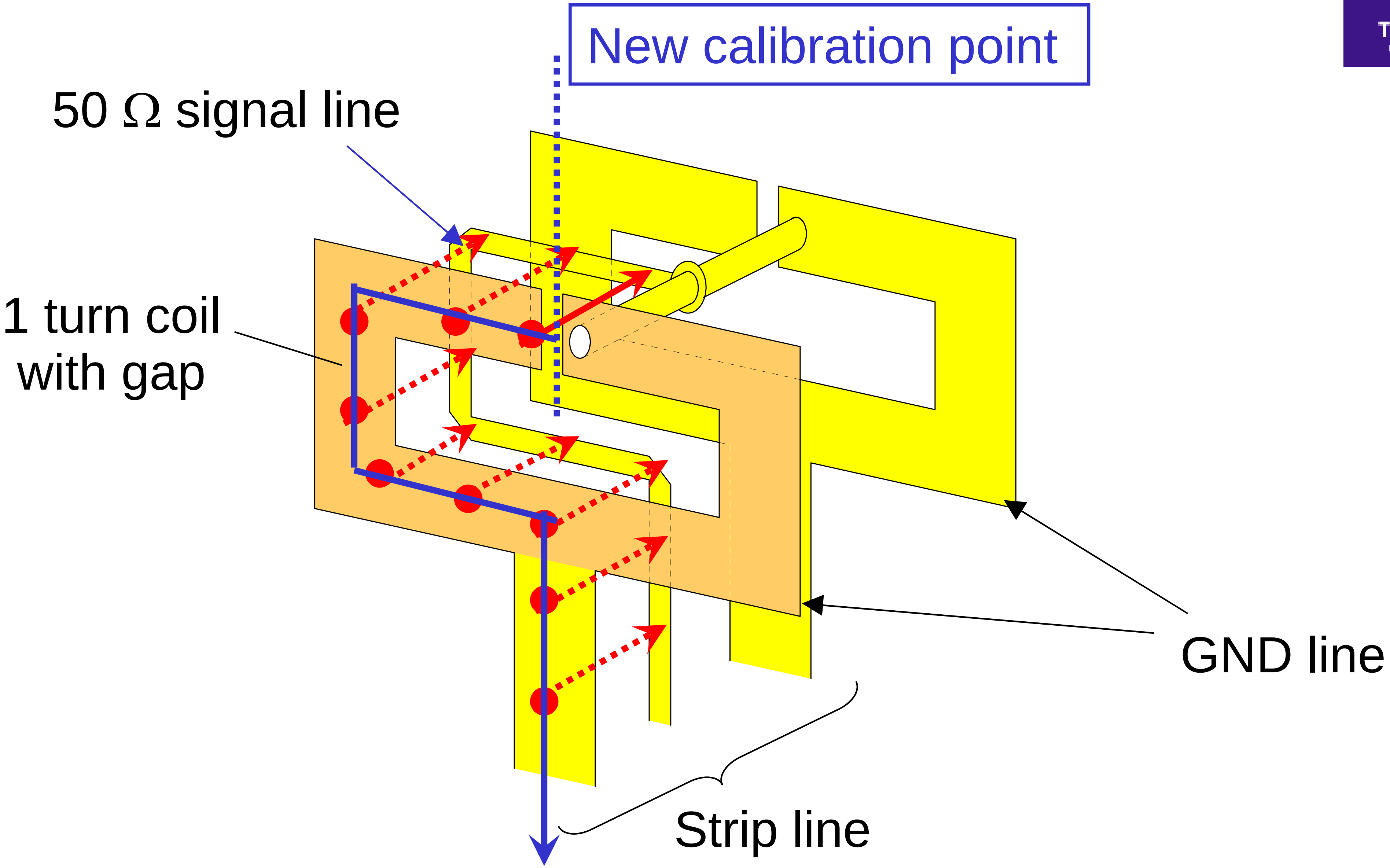
Planar Shielded-loop coil



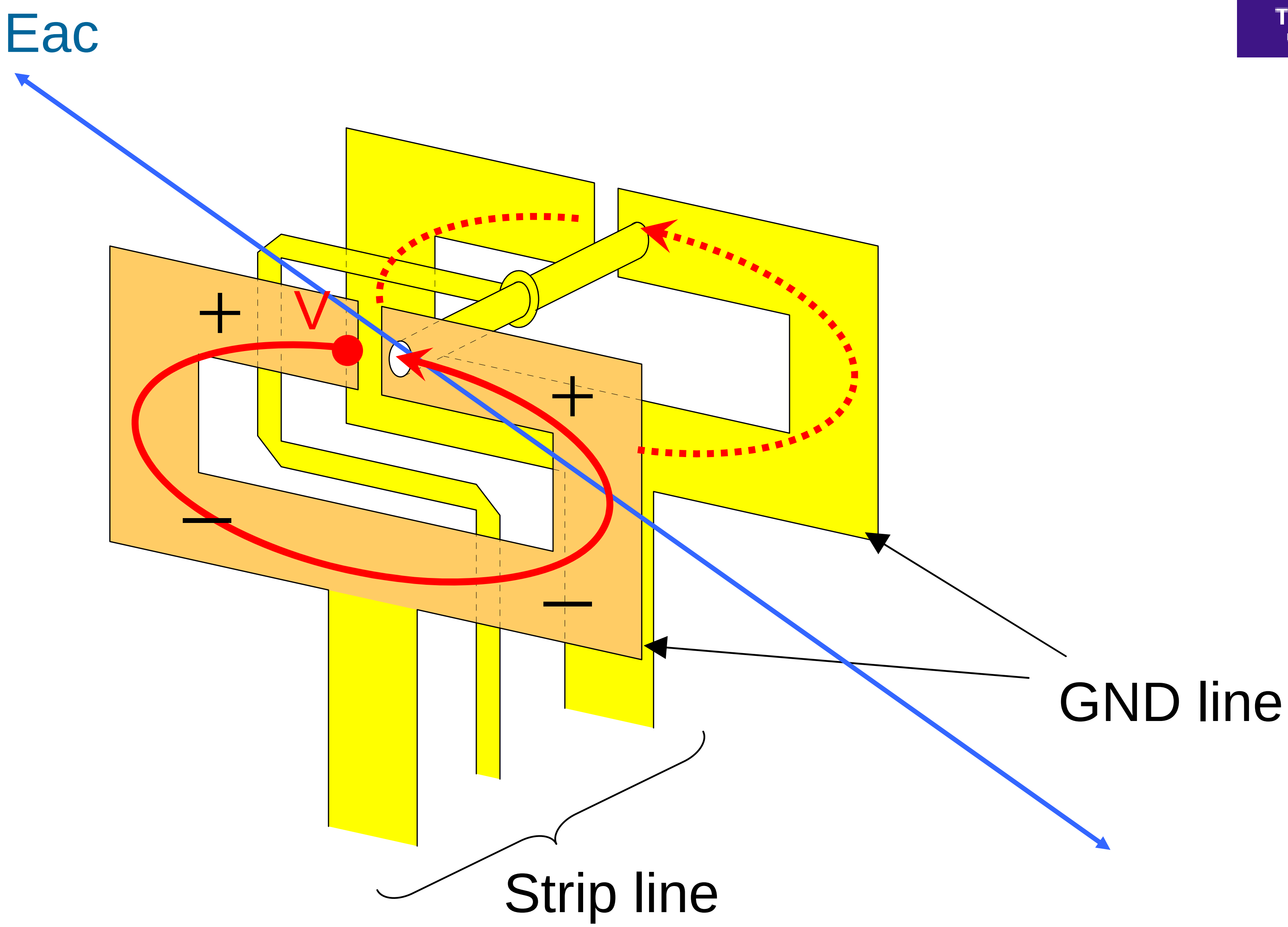
Voltage transfer along the strip line, I



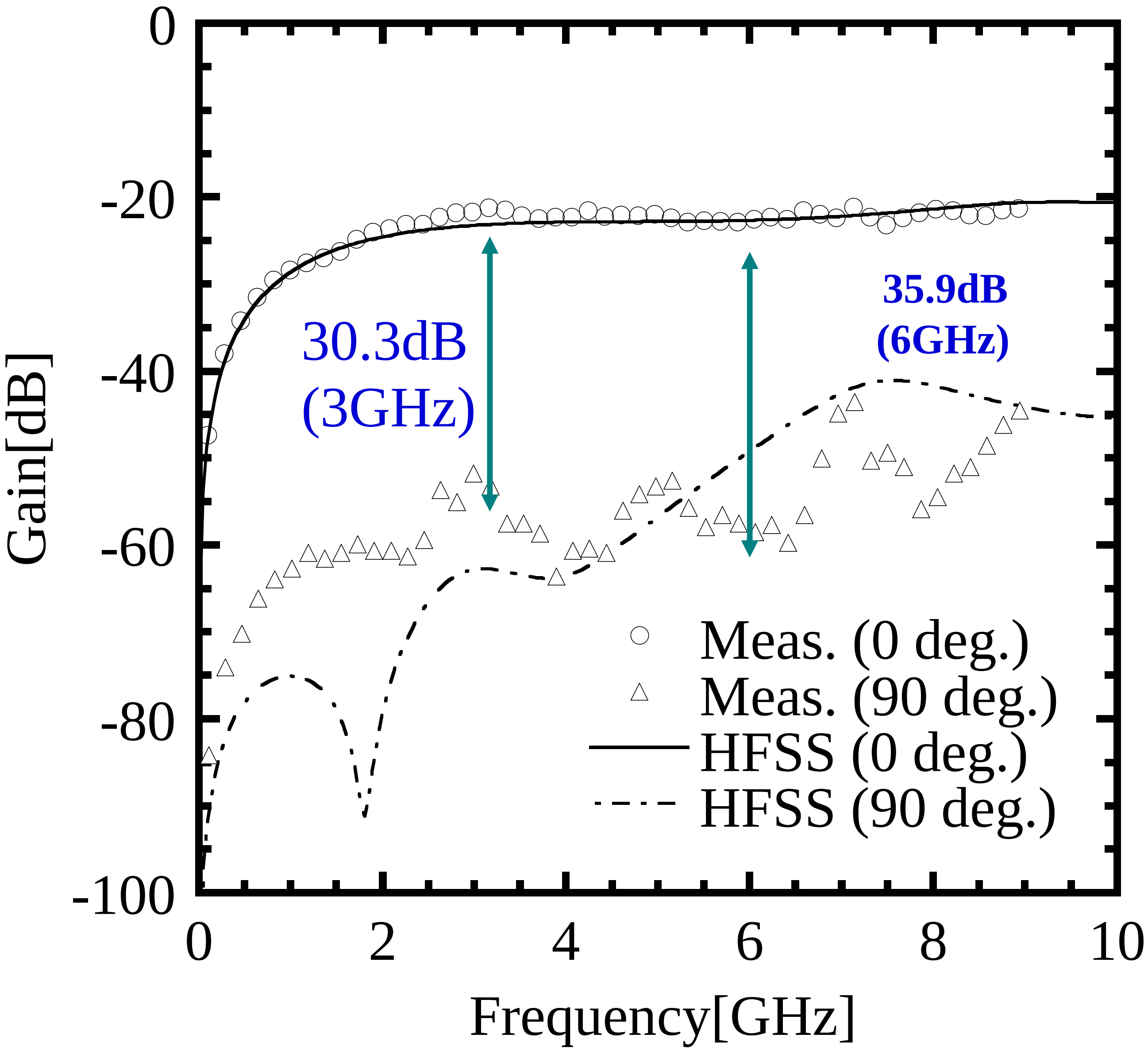
Voltage transfer along the strip line, II



E-filed Voltage Suppression



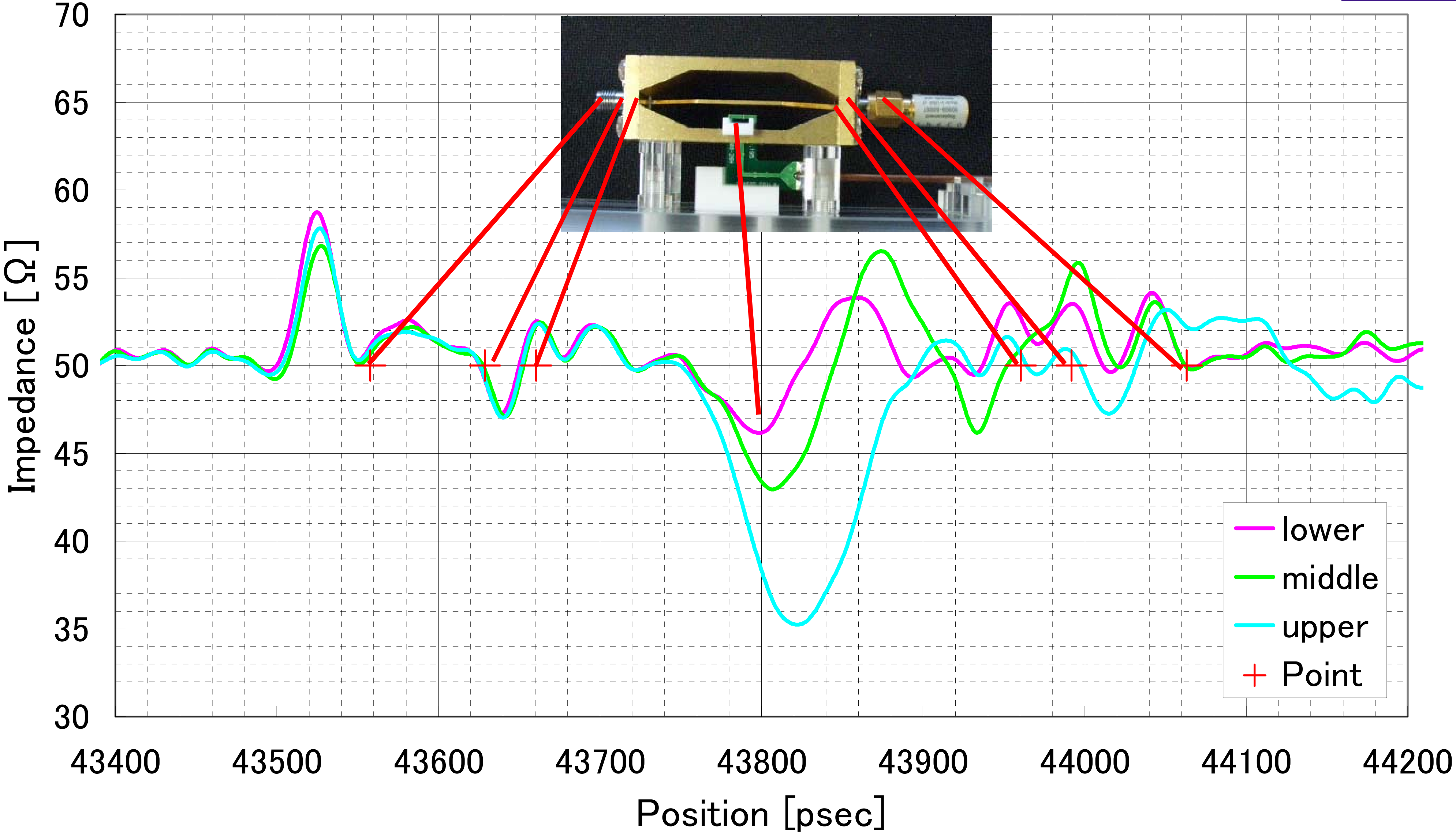
E-voltage suppression



Comparison of E- and M- voltages extracted by simulation & experiments.

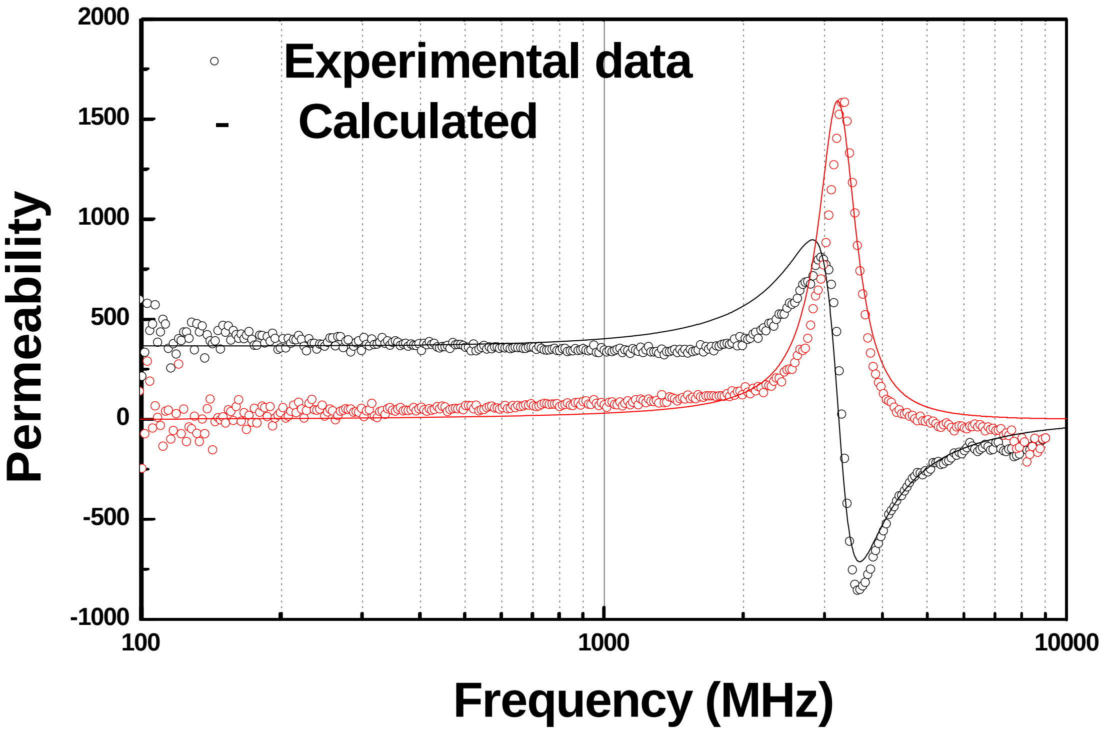
Simulated by ANSOFT HFSS Ver. 8.0.21

TDR Profiles



Validity check

1. Comparison with L.L.G. equation



FeCoBN:
thickness 978 nm, $4\pi Ms \sim 22kG$, $Hc \sim 5Oe$,
$Hk \sim 60$ Oe, resistivity ~ 73.8 $\mu\Omega \cdot cm$

By Prof. J-R Kim, Hanyang Univ., Korea

2. Int'l cross measurements

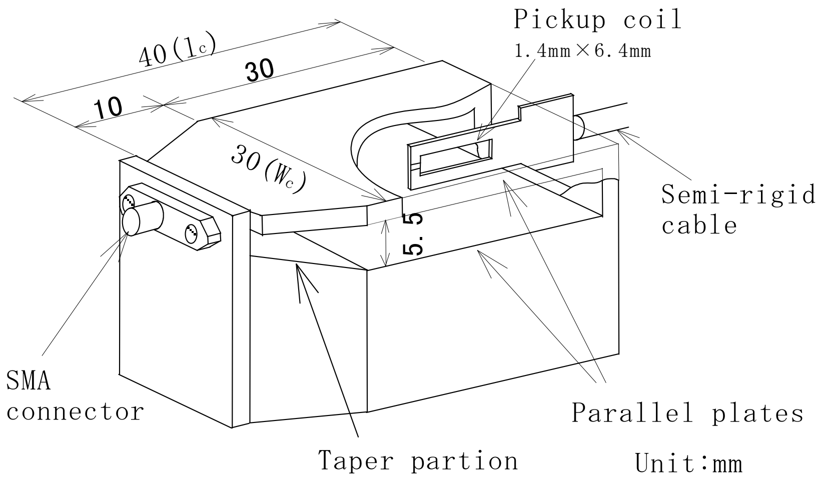
Tohoku U, Japan (Yamaguchi)
- Frequency domain
- TEM cell/Pick-up coil

NIST, USA (Silva)
- Time domain
- Coplanar line

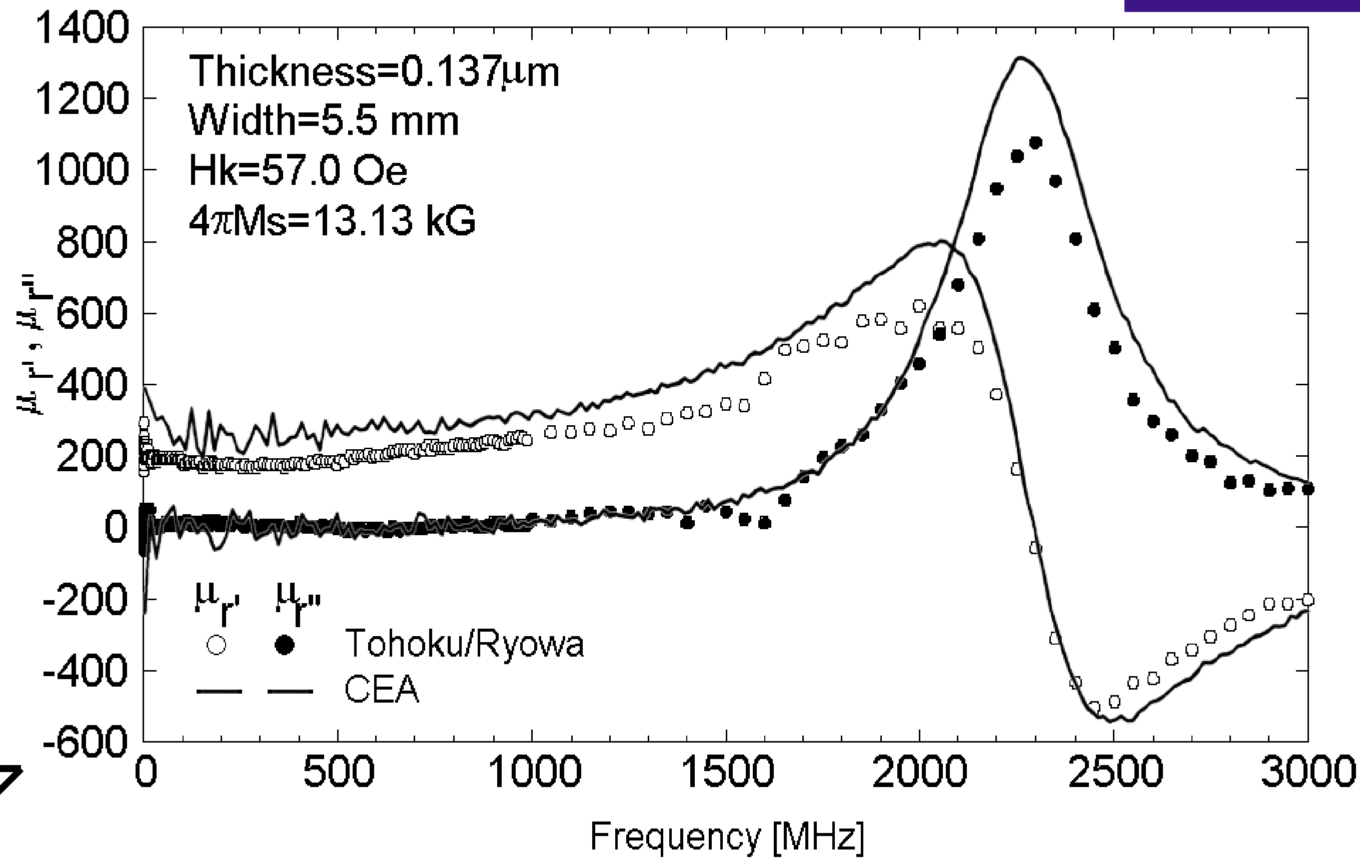
CEA, France (Acher)
- Frequency domain
- Microstrip line

FMR frequencies agreed within the error of 15%

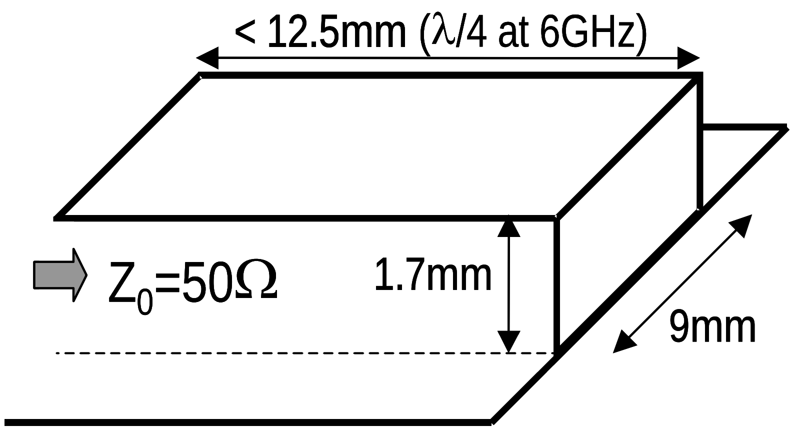
Int’l Cross Measurements, I



A jig for the pickup coil method.



on a CEA-made 0.14μm thick CoNbZr film.



A jig for the transmission line method.

M. Yamaguchi, O. Acher et al, Journal of Magnetism and Magnetic Materials 242-245 (2002), 970-972.

Completed System (PMM-9G1, by Ryowa)

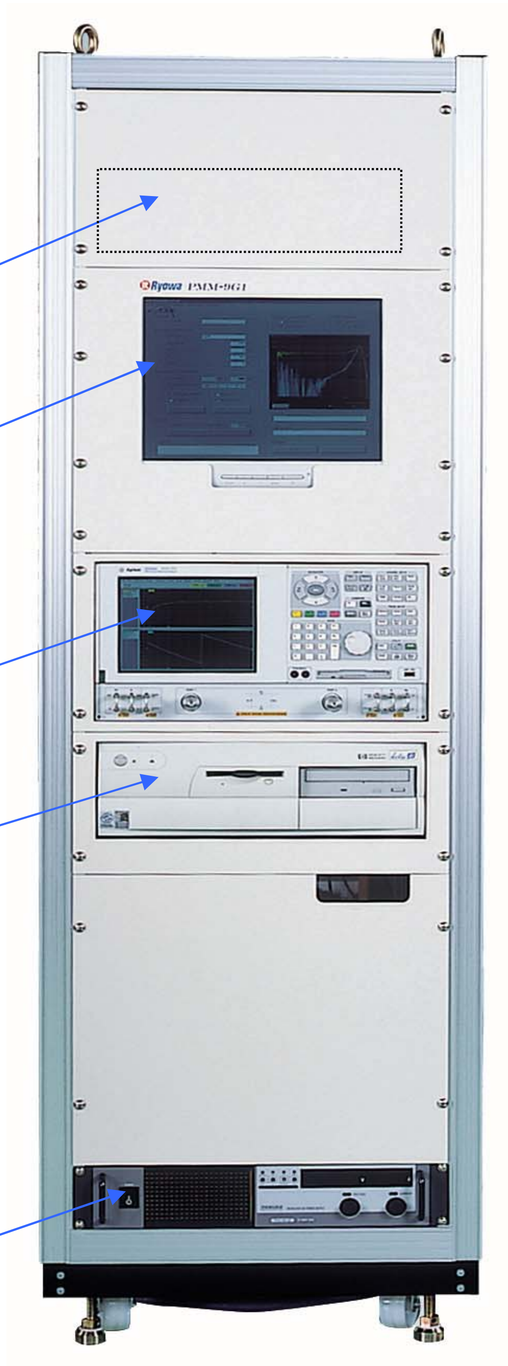
Printer

Display

Network Analyzer

PC

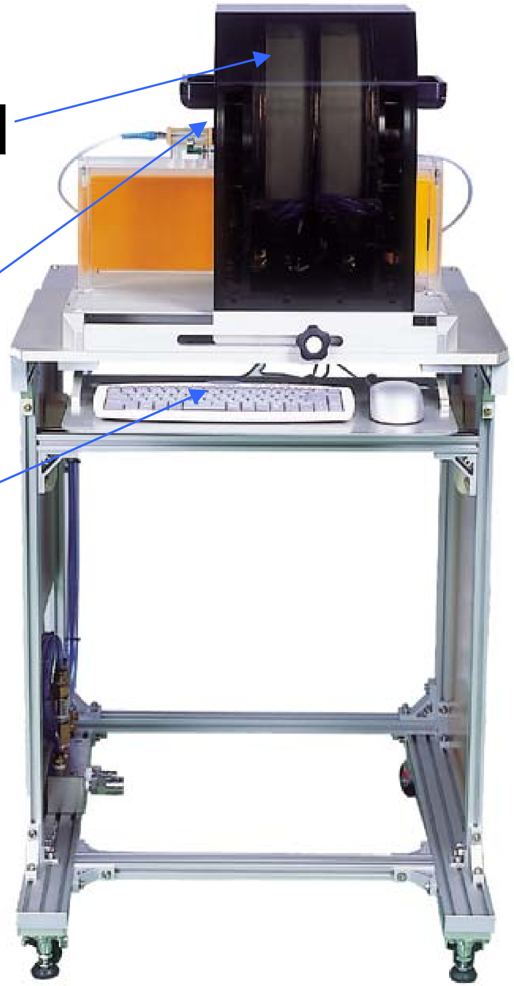
Power Source



Solenoid Coil

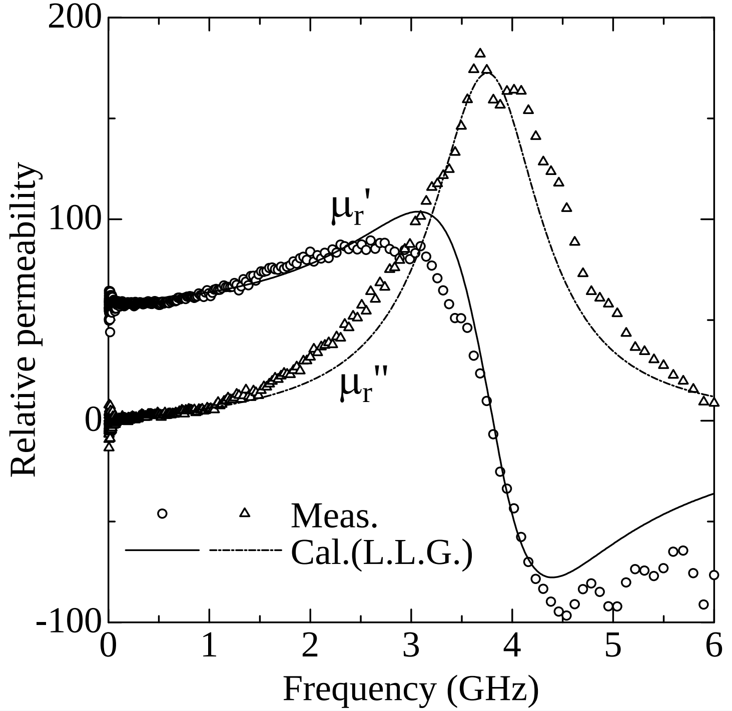
Main jig

Key Board



M. Yamaguchi et al, IEEE Intermag2003, EA-03, Boston USA April 2003.

Granular films

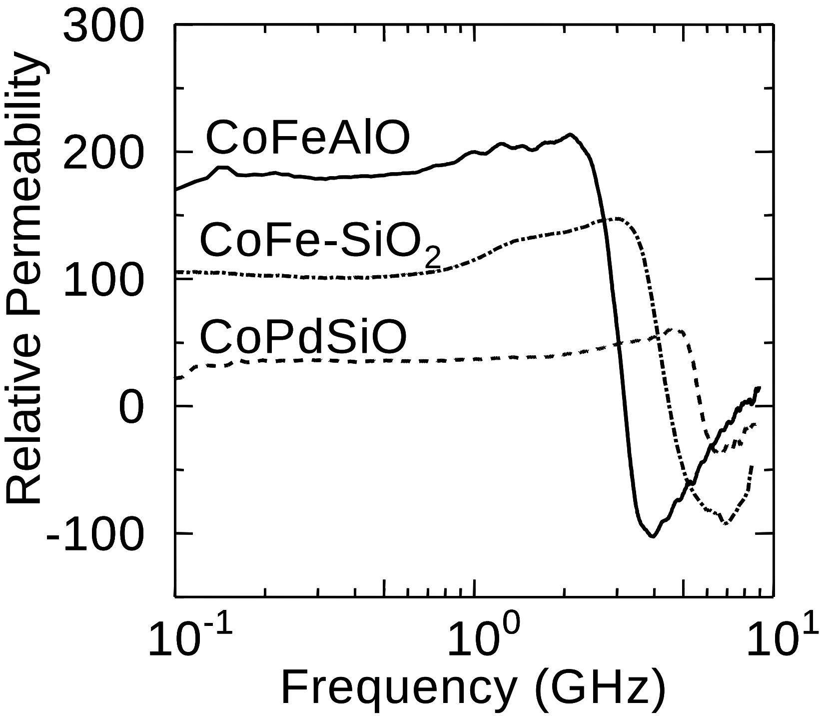


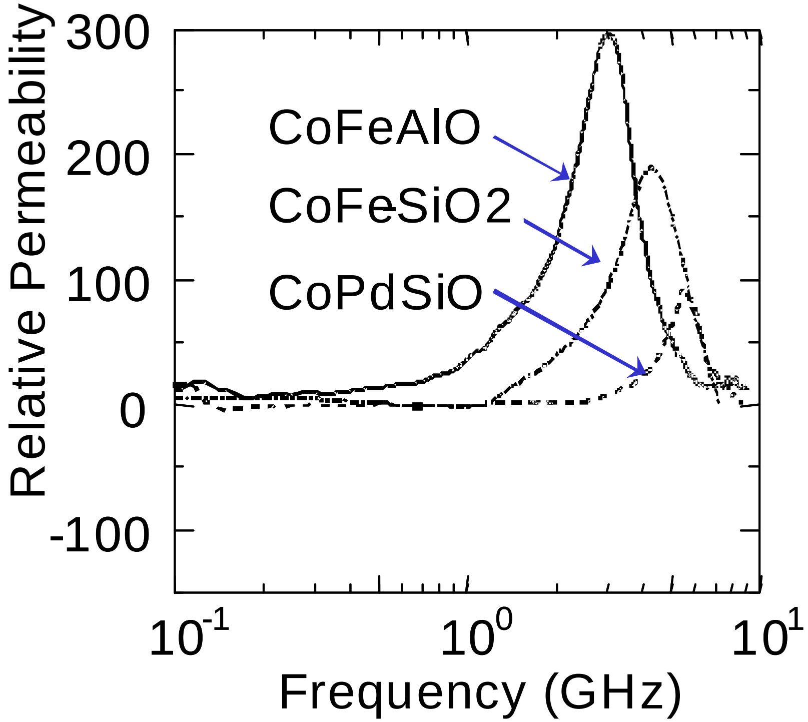
CoZrO

Thickness 1.82μm, Resistivity 1800μΩcm

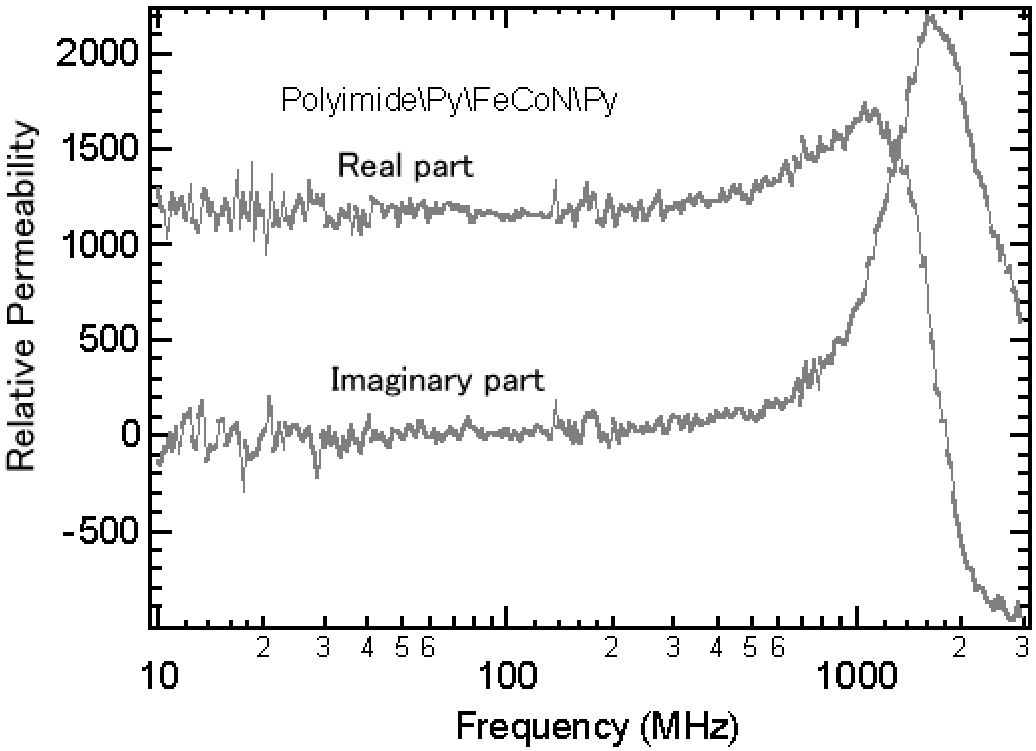
S. Ohnuma et al, 25th Annual Conference on Magnetics in Japan, 25pC-1, (2001.9).

CoFeAlO: S. Ohnuma et al, *J. Appl. Phys.*, **85**, (1999) 4574.
CoFe-SiO$_2$: M. Munakata, et al, *J. Magn. Soc. Japan*, **28**, (2004) 240.
CoPdSiO: S. Ohnuma et al, *J. Magn. Soc. Japan*, **23**, (1999) 240.

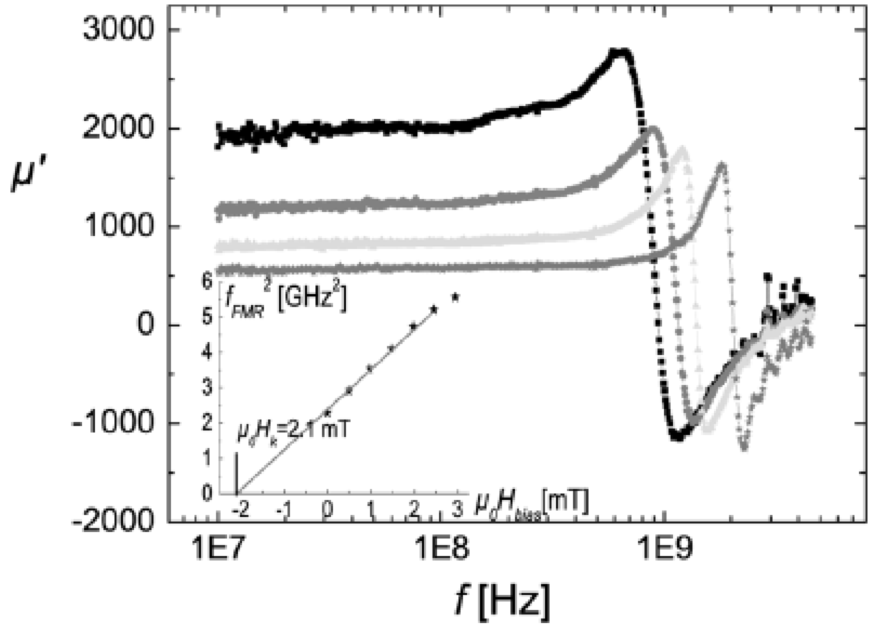


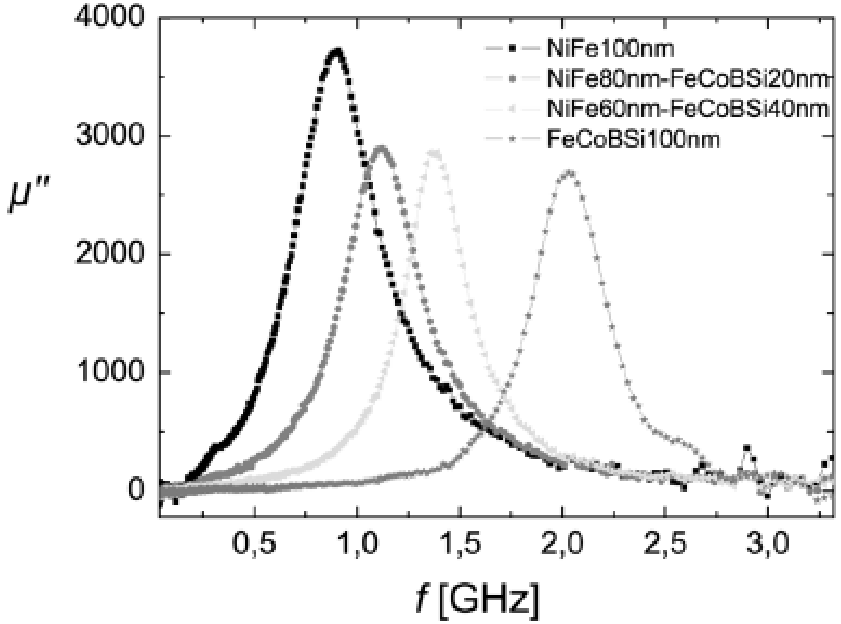


Metallic films (FeCo-base system)



NiFe/CoFeN/NiFe
(by Prof. Wang, Stanford U)

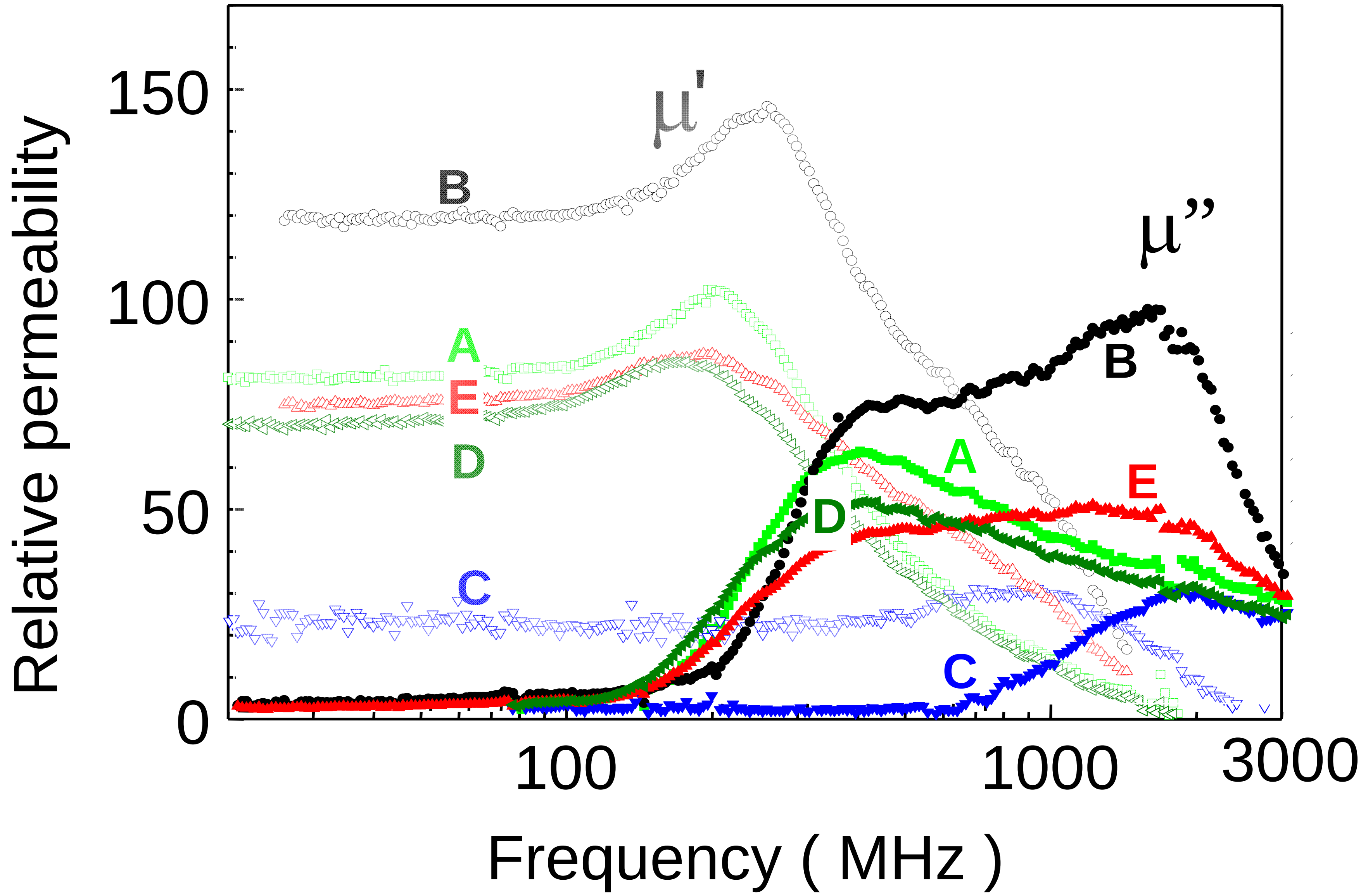




FeCoBSi(80 nm)/NiFe(20 nm) bilayer
A. Gerber, et al, IEEE Trans. Magn., **43,** 2624 (2007).

Spin-Spray ferrite films

A, D : NiZn-Ferrite films, B, C, E : NiZnCo ferrite films



Slit works on magnetic film

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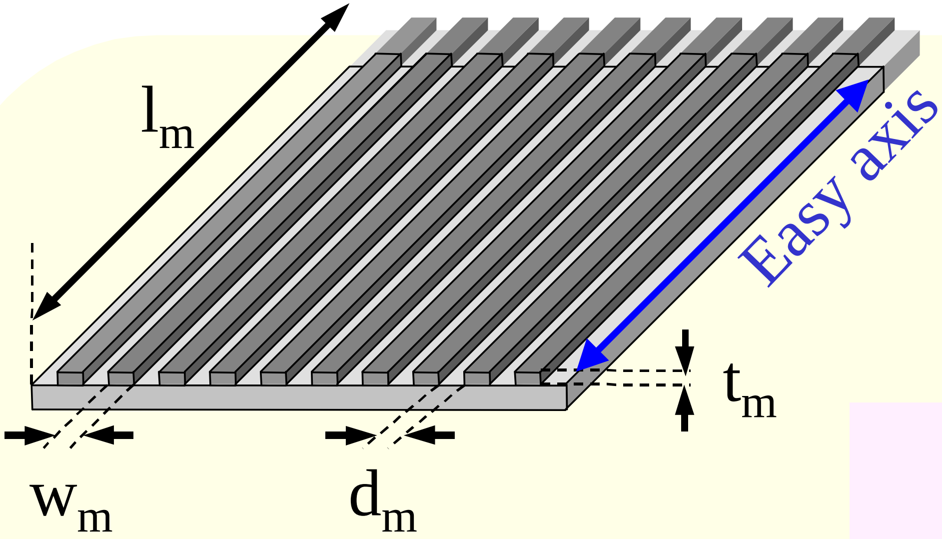


l_m = 4mm
w_m = 20μm
t_m = 0.2μm
d_m = 2.3 μm,3.3 μm,4.0 μm

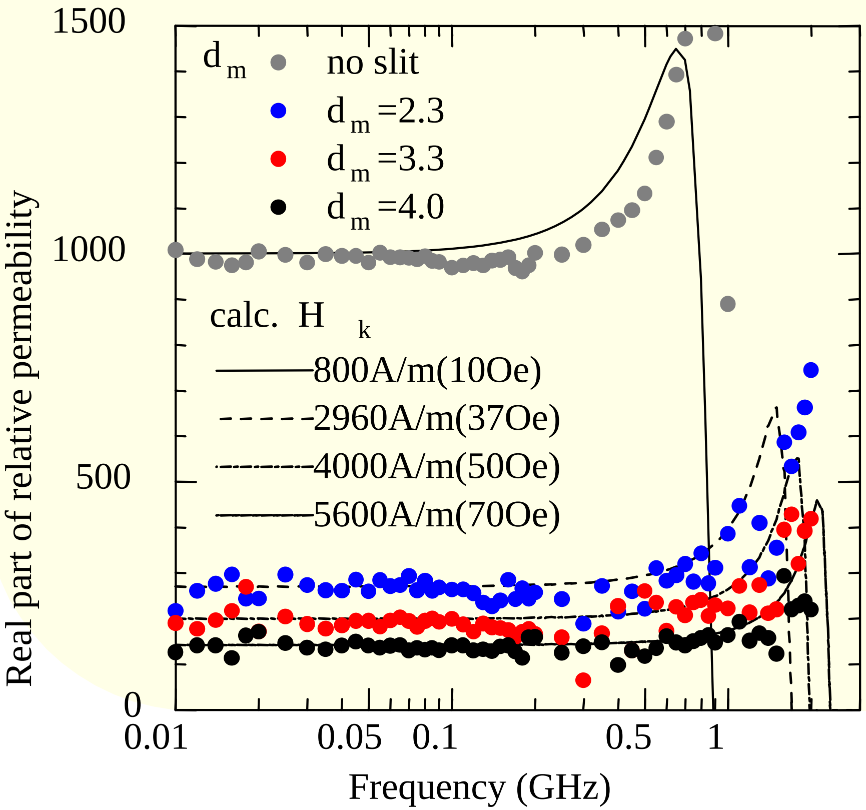
$$H_{keff} = H_k + N_d M_s$$

H_k : anisotropy field
N_d : demagnetizing factor
M_s : saturated magnetization

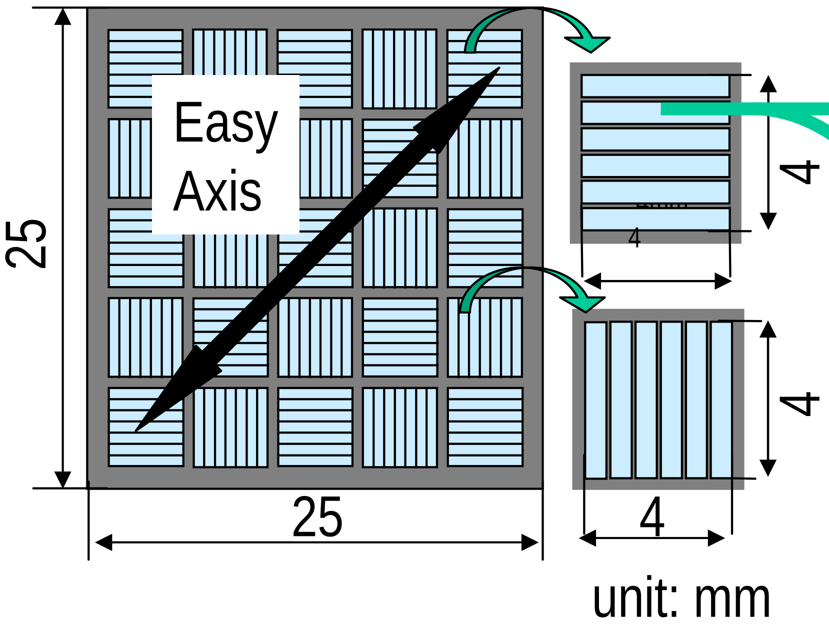
$$\mu_{eff} = \frac{M_s}{H_k + N_d M_s}$$

$$f_r = \frac{\gamma}{2\pi}\sqrt{\frac{M_s H_k + N_d M_s^2}{\mu_0}}$$

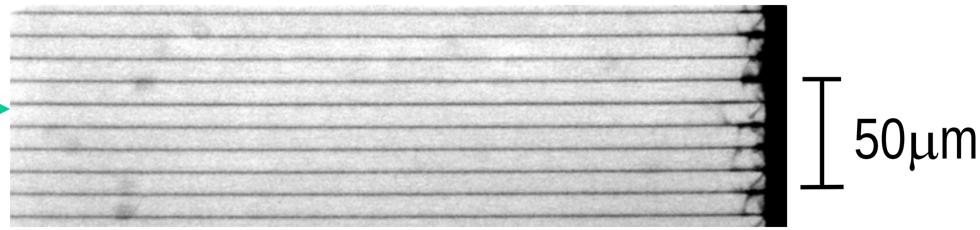
γ : gyromagnetic constant



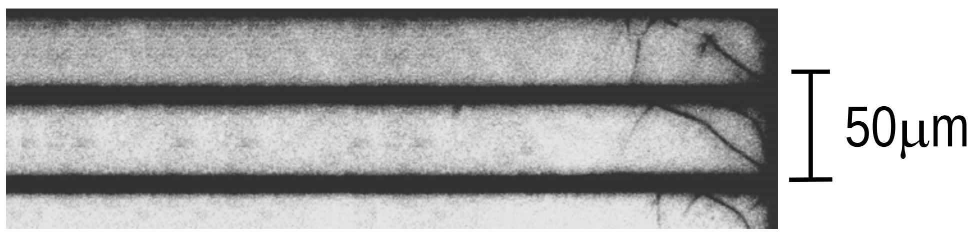
Observed domain structures (1)



Test pattern of bi-directional micro wire array



(a) 10μm wide micro wire array



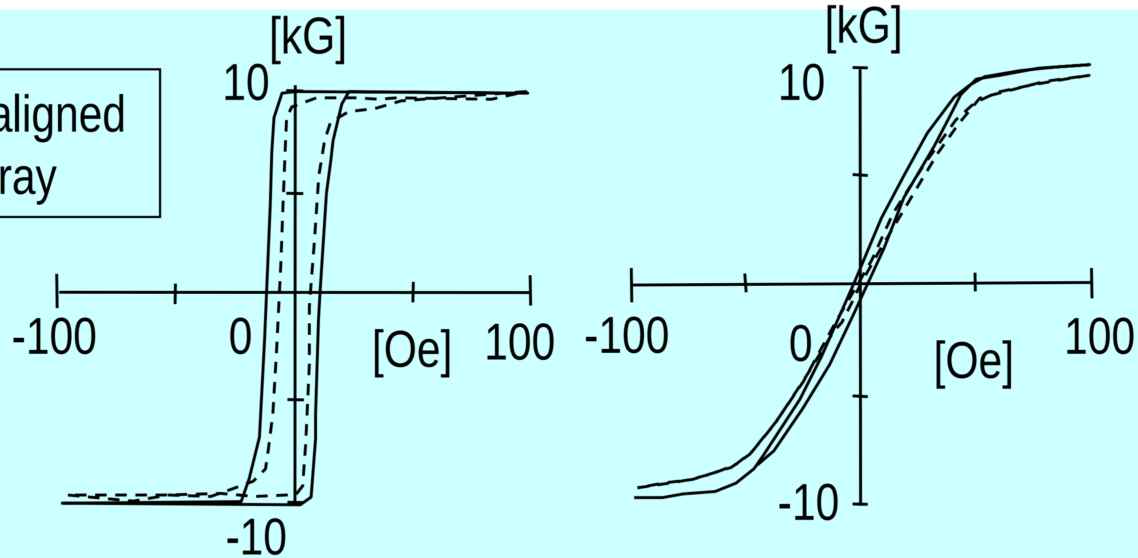
(b) 30μm wide micro wire array

Observed domain structure.

<u>0.1mm thick</u> *and 2mm long samples.*

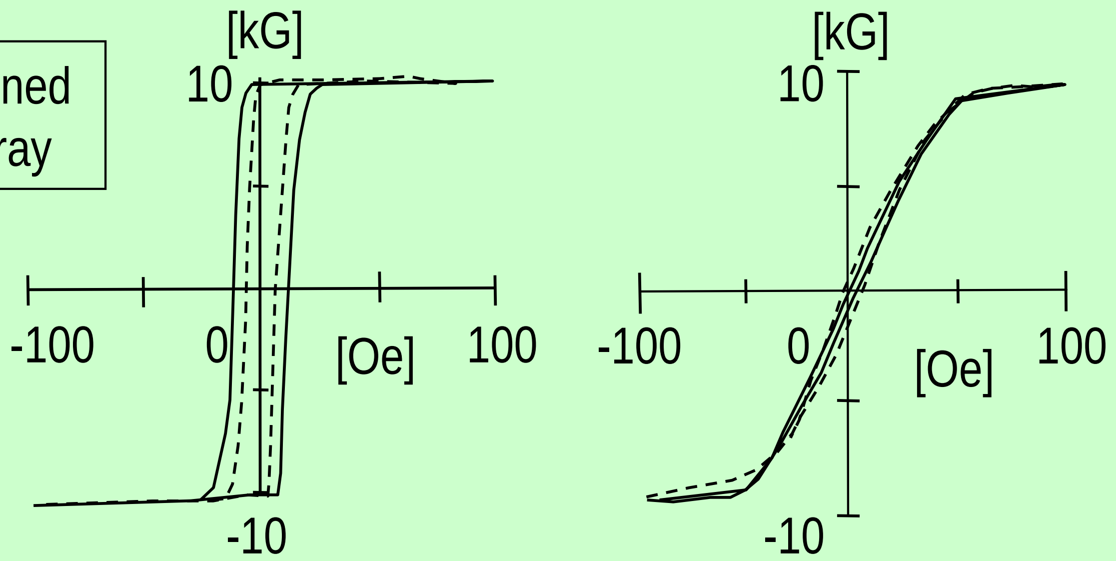
Hysteresis curves

Horizontally aligned micro wire array



(a) Easy axis direction (b) Hard axis direction

Vertically aligned micro wire array

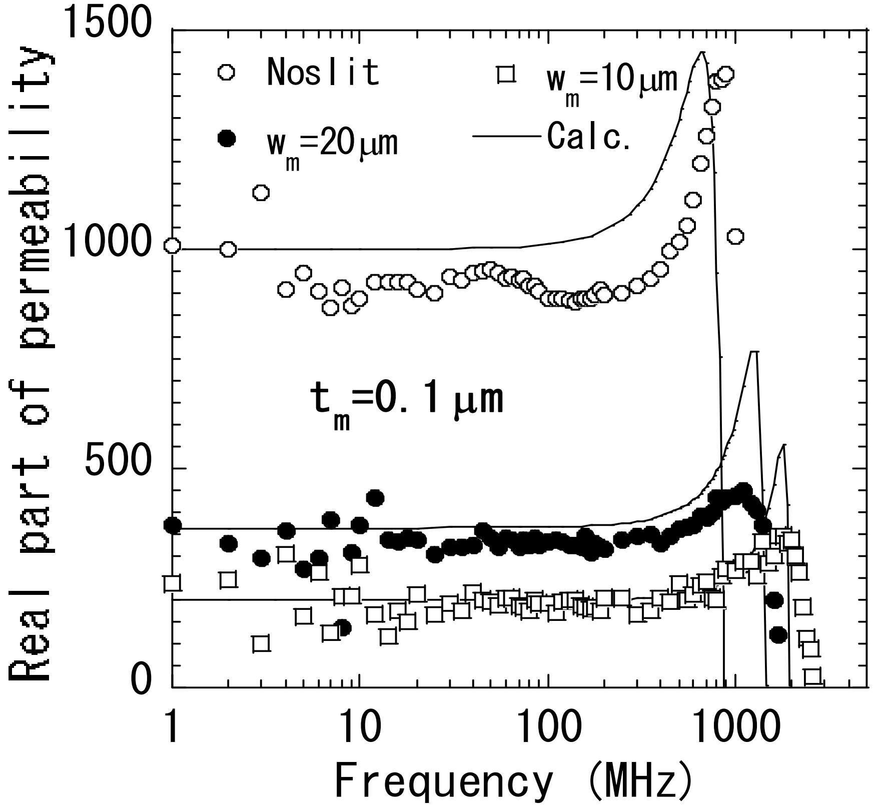


(a) Easy axis direction (b) Hard axis direction

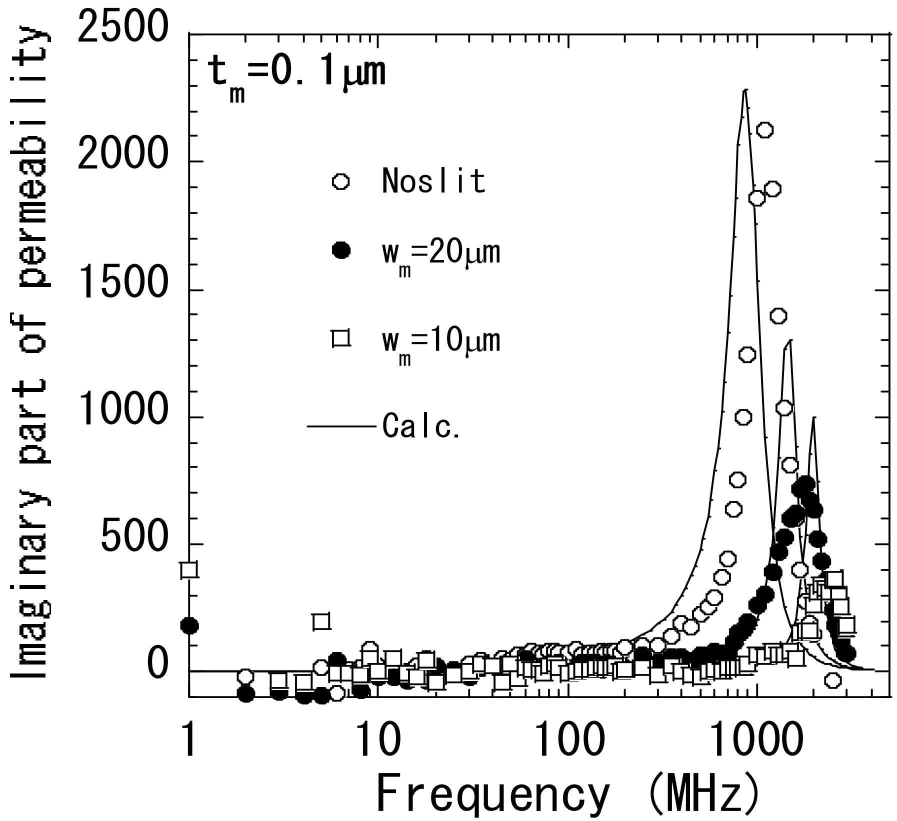
0.1mm thick
10 μm wide
0.6 μm spacing
2mm long

Broken lines:
before annealing
Solid lines:
after annealing

Frequency profile of complex permeability



(a) Real part



(b) Imaginary part

Width: varied, 0.1μm thick, 0.6 μm spacing, 4mm long

no heat treatment

Possible advantages of magnetic thin-film inductors

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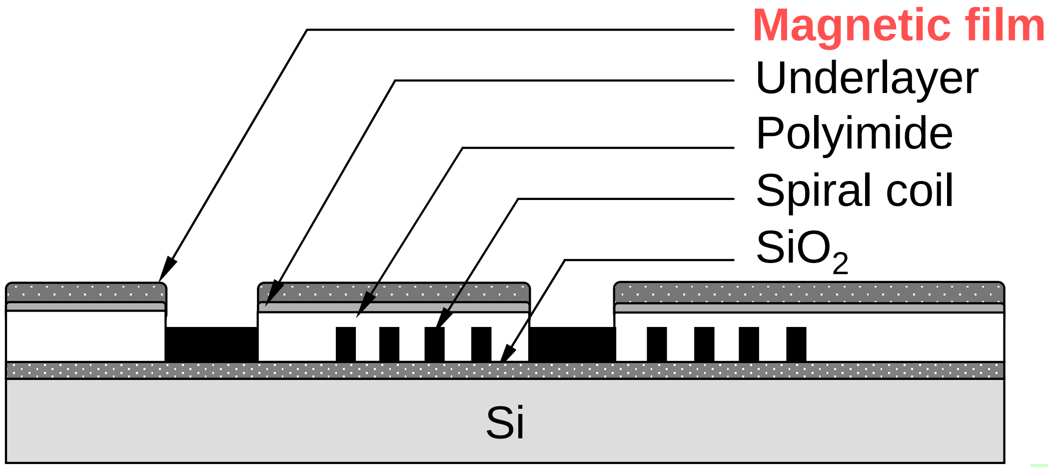
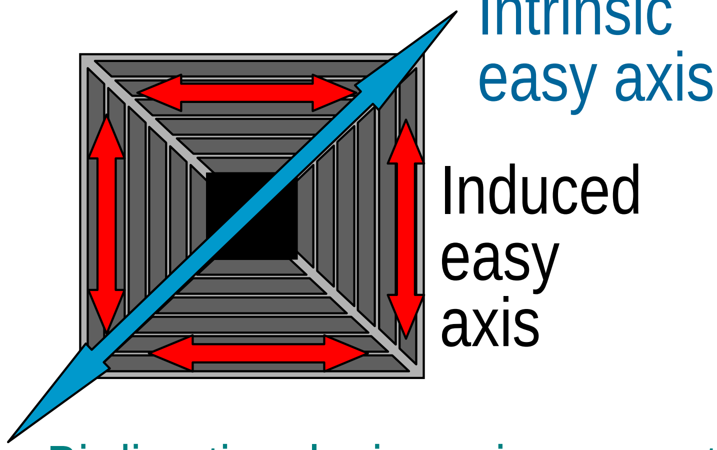
- **Miniaturization**
  Magnetic film enhances magnetic flux.
- **Low coil loss**
  Coil length reduces with miniaturization.
- **Low eddy current loss in Si and SiGe**
  Magnetic flux is mostly associated with magnetic film.

} Toward High efficiency

- **Thin insulator between coil and Si**
  because low eddy current loss in Si.
- **High self-resonance frequency???**
  Size is small but magnetic film can be a electrode of a capacitor...

Spiral inductor





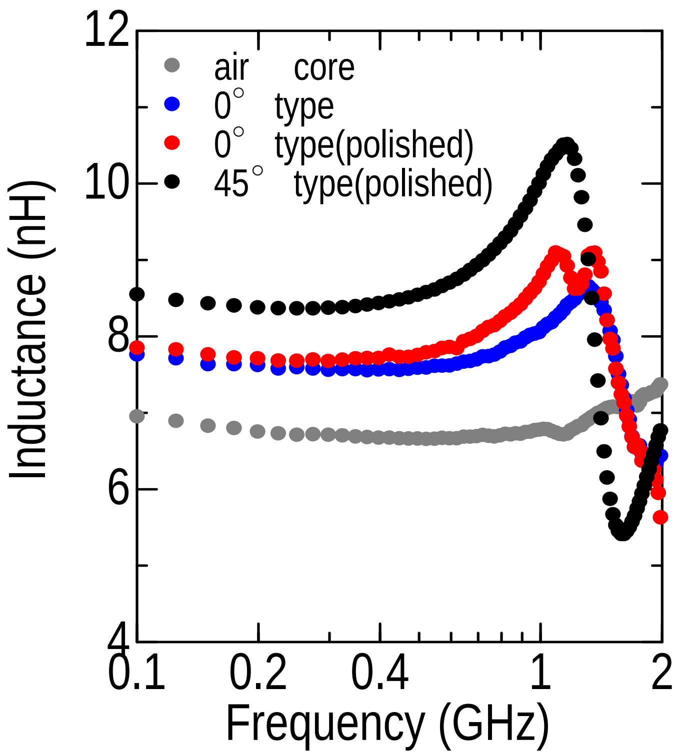
Bi-directional micro wire array structure

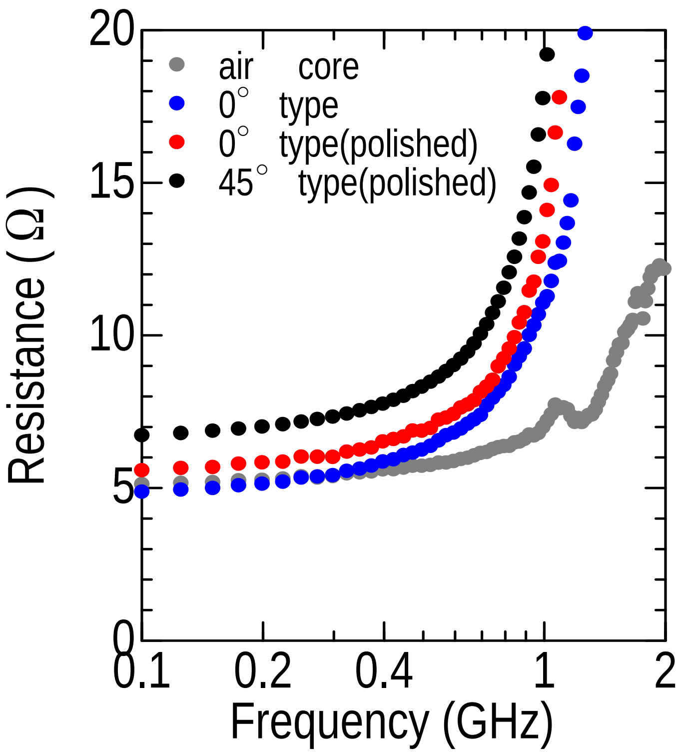
Coil	Spiral:	4	turns
	Width:	11.0	μm
	Spacing:	11.0	μm
	Thickness:	2.6–3.0	μm
	Area:	337 x 337	μm^2
Magnetic thin film	Thickness:	0.1, 0.3	μm
	Wire array patterns:	None, Parallel or Micro wire array	
Substrate	Thickness:	600	μm

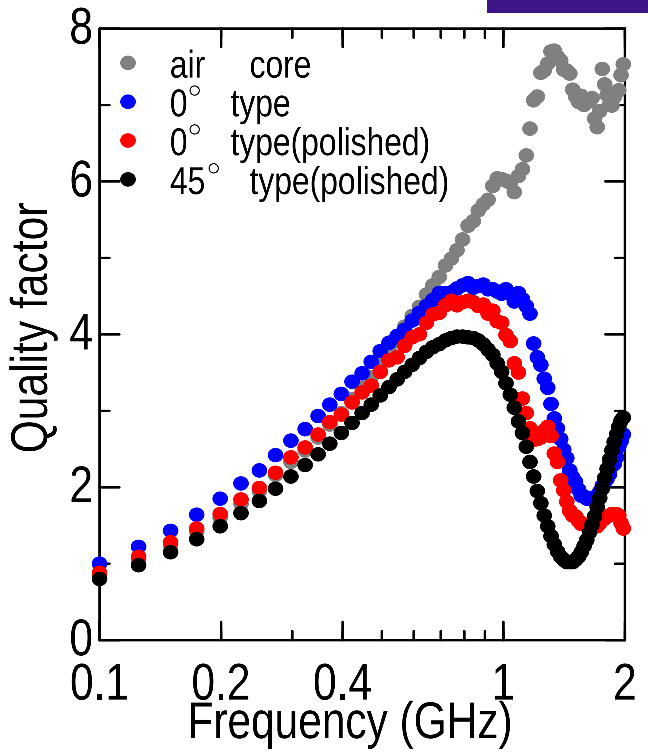
Advantages:

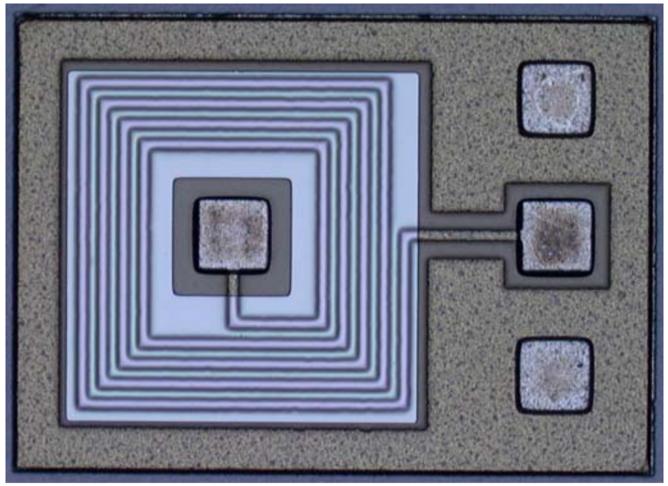
- Enhace the air-core inductance up to 100%
- Post Si process compatible
- *by* micro wire array structure:
  - Enhance FMR frequency
- *by* bi-directional wire structure
  - Utilize 100% area of magnetic film

Non-patterned CoNbZr film inductor



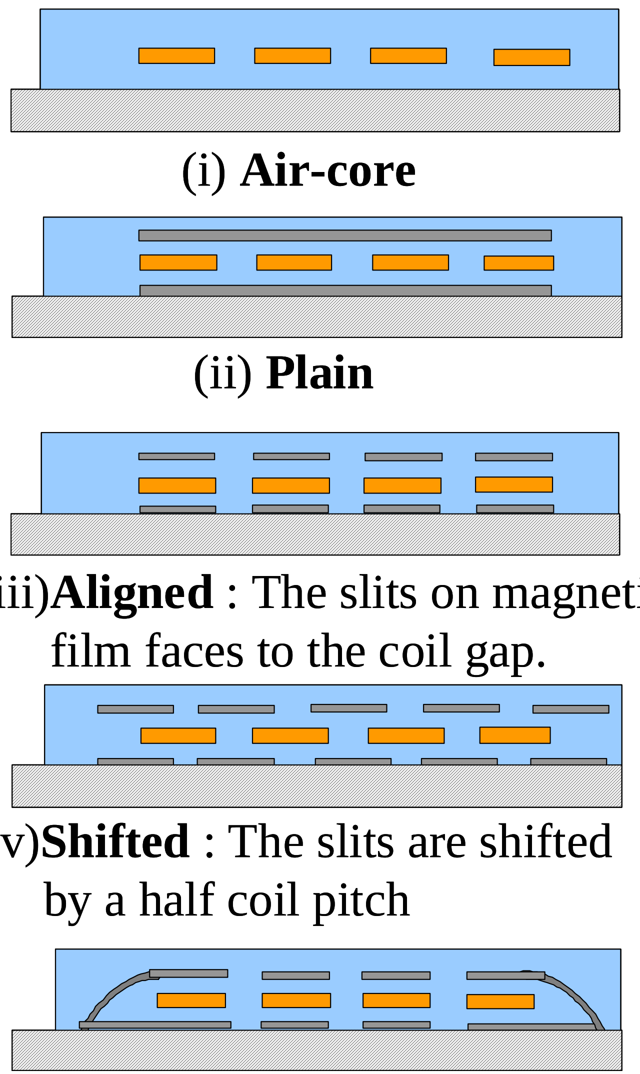






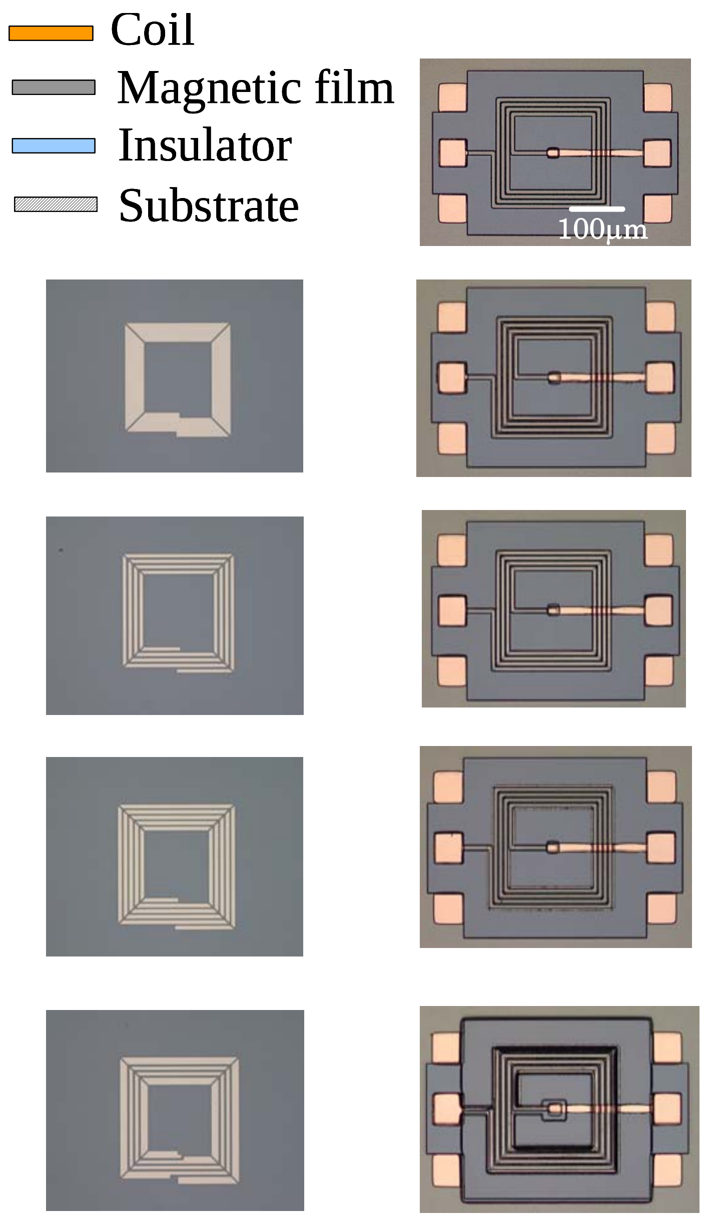
■L=10.1nH (+ 50%) but R=19.2Ω and Q=3.4

Sandwich structure thin film inductors



(v)**Closed** : The top and bottom magnetic layers are terminated at the edges

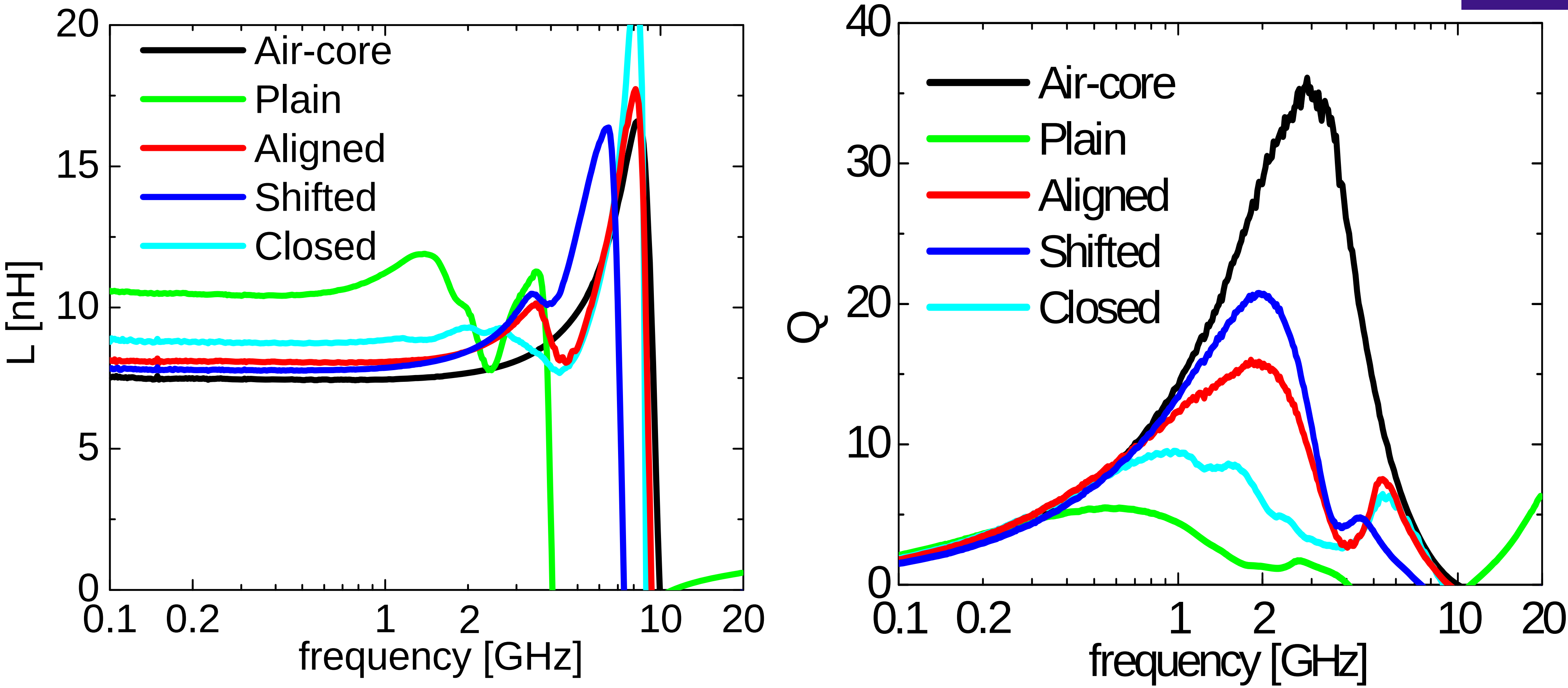
(a) Cross sectional structure



(b) Magnetic film patterning

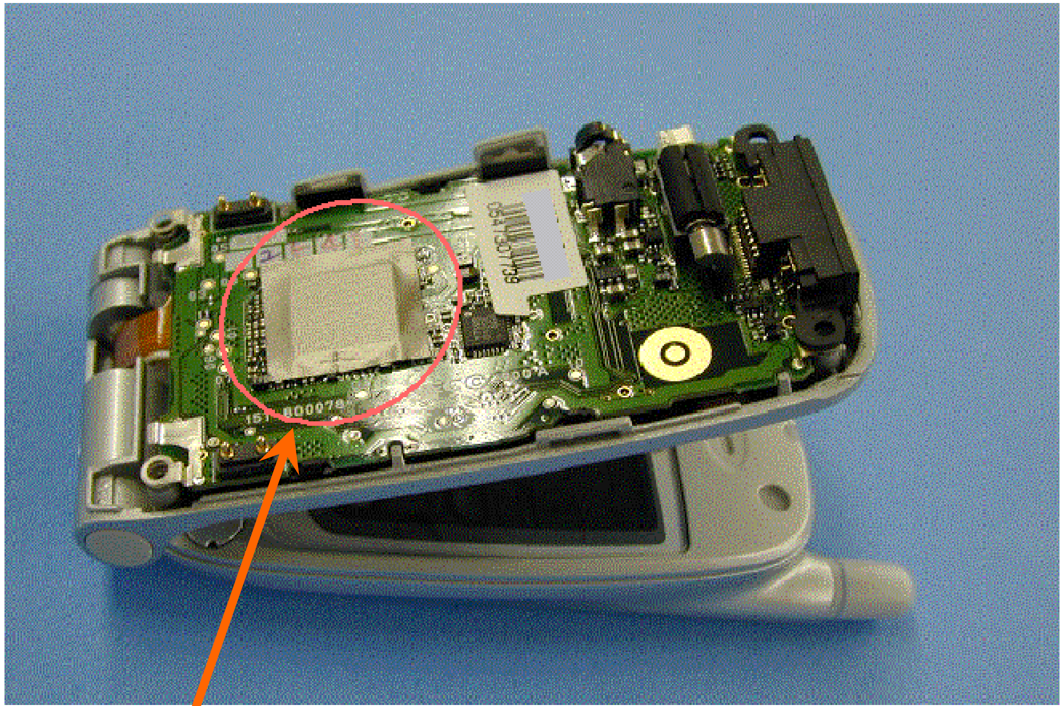
(c) Outlook of the completed inductor

L & Q



20
15
10
5
0
L [nH]
0.1
0.2
1
2
10
20
frequency [GHz]
Air-core
Plain
Aligned
Shifted
Closed
40
30
20
10
0
Q
0.1
0.2
1
2
10
20
frequency [GHz]
Air-core
Plain
Aligned
Shifted
Closed

Intra-EMI problems of modern IT equipments



Complimentary: NEC-Tokin Co.

Noise Suppression Sheet (NSS)

- To reduce unexpected signal to noise couplings
- By means of FMR loss generation in magnetic materials

High Freq. operation

- Signal and communication frequencies conflict.
- Wave length becomes similar to device and Equipment size.

High Density Packaging

- For further miniaturization
- For new device installation (camera, et al)

Low Power drive

- Low S/N ratio
- radiating wave source (Common Mode Current)

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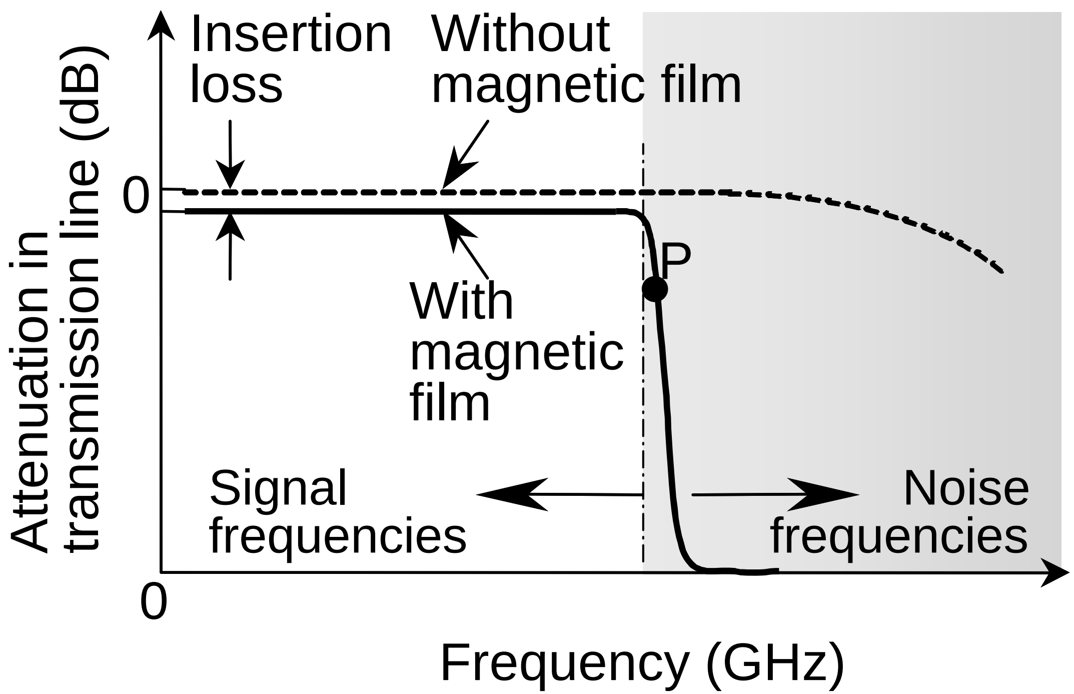
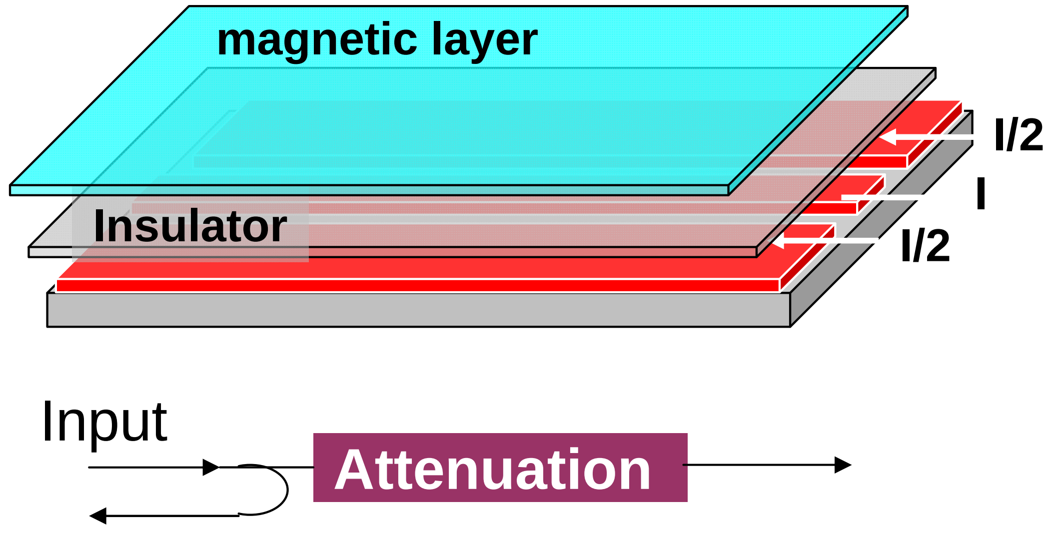
Idea of thin film noise suppressor

Ideal frequency profile



Schematic diagram



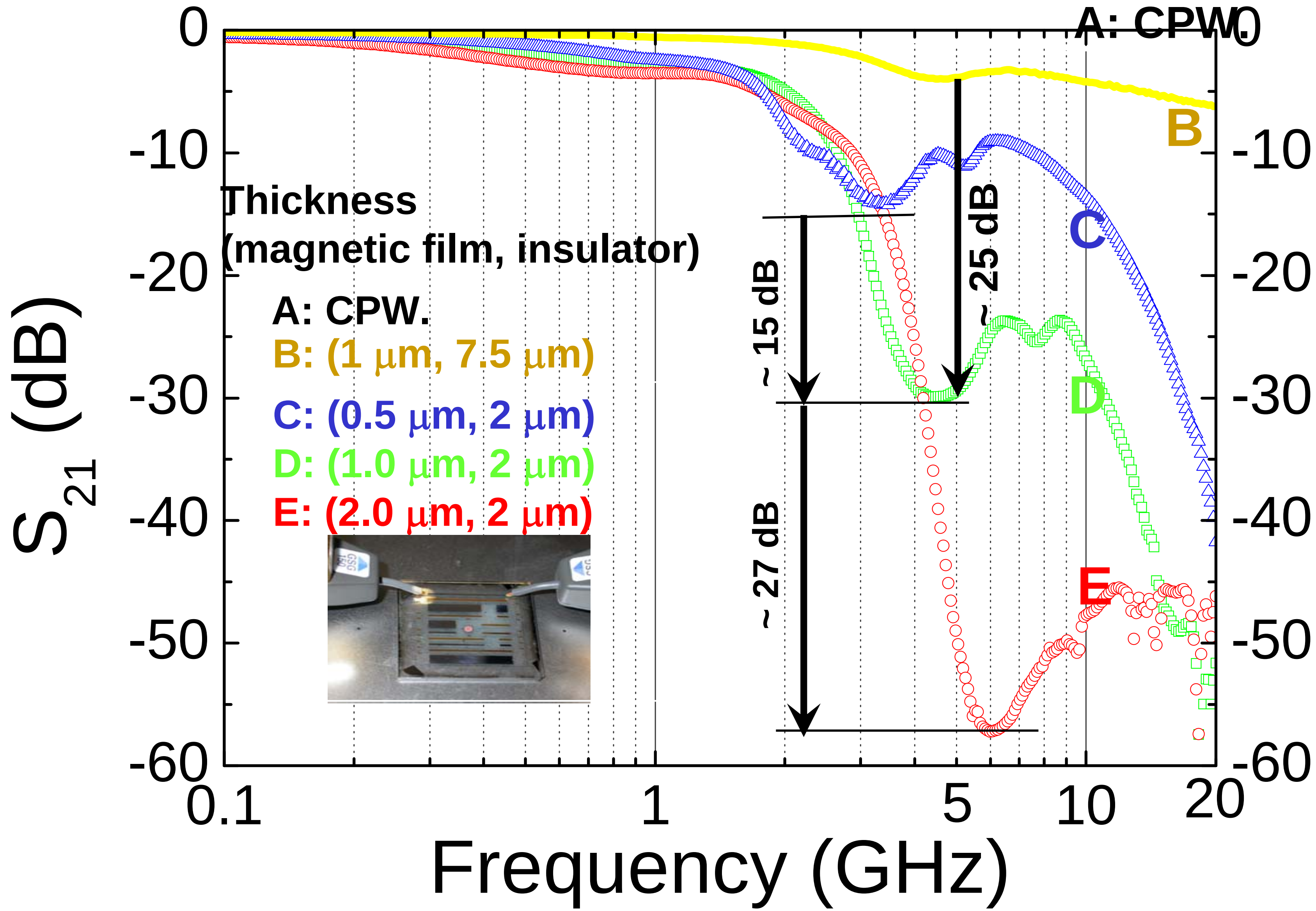
Reflection, S_{11} Transmission, S_{21}

$$P_{loss}/P_{in} = 1-(|S_{21}|^2+|S_{11}|^2)$$

Gap length vs. transmission properties

CoNbZr magnetic film

15 mm(L) x 2 mm(W) x 0.5, 1, 2 μm(T)



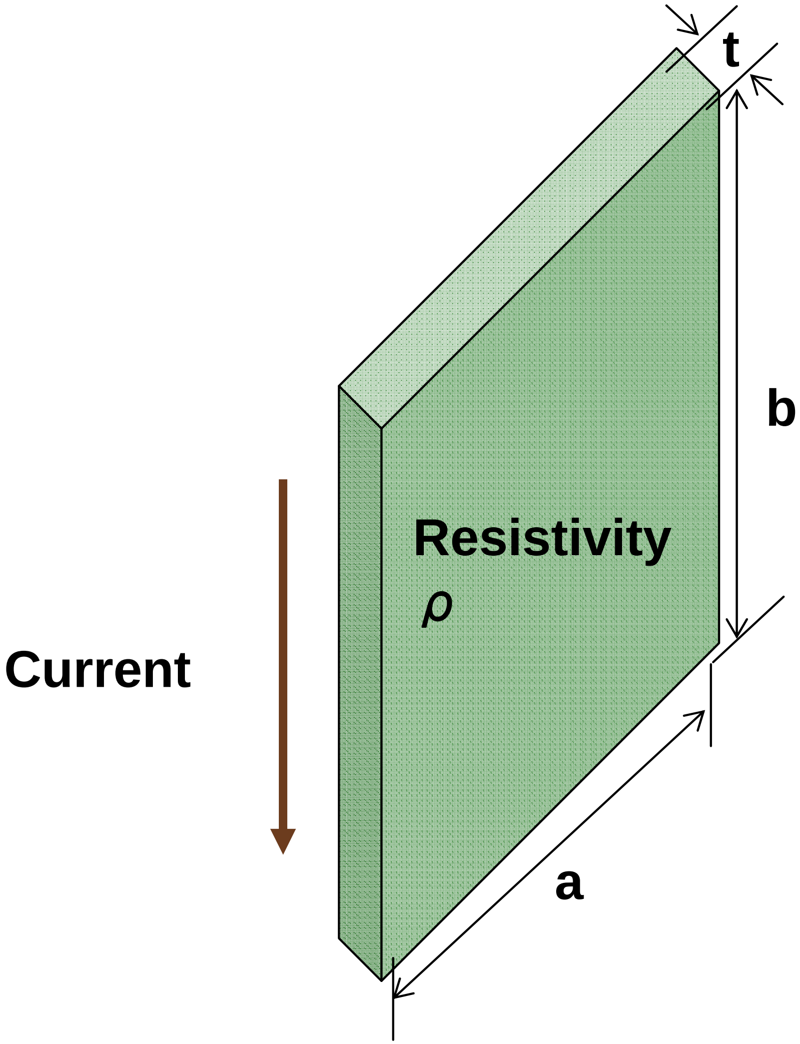
Ki Hyeon Kim, S. Ohnuma, M. Yamaguchi, IEEE Trans. Mag.,40(4), (2004)

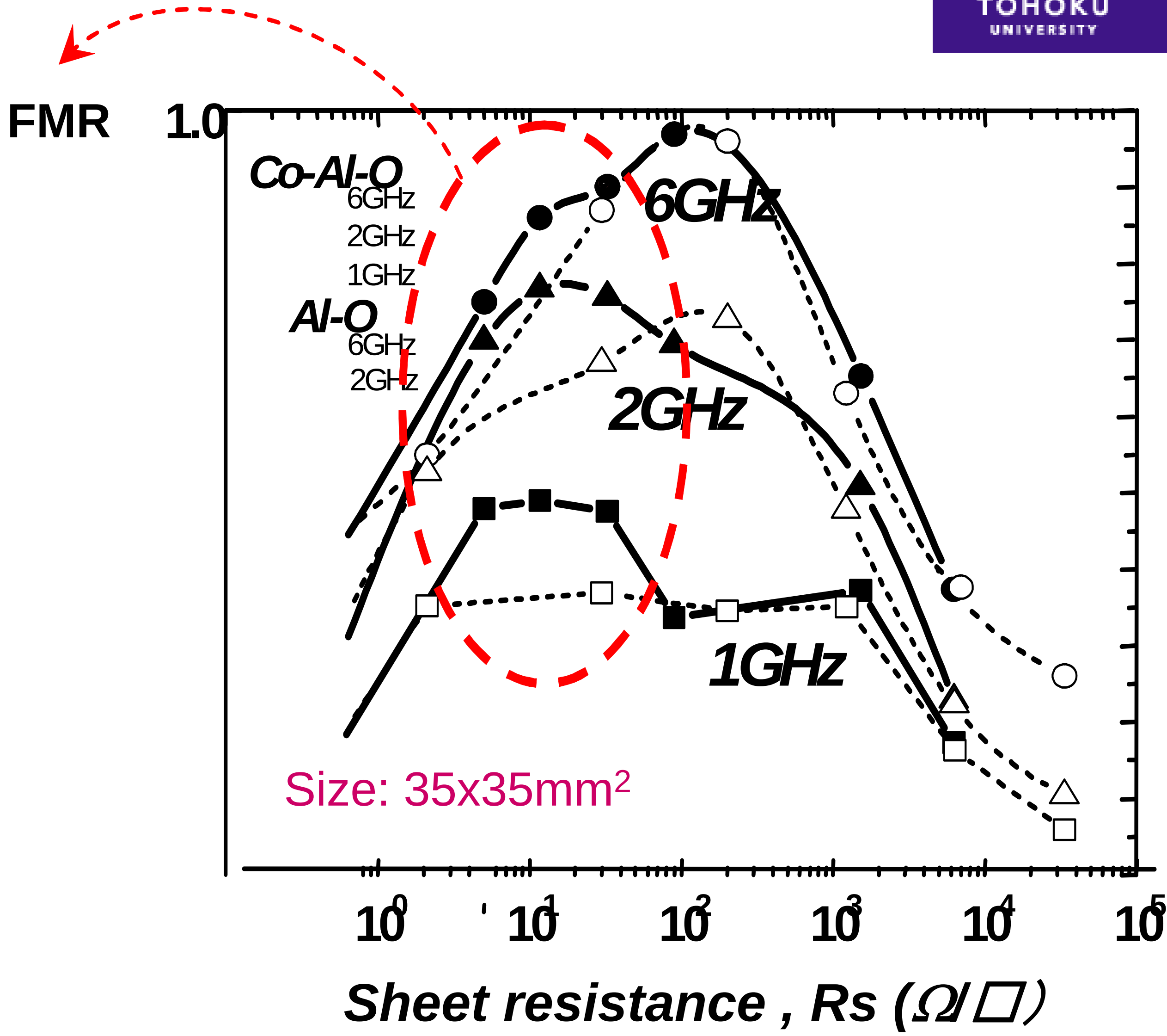
Sheet resistance

$$Rs = \frac{\rho}{t}$$ [Ω/square]

ρ : Resistivity

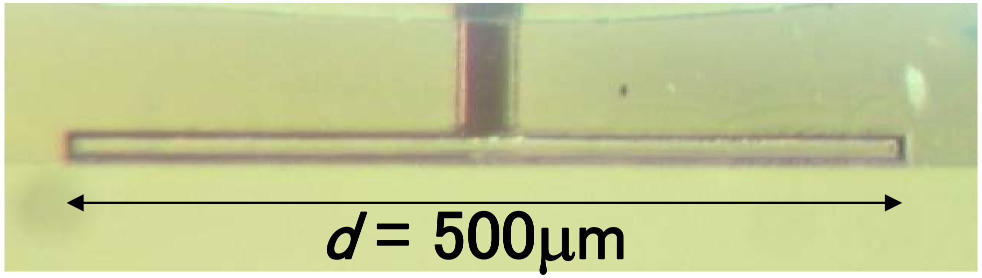
t: Film thickness



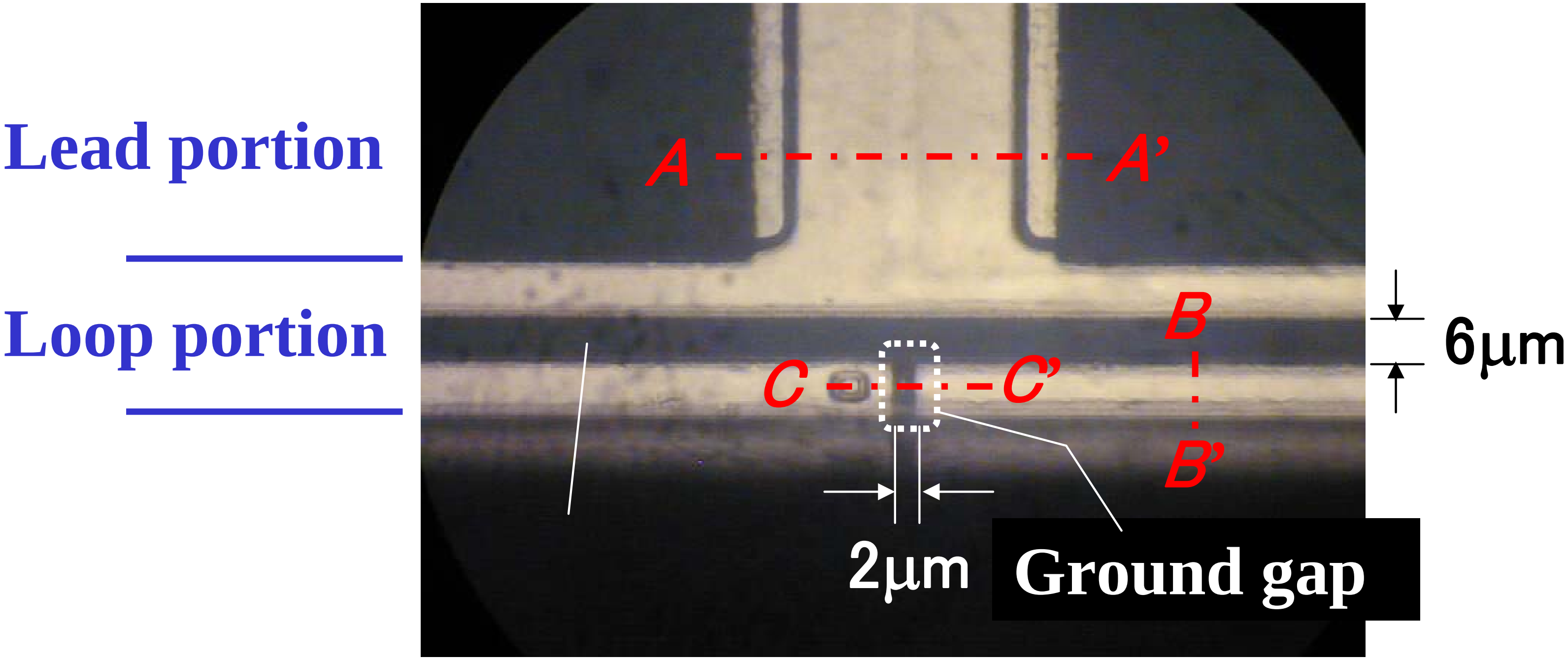


S. Ohnuma et al: Intermag2005

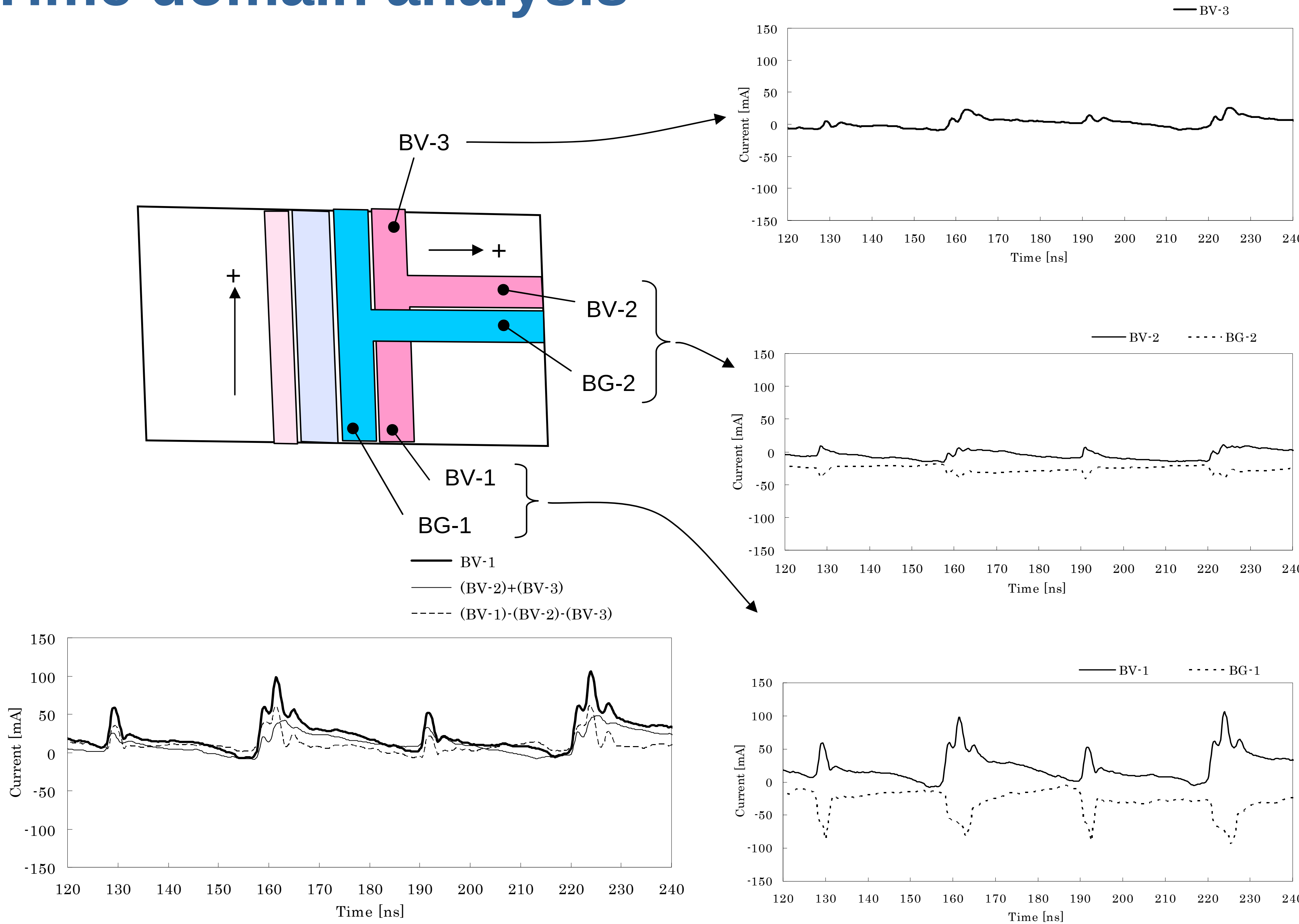
Thin-film shielded-loop coil



d = 50, 100, 200, 500μm



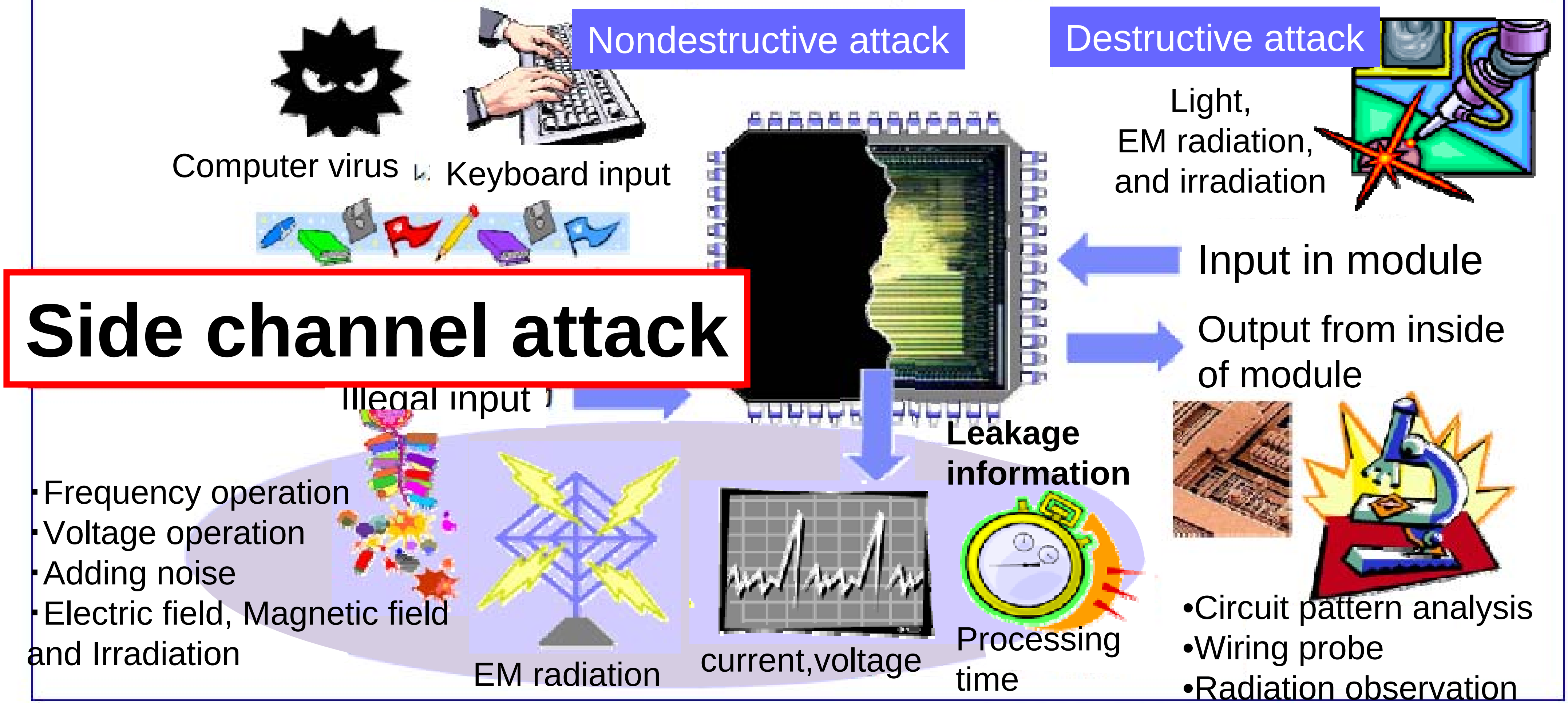
Time domain analysis



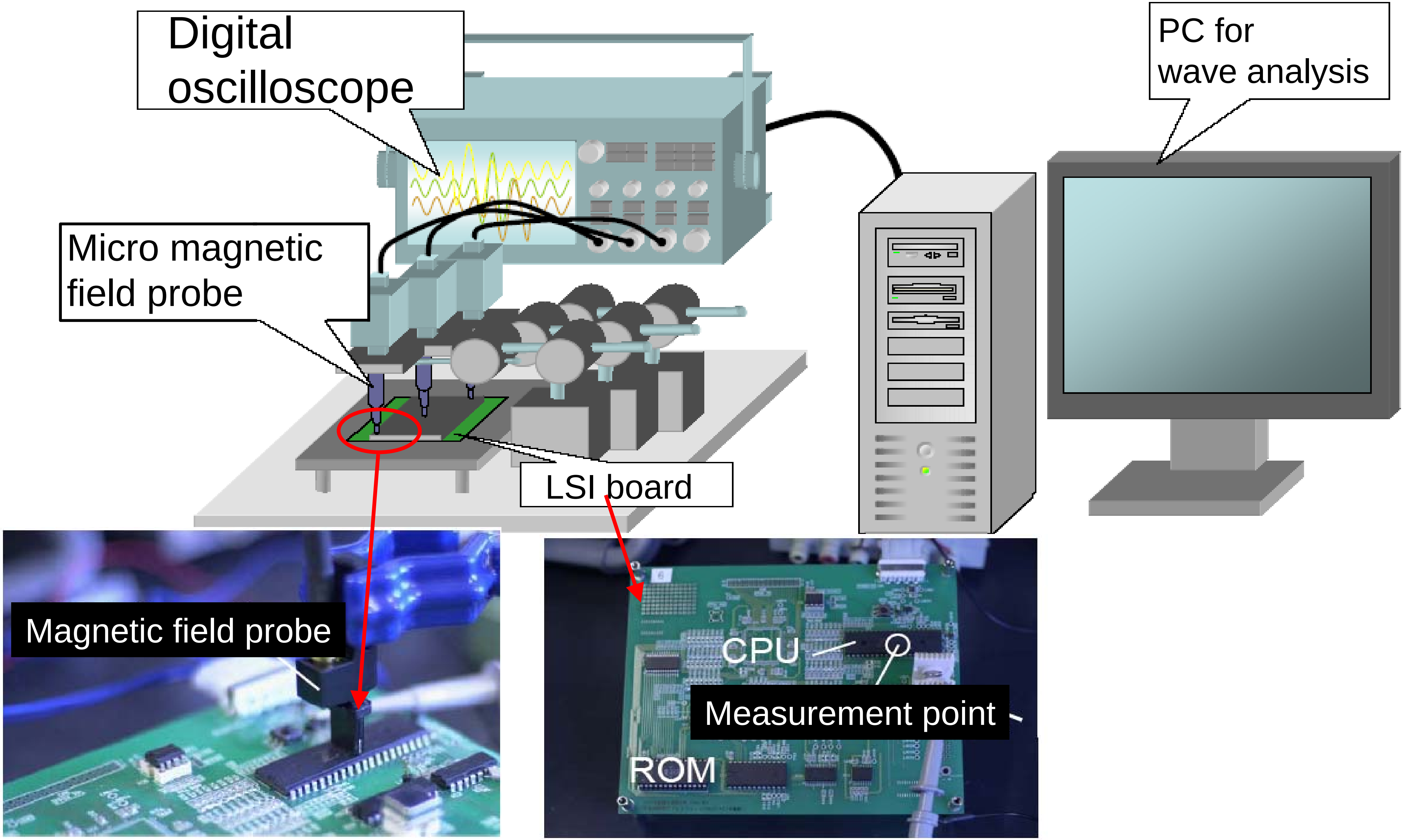
Side channel attack on cryptographic modules

A variety of side channel attack methods

- Analysis by combining various I/O to the module



Electromagnetic radiation analysis system that use micro magnetic field probe

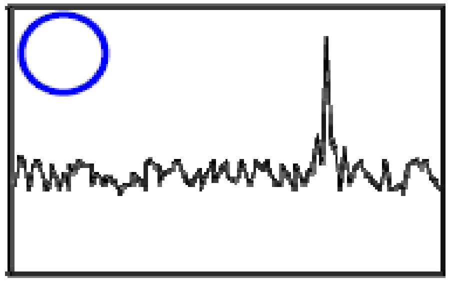


Differential Electromagnetic Analysis (DEMA)

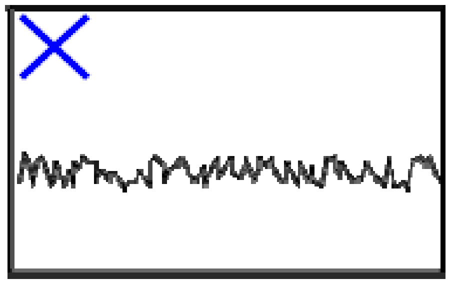
Electromagnetic radiation from CPU depends changes of the data.
…DEMA is attack method that uses change in EM wave radiated from CPU while encryption.

Outline of DEMA

I) Acquire wave form corresponding to various plaintexts (ciphertexts).
II) Assume a part of the key.
III) Assume 1 bit of internal variety from the key assumed.
IV) Classify to two groups according to an internal variable is 0 or 1.
V) Calculate difference between averages of the two groups.
VI) Repeat II)-V) changing assumption of the key.
VII) Consider the one with the maximum peak to be a correct key.



Assume the correct key



Assume the false key

Relation between sampling frequency and analytical accuracy