



IMT Atlantique

Bretagne-Pays de la Loire
École Mines-Télécom

MAGNON INTERFEROMETRY IN HOMOGENEOUS THIN FILM

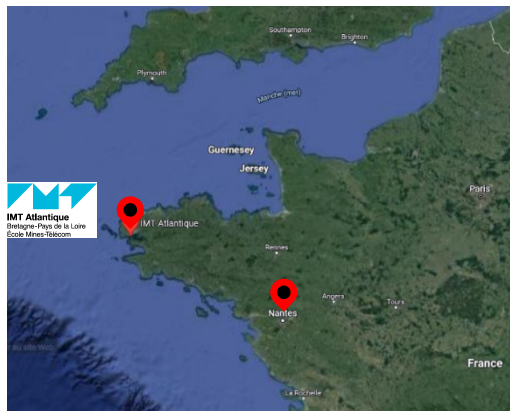
VINCENT VLAMINCK

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CHIRON WORKSHOP 2022

Computer Sciences & Information System Engineering School



- 2 Campus (Brest and Nantes)
- 1600 students (~200 PhD)
- 260 faculty members
- 140th QS World University for Computer Sciences & Information System



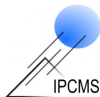
Magnonic Lab

- Nanoscale magnetization dynamics
- Spin Cavitronic

Collaborative project “MagFunc”

*Non-Reciprocal 3D Architectures
for **Magnonic Functionalities***

<https://nanomag.univie.ac.at/research/magfunc/>



PhD student
Loic Temdié (Cameroon)

CONTENT

1. **SPIN WAVE SPECTROSCOPY IN CONTINUOUS FILM**
 - . k-resolved characterization
2. **SPIN WAVE BEAM FROM CONSTRICTED CPW**
 - . Design of sharply constricted CPW
 - . Discrete mapping with μm -size probing antenna
 - . Fresnel approach
3. **SPIN WAVE DIFFRACTION FROM CURVED ANTENNA**
 - . Near Diffraction Model
 - . Concentrator
 - . « Young-Slit » device
4. **CAUSTIC EFFECTS FROM IN-PLANE MODES**
 - . Model for in-plane mode
 - . Self-focusing from constriction
 - . Towards caustic beam transduction



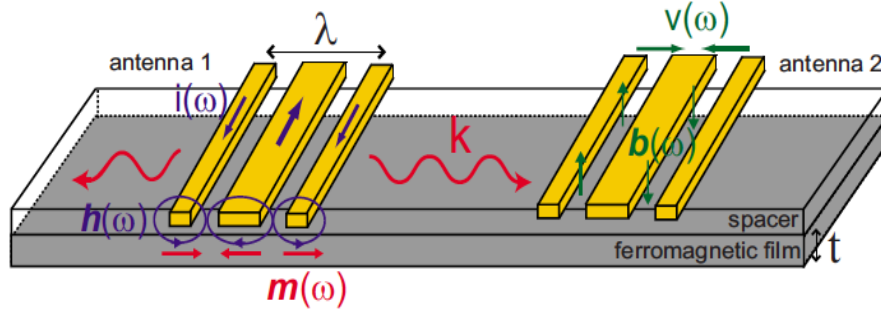
1. Sub- μ Spin Wave SPECTROSCOPY

(k-resolved magnetic resonance)



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Submicron Spin Wave Transduction in strips



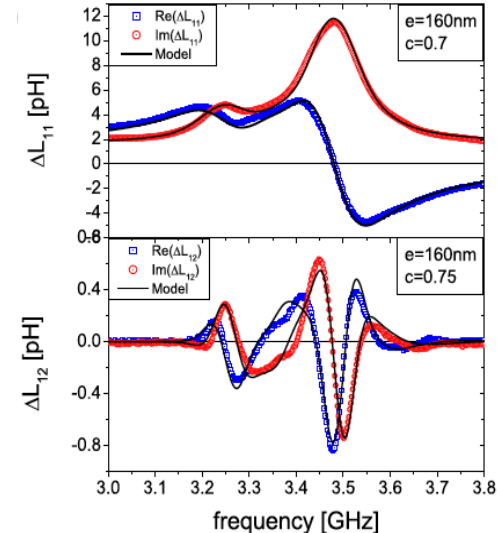
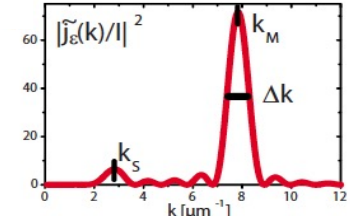
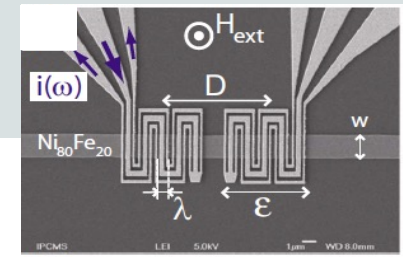
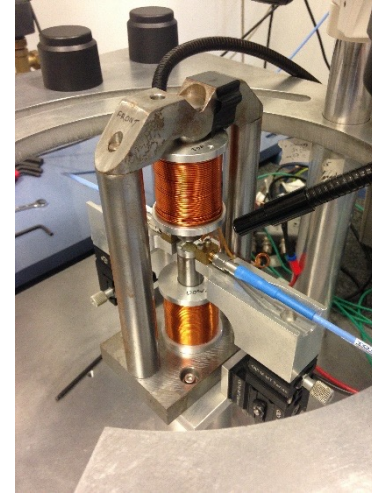
$I(\omega, k) \rightarrow h(\omega, k) \rightarrow m(\omega, k) \Rightarrow \Delta Z(\omega)$ (change of inductance)

$$\Delta L_{ij} = \frac{1}{i\omega} (Z_{ij}(H_{res}) - Z_{ij}(H_{ref}))$$

$$\Delta L_{ij} = \frac{\mu_0}{2\pi} \int_{-\infty}^{+\infty} dk \left| \frac{j(k)}{I} \right|^2 \frac{e^{-ikD}}{\frac{1}{\mu_s^-} - \frac{1}{\mu_s^+}}$$

$$(\mu_s^{+, -} = \lim_{z \rightarrow s^{+, -}} \frac{B_z}{\mu_0 H_x})$$

- ✓ Transduction of sub-micron spin waves in metallic strips
- ✓ Efficient model for plane wave modes



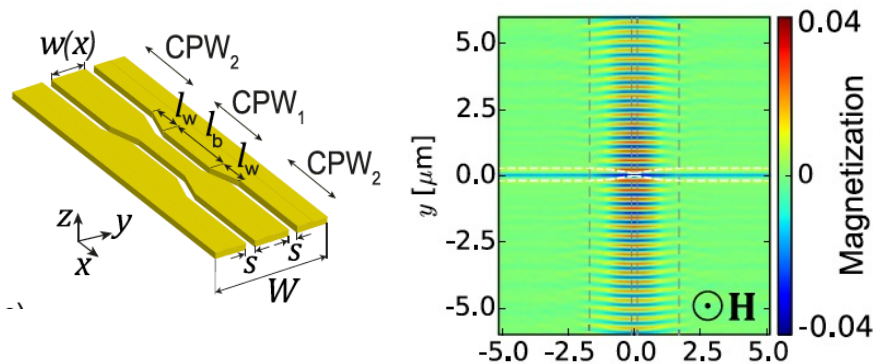
V. Vlaminck et al., *Phys. Rev. B* **81**, 014425 (2010)

SPIN WAVE BEAM IN CONTINUOUS FILMS

Observation of a focused emission from a constricted CPW

(i) Micromagnetic simulation (out-of-plane)

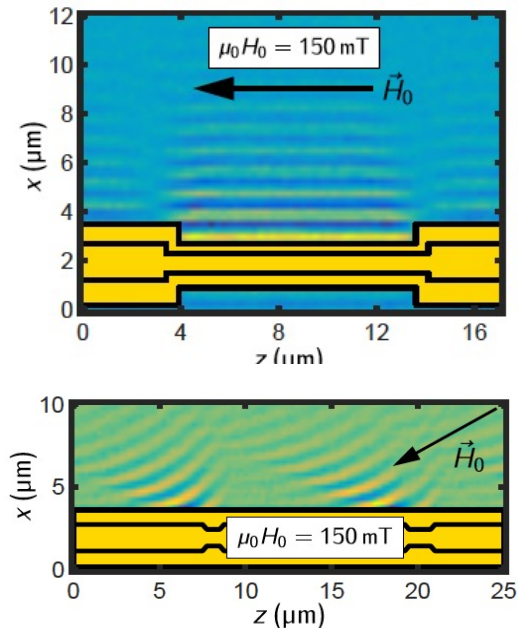
Scientific Reports **6**, 22367 (2016)



Interesting results,
but no explanation for the beamforming

(ii) Time resolved Kerr microscopy (in-plane)

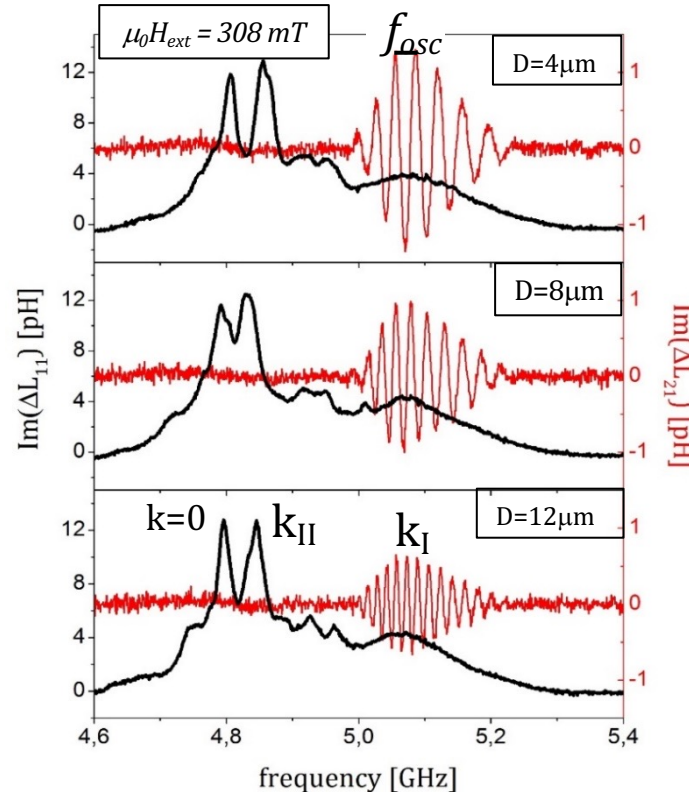
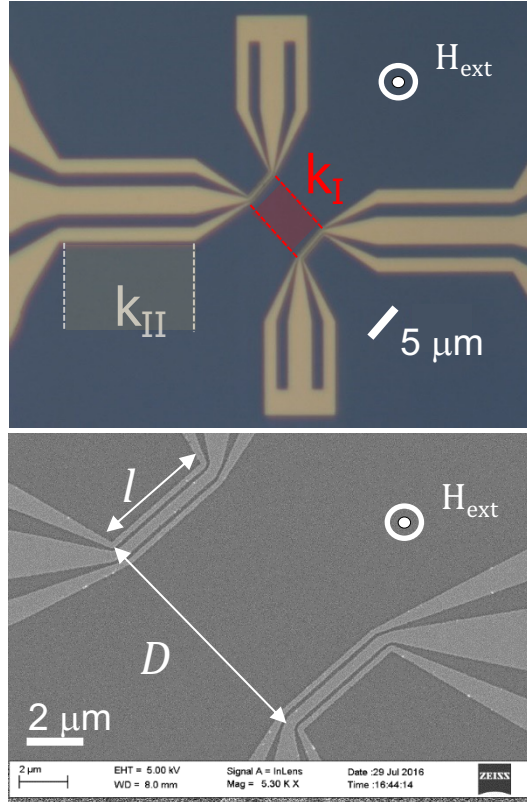
Phys. Rev. B **96**, 100401(R) (2017)



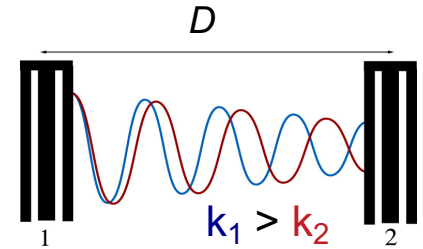
Spin Wave Transduction in continuous 30 nm YIG films (i)

(i) Using several devices at different distances

N. Loayza et al., Phys. Rev. B 98, 144430 (2018)



$$m(x, t) = m_0 e^{-\frac{x}{L_{att}}} e^{i(\omega t - kx)}$$



Oscillation due to $\neq$ phase delays (spectral width)

$$\delta\phi = \delta k D$$

$$v_g = f_{osc} D$$

$$\text{Attenuation } L_{att} = \frac{2v_g}{\Delta\omega}$$

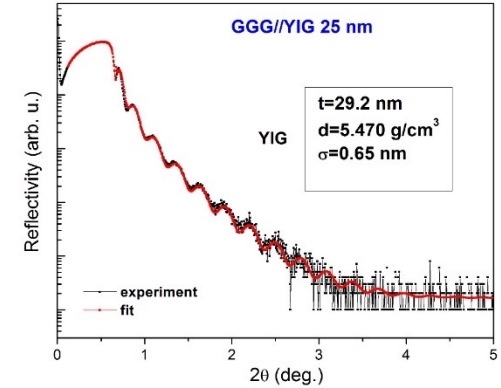
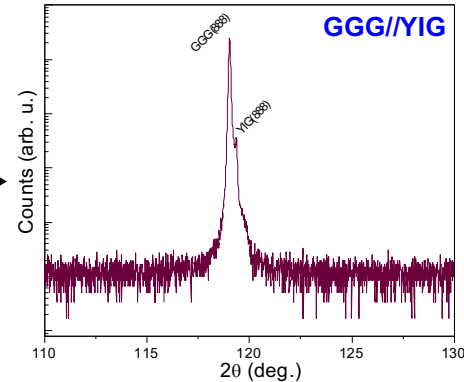
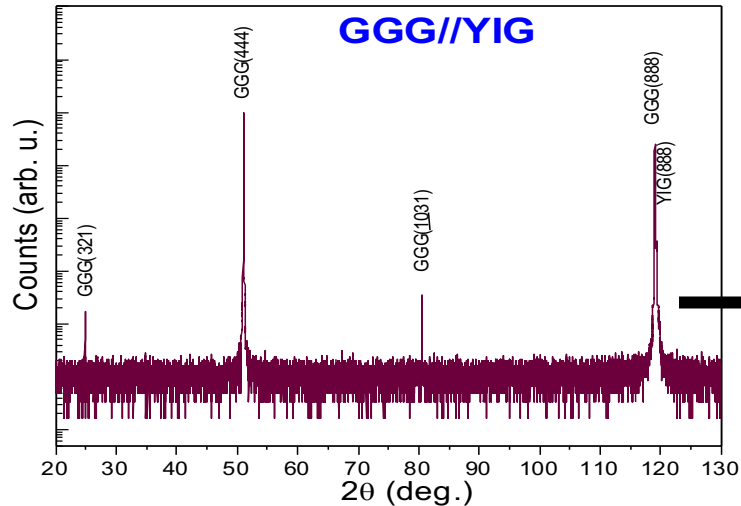
$$\text{Out-of-plane } \Delta\omega = 2\alpha\omega$$

$$\text{Out-of-plane } \Delta\omega = \alpha (2\omega_0 + \omega_M)$$

XRD ON THE YIG FILMS

Thin YIG ($\text{Y}_3\text{Fe}_5\text{O}_{12}$) films grown at Argonne National Laboratory

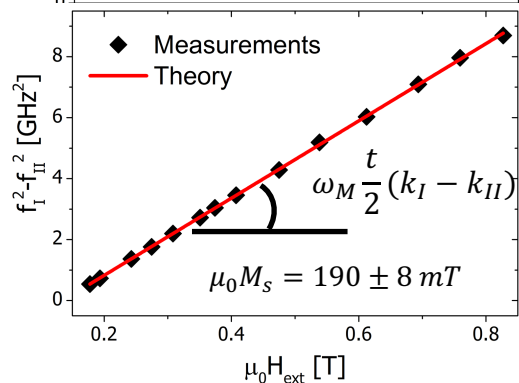
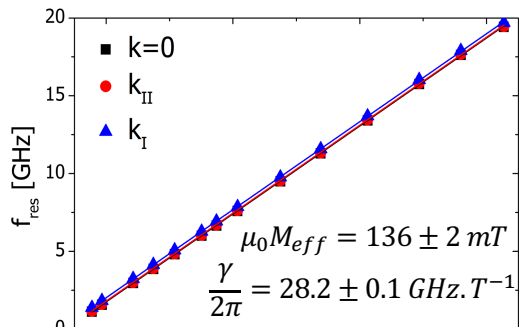
- sputtering power of 75 W
- low deposition rate $0.25\text{\AA}.\text{s}^{-1}$
- Annealed ex-situ at 800 °C with continuous air flow



Spin Wave Transduction in 30nm YIG films (i)

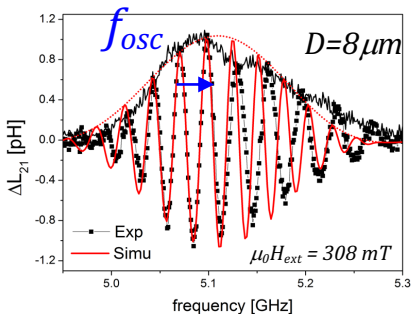
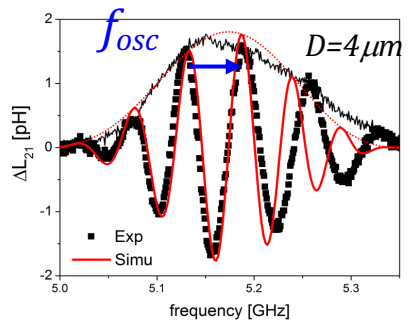
k-resolved FMR

$$\omega_{\perp}^2 = \omega_H(\omega_H + \omega_M P(k)) ; \omega_H = \gamma \mu_0 (H_{\text{ext}} - M_s + H_K)$$



Uniaxial out-of-plane anisotropy: $\mu_0 H_K \approx 60 \text{ mT}$

Estimation of the group velocity

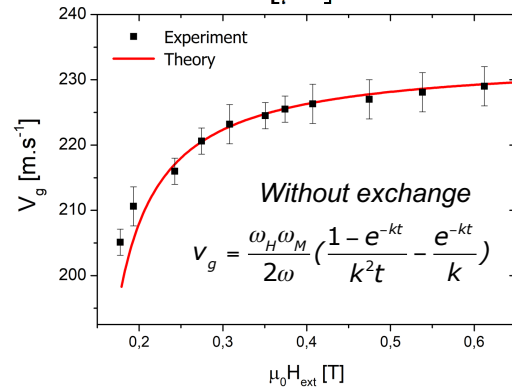
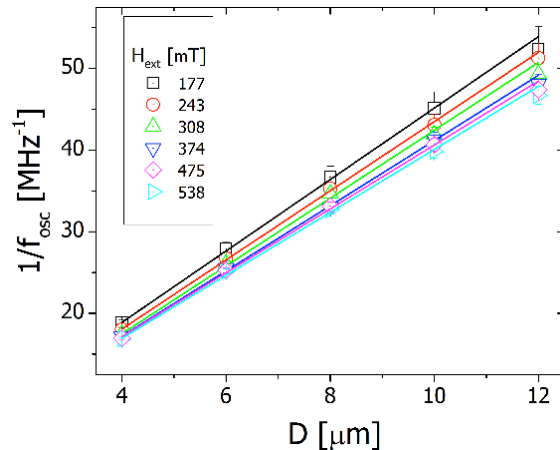


Little disagreement with simulation

$$f_{\text{osc}}(\text{simu}) < f_{\text{osc}}(\text{exp}) \text{ for } f > f_{\text{res}}$$

→ Increase of v_g with k due to exchange

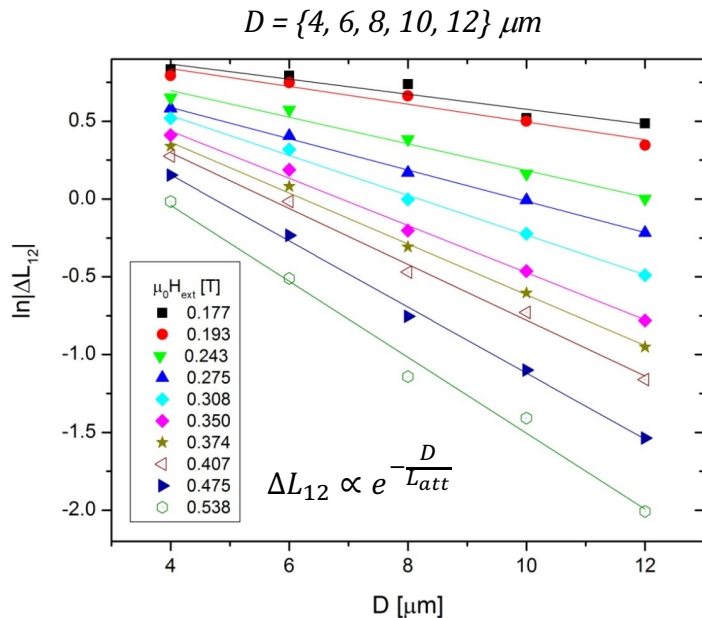
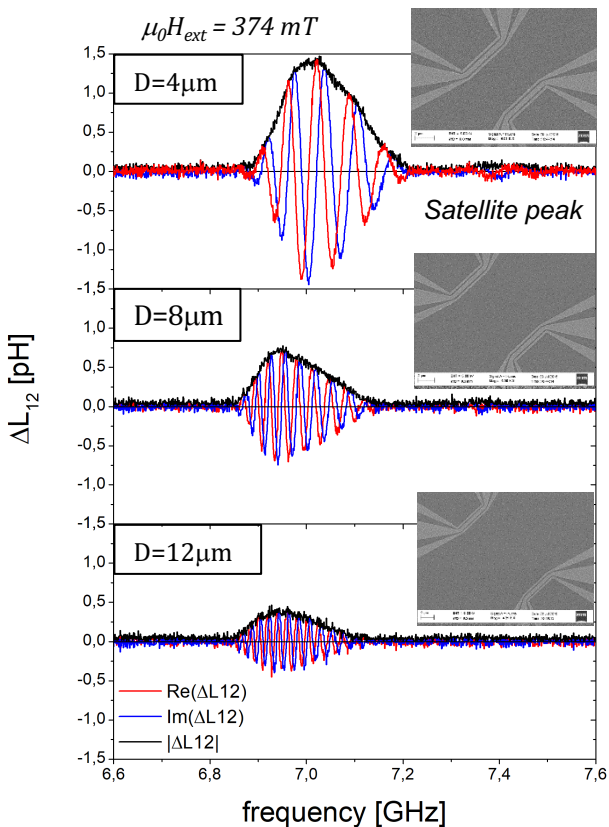
$$D = \{4, 6, 8, 10, 12\} \mu\text{m}$$



Spin Wave Transduction in 30nm YIG films (i)

Estimation of the attenuation and effective damping from several D

N. Loayza et al., Phys. Rev. B 98, 144430 (2018)



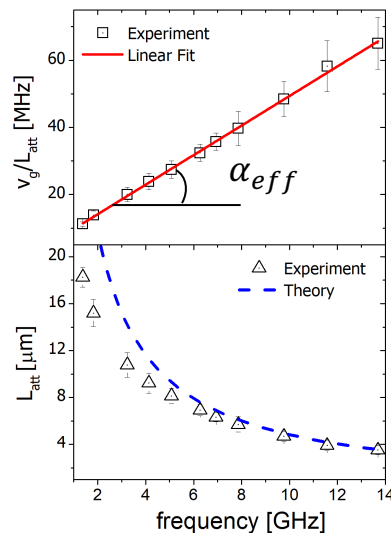
$$\alpha_{\text{eff}} = 7.5 \pm 0.2 \cdot 10^{-4}$$

Linear dependence suggesting minor dispersion of the emission

→ **Validate SW transduction in continuous films (no need for strips)**

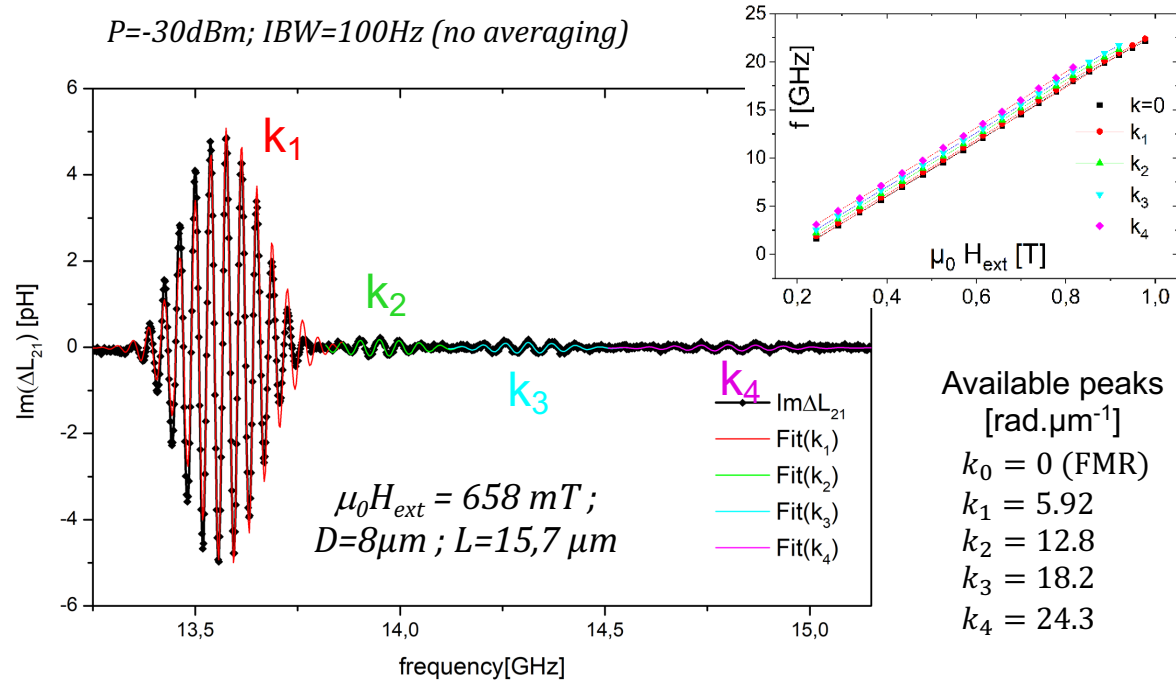
Attenuation length:

$$L_{\text{att}} = \frac{2v_g}{2\alpha\omega}$$



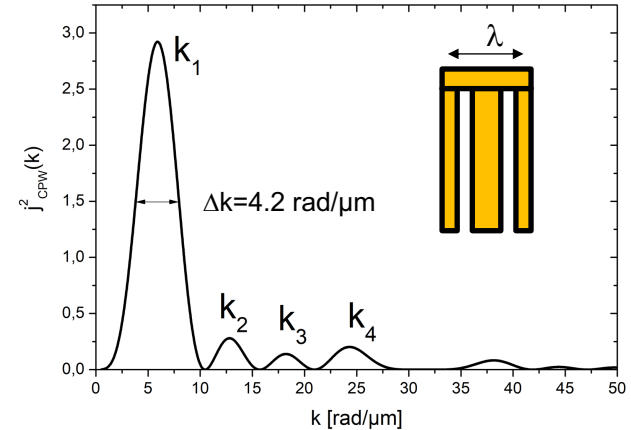
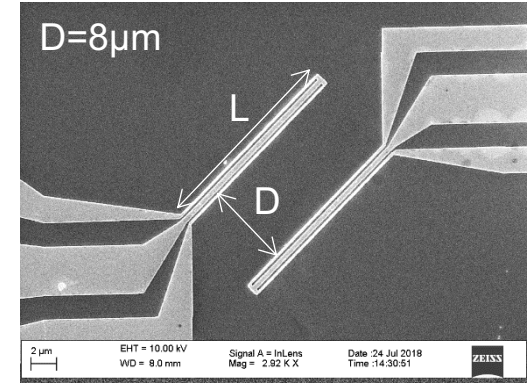
k-RESOLVED FMR (Satellite peaks)

Characterization from a single device that display several satellite peaks



Available peaks
[rad. μm^{-1}]

- $k_0 = 0$ (FMR)
- $k_1 = 5.92$
- $k_2 = 12.8$
- $k_3 = 18.2$
- $k_4 = 24.3$

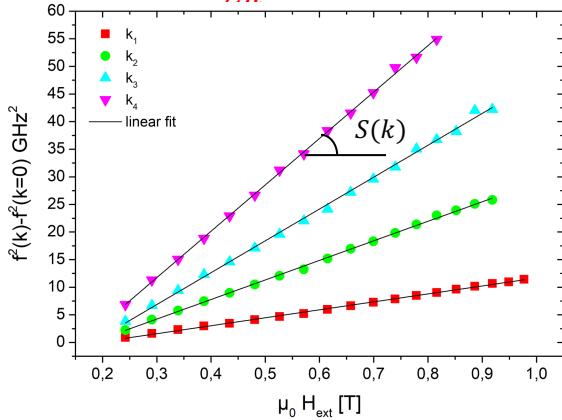


k-RESOLVED FMR (ii)

$$f_{k_1}^2 - f_0^2 = \boxed{S(k)} \mu_0 H_{ext} + \boxed{I(k)}$$

slope Intercept

$$S(k) = \frac{\gamma}{2\pi} (f_M P(k) + 2\eta k^2)$$



$$\mu_0 M_{eff} = 185 \pm 2 \text{ mT}$$

$$\mu_0 M_s = 190 \pm 2 \text{ mT}$$

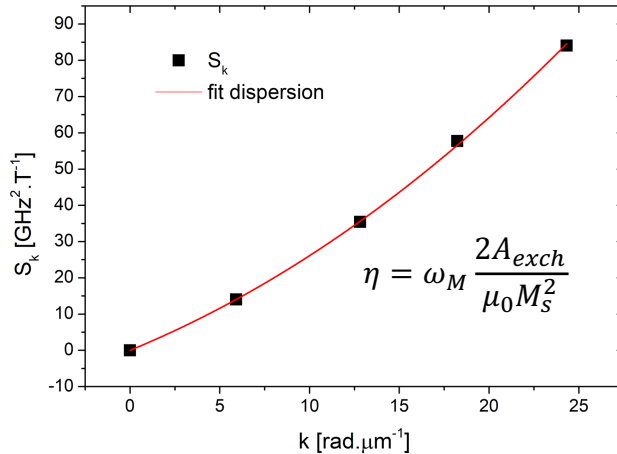
$$\frac{\gamma}{2\pi} = 28.07 \pm 0.1 \text{ GHz} \cdot \text{T}^{-1}$$

No anisotropy K_u in this series

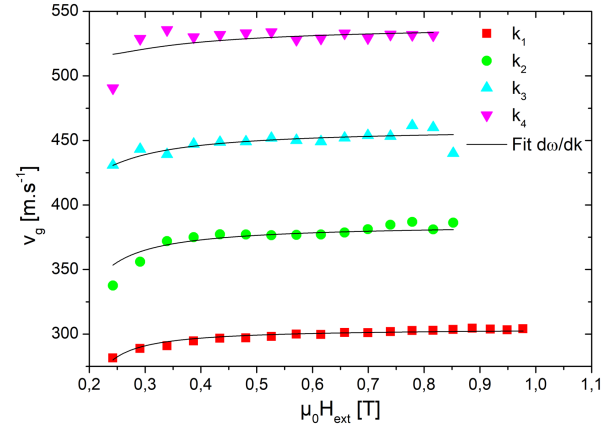
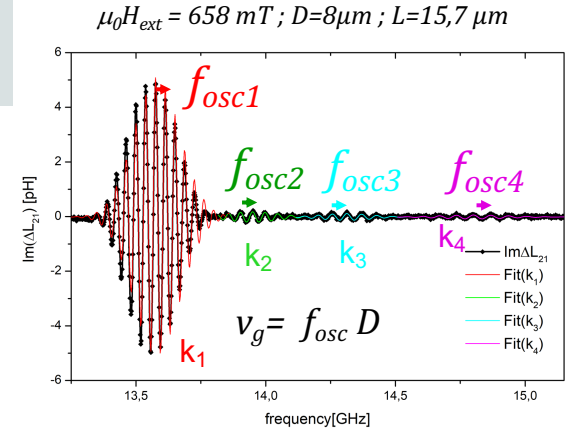
$$I(k) = -\eta^2 k^4 + \left(\frac{2\pi\eta k^2}{\gamma} - \mu_0 M_{eff} \right) S(k)$$

Parabolic inflection dominated
by the exchange

$$2\eta > f_M \frac{t^2}{6}$$



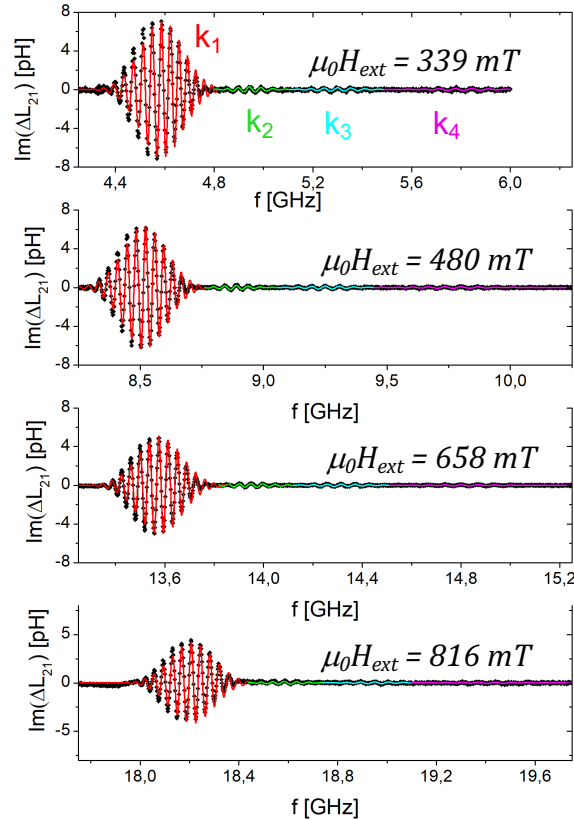
$$A_{exch} = 3.3 \pm 0.2 \text{ pJ} \cdot \text{m}^{-1}$$



Increase of v_g with k
→ need to account for A_{exch}

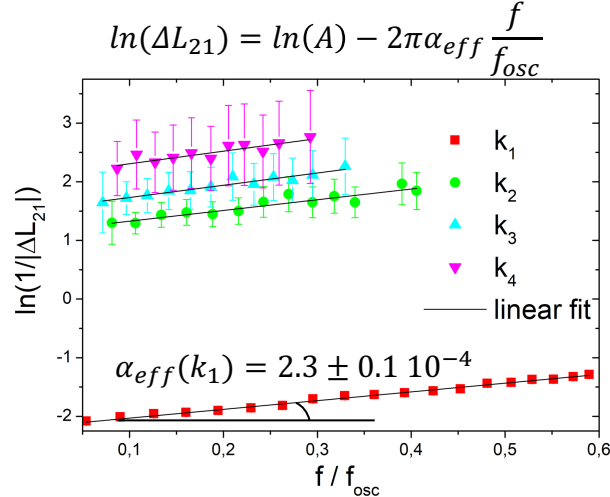
k-DEPENDENCE OF THE DAMPING ...(ii)

Tracking the H-dependence of $L_{att} = \frac{2v_g}{\Delta\omega}$

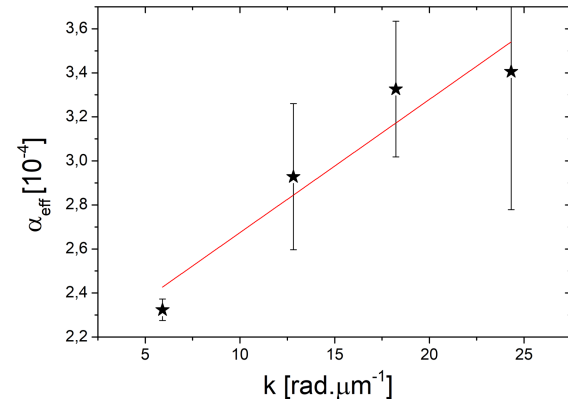
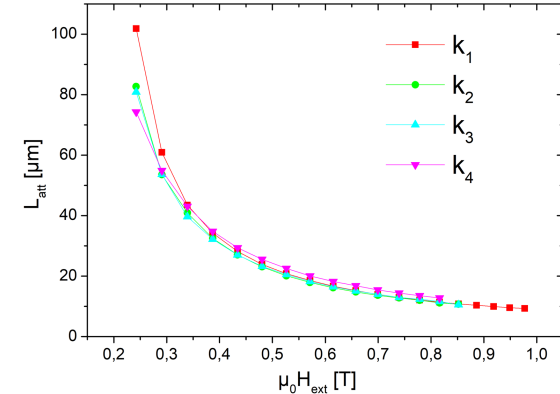


$$\Delta L_{21} = A e^{-\frac{D}{L_{att}}}$$

$$k_2 = 12.8 ; k_3 = 18.2 ; k_4 = 24.3 \text{ [rad/}\mu\text{m]}$$



- Lower damping on this series
- Possibility to evaluate α_{eff} from a single device
- Slight variation of α_{eff} with the different k-vectors ... ???



2. SPIN WAVE BEAM FROM CONSTRICTED CPW

- _ DESIGN OF SHARPLY CONSTRICTED CPW
- _ DISCRETE MAPPING WITH μM -SIZE PROBING ANTENNA
- _ FRESNEL APPROACH

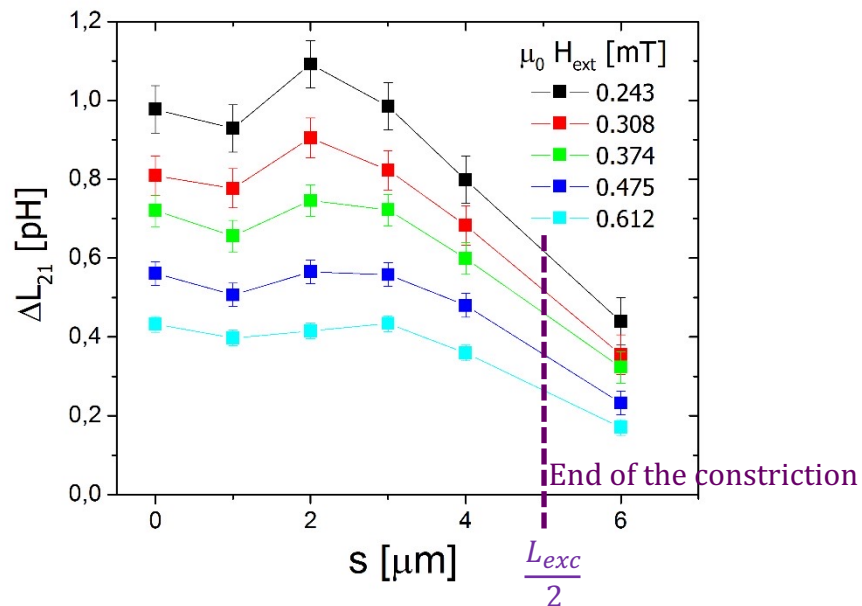
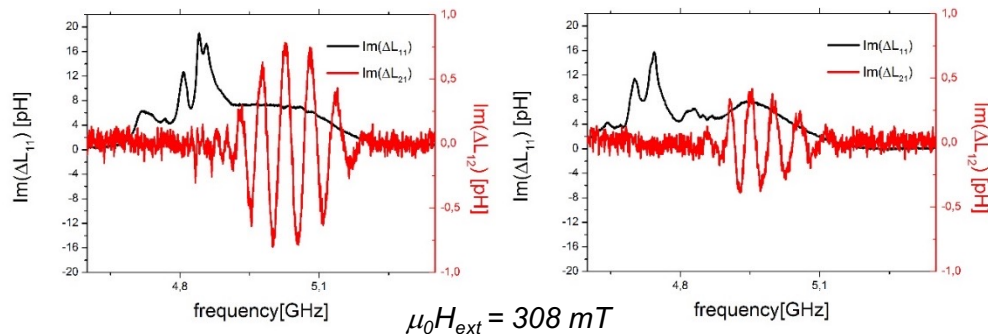
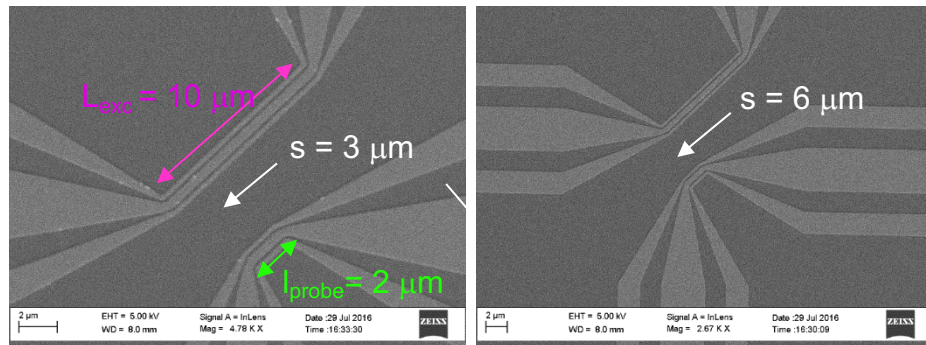


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DISCRETE MAPPING - GEOMETRY #1

Non-identical pairs of antenna (with different length): $L_{\text{exc}}=10\mu\text{m}$, $l_{\text{probe}}=2\mu\text{m}$

$$\lambda_{\text{SW}} = 1 \mu\text{m} ; D = 5 \mu\text{m} ; s = \{0,1,2,3,4,6\} \mu\text{m}$$

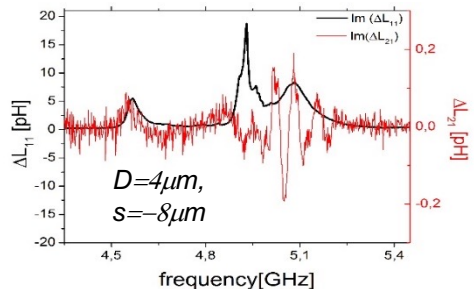
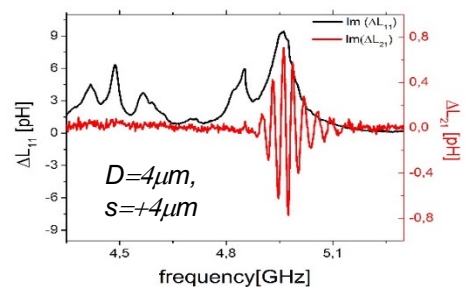
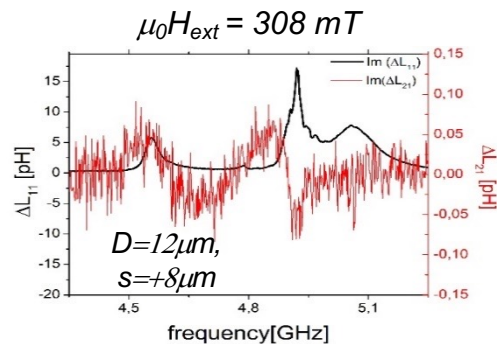
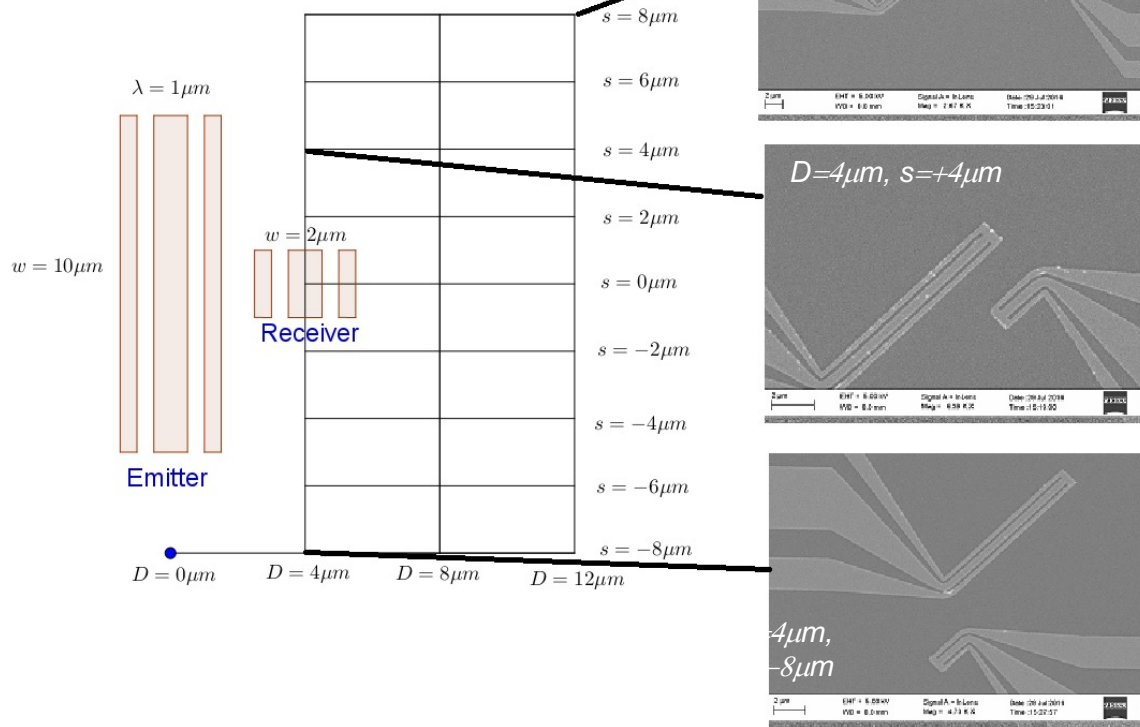


- Drop of amplitude outside of the constriction
- Oscillations within the width of the emitter antenna

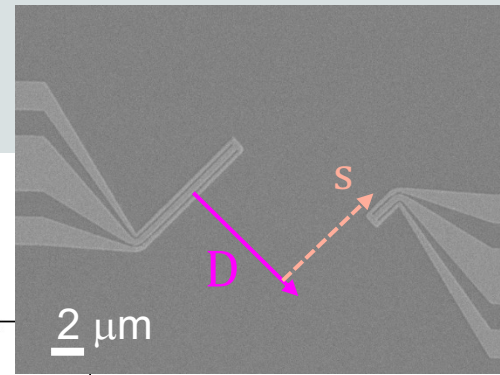
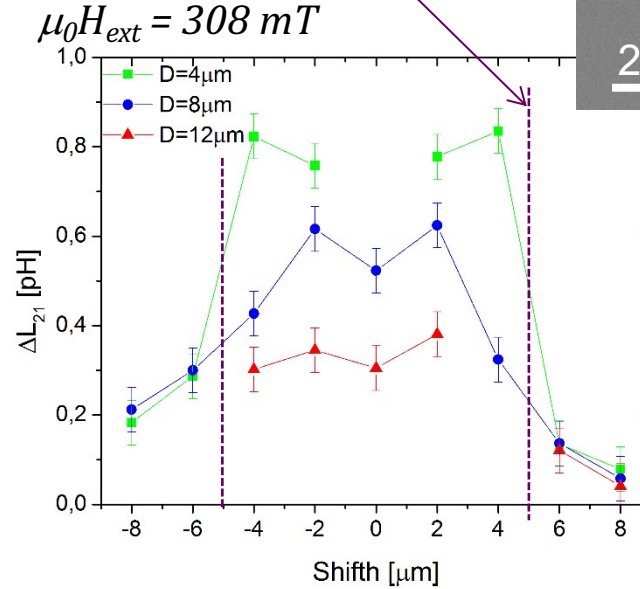
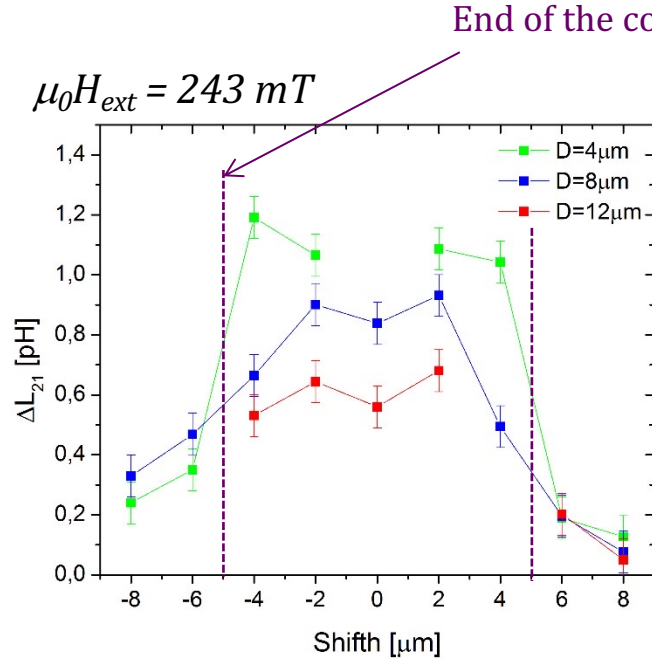
DISCRETE MAPPING - GEOMETRY #2

Non-identical pairs of antenna
($L_{\text{exc}}=10\mu\text{m}$, $L_{\text{probe}}=2\mu\text{m}$)

$D=\{4,8,10\} \mu\text{m}$; $s=\{0,\pm 2,\pm 4, \pm 6, \pm 8\} \mu\text{m}$



DISCRETE MAPPING - GEOMETRY #2 ($|\Delta L_{21}|(S)$)

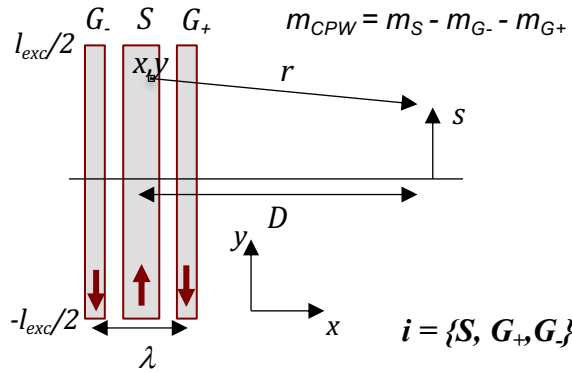


- Asymmetric drop of amplitude outside the width of the constriction
- Oscillations within the width of the emitter antenna

FRESNEL DIFFRACTION MODEL FOR MSFVW

Near-Field : $R_F = (\lambda D)^{1/2} < l_{exc}$

Diffraction of circular waves with damping
from 3 rectangular apertures: G-S-G



$$\tilde{m}_i(D, s) = \int_{-\frac{l}{2}}^{\frac{l}{2}} dy \int_{-\frac{w_i}{2}}^{\frac{w_i}{2}} dx \frac{1}{\sqrt{r_i}} e^{-\frac{r_i}{L_{att}}} e^{ik r_i}$$



Remarkable agreement for
such a simple model

$f=5.15\text{GHz} - \mu_0 H_{ext}=308\text{mT}$

Fresnel model

$k_{res} = 6,17 \text{ rad}/\mu\text{m}$
 $L_{att}=13,8\mu\text{m}$

MuMax 3 (done by D. Stoeffler)

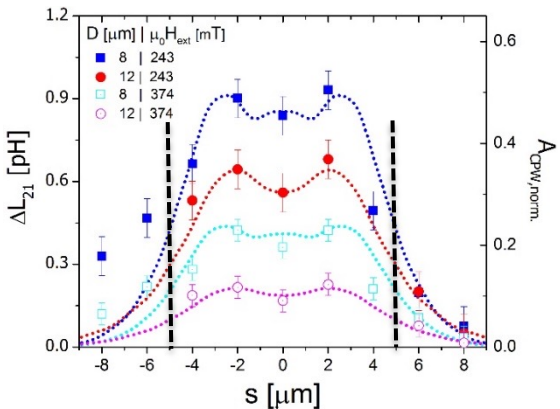
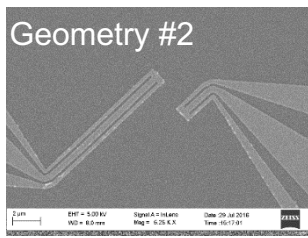
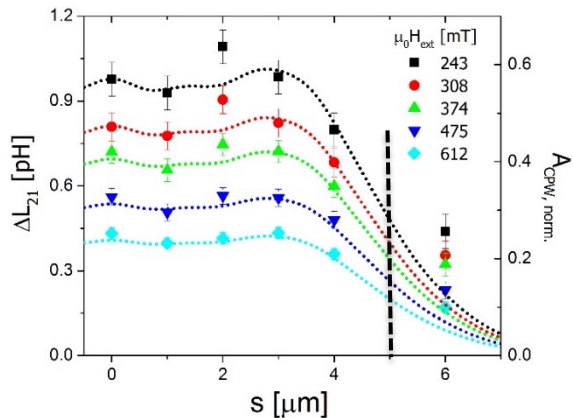
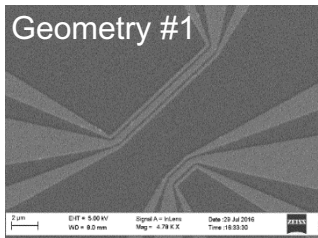
$f=5.25\text{GHz} - \mu_0 H_{ext}=308\text{mT}$

Fresnel model

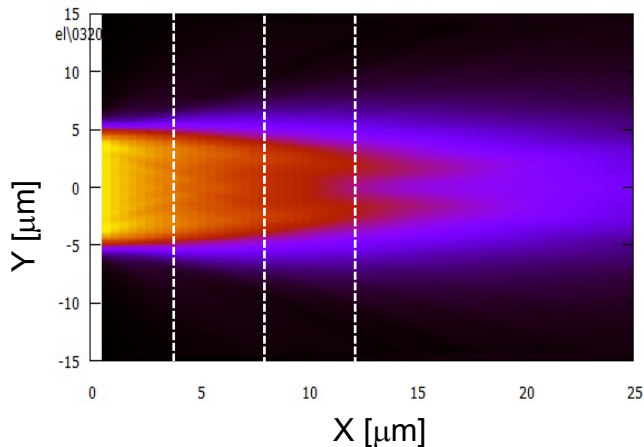
$k_{res} = 7,98 \text{ rad}/\mu\text{m}$
 $L_{att}=14,5\mu\text{m}$

MuMax 3 (done by D. Stoeffler)

COMPARISON OF FRESNEL SIMULATIONS WITH EXPERIMENTS



*Simu using $L_{att}(f,H,k)$ and
summing over the $2\mu\text{m}$
probe antenna length*



- ✓ Diffraction features well explained with near-field Fresnel model
- ✓ Discrete mapping of SW with non-identical pairs of antenna



3. SPIN WAVE DIFFRACTION FROM CURVED ANTENNA

- _ NEAR DIFFRACTION MODEL
- _ CONCENTRATOR
- _ « YOUNG-SLIT » DEVICE

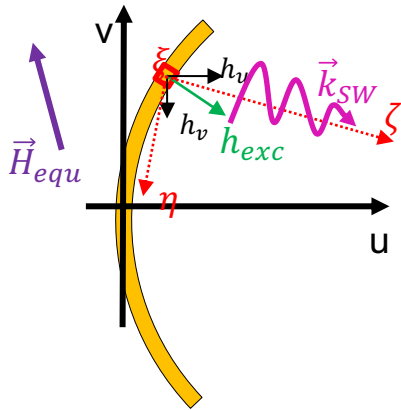


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NEAR-FIELD DIFFRACTION MODEL FOR ARBITRARILY SHAPED ANTENNA

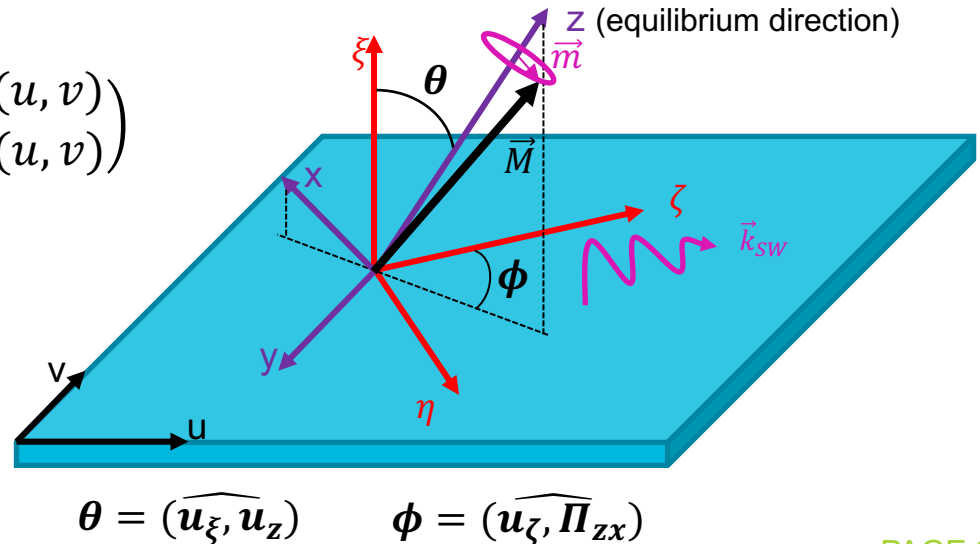
Goal: Use Kalinikos approach [J. Phys. C:Solid State Phys. 19 (1986)] to express $\vec{m}(u, v, t)$ in the Lab coordinate for any geometry of excitation: (i) curvilinear antenna ($\vec{h}_{exc}(k_u, k_v)$), and (ii) arbitrary orientation $\vec{H}_{ext}$:

$$\vec{m}(u, v, t) = e^{i\omega t} \iint_{-\infty}^{+\infty} dk_u dk_v \{ \vec{\chi}(k_u, k_v) \cdot \vec{h}_{exc}(k_u, k_v) \} e^{-i(k_u u + k_v v)}$$



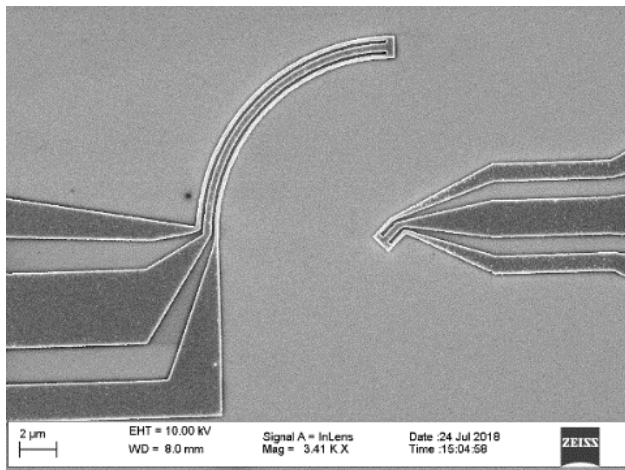
$$\vec{m}(u, v) = \begin{pmatrix} m_x(u, v) \\ m_y(u, v) \end{pmatrix}$$

- Lab Frame (u, v, ξ)
- Frame of the propagating SW (ξ, η, ζ)
- Frame for the magnetization (x, y, z)
(z =Equilibrium direction)



GEOMETRY #1: CONCENTRATOR (MuMax3 vs NFD model)

Circular antenna
($\frac{\pi}{2}$ arc ; R=10 μ m)

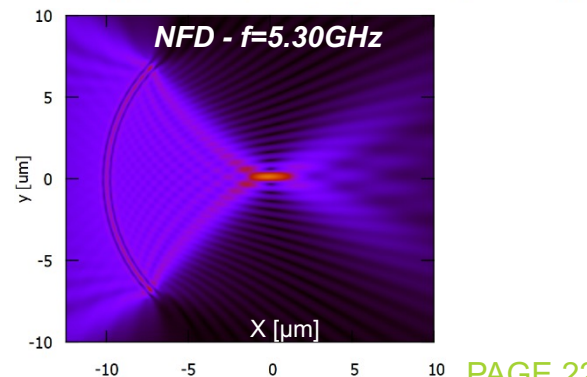
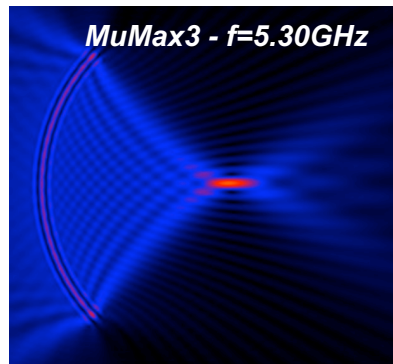
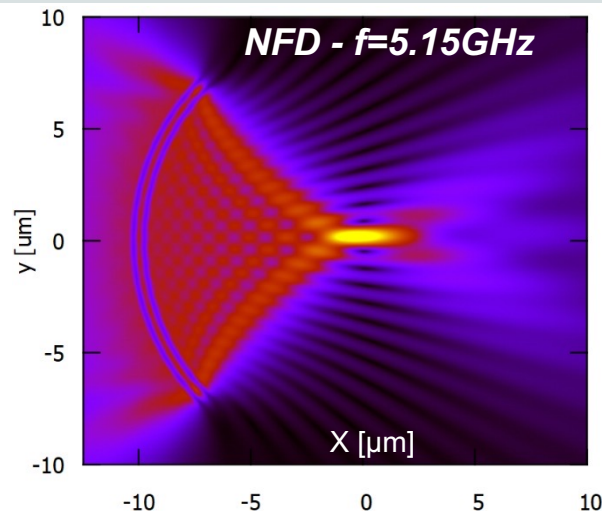
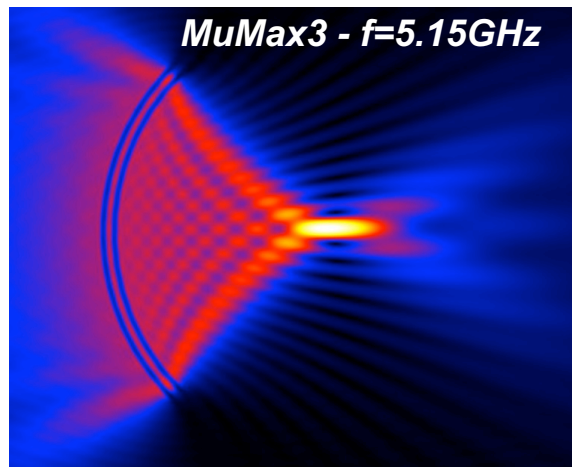


Simulation parameters YIG (t=30nm):

$$\mu_0 H_{ext} = 308 \text{ mT} ; \mu_0 M_s = 198 \text{ mT}$$

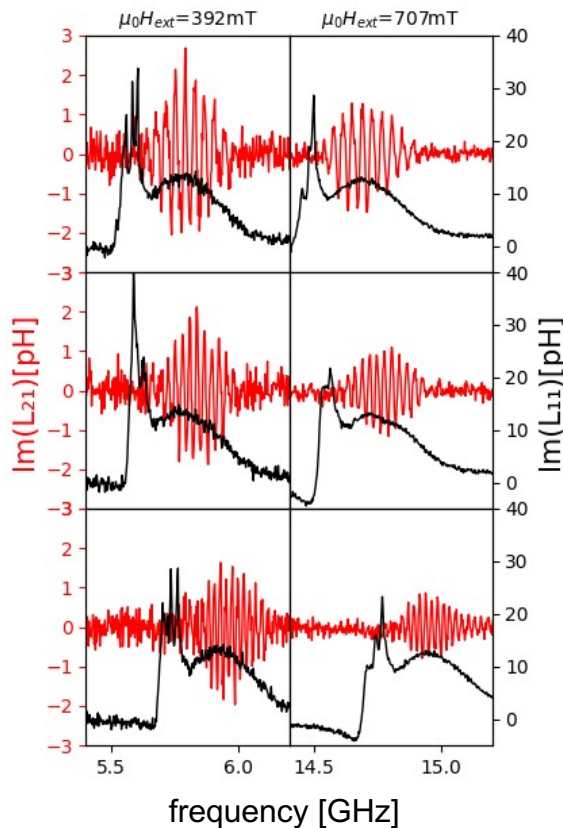
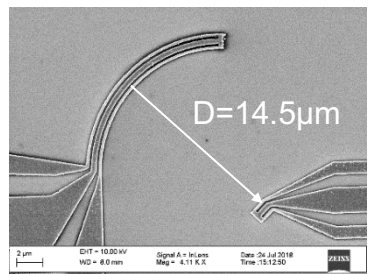
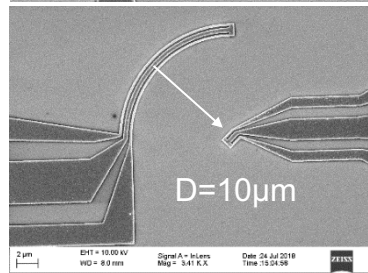
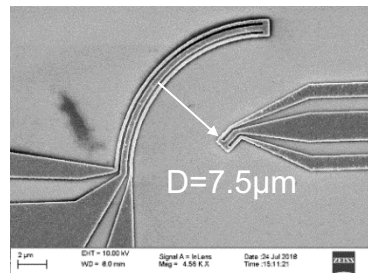
$$K_u = 4.88 \text{ kJ.m}^{-3} ; A_{exc} = 4 \text{ pJ.m}^{-1}$$

$$\frac{\gamma}{2\pi} = 28.26 \text{ GHz.T}^{-1} ; \alpha = 7.5 \cdot 10^{-4}$$



CONCENTRATOR - MEASUREMENT $\Delta L_{21}(D)$

Probing the interference pattern along x-axis $D = \{7.5, 10, 12, 14.5, 18\} \mu\text{m}$

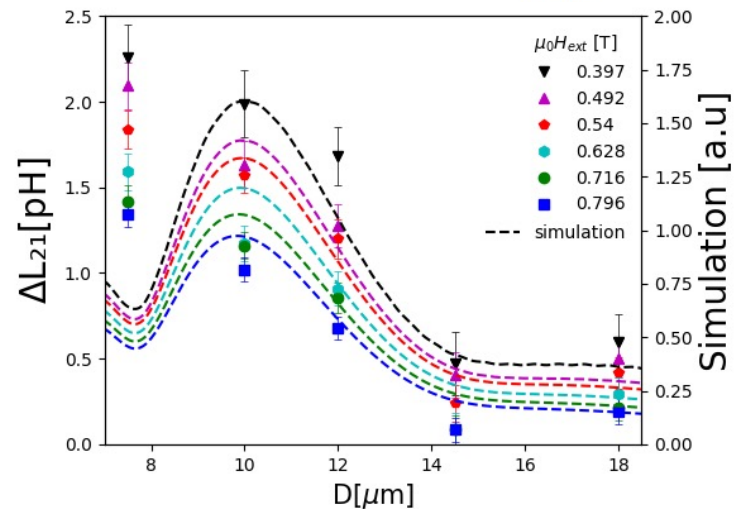
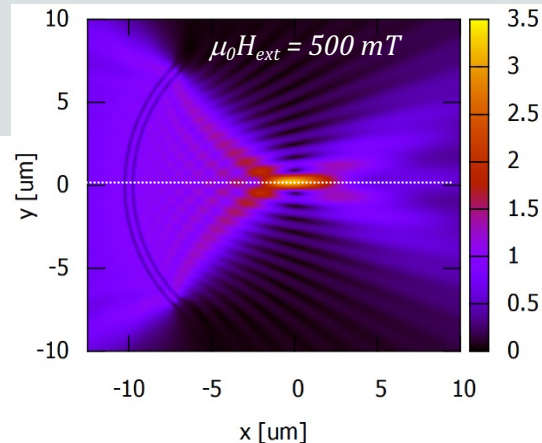


Simu YIG 30nm

$$\mu_0 M_s = 190 \text{ mT}$$

$$A_{exc} = 3.5 \text{ pJ.m}^{-1}$$

$$\alpha = 2.3 \cdot 10^{-4}$$

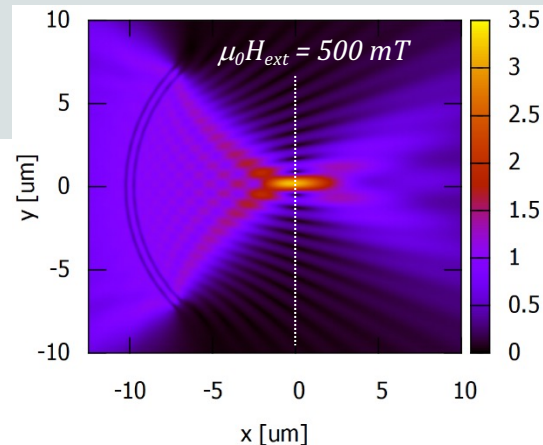
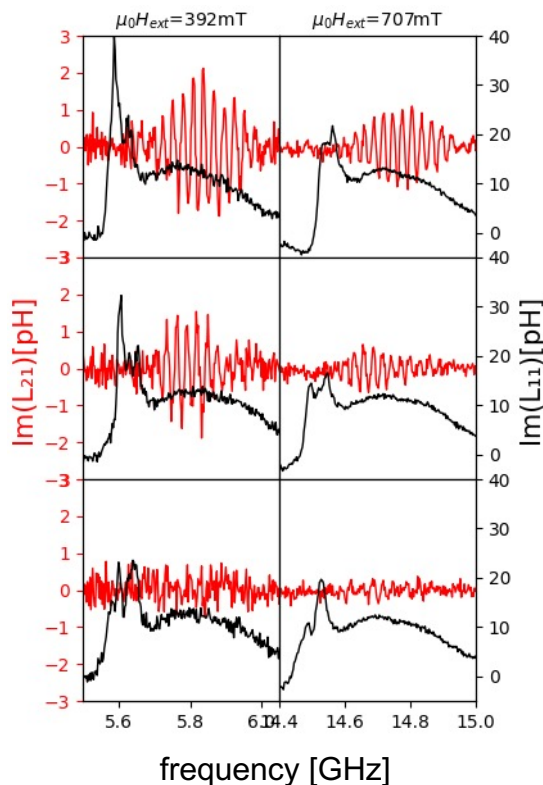
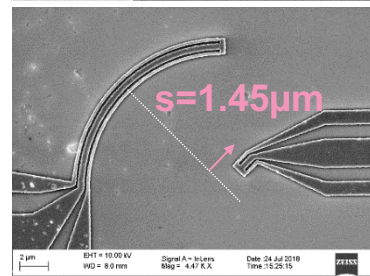
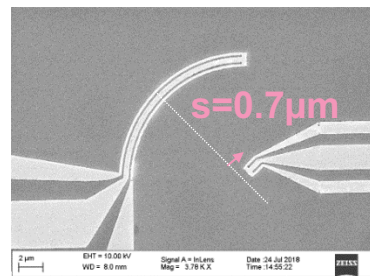
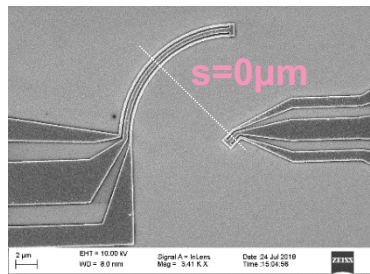


Limitation for defining a punctual probe

CONCENTRATOR - MEASUREMENT $\Delta L_{21}(s)$

Probing the interference pattern along y-axis across the focal point $D=10\mu\text{m}$

$$s = \{0, 0.7, 1.45, 2.55\} \mu\text{m}$$

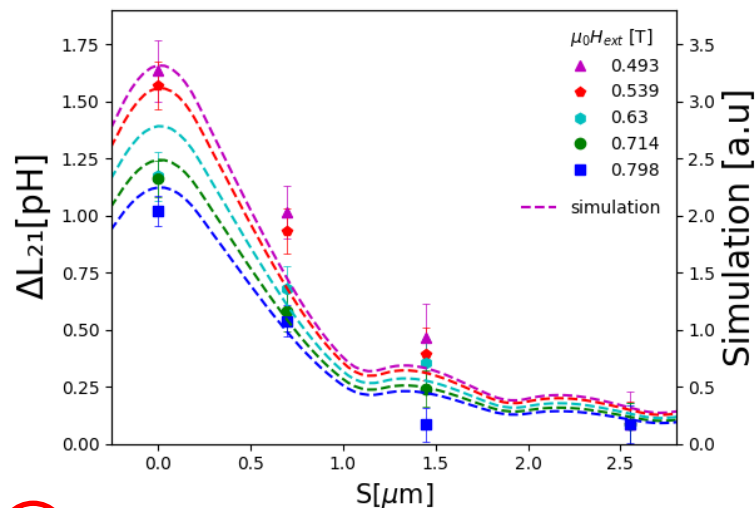


Simu YIG 30nm

$$\mu_0 M_s = 190 \text{ mT}$$

$$A_{exc} = 3.5 \text{ pJ.m}^{-1}$$

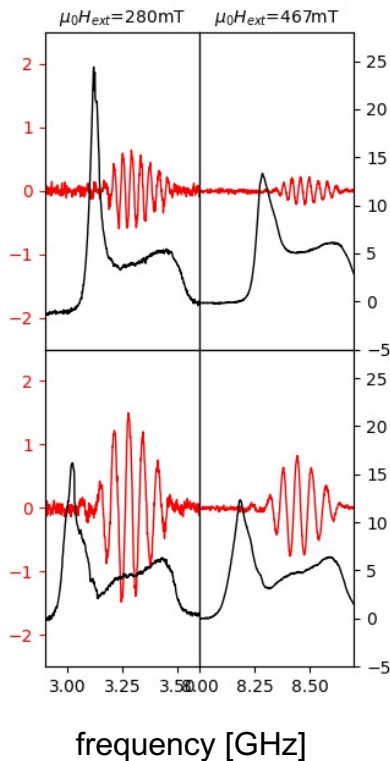
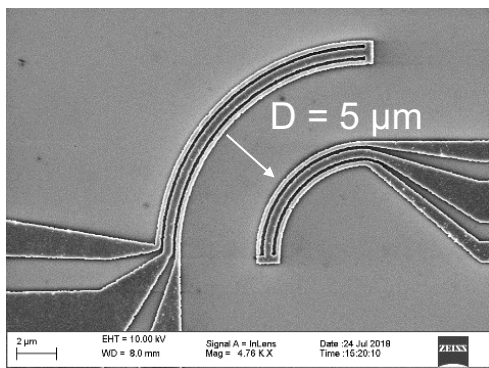
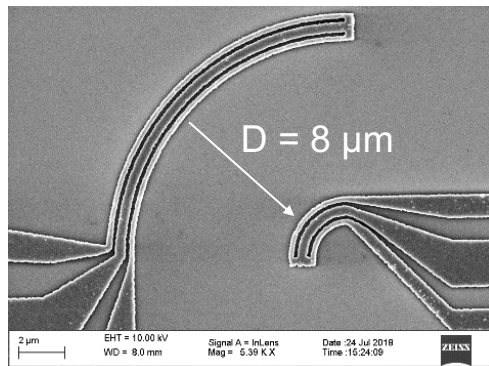
$$\alpha = 2.3 \cdot 10^{-4}$$



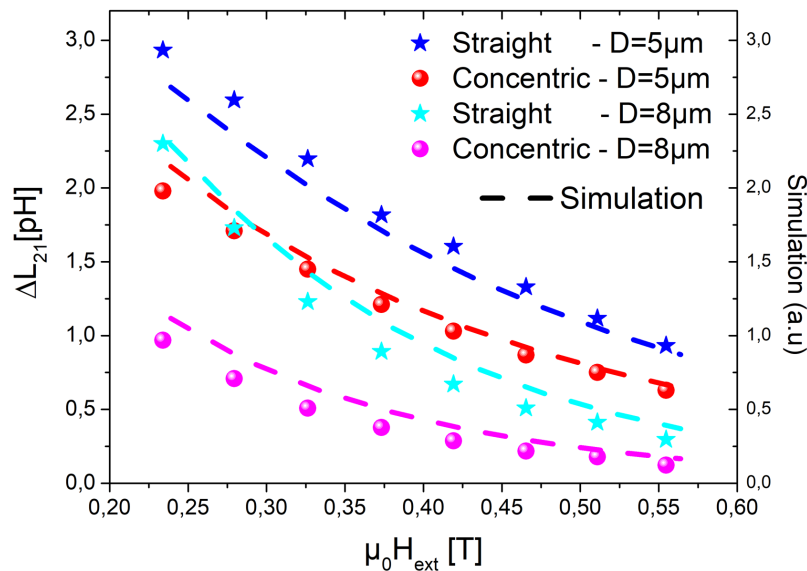
Fast decay across the focal point

GEOMETRY #2: CONCENTRIC ANTENNA

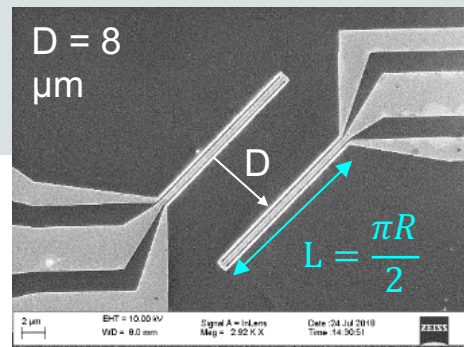
Comparison between straight and curved antenna of same length $L = \frac{\pi R}{2}$



Simu YIG 30nm
 $\mu_0 M_s = 198 \text{ mT}$, $\mu_0 M_{eff} = 136 \text{ mT}$,
 $A_{exc} = 3.5 \text{ pJ.m}^{-1}$; $\alpha = 7.5 \cdot 10^{-4}$



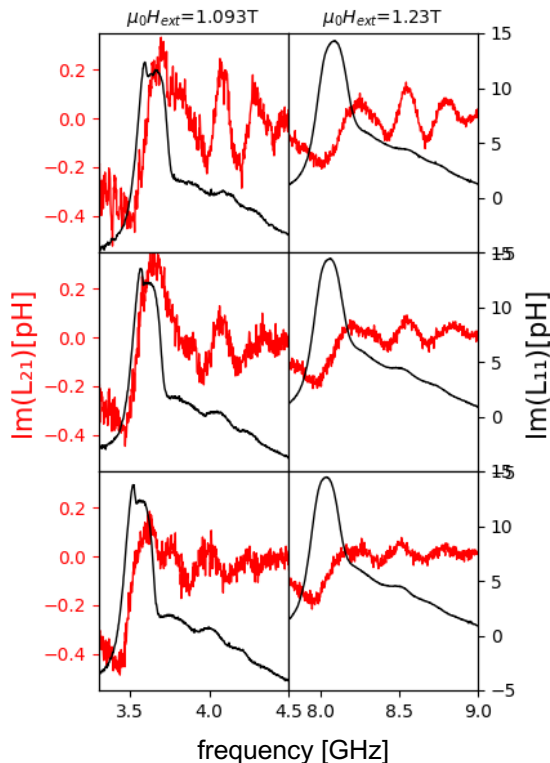
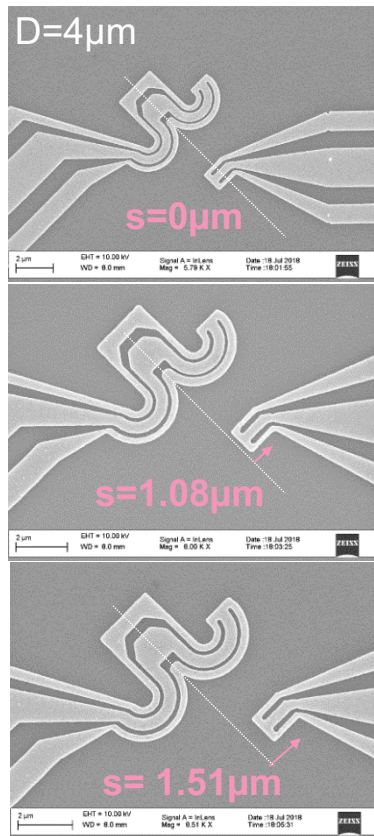
Very good agreement between measurement and NFD model



GEOMETRY #3: “YOUNG-SLIT” SPIN WAVE

Probing the interference pattern along y-axis at $D=4\mu\text{m}$

$$s = \{0, 0.47, 0.9, 1.38, 2.0, 3.0, 2.55\} \mu\text{m}$$

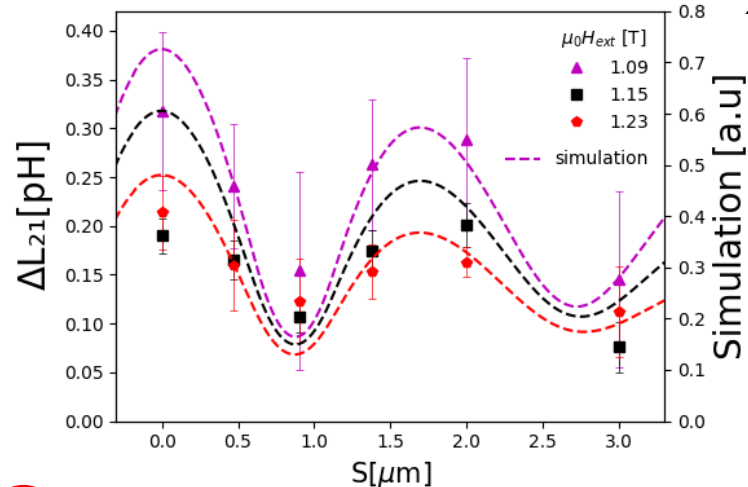
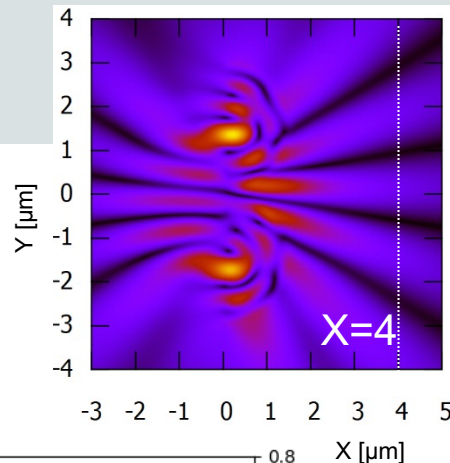


Simu Py 20nm

$$\mu_0 M_s = 1 \text{ T}; H_K = 0$$

$$A_{exc} = 7.5 \text{ pJ.m}^{-1}$$

$$\alpha = 5.5 \cdot 10^{-3}$$



First demonstration of a Young-2slit spin wave experiment

4. CAUSTIC EFFECTS FROM IN-PLANE MODES

- _ MODEL FOR IN-PLANE MODE
- _ SELF-FOCUSING FROM CONSTRICTION
- _ TOWARDS CAUSTIC BEAM TRANSDUCTION

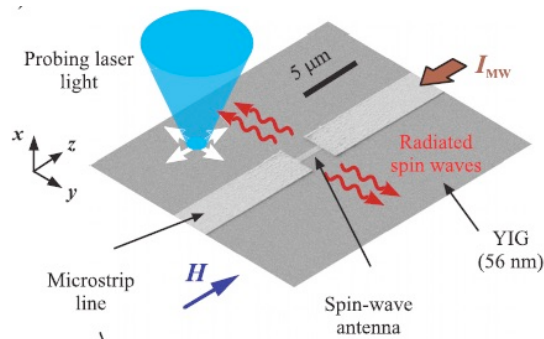


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NEAR-FIELD FOCUSING OF SPINWAVES

“Tight” focusing of a spin wave beam excited in extended nanometer-thick films

Appl. Phys. Lett. 116, 062401 (2020)



Near-Field
Diffraction simu

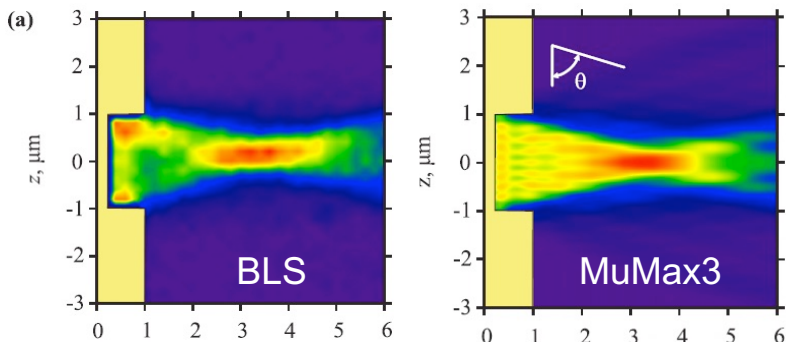
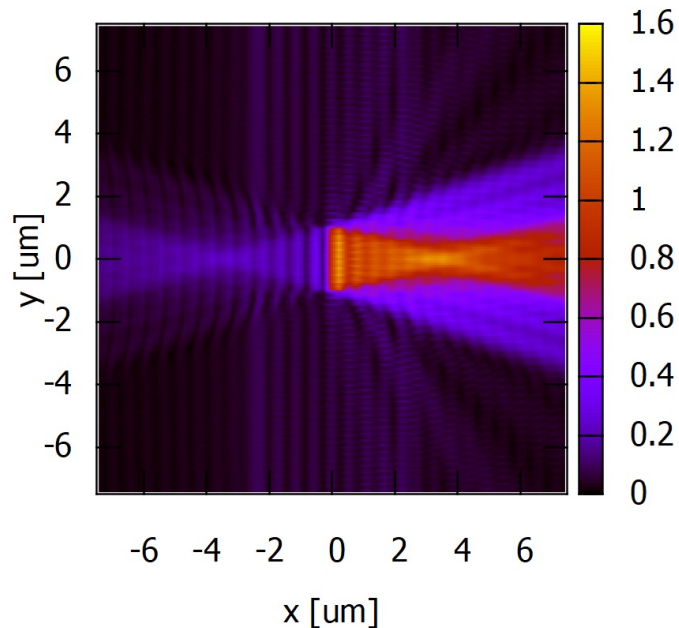
YIG 30nm

$$\mu_0 H_{ext} = 50 \text{ mT}$$

$$\mu_0 M_s = 0.17 \text{ T};$$

$$A_{exc} = 3,66 \text{ pJ} \cdot \text{m}^{-1}$$

$$\alpha = 1.4 \cdot 10^{-4}$$

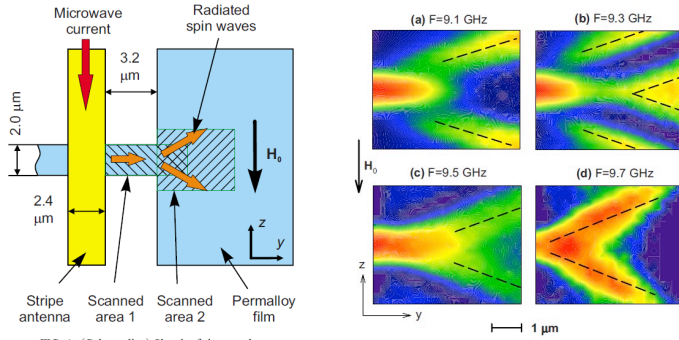


**Micromagnetic simulation not
always necessary for mapping
near-field diffraction pattern**

EMISSION OF CAUSTIC BEAM FROM A TRANSITION

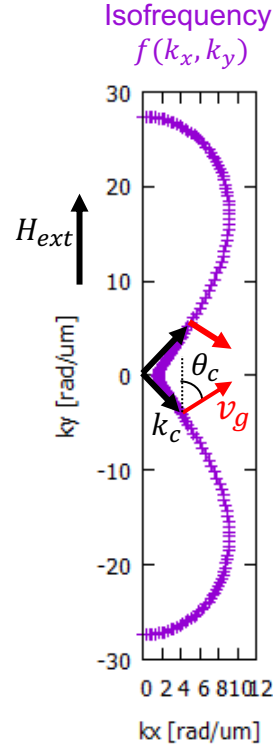
Caustic beams from a transition btw a waveguide and a continuous area

- V. Demidov et. al., *Phys. Rev. B* **80**, 014429 (2009)

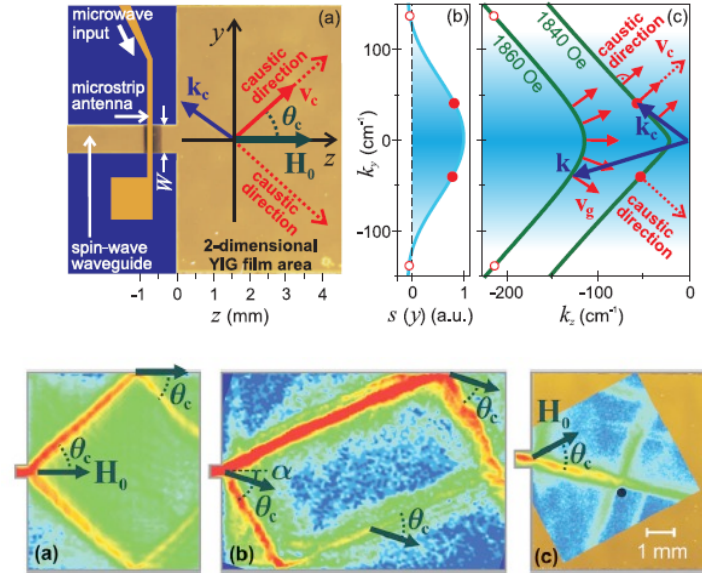


Caustic beams when the direction of group velocity is the same for different wave vectors k :

$$\frac{d^2 k_z}{dk_y^2} = 0$$

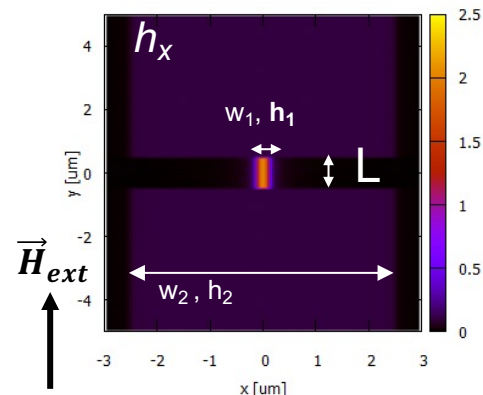


- T. Schneider, et. al, *PRL* 104, 197203 (2010)

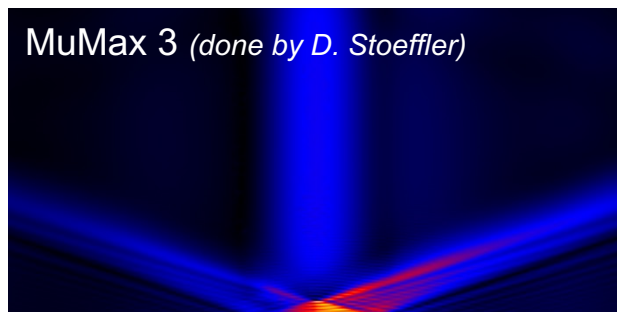


EMISSION OF CAUSTIC BEAM FROM A CONSTRICTION

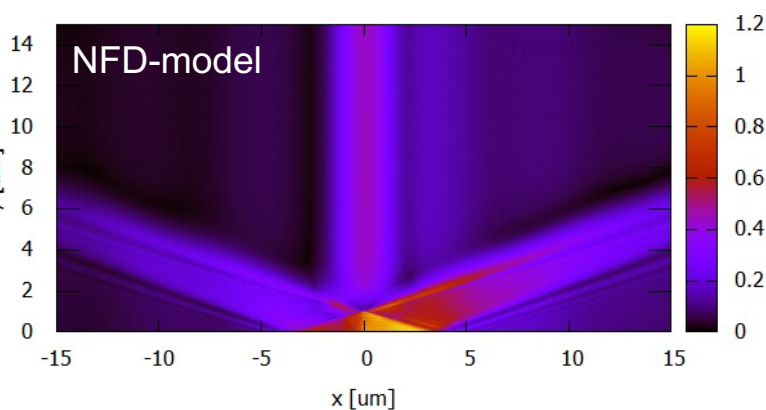
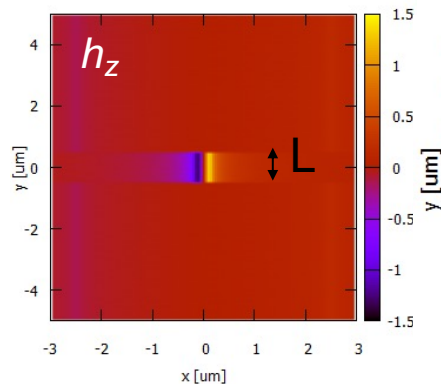
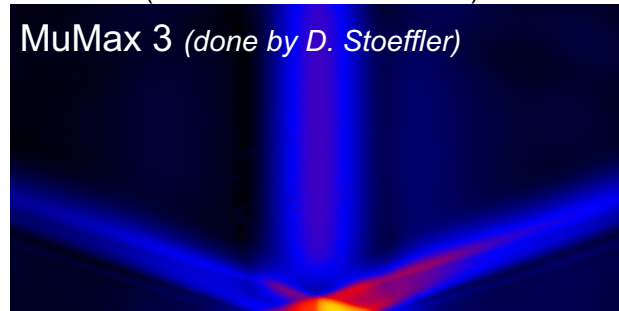
Sufficiently sharp constriction to enhance the exciting field and broaden the k-space emission



Abrupt discontinuity of $\vec{h}$



Smooth transition of $\vec{h}$ at the constriction
(based on T. Brächer thesis)



Simulations CoFeB 25nm
 $f = 13\text{GHz}$; $\frac{\gamma}{2\pi} = 28.26\text{ GHz} \cdot \text{T}^{-1}$
 $\mu_0 H_{ext} = 100\text{mT}$; $\mu_0 M_s = 1.57\text{T}$
 $A_{exc} = 16\text{pJ} \cdot \text{m}^{-1}$; $\alpha = 3 \cdot 10^{-3}$

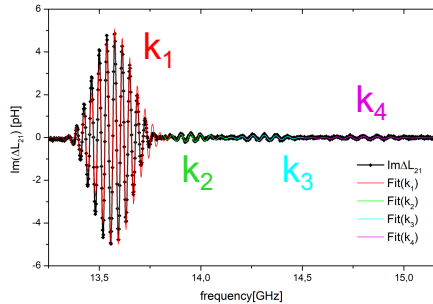
Good agreement btw NFD-model and MuMax3
 → **Possibility to shape caustic beams from a sharp constriction**

CONCLUSION



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SUMMARY – CONCLUSION (I)



I. ☺ k-resolved spectroscopy provides fine characterization of A_{exch} , $L_{\text{att}}(k)$, $v_g(k)$, $\alpha_{\text{eff}}(k)$

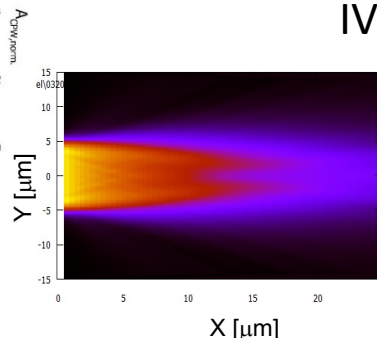
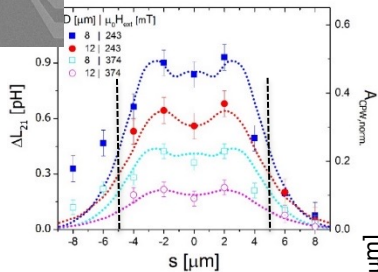
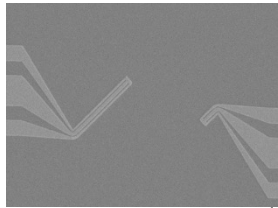
II. ☺ Two series of sputtered 30nm thin YIG (ANL) (out-of-plane) measurement

$$A_{\text{exch}} = 3.3 \pm 0.2 \text{ pJ} \cdot \text{m}^{-1} : L_{\text{att}}(k) \text{ up to } 100 \mu\text{m} @ 3\text{GHz, and } 10 \mu\text{m} @ 23\text{GHz}$$

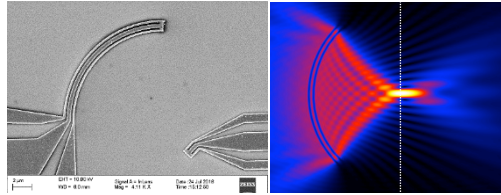
$$v_g(k) = [250..550 \text{ m} \cdot \text{s}^{-1}] : \alpha_{\text{eff}}(k) \# \{2 \cdot 10^{-4}; 7 \cdot 10^{-4}; 10^{-3}\} ()$$

III. Focused spin wave beam from constriction explained in terms of Fresnel diffraction

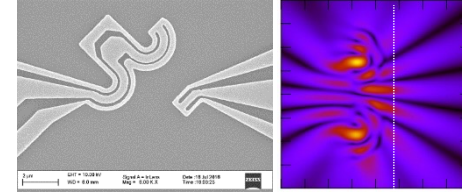
IV. Remarkable agreement btw simple circular wave model and MuMax3 simulation for a straight antenna



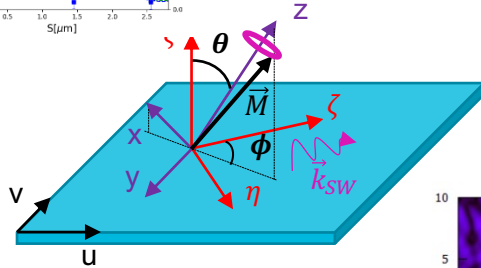
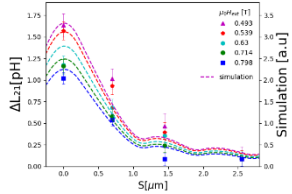
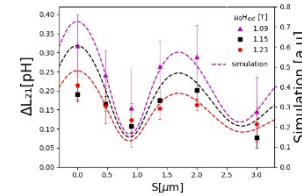
SUMMARY – CONCLUSION (II)



- I. All-electric measurement of near-field diffraction pattern of 3 curvilinear antennas:
concentrator ; concentric ; Young-2-Slit

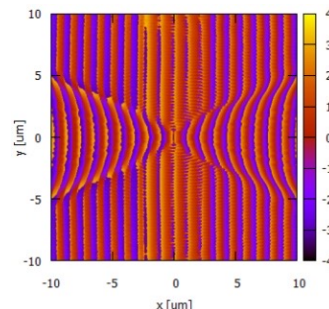
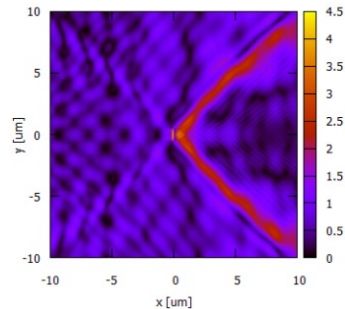


- II. Kalinikos formalism adapted to curvilinear excitation field: → good agreement with MuMax3
→ well verified with experiment



- III. On-going exploration for in-plane diffractive effects:

- Caustic beam shaping and stirring from a constricted stripline
- Caustic beam transduction



REMERCIEMENTS – AGRADECIMIENTO - ACKNOWLEDGEMENT

Thank you !



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