

6th July 2022

DEVELOPMENT OF A MAGNETIC SENSOR BASED ON MAGNONIC MATERIALS

O. Haas, B. Dufay, S. Saez



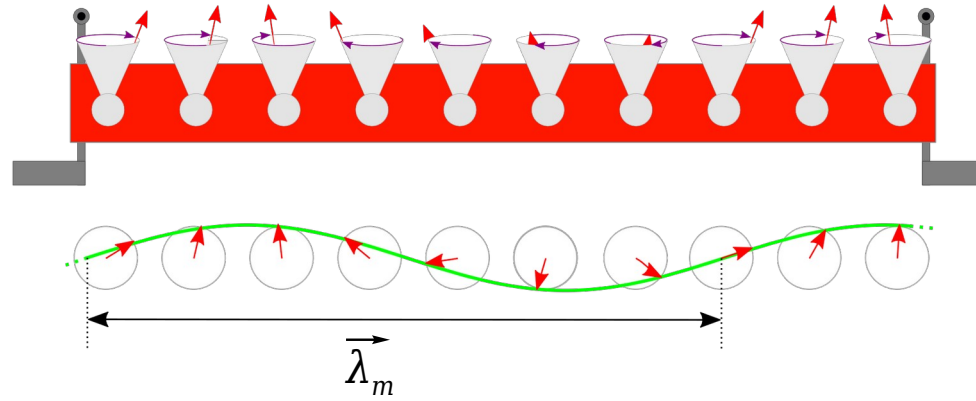
1. Introduction : measurement principle of the sensor
 - Spin wave and dependence to the external applied magnetic field
 - Conditioning circuitry
2. Optimization of the intrinsic sensitivity
 - Stationary spin waves
 - Spin wave rejection band
3. Voltage sensitivity and noise performances
4. Conclusion

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1. Measurement principle of the sensor

A. Sensing element

input



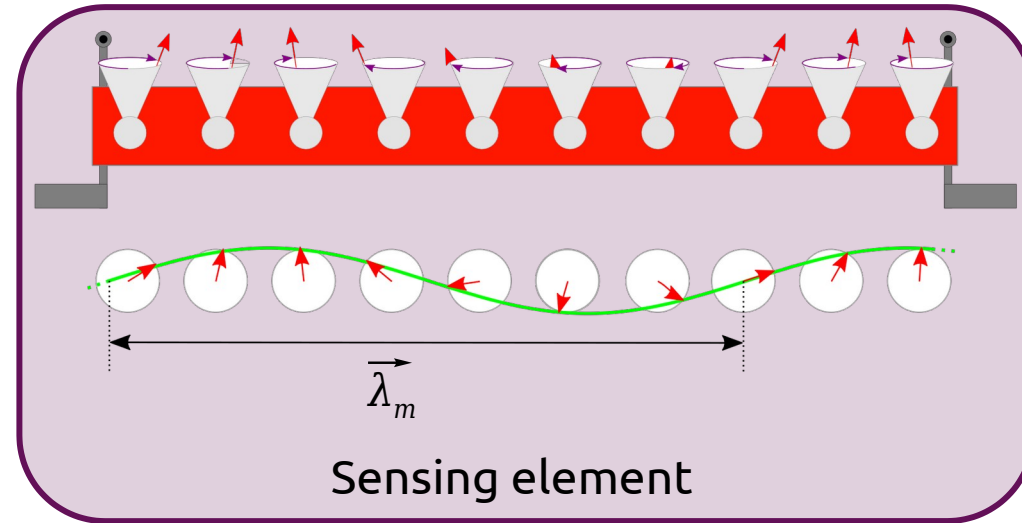
output



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input

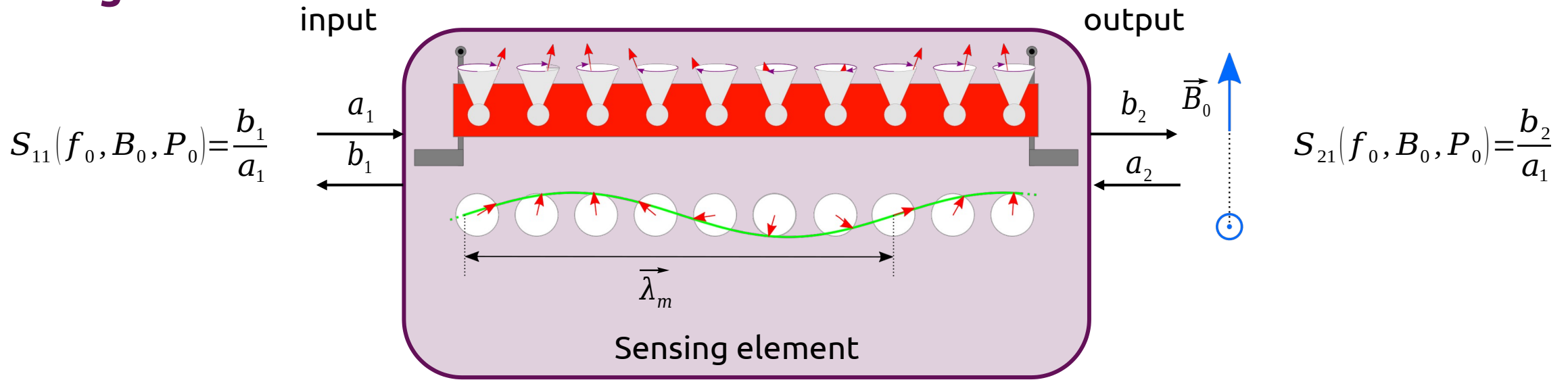


output



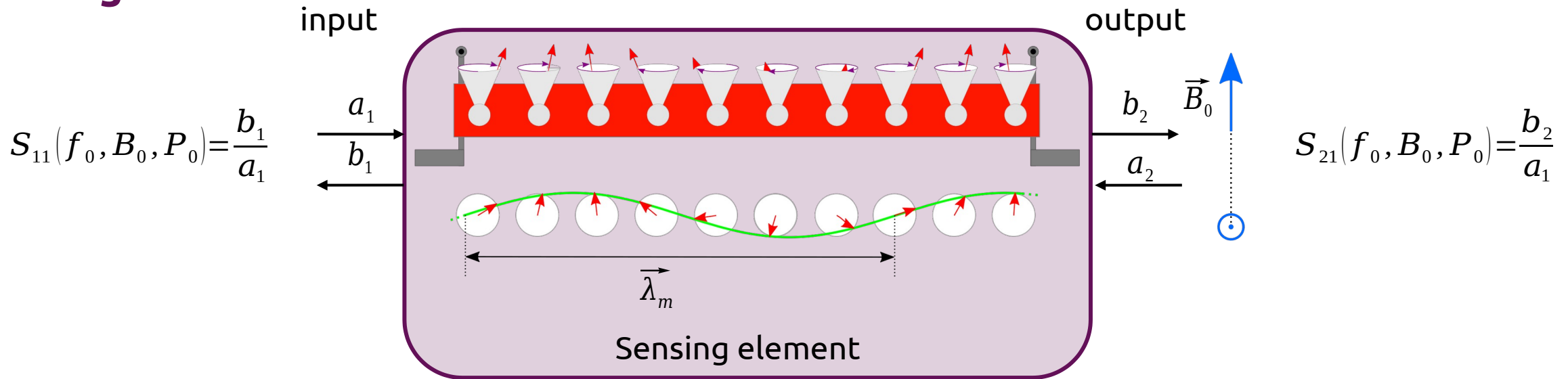
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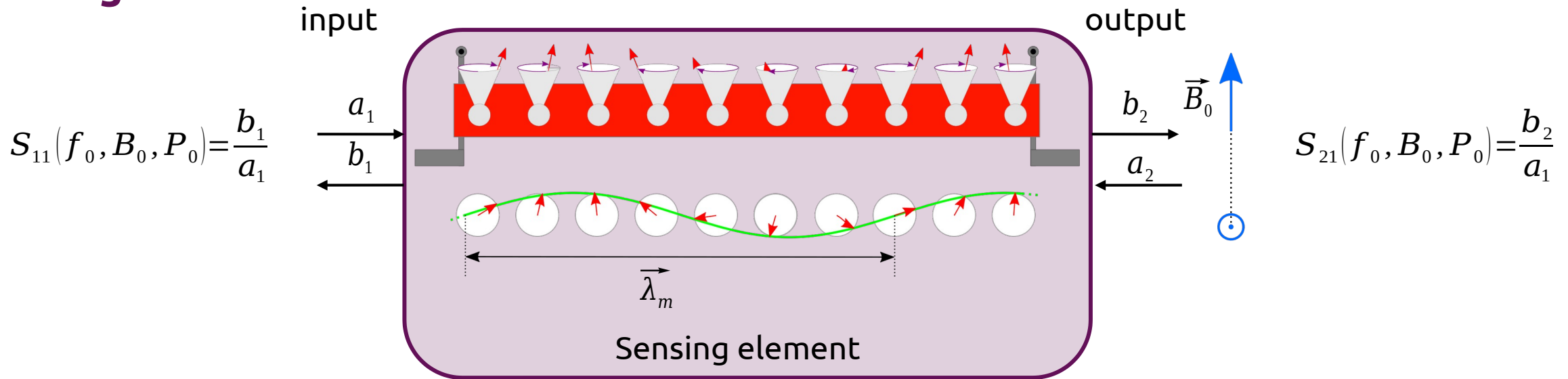


- ▶ High frequency (GHz) excitation → large spin wave wavelength → dipolar interactions between neighboring spins → **Magnetostatic spin wave**
- ▶ Magnetic field applied parallel to the surface and perpendicular to the propagation direction → **Magnetostatic Surface Spin Wave (MSSW)**
- ▶ MSSW dispersion equation :

$$f^2 = \left(\gamma \mu_0 H_{eff} + \frac{\gamma \mu_0 M_s}{2} \right)^2 - \left(\frac{\gamma \mu_0 M_s}{2} \right)^2 e^{-2kd}$$

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γ : gyromagnetic ratio

H_{eff} : applied magnetic field

d : material thickness

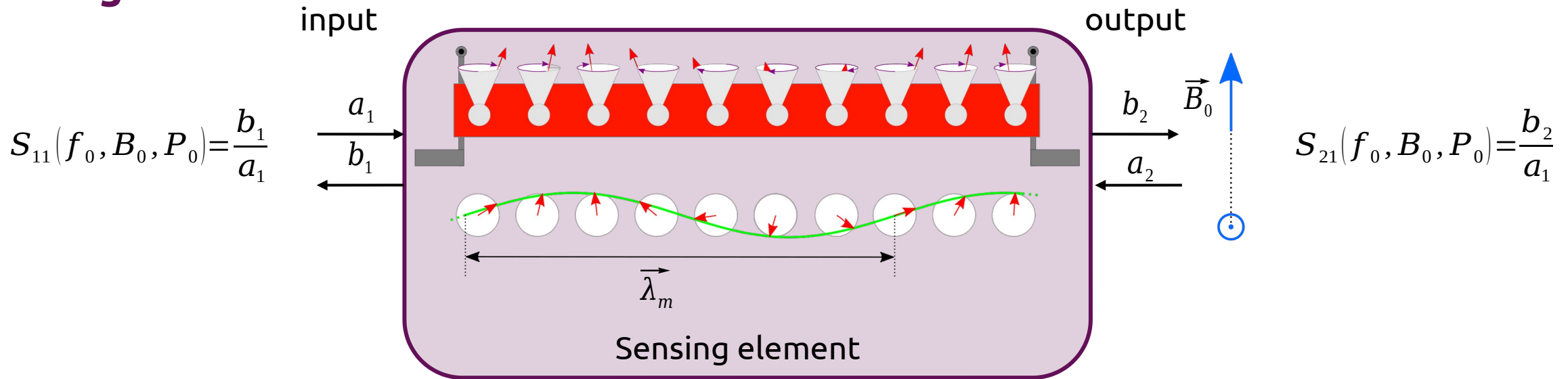
μ_0 : vacuum permeability

M_s : saturation magnetization

k : wave number

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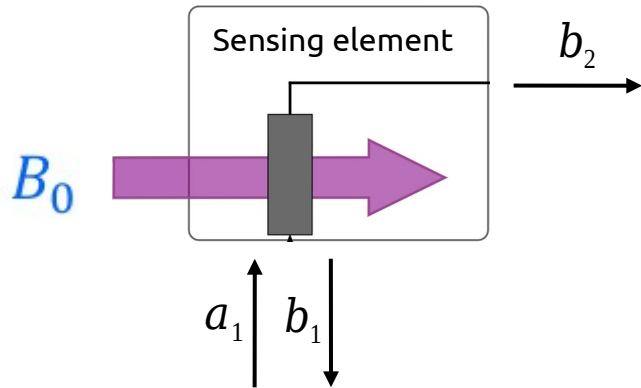


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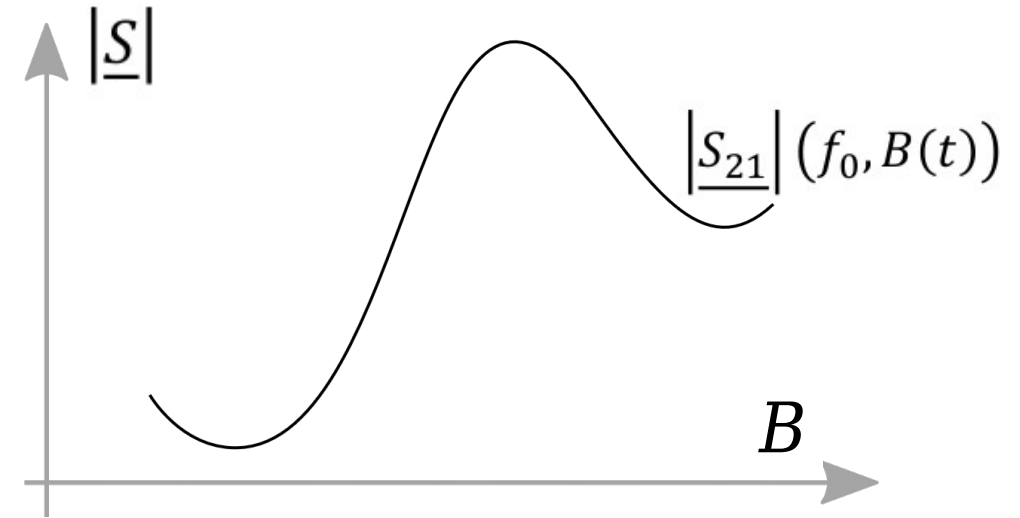
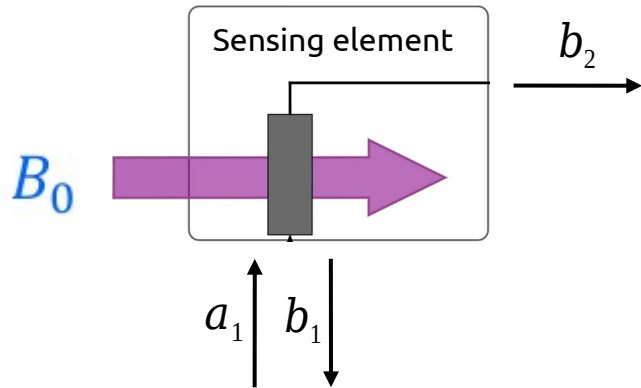
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For $\mathbf{B} = \mu_0 \cdot \mathbf{H} = 7.35 \text{ mT}$ → f ranges from 1.1GHz ($k=0$) to 2.65GHz ($k \rightarrow \infty$)

B. Conditioning circuitry



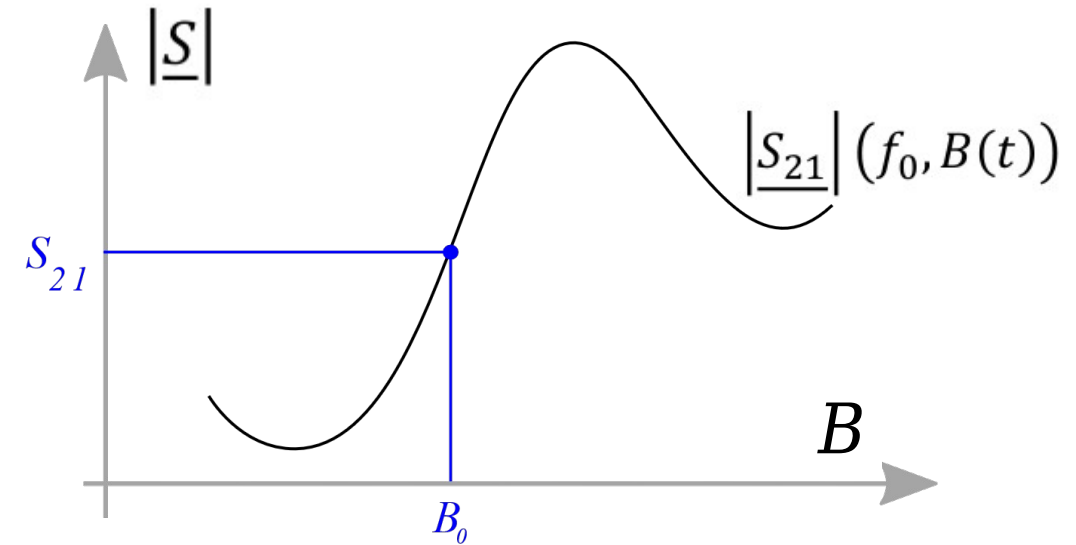
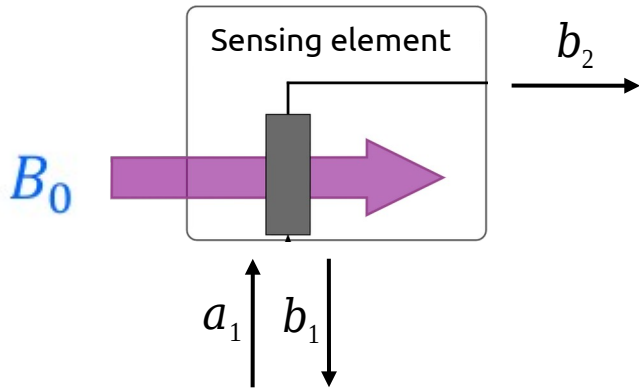
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Characteristics of the sensing element

$$\underline{S}_{21}(f_0, B)$$

B. Conditioning circuitry



Characteristics of the sensing element

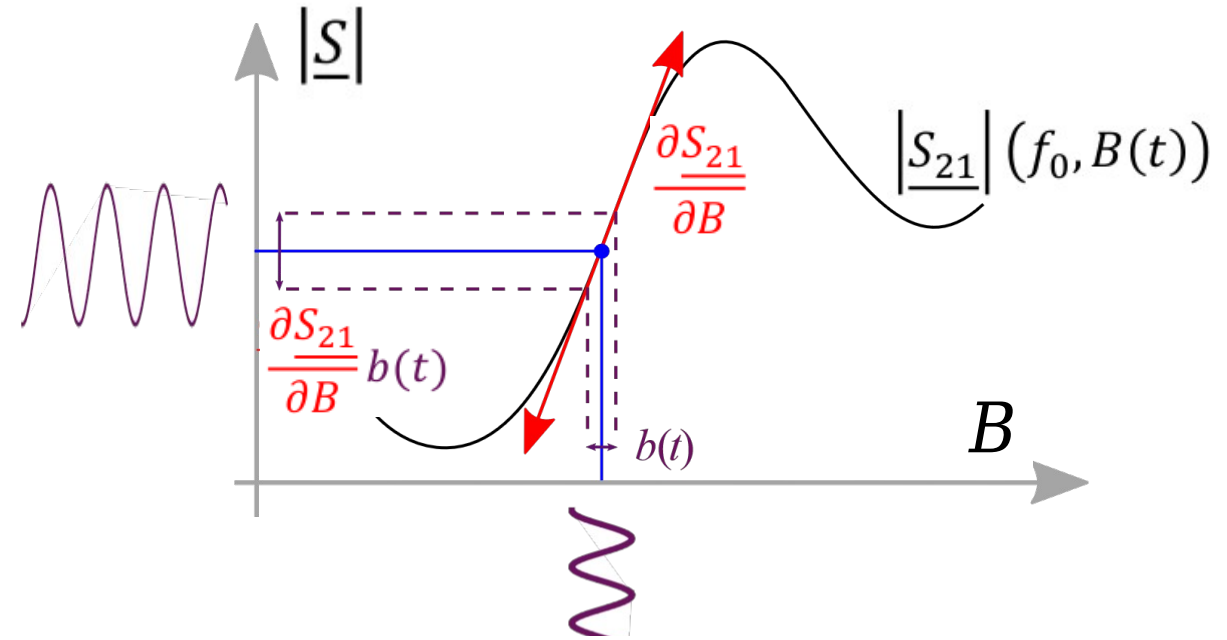
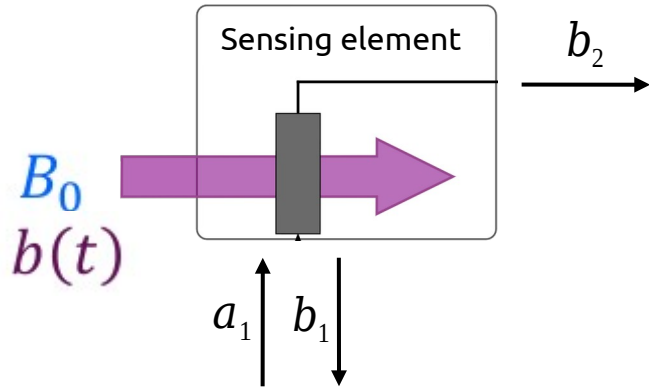
$$\underline{S_{21}}(f_0, B)$$

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Biasing : set the magnetic working point

1. Measurement principle of the sensor

B. Conditioning circuitry



Characteristics of the sensing element

$$\underline{S}_{21}(f_0, B) \approx \underline{S}_{21}(f_0, B_0) + \frac{\partial \underline{S}_{21}}{\partial B}(f_0, B_0) b$$

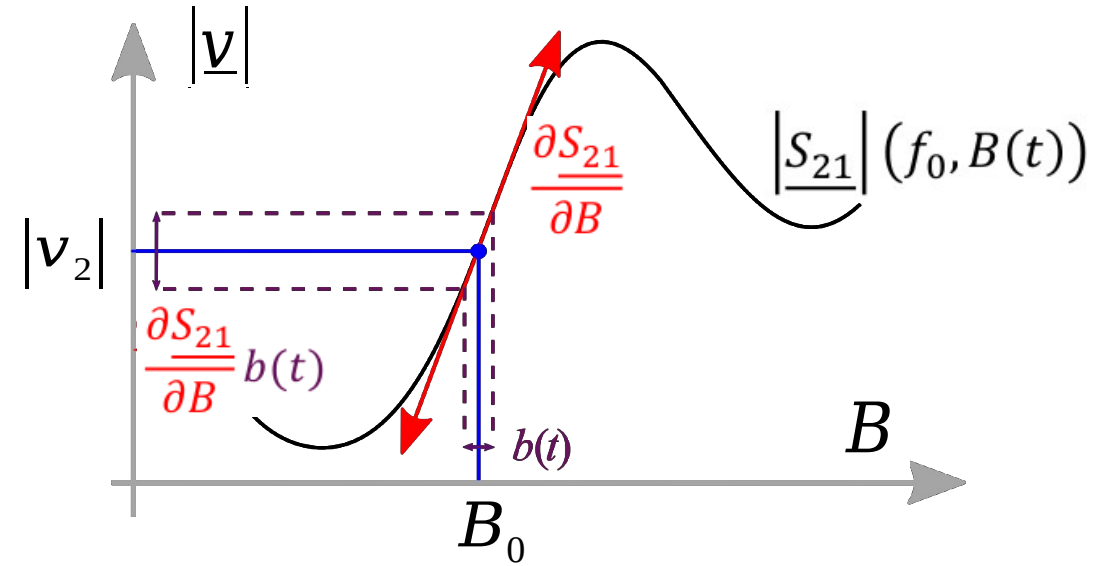
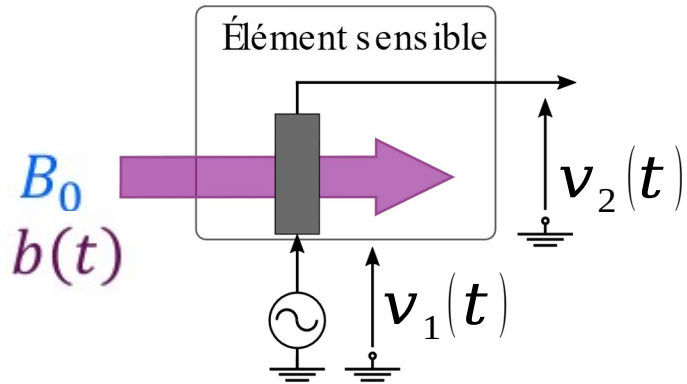
Biasing : set the magnetic working point
Linearization around this working point

Performance criteria

Intrinsic sensitivity $\underline{s}_i = \frac{\partial \underline{S}_{21}}{\partial B} \quad T^{-1}$

1. Measurement principle of the sensor

B. Conditioning circuitry



Output signal

$$\underline{v}_2(t) = \underline{S}_{21}(f_0, B) \hat{v}_1 \exp(j2\pi f_0 t)$$

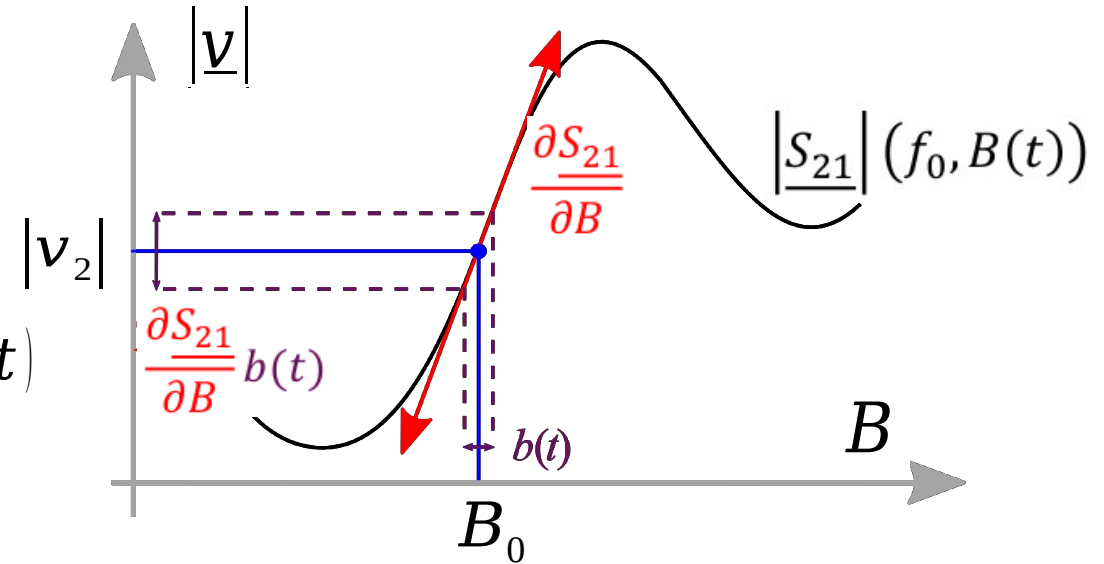
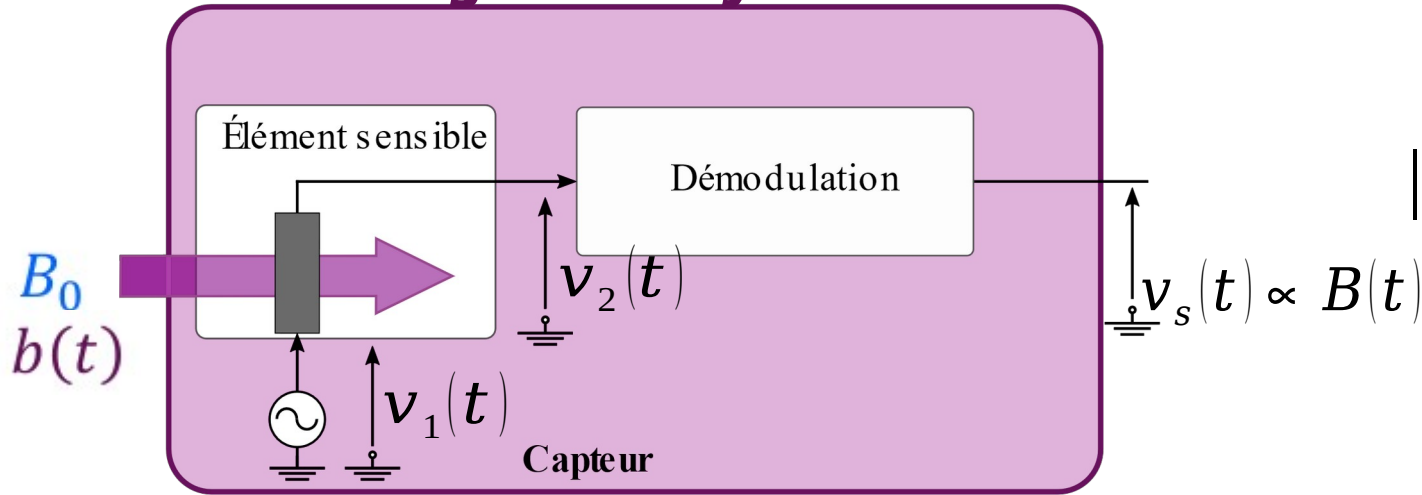
$$v_2(t) = \Re \left\{ \left[\underline{S}_{21}(f_0, B_0) + \underbrace{\frac{\partial \underline{S}_{21}}{\partial B}(f_0, B_0) b}_{\underline{S}_i} \right] \hat{v}_1 \exp(j2\pi f_0 t) \right\}$$

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$$v_s(t) = \frac{G \hat{v}_1}{2} \Re \{ S_{21}(f_0, B_0) \} + \underbrace{\frac{G \hat{v}_1}{2} \Re \{ s_i \}}_{S_v} b$$

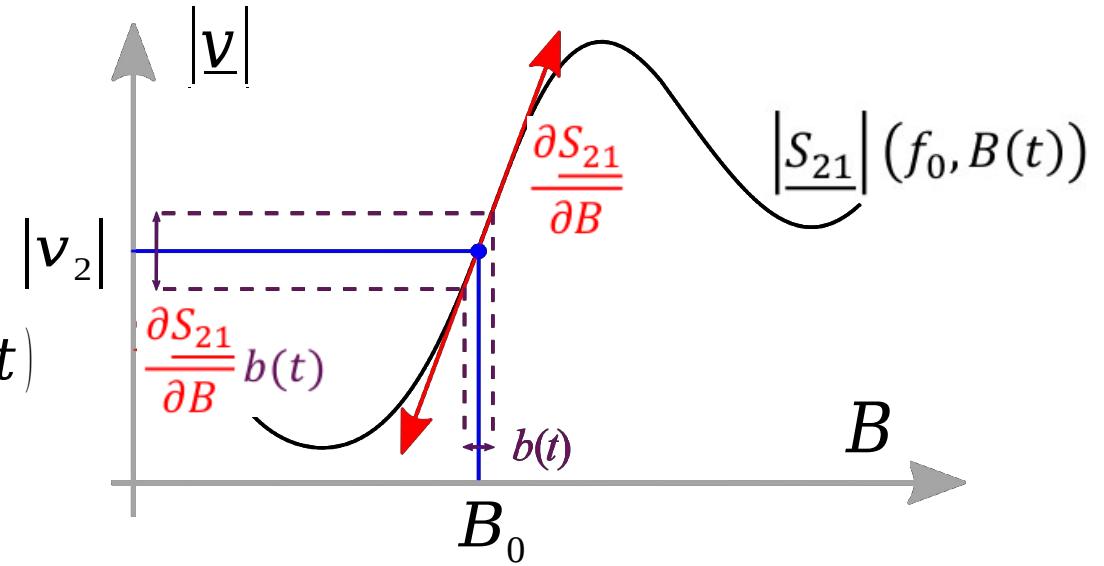
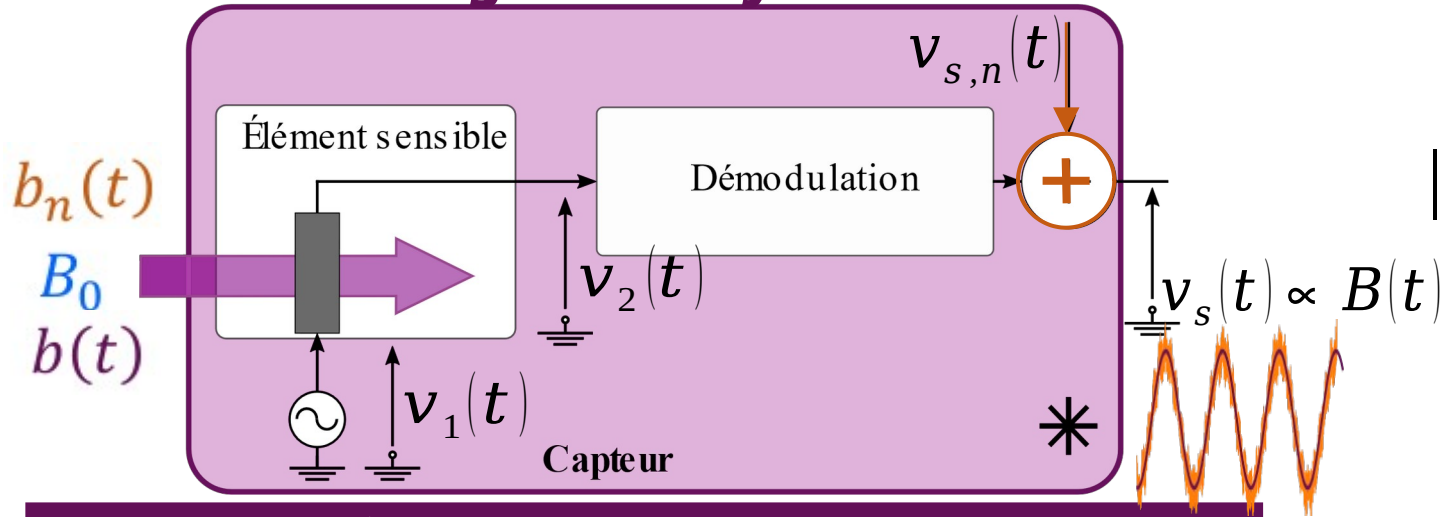
Demodulation stage

Performance criteria

Intrinsic sensitivity	$s_i = \frac{\partial S_{21}}{\partial B}$	T^{-1}
Voltage sensitivity	$S_v = \frac{\hat{v}_1}{2} \Re \{ s_i \}$	V/T

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Demodulation stage

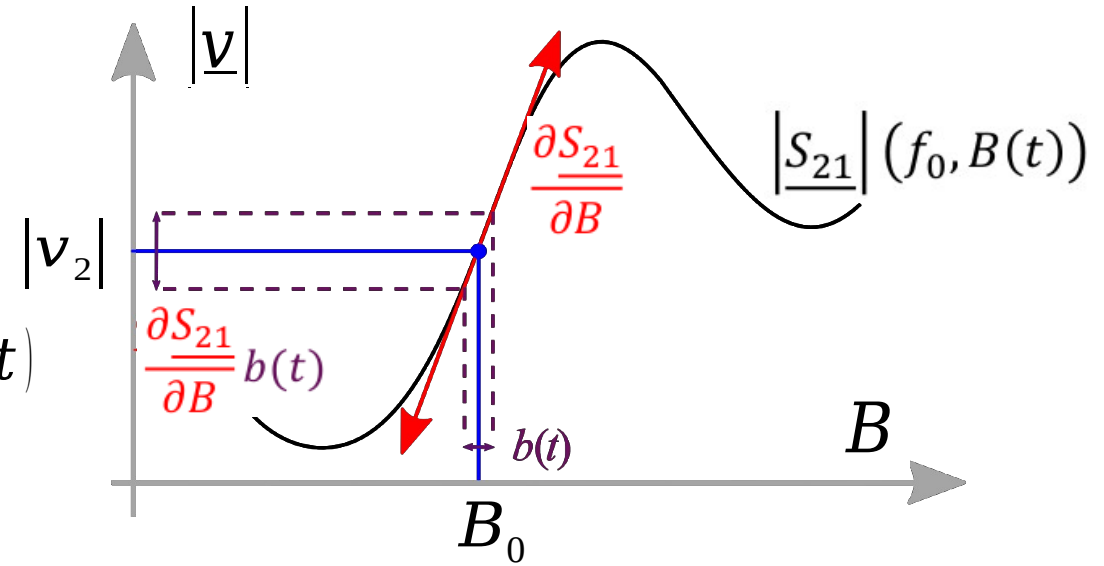
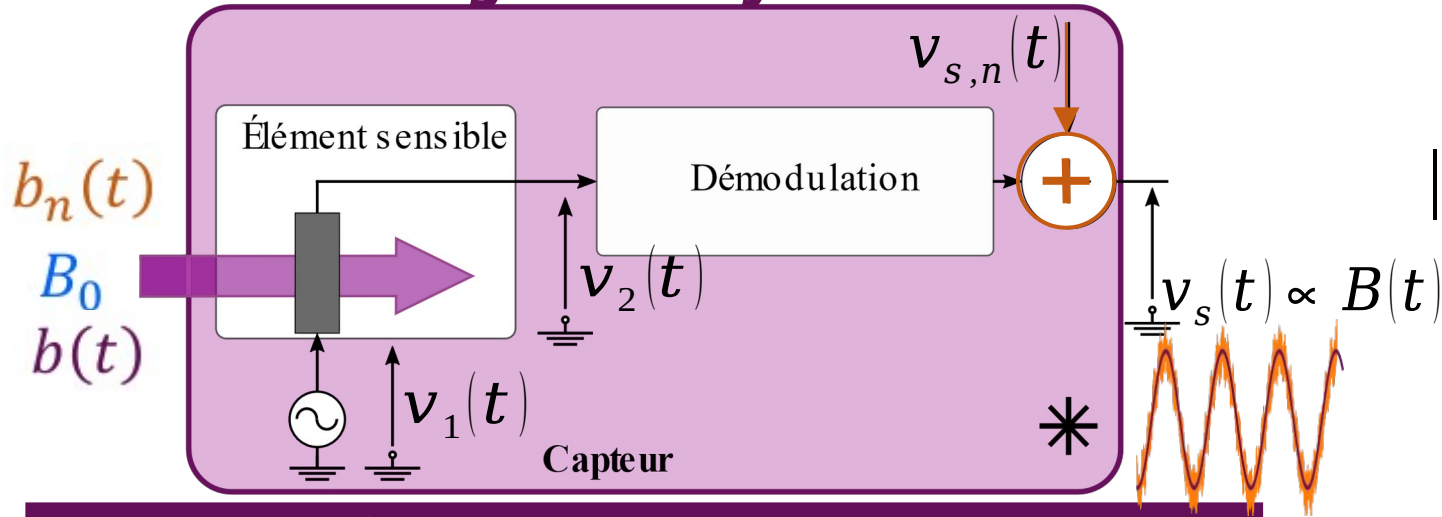
Spurious random signal : noise

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Noise spectral density	$v_{s,n}$	V/\sqrt{Hz}

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Voltage sensitivity	$\underline{S}_v = \frac{\hat{v}_1}{2} \Re \{ \underline{s}_i \}$	V/T
Noise spectral density	$v_{s,n}$	V/\sqrt{Hz}
Equivalent magnetic noise	$b_n = \frac{2v_{s,n}}{G S_v}$	T/\sqrt{Hz}

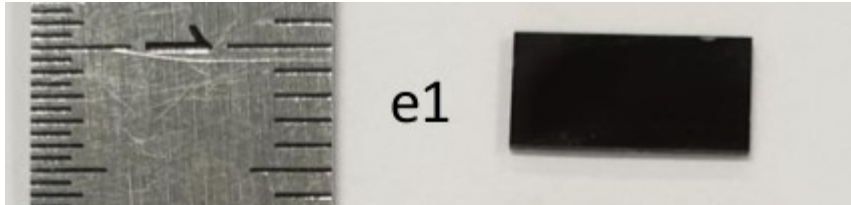
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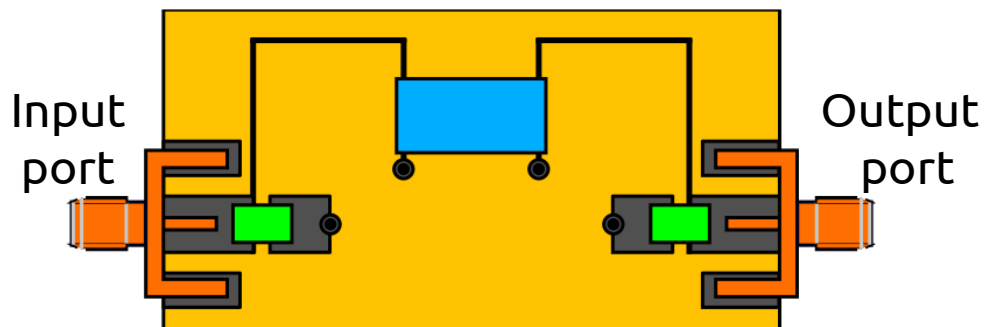
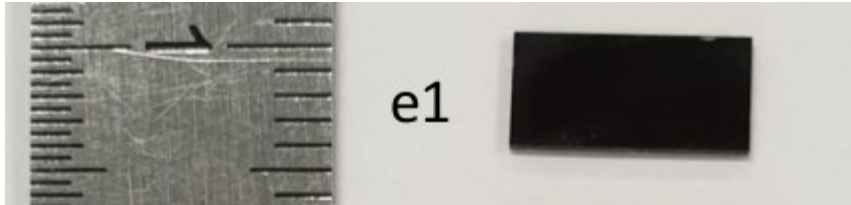
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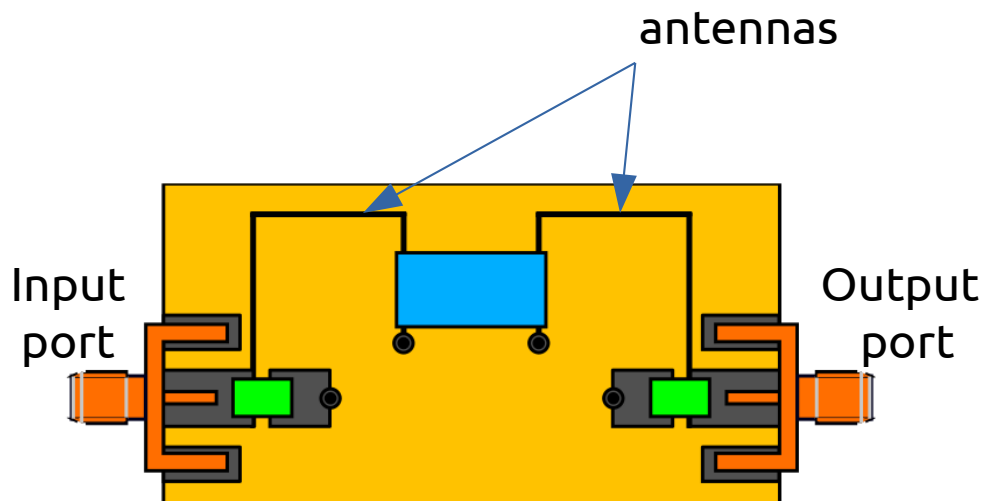
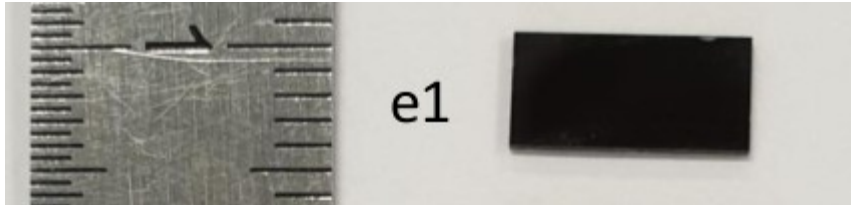
A. Stationary spin waves (sample **s1**)

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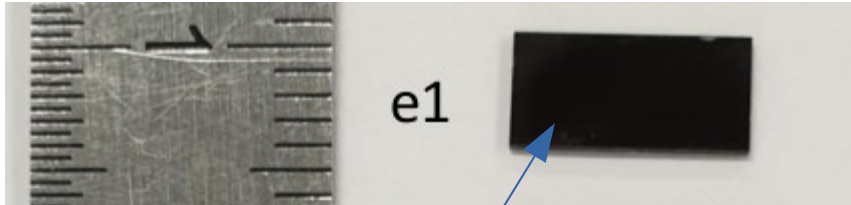
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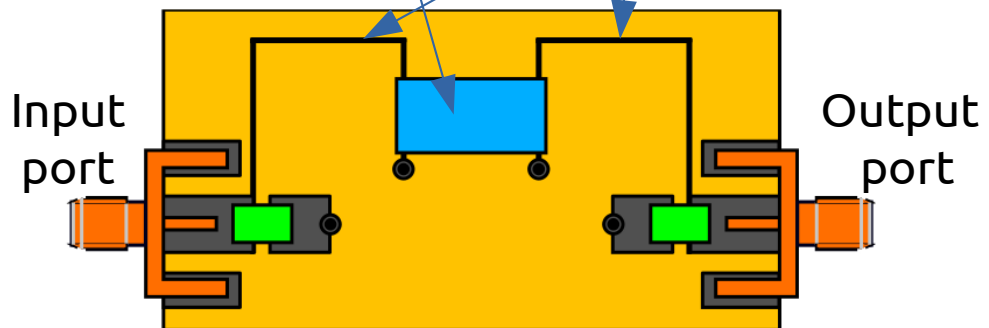
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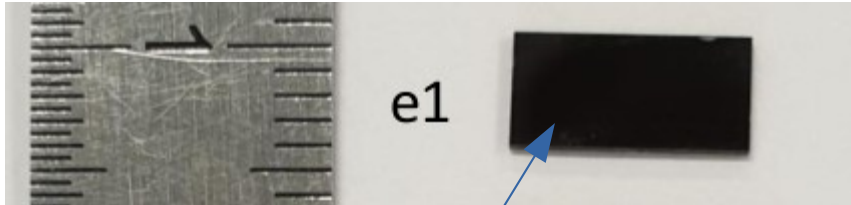
A. Stationary spin waves (sample s1)

YIG materials
(wave-guide)

antennas



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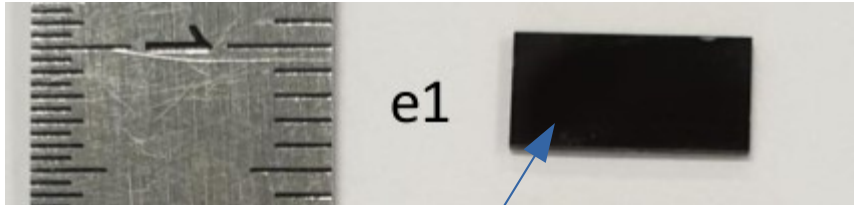
YIG materials
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antennas

Input
portOutput
port

Impedance matching

A. Stationary spin waves (sample s1)



- Spin wave reflection at both ends of the wave-guide (YIG material)

YIG materials
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antennas

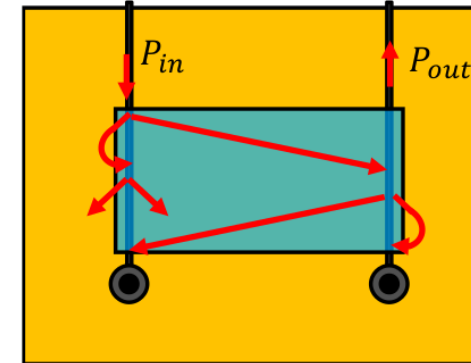
Input port

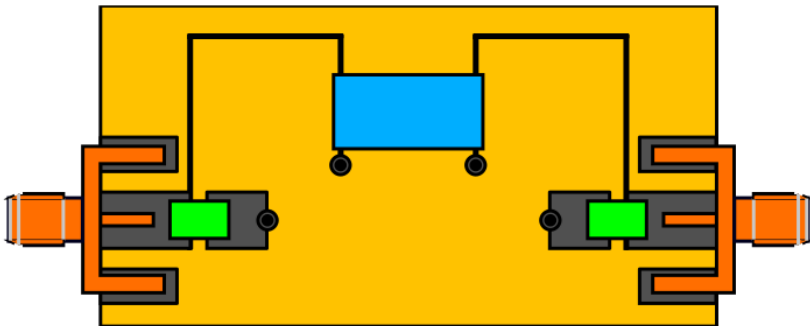
Output port

Impedance matching

Excitation antenna

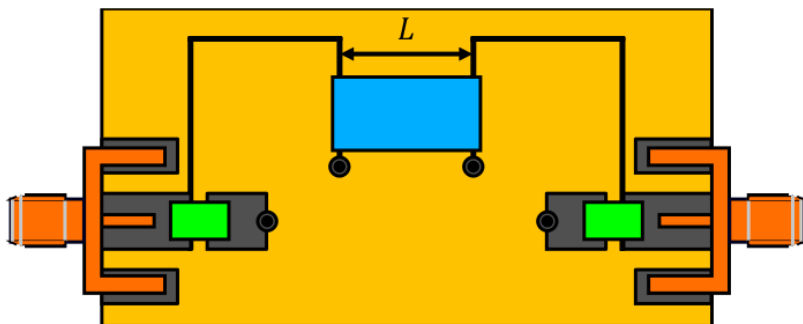
Measurement antenna



A. Stationary spin waves (sample **s1**)

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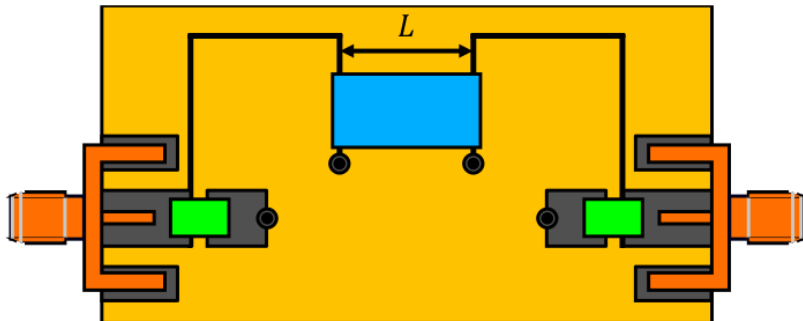
- ▶ Constructive and destructive effect appearing when half spin wavelength matches the length L of the material



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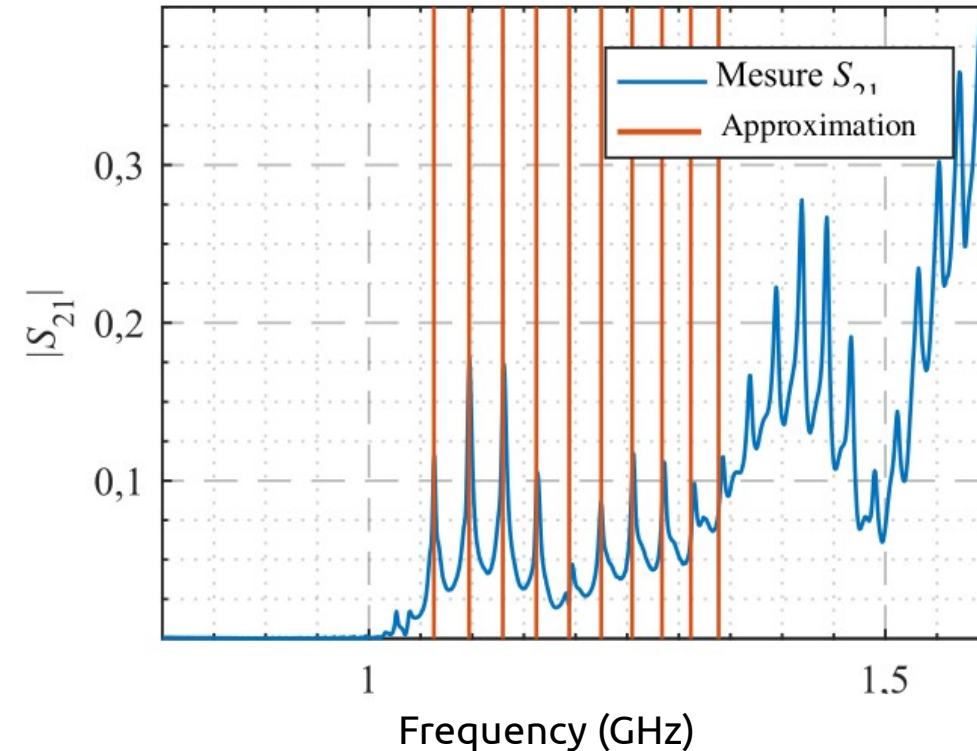
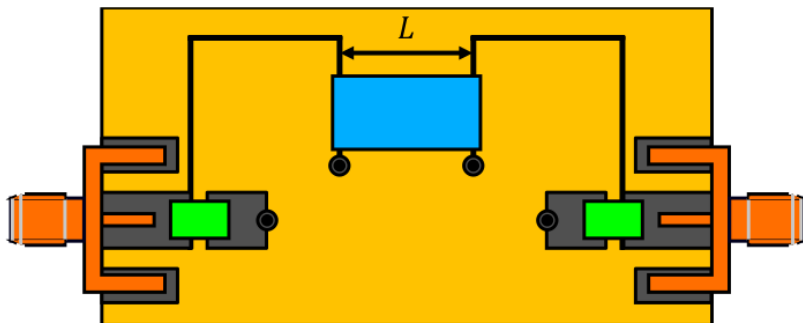
→ Setting wave number $k = n \frac{\pi}{L}$ in $f^2 = \left(\gamma \mu_0 H_{eff} + \frac{\gamma \mu_0 M_s}{2} \right)^2 - \left(\frac{\gamma \mu_0 M_s}{2} \right)^2 e^{-2kd}$



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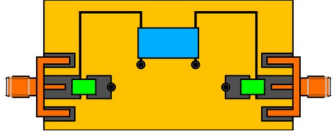
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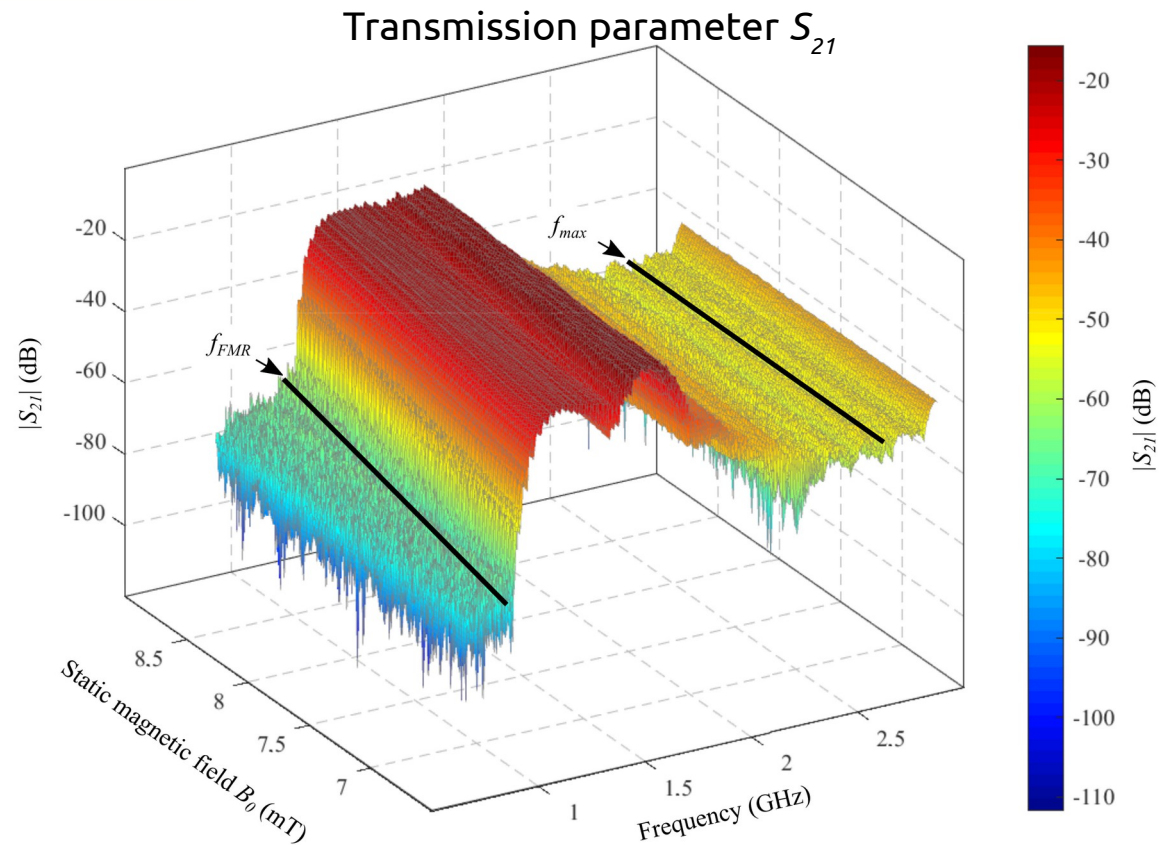
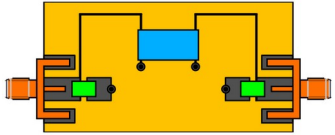


2. Optimization of the sensitivity

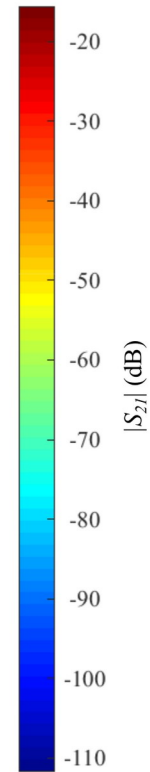
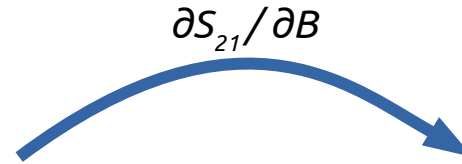
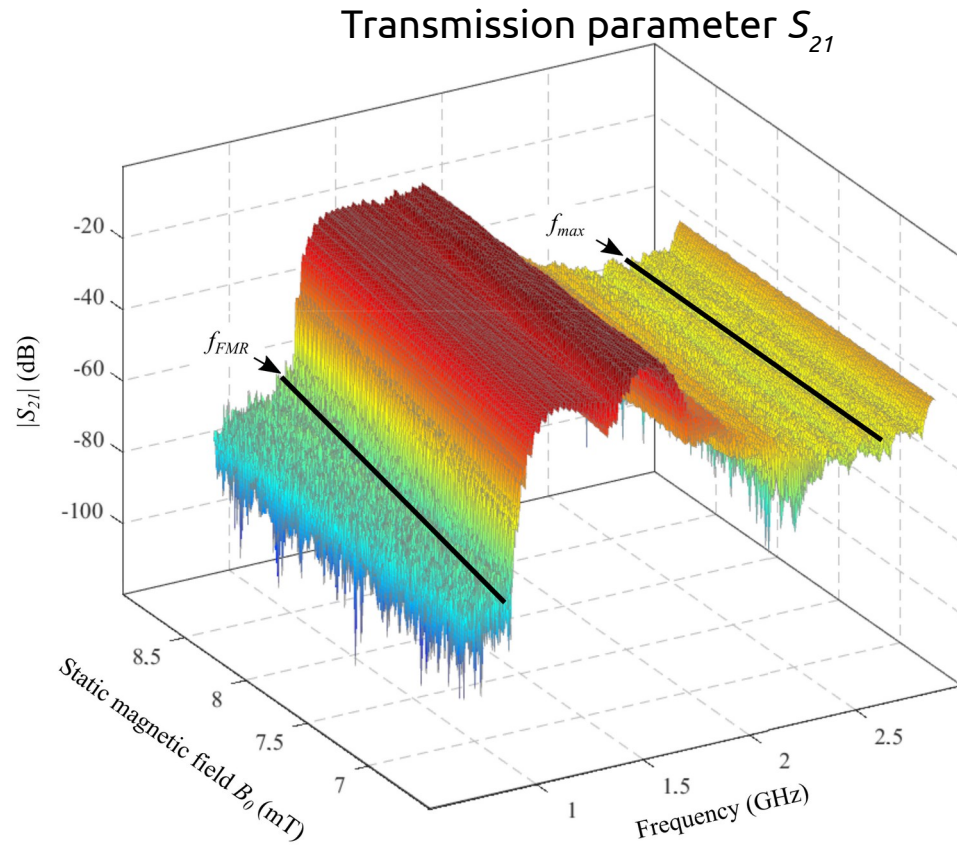
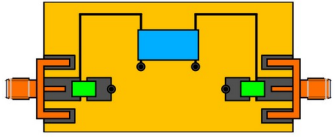
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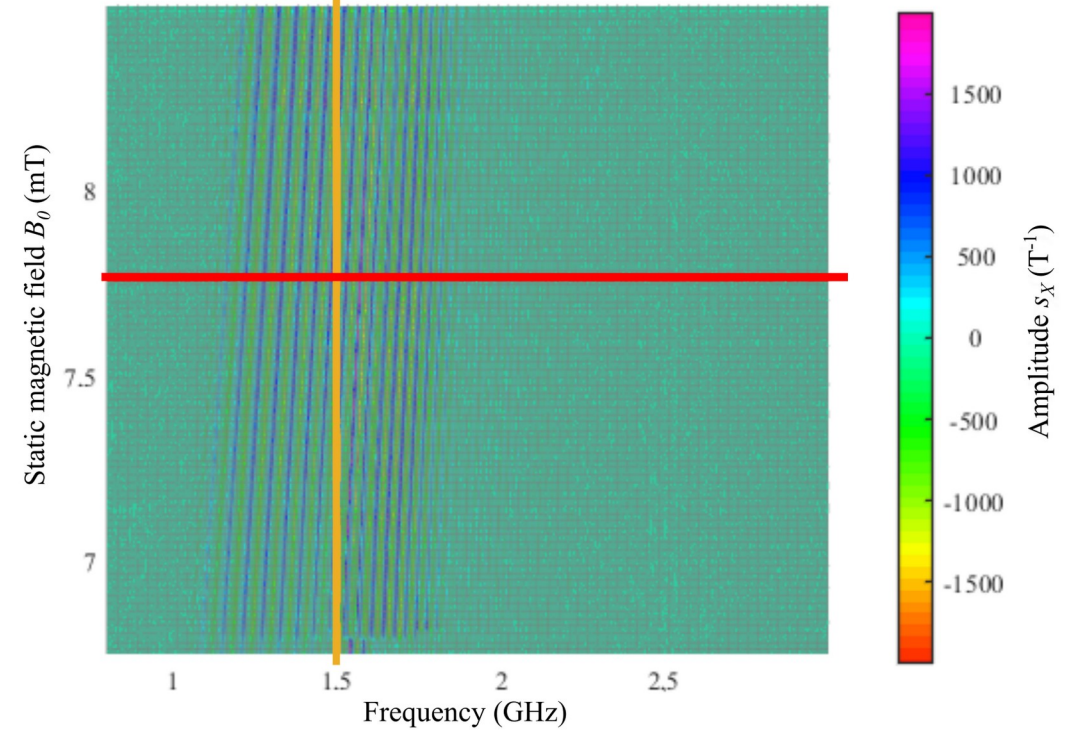
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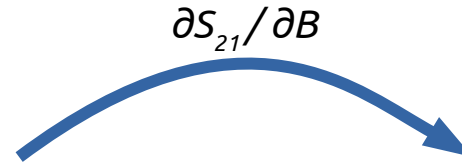
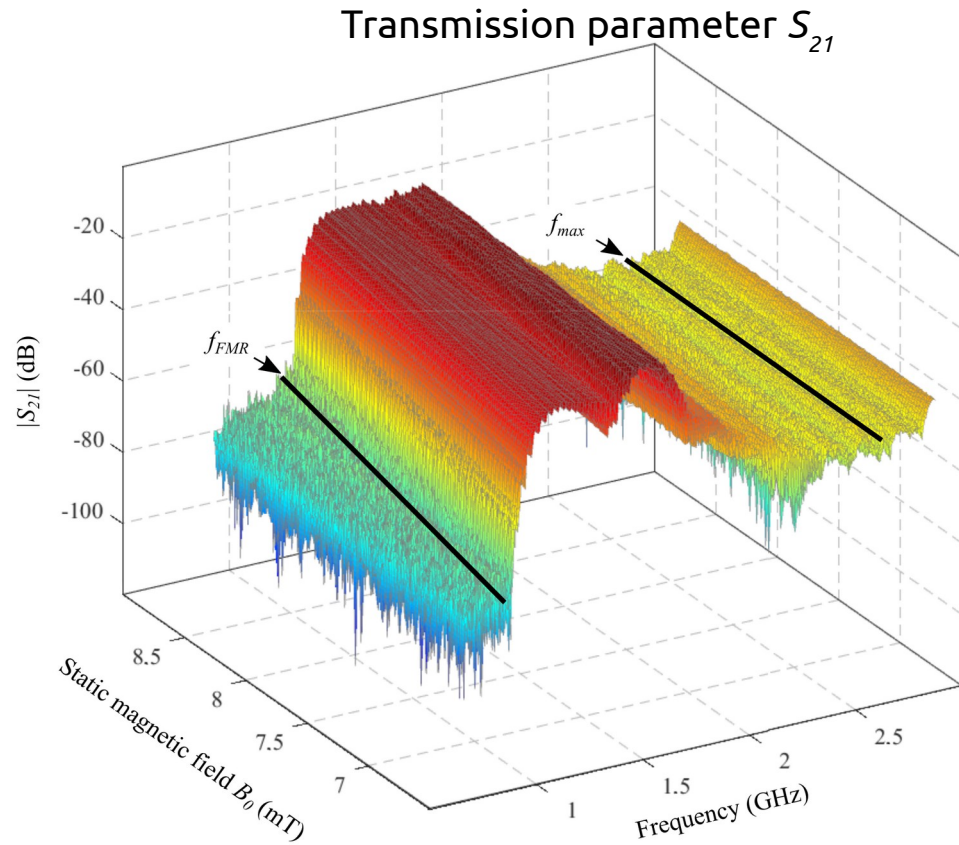
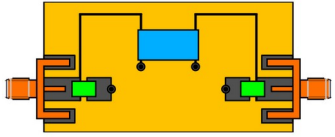
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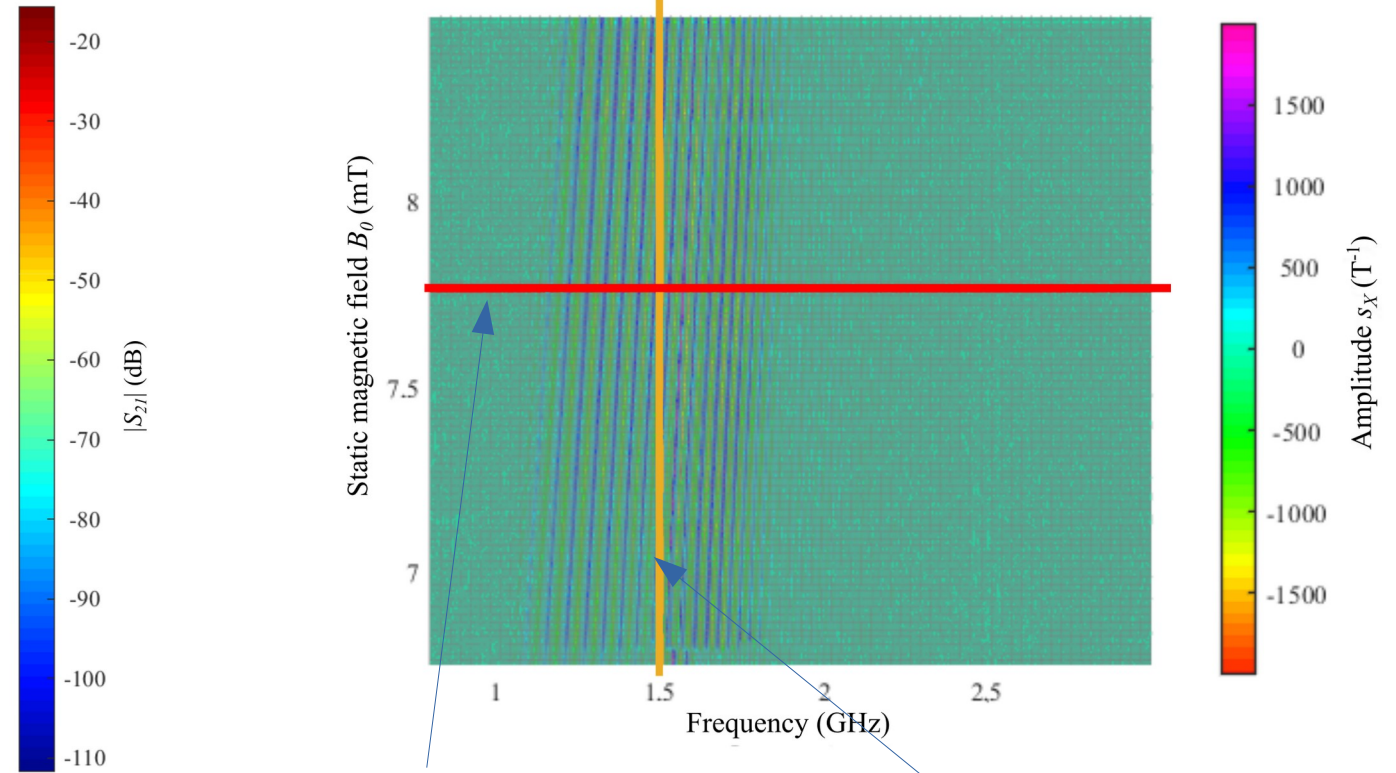
Intrinsic sensitivity



A. Stationary spin waves (sample s1)



Intrinsic sensitivity

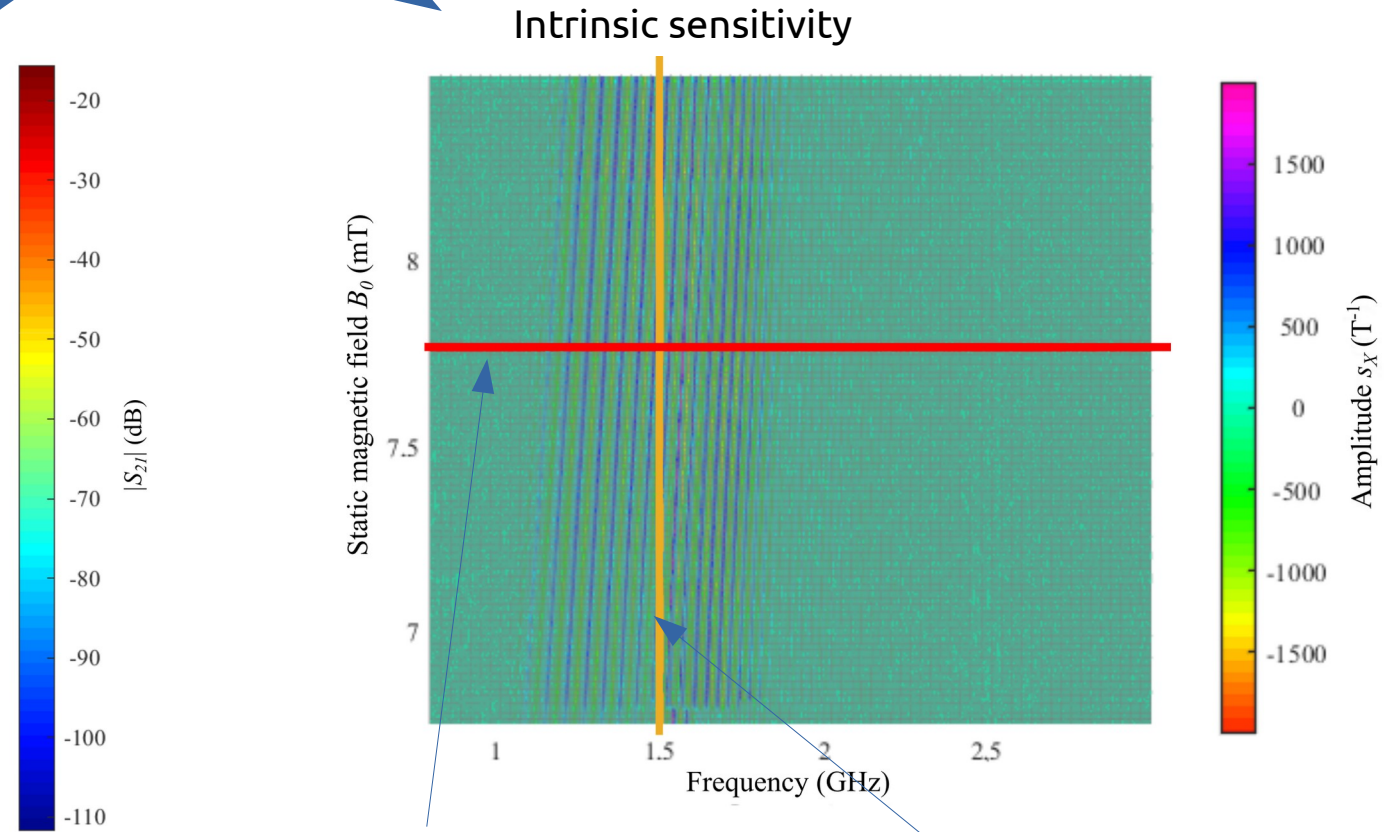
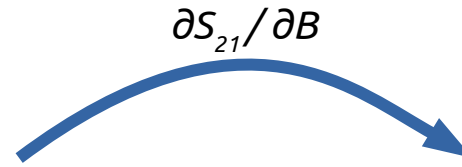
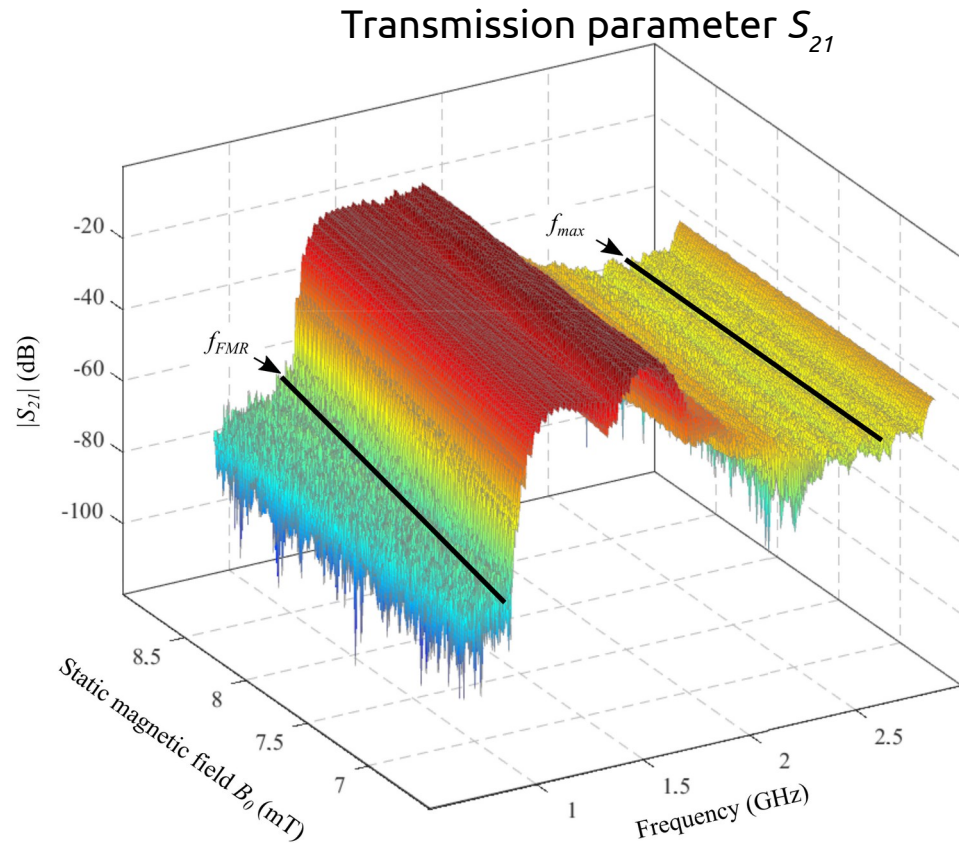
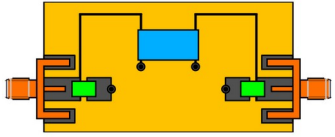


Constant magnetic field

Constant frequency

2. Optimization of the sensitivity

A. Stationary spin waves (sample s1)



Constant magnetic field

Constant frequency

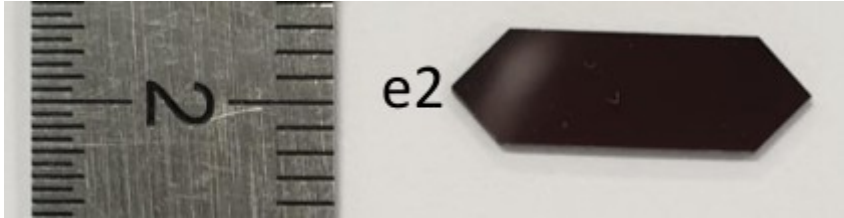
→ Need to determine the best conditioning parameters (B_0, f_0)

2. Optimization of the sensitivity

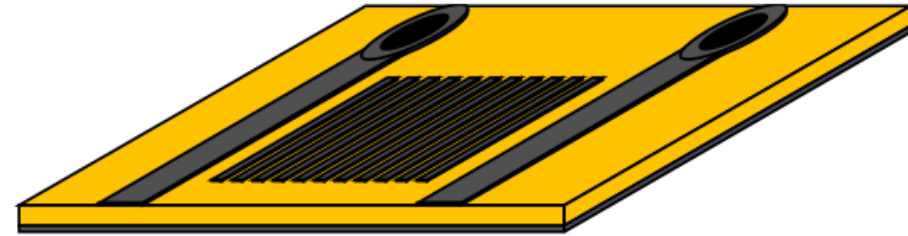
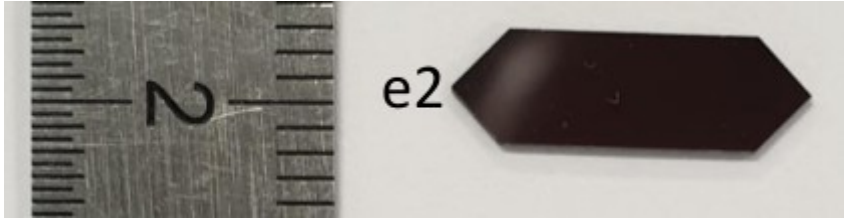
B. Spin-wave filtering (sample s2)

2. Optimization of the sensitivity

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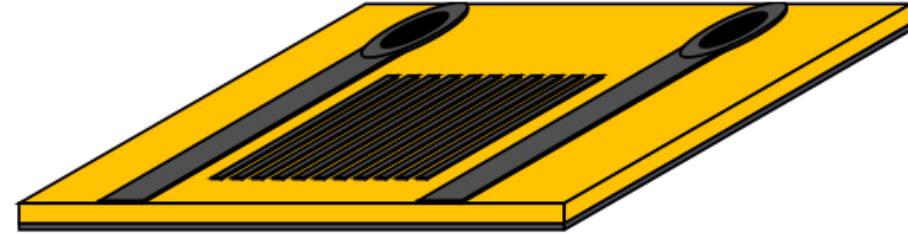
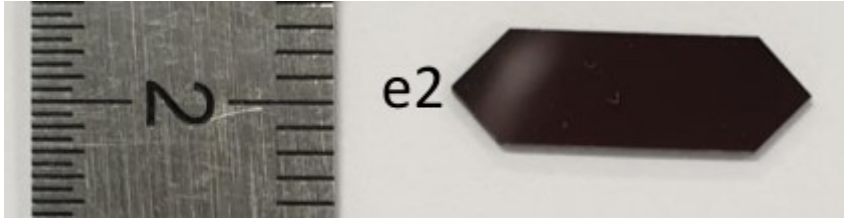


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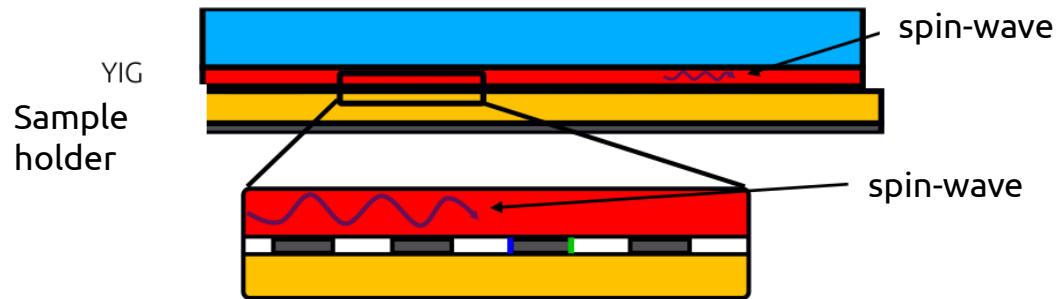


→ Creation of a rejection band, similarly to SAW filters.

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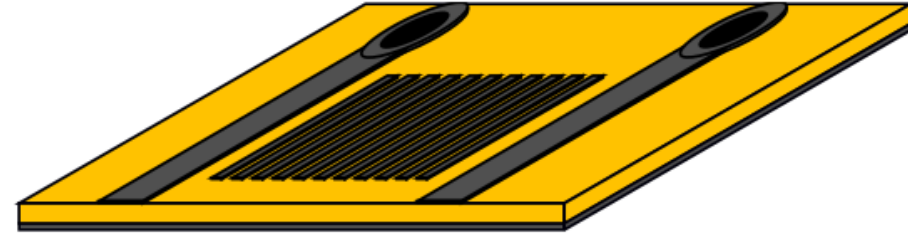
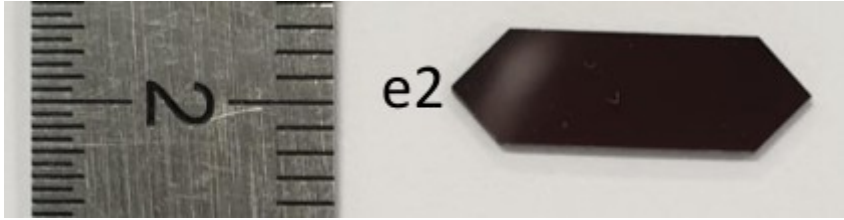


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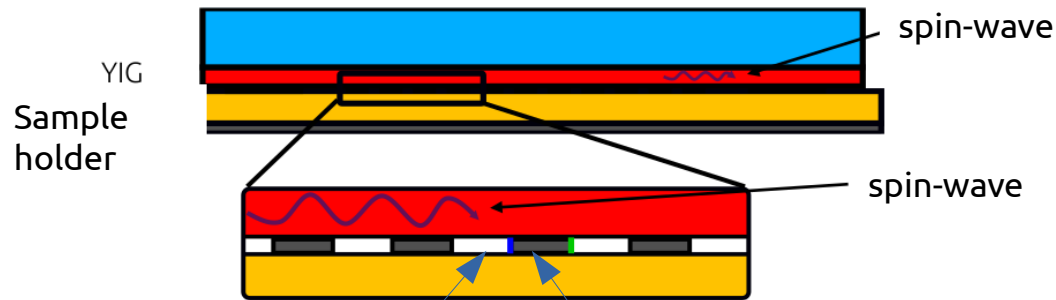


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B. Spin-wave filtering (sample s2)



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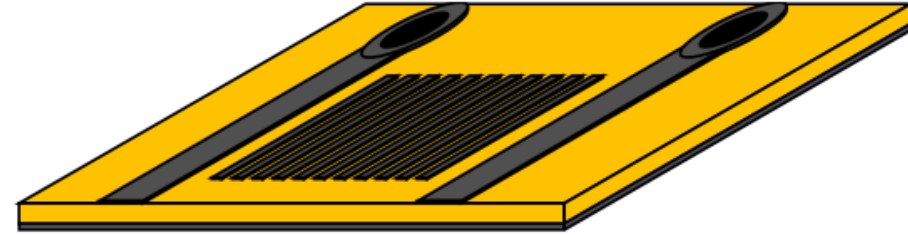
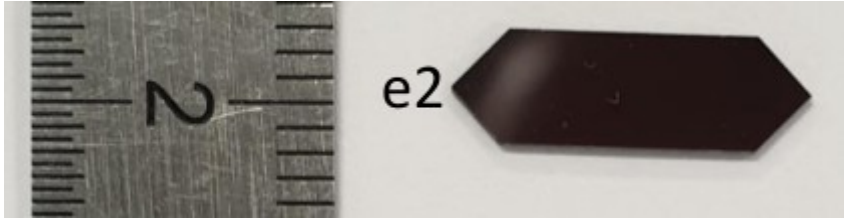
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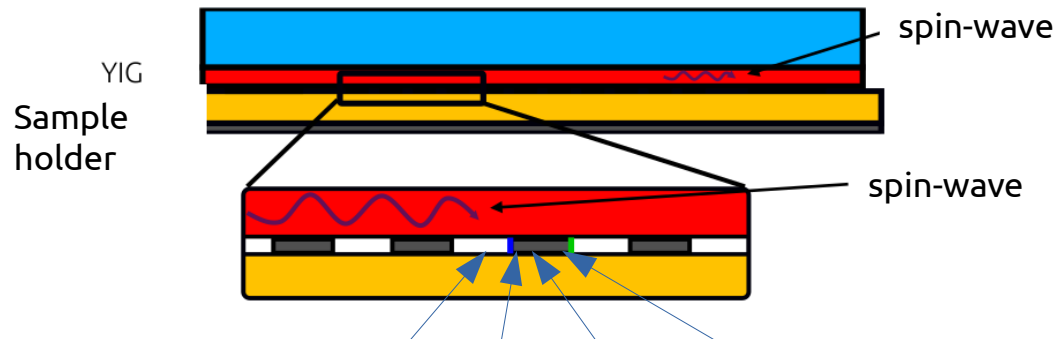
Propagation **without** conductive material

Propagation **with** conductive material

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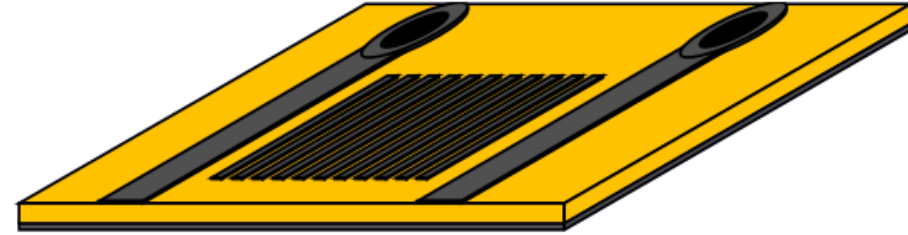
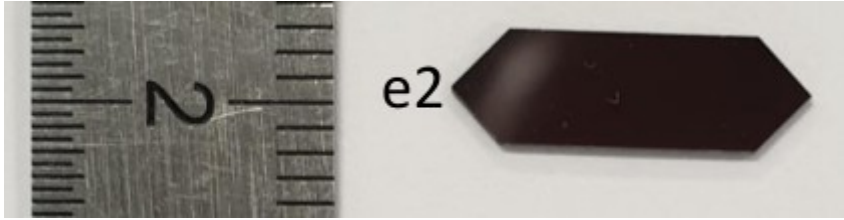


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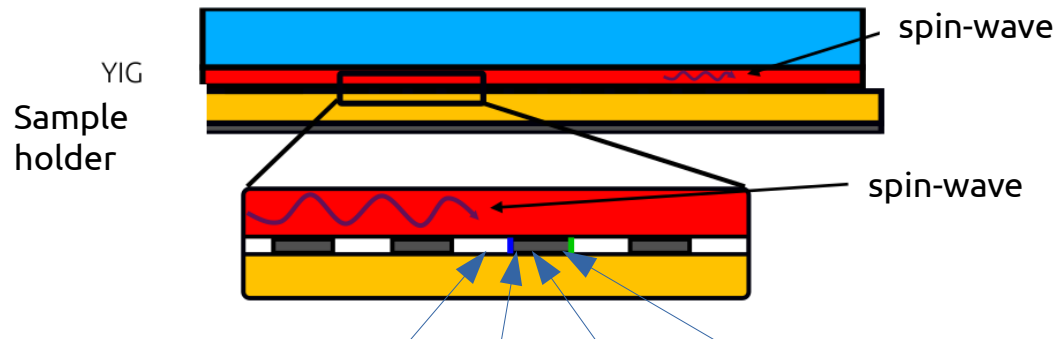
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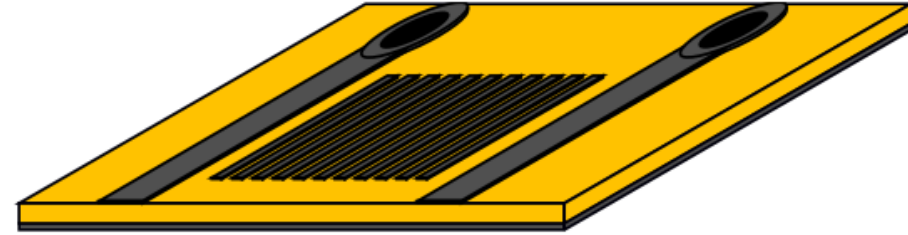
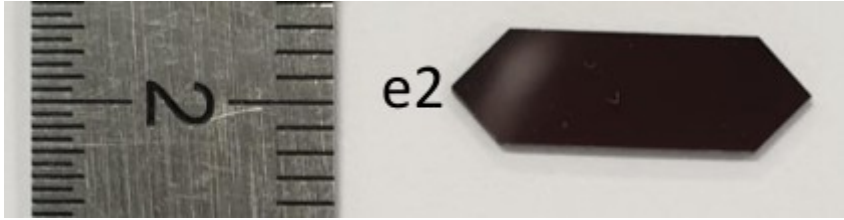
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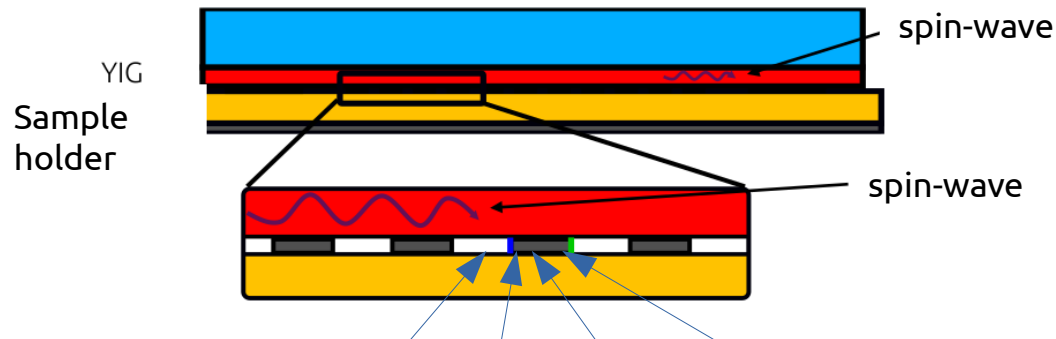
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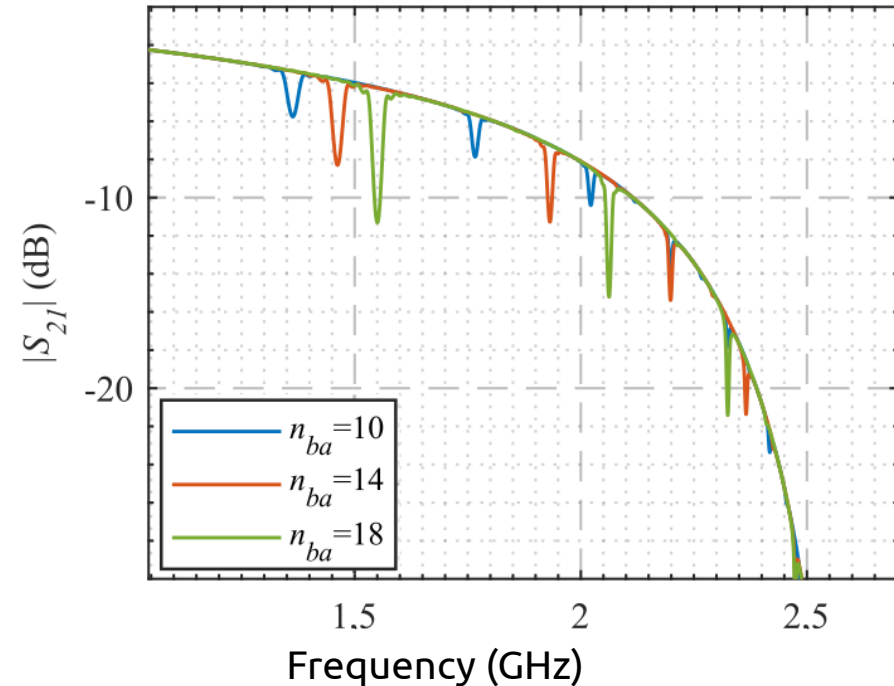


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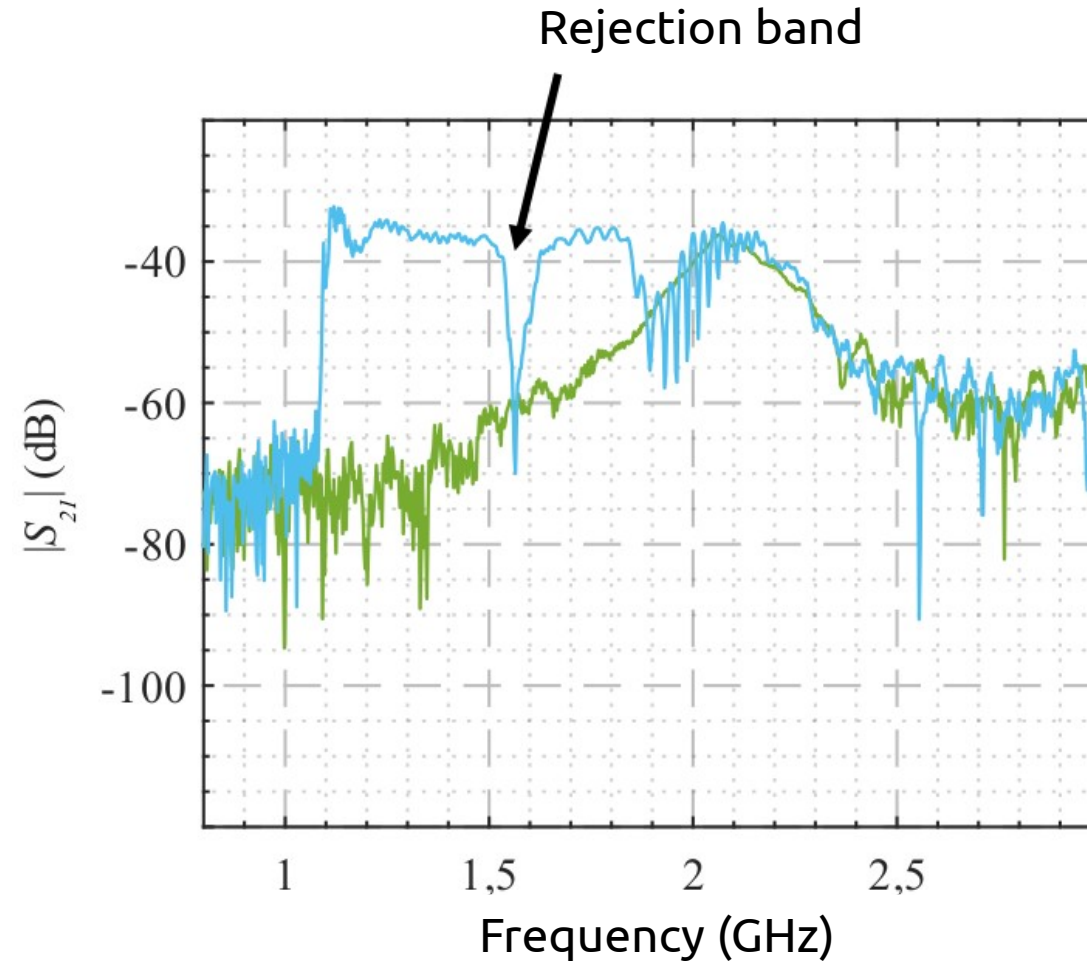
2. Optimization of the sensitivity

B. Spin-wave filtering (sample s2)

Filter used : 14 strips → Spatial periodicity = 608 μm → rejection frequency of 1.55 GHz

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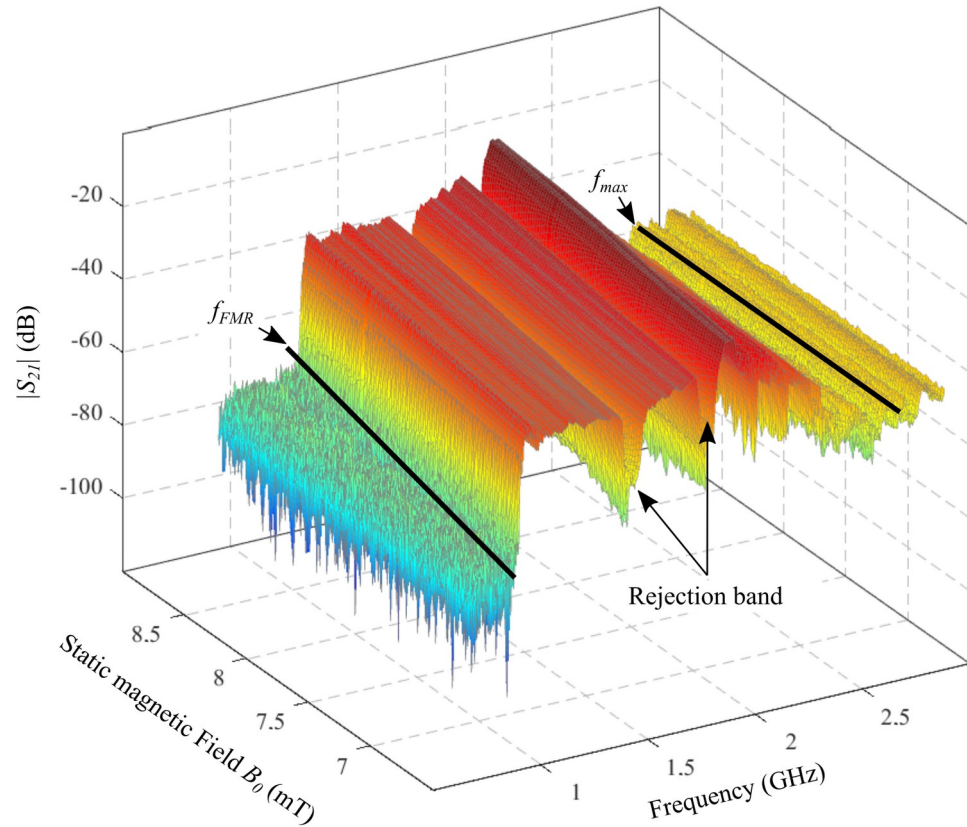


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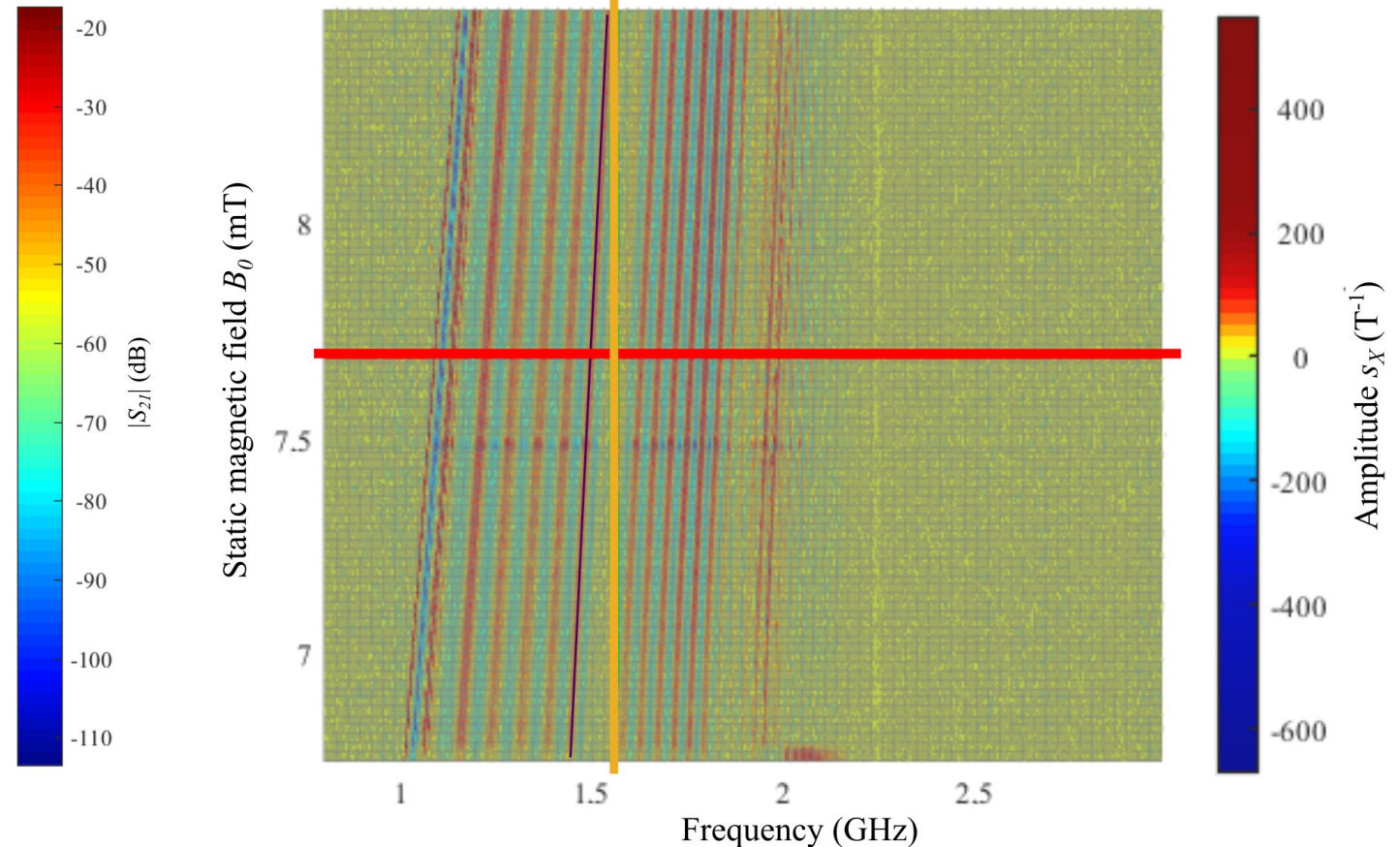
Transmission parameter S_{21}



$$\frac{\partial S_{21}}{\partial B}$$



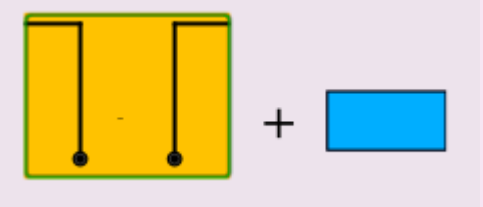
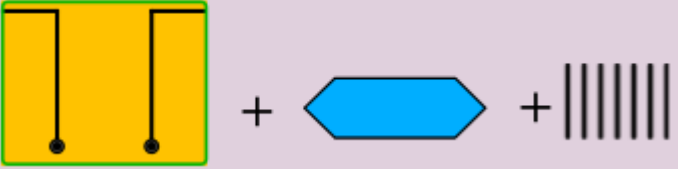
Intrinsic sensitivity



2. Optimization of the sensitivity

C. Comparison

C. Comparison

Sensing element	Intrinsic sensitivity (T^{-1})
s1 	1300 T^{-1} at 1.5GHZ, 7.23mT
s2 	400 T^{-1} at 1.1GHZ, 7.9mT

1. Introduction : measurement principle of the sensor
 - Spin wave and dependence to the external applied magnetic field
 - Conditioning circuitry
2. Optimization of the intrinsic sensitivity
 - Stationary spin waves
 - Spin wave rejection band
3. Voltage sensitivity and noise performances
4. Conclusion

A. Conditioning circuitry

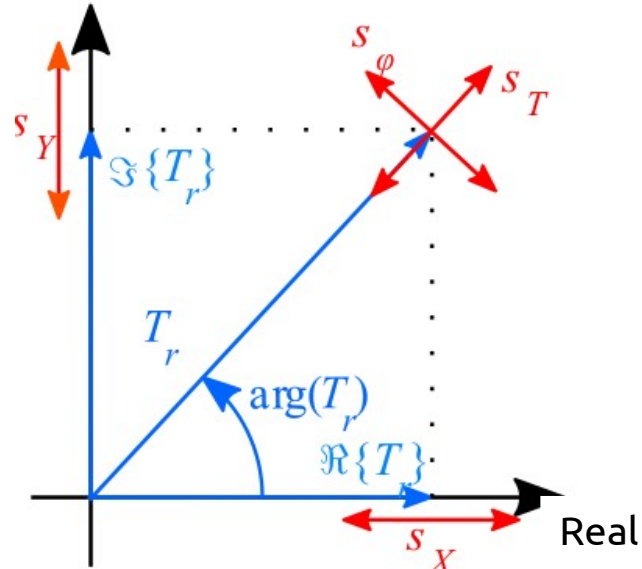
A. Conditioning circuitry

- ▶ Output voltage expression at sensing element ends :

$$\underline{v}_2(t) = \left[\underline{T}_r(f_0, B_0) + \frac{\partial \underline{T}_r}{\partial B}(f_0, B_0)b \right] \hat{v}_1 \exp(j2\pi f_0 t)$$

- ▶ Sensitivity with complex components

Imaginary

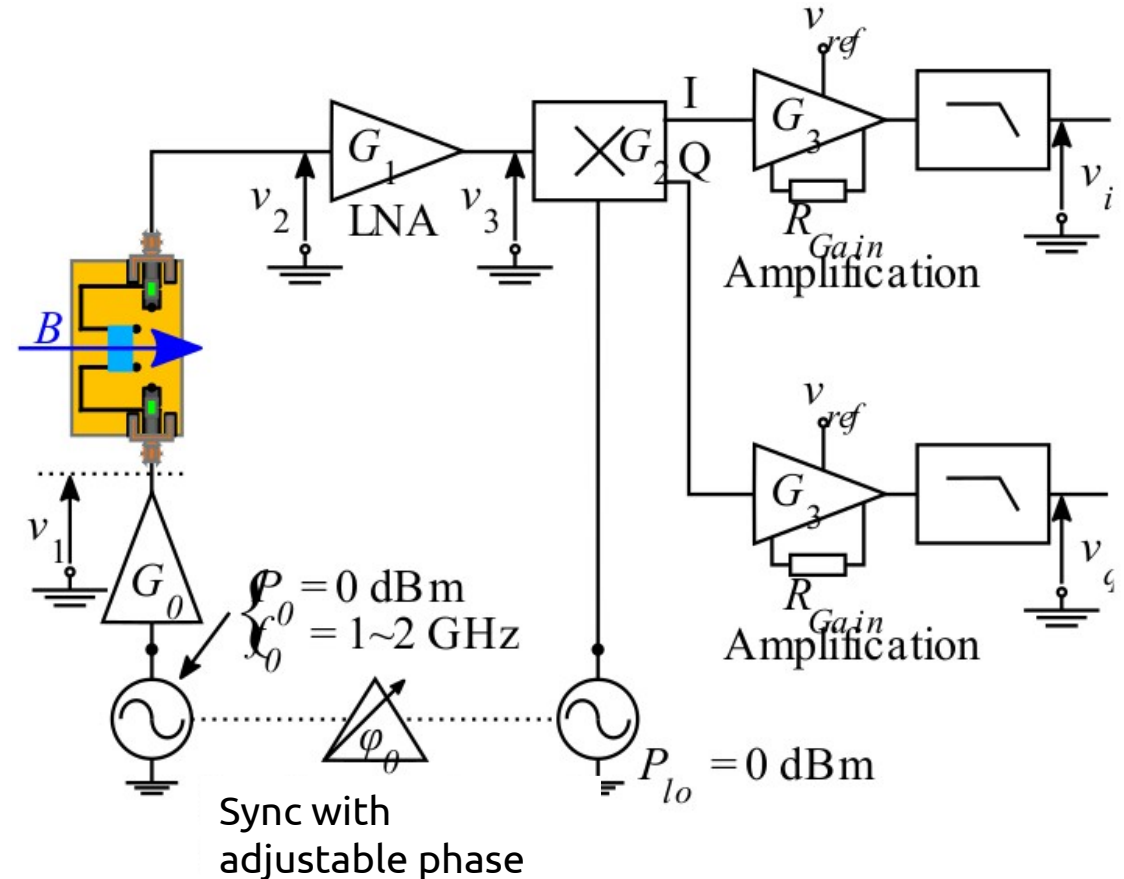
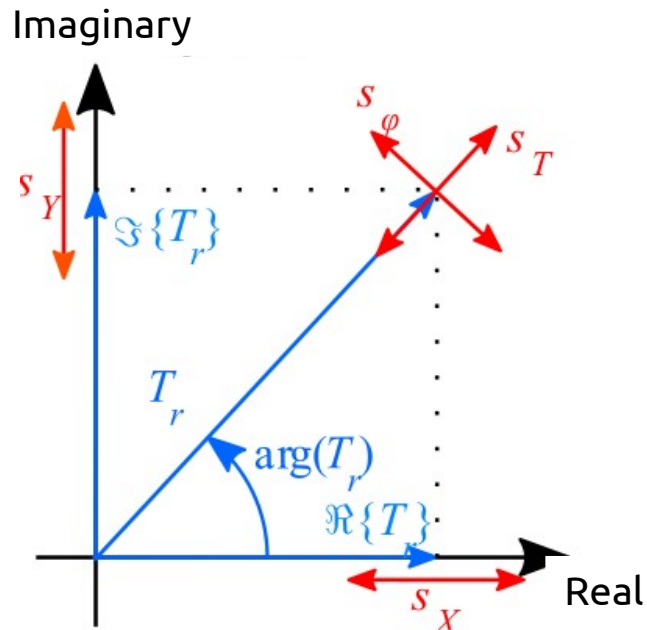


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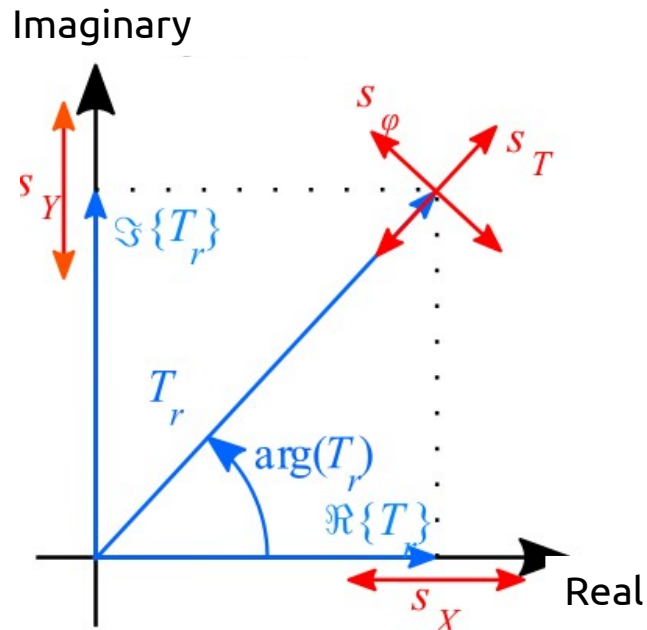


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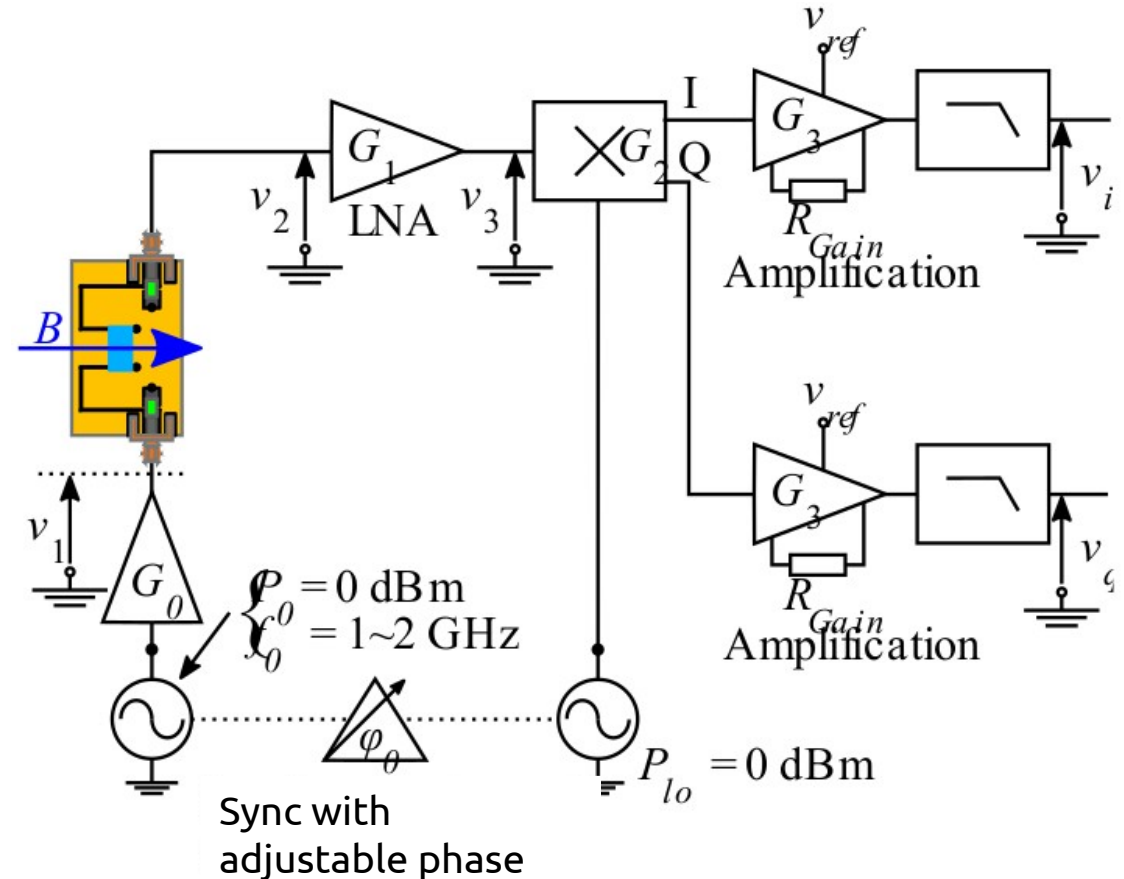
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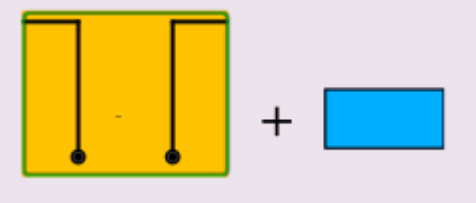
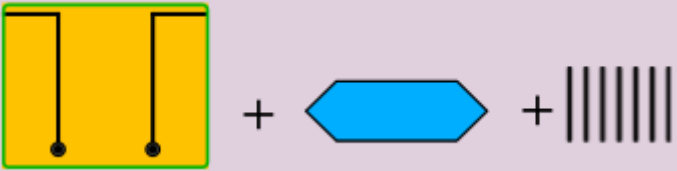
Signal variations

- ▶ Amplitude and phase : S_T and S_ϕ
- ▶ Real and imaginary : S_x and S_y
- ▶ → Choose optimal value of ϕ_0



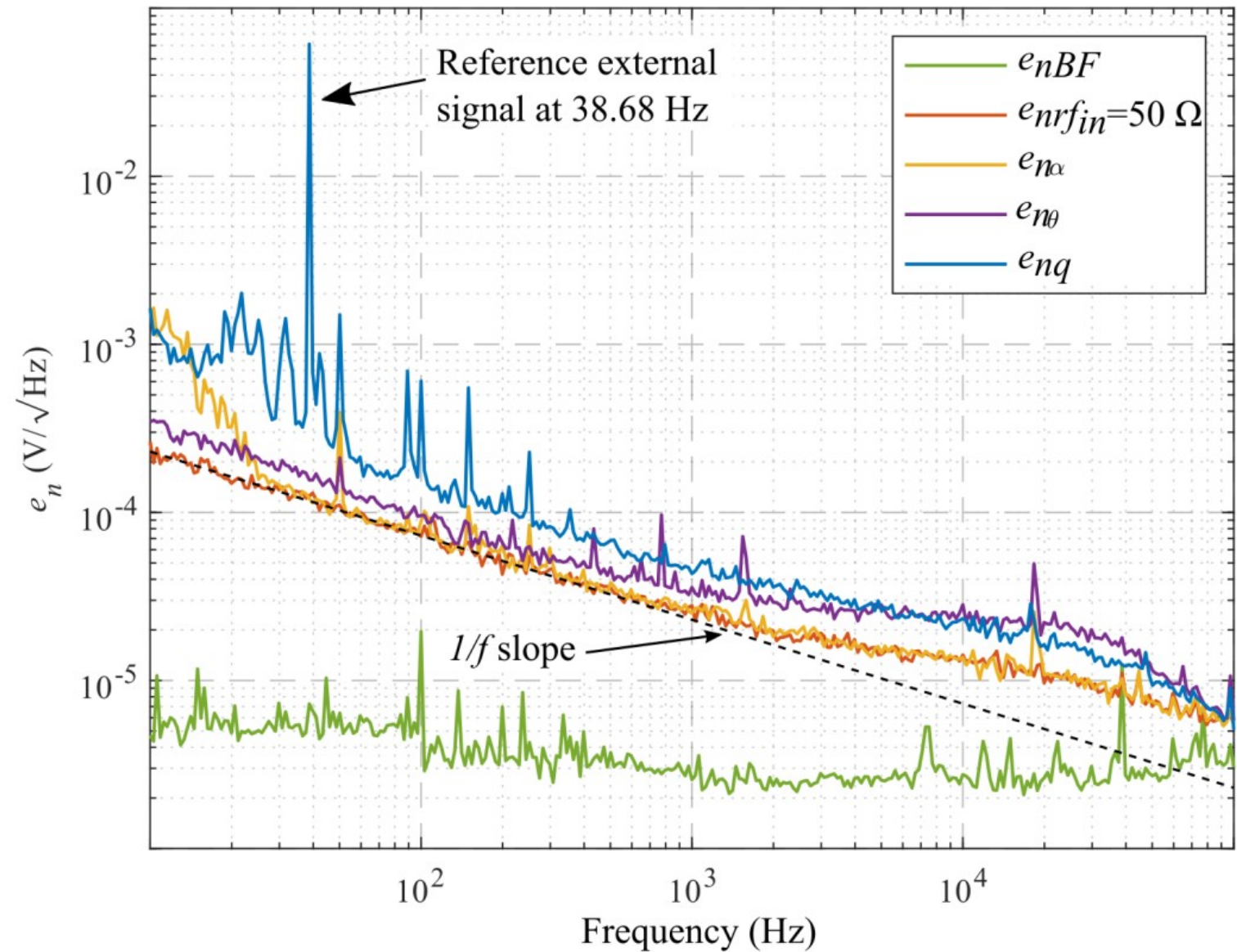
B. Voltage sensitivity performances

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	Sensing element	S_x (V/T)	S_y (V/T)	S_T (V/T)	S_ϕ (rad/mT)
s1		22	25	12	20
s2		1.5	2.0	0.7	-12

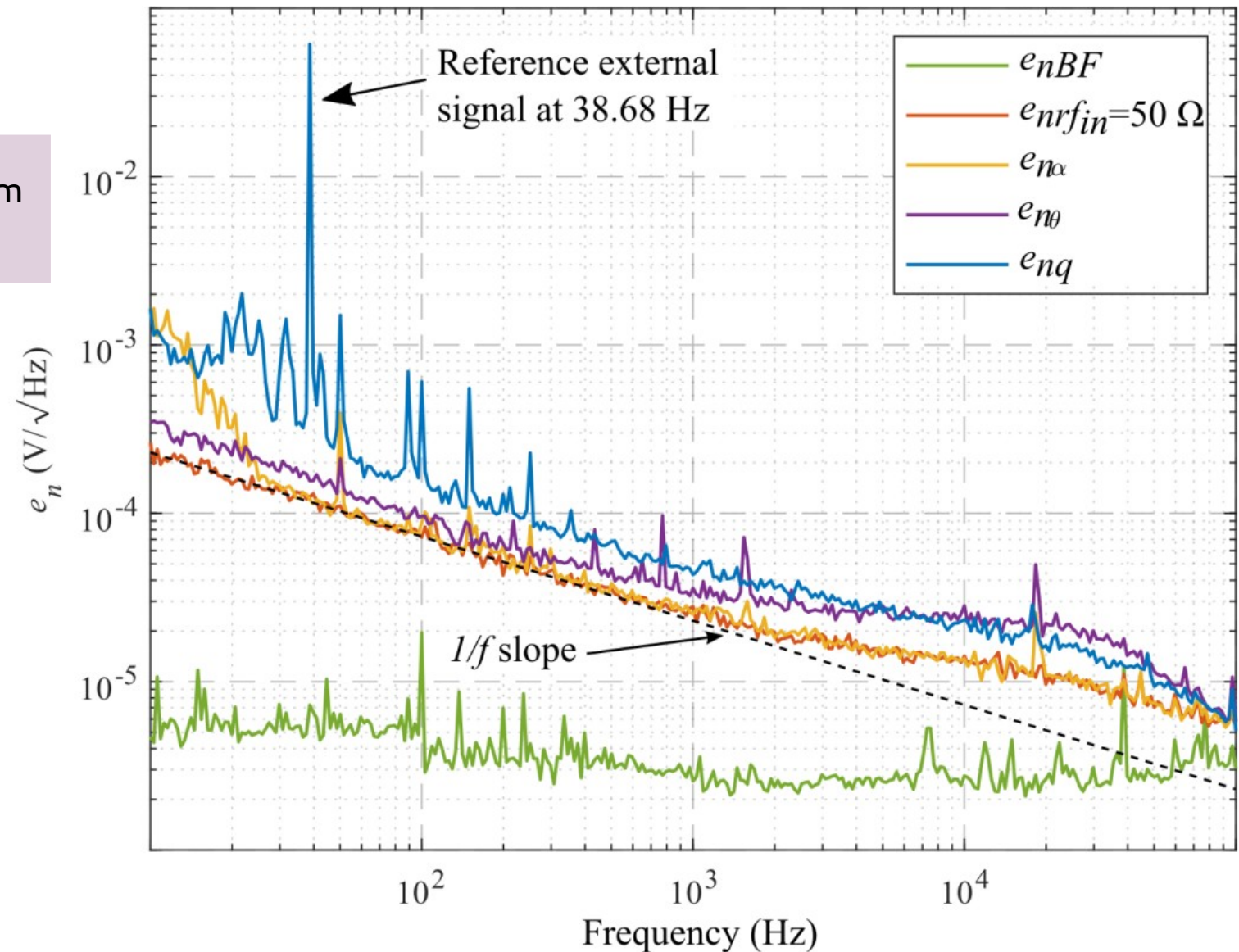
C. Noise measurements

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- ▶ Noise level dominated by the noise from excitation generator.



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Conclusions

- ▶ Magnetic sensor based on magnonic materials
 - Sensitivity reaches about **20 V/T**
 - Equivalent magnetic noise level as low as **100 pT/√Hz** at 1kHz
- ▶ First ways of optimization
 - Spatial filtering of spin wave (rejection band) sounds promising but the actual realization does not improve the results.
 - A great attention has to be given to conditioning parameters (f_0 , B_0 , φ_0).

Conclusions

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Perspectives

- ▶ Increase the intrinsic sensitivity
 - Better spin wave filtering
 - Other geometries
 - Needs of a theoretical model as to determine relevant factors
- ▶ Reduce noise level of the electronic circuitry
 - Excitation generator
 - Other detection method (phase detector, ...)