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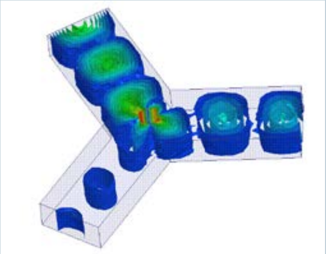

Low-loss millimeter-wave self-biased circulators: materials, design and characterization

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SPCD 2016

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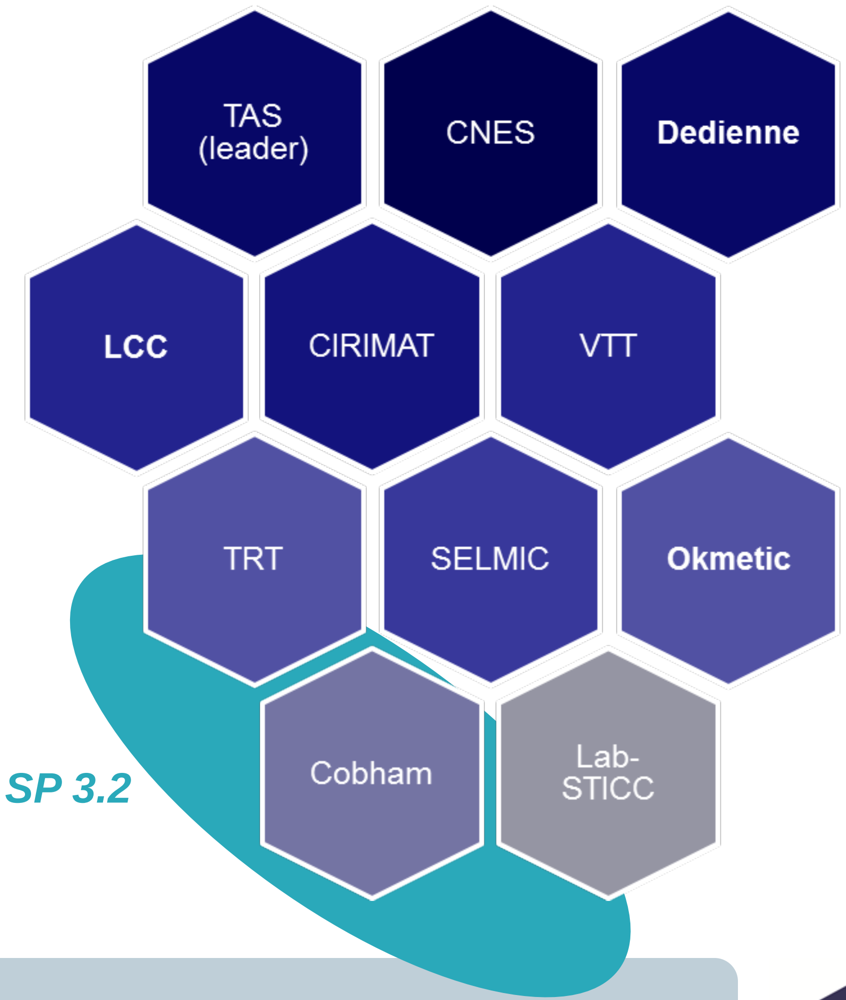
MM_WIN project

➲ Advanced Millimeter Wave Interconnects



SP 3.2 Minaturized Self-biased Circulators

- **Development of new pre-oriented materials for mm-wave applications (up to 40 GHz)**
- **Static and dynamic characterization of pre-oriented polycrystalline hexaferrites**
- **Proof of concept : rectangular waveguide mm-wave self-biased circulator**
- **Ultra-compact planar self-biased circulators**
- **Integration into RF front-end**

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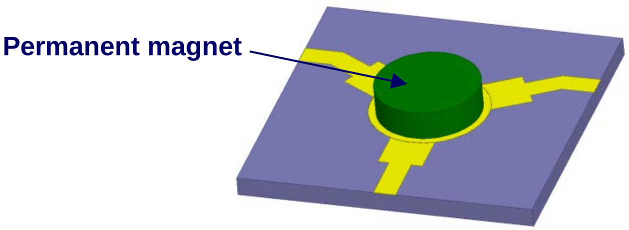
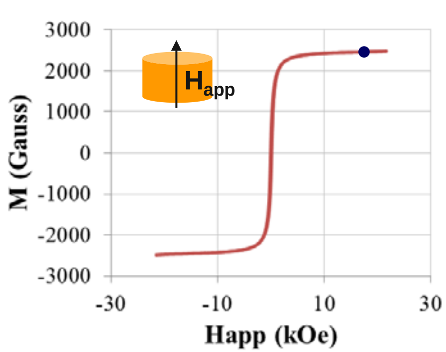
Self-biased circulators

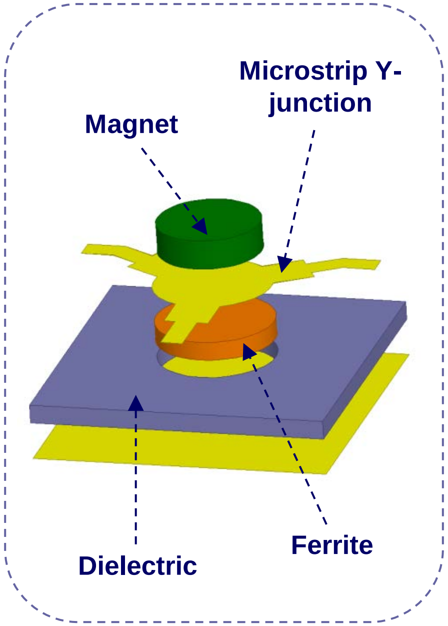
Classical circulator



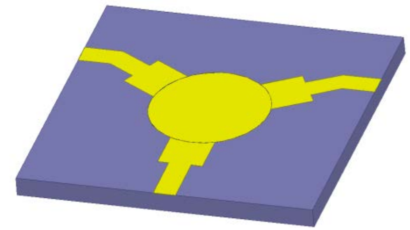


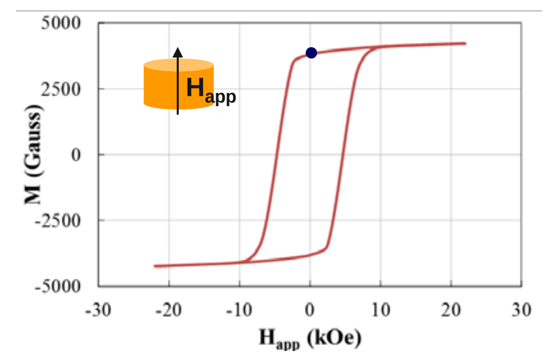
Hysteresis cycle of a soft ferrite

- Soft ferrite
- Magnetization state: saturation
- Need a permanent magnet



Self-biased circulator



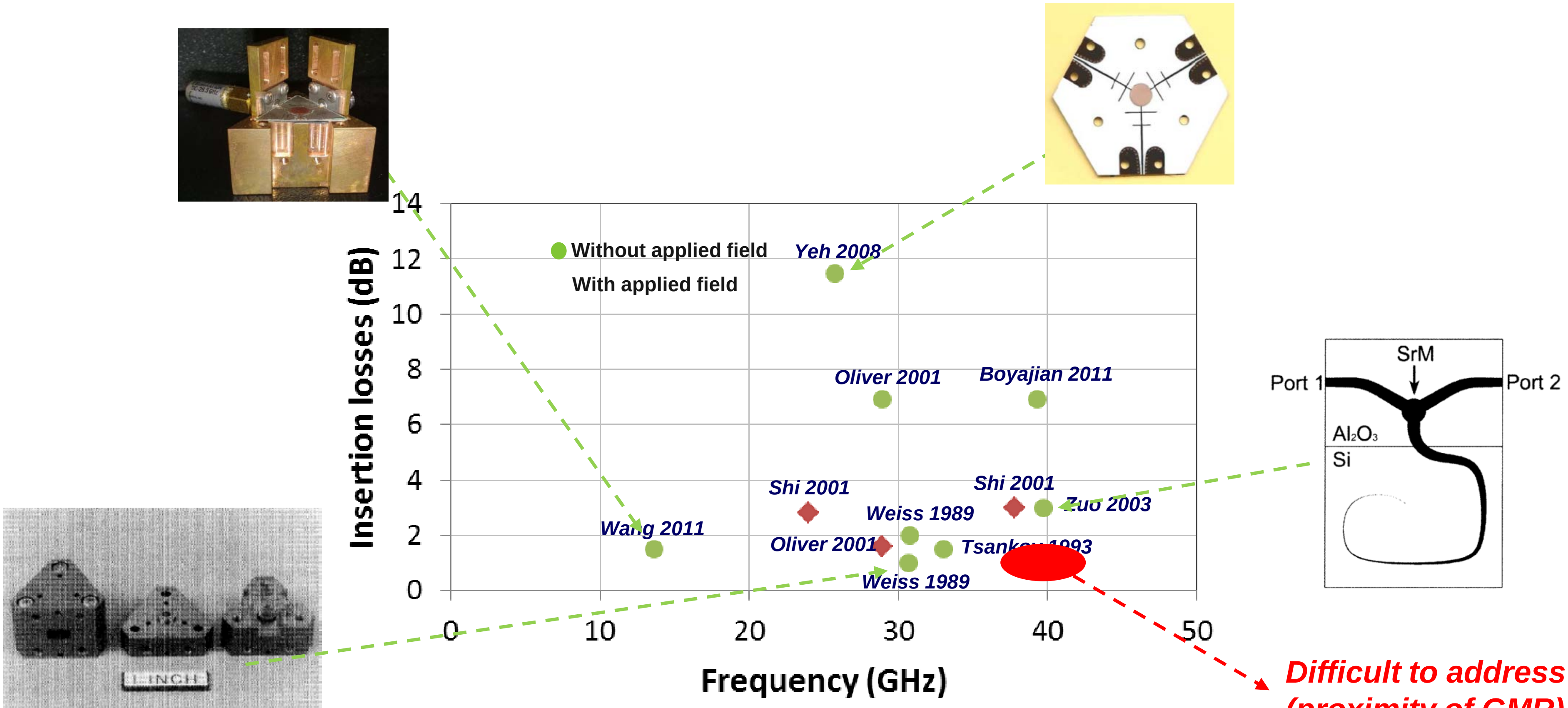


Hysteresis cycle of a pre-oriented hexaferrite

- Pre-oriented hexaferrite
- Magnetization state: remanence
- No permanent magnet
- Easier integration

Self-biased circulators

➲ **State of the art**



Insertion losses as a function of frequency measured for hexaferrite-based circulators

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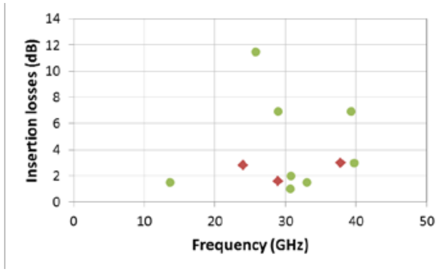
Self-biased circulators

➲ Choice of materials



- **Single crystal hexaferrites**
  - ☺ *High anisotropy field (compatible with mm-wave applications)*
  - ☺ *Low ΔH*
  - ☹ *Low remanent magnetization (permanent magnet needed)*

- **Pre-oriented hexaferrite composites**
  - ☺ *High anisotropy field (compatible with mm-wave applications)*
  - ☺ *High remanent magnetization (self-biased working mode)*
  - ☹ *High ΔH (porosity)*
  - ☹ *High $\tan\delta_d$ (use of organic binder)*

- **Polycrystalline pre-oriented hexaferrites (mainly BaM and SrM)**
  - ☺ *High anisotropy field (compatible with mm-wave applications)*
  - ☺ *High remanent magnetization (self-biased working mode)*
  - ☹ *Moderate ΔH (porosity)*

➡ Use of SrM with La,Co substitution to increase anisotropy field

Hexaferrites

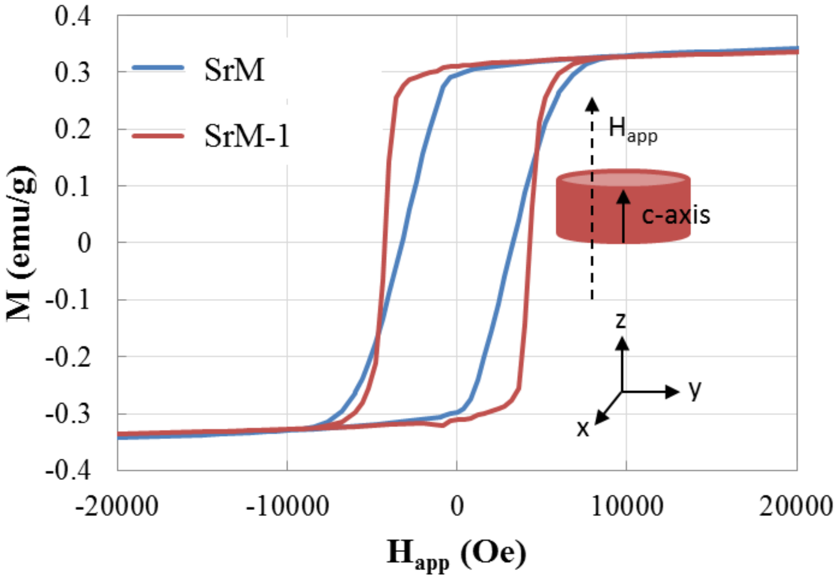
➲ Materials: Substituted strontium hexaferrites (called SrM-1 and SrM-2)

❑ Synthesis:

- Powder preparation (solid state reaction)
- Powder calcination
- Orientation during pressing
- Sintering at high temperature

❑ Effects of substitution:

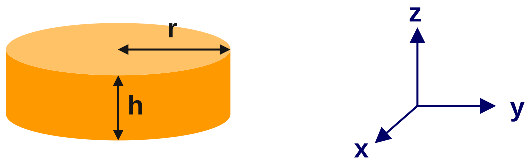
- Increase of M_r/M_s
- Increase of H_k (higher working frequency / pure SrM)



Comparison of SrM and SrM-1 hysteresis cycles measured using a SQUID

Hexaferrites

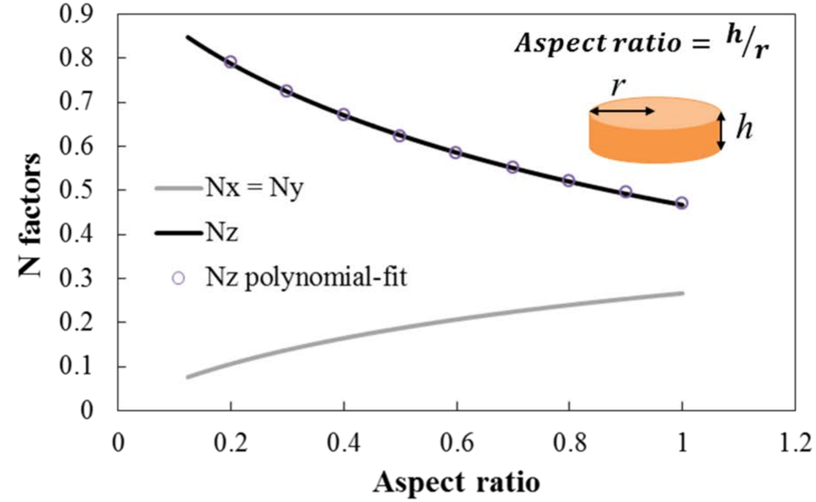
➲ Extrinsic properties of hexaferrite pucks



- **Internal field**

$$\vec{H}_{int} = \vec{H}_{\boldsymbol{k}} + \vec{H}_{app} - \overline{N} \times \vec{M}$$

with $$\overline{N} = \begin{pmatrix} N_x & 0 & 0 \\ 0 & N_y & 0 \\ 0 & 0 & N_z \end{pmatrix}$$



Evolution of demagnetization coefficients as a function of aspect ratio

- **Interpolation of N_z as a function of shape factor + integration into EM simulators**
- **Shape-dependant magnetic properties: taken into account during the simulations**

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Modeling of circulators

- Use of Ansys HFSS and CST Microwave Studio softwares (Polder's model => only valid for fully saturated ferrites)
- Use of Polder's model for highly pre-oriented hexaferrites:

$$H_{int\ Polder} = H_{app} + H_A - N_z \times M_r \qquad M_{Polder} = M_r$$

Polder's model

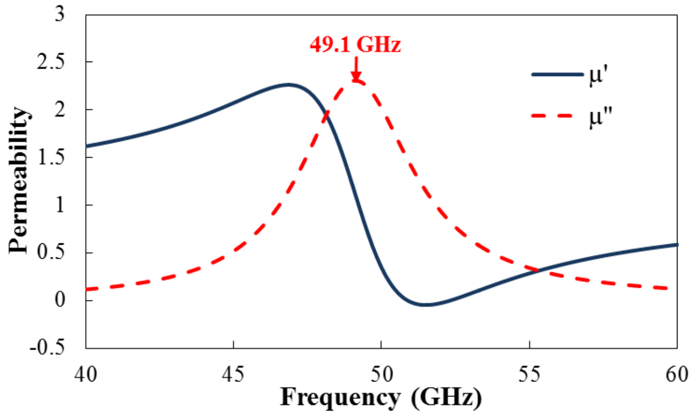
$$\mu = 1 + \frac{\omega_H \omega_M}{\omega_H{}^2 - \omega^2}$$

$$\kappa = \frac{\omega \omega_H}{\omega_H{}^2 - \omega^2}$$

$$\omega_H = \gamma (H_{\text{int}} + i\Delta H)$$

$$\omega_M = \gamma . 4\pi M_z$$

$$\gamma = 5.6\pi \cdot 10^6 \, rad \cdot s^{-1} / Oe$$



Permeability spectra of SrM-1 puck calculated using Polder's model

Self-biased circulators: 1st run

➲ 1st run: comparison between SrM-1 and SrM-2

➲ Realization

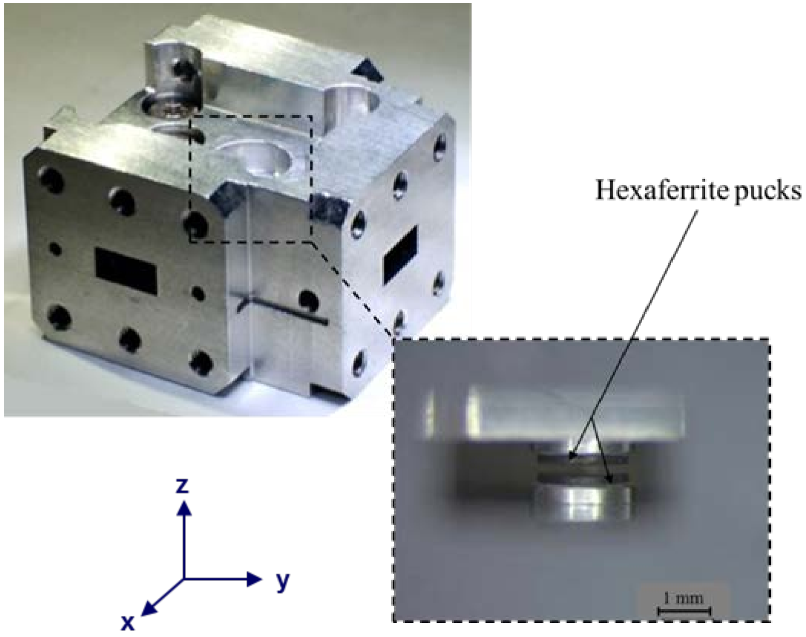
- ➢ Y-junction in rectangular waveguide technology (WR-19)
- ➢ Hexaferrite machining
  (c-axis perpendicular to the plane)
- ➢ Sticking at the center of the Y-junction

➲ Measurement

- ➢ Microwave measurement around 40 GHz
- ➢ TRL calibration
- ➢ Measurement in isolator mode (load connected to one of the port)
- ➢ Static magnetic field applied with an electromagnet (when needed)

➲ Retro-simulations

- ➢ Evaluate the material properties (ΔH, H_k)



Photograph of the circulator in rectangular waveguide technology (Insert: hexaferrite pucks placed in the middle of the Y-junction)

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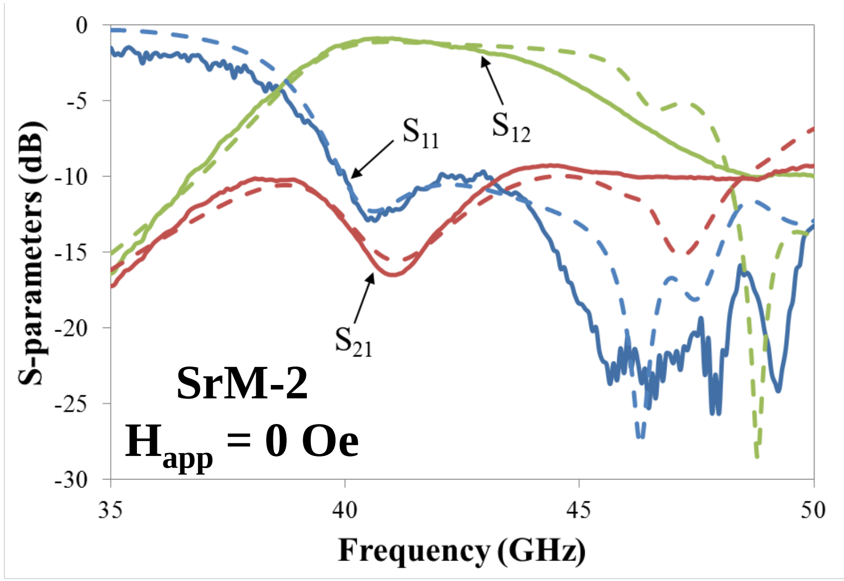
Self-biased circulators: 1st run

➲ **Measurements without applied field**

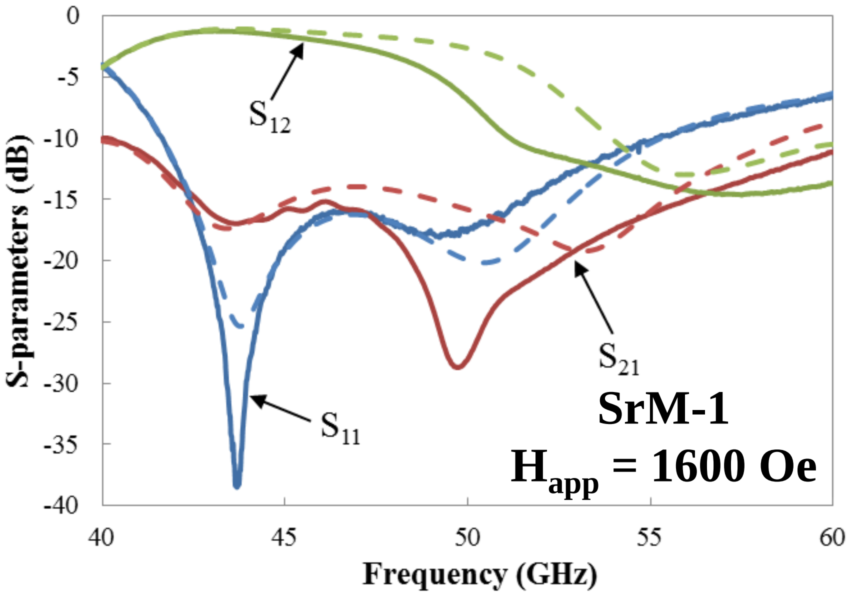


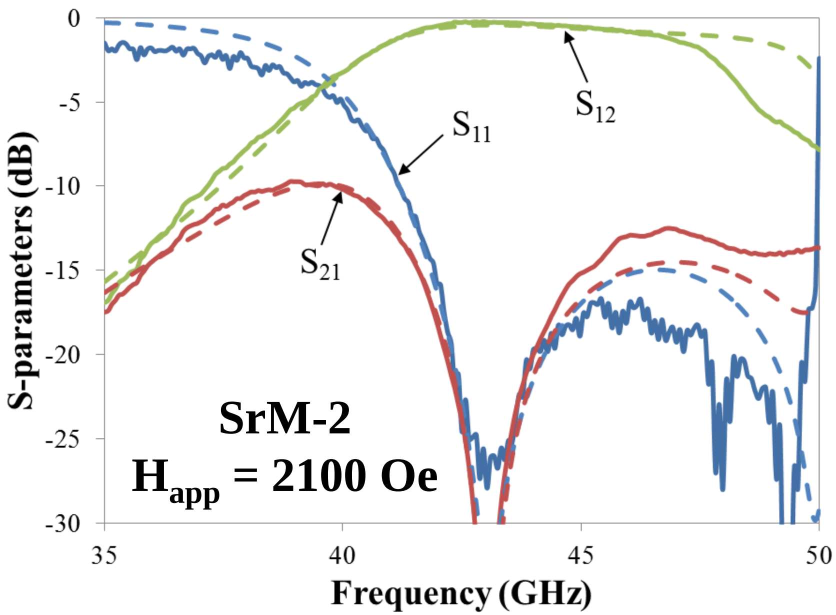
Material	IL_{min} (dB) @f GHz	Isolation (dB)	Adaptation (dB)	$BPR_{Iso < -15dB}$ (%)
SrM-1	1,79 @41,4 GHz	28,1	12,5	7,2
SrM-2	0,87 @41 GHz	16,5	12,6	3,2

- **Good agreements between retro-simulations and measurements**
- **Quite similar working frequencies**
- **$IL_{SrM-1} = 2 \times IL_{SrM-2}$**

Self-biased circulators: 1st run

➲ **Measurements with applied field**





Material	IL_{min} (dB) @f GHz	Isolation (dB)	Adaptation (dB)	$BPR_{Iso < -15dB}$ (%)
SrM-1	1,23 @43,2 GHz	16,5	24,6	11,2
SrM-2	0,21 @42,9 GHz	41,3	25,6	9,7

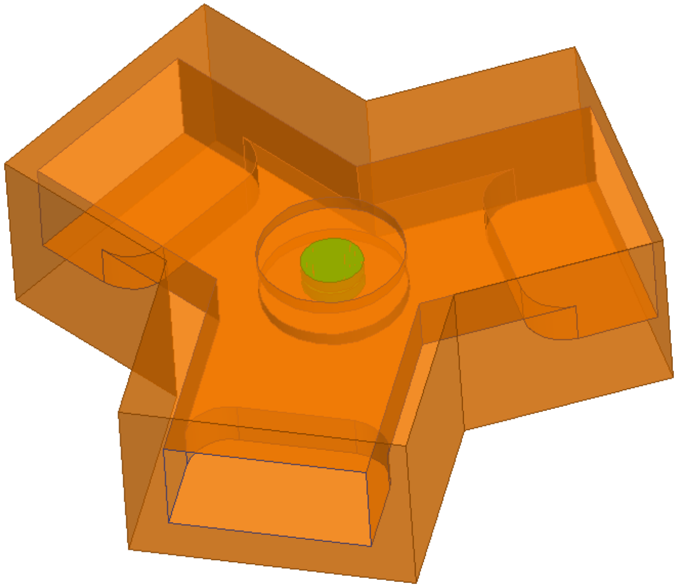
- **Performances improvement with a low applied field (Y-junction dimensions can be optimized)**
- **SrM-2: best candidate (ΔH 3 times lower than those of SrM-1)**

Self-biased circulators: 2nd run

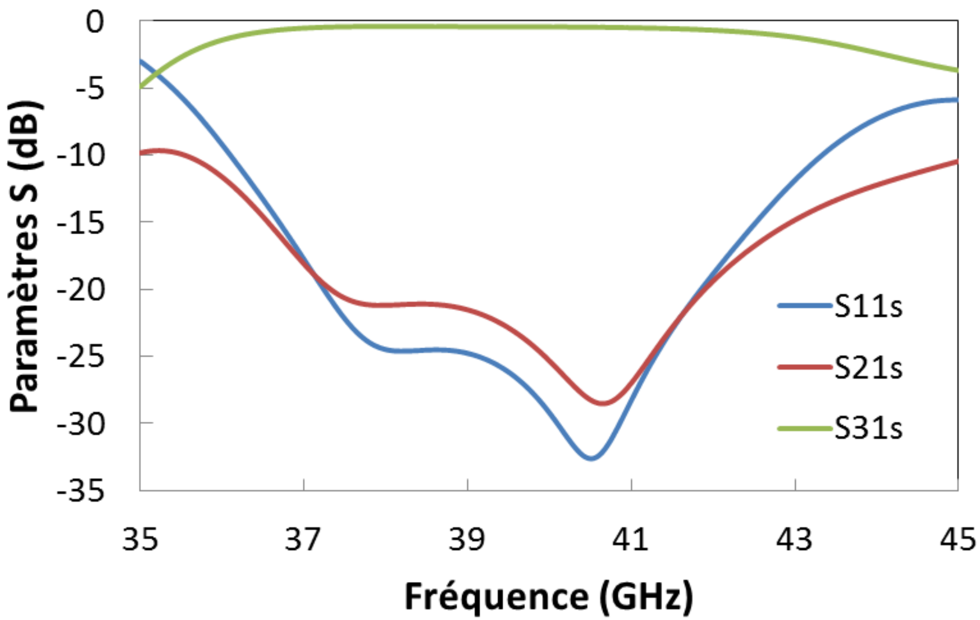
➲ **SrM-2 properties:**

M_S (G)	H_k (kOe)	M_r/M_S	ΔH (Oe)	ε_r
4240	19.75	0.88	400	21

➲ **Y-junction optimization:**



Optimized structure

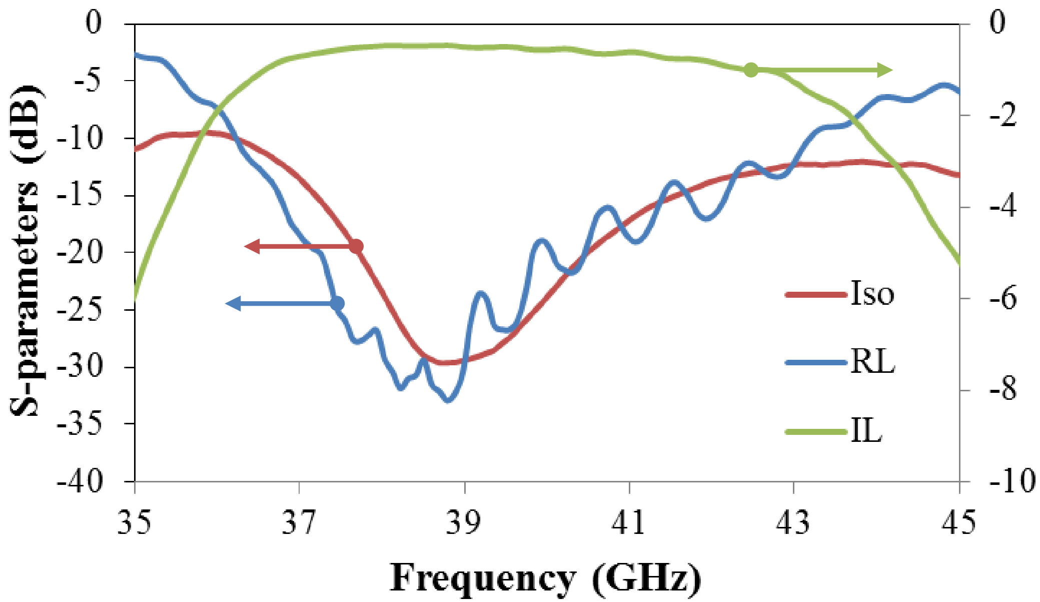


Simulated optimized performances of SrM-2-based circulator

H_{app} (Oe)	IL_{min} (dB) @f GHz	Isolation (dB)	RL (dB)	$RBW_{Iso < -15dB}$ (%)
0	0.41 @38.1 GHz	21.2	24.6	16.9

Self-biased circulators: 2nd run

➲ Microwave measurement



Measured S-parameters of the optimized Y-junction

IL_{min} (dB) @ f GHz	0,41 @ 38,9 GHz
Isolation (dB)	26,5
RL (dB)	30,7
$RBW_{Iso < -15\ dB}$ (%)	10,4

⇨ **IL_{max} in BW = 0,52 dB**

⇨ **Ripple = 0,11 dB**

- **Significant improvement compared to 1st run**
- **Hexaferrites: competitive / spinel ferrites**

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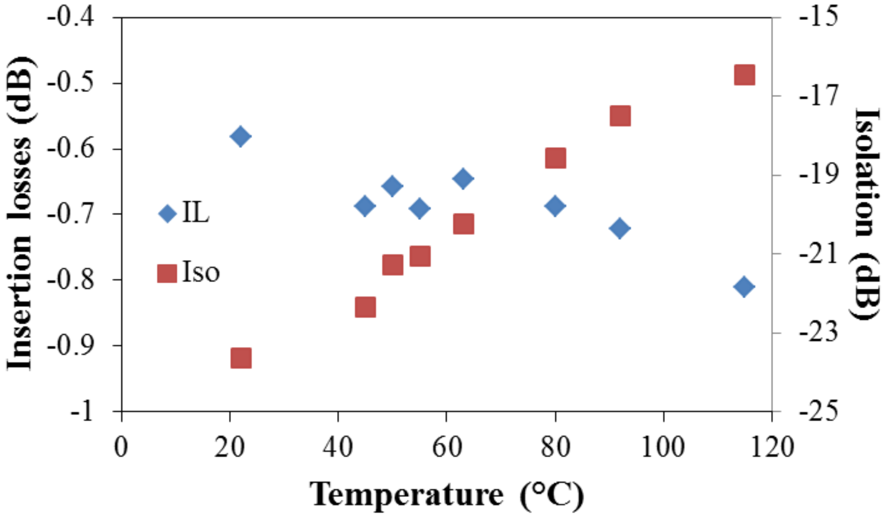
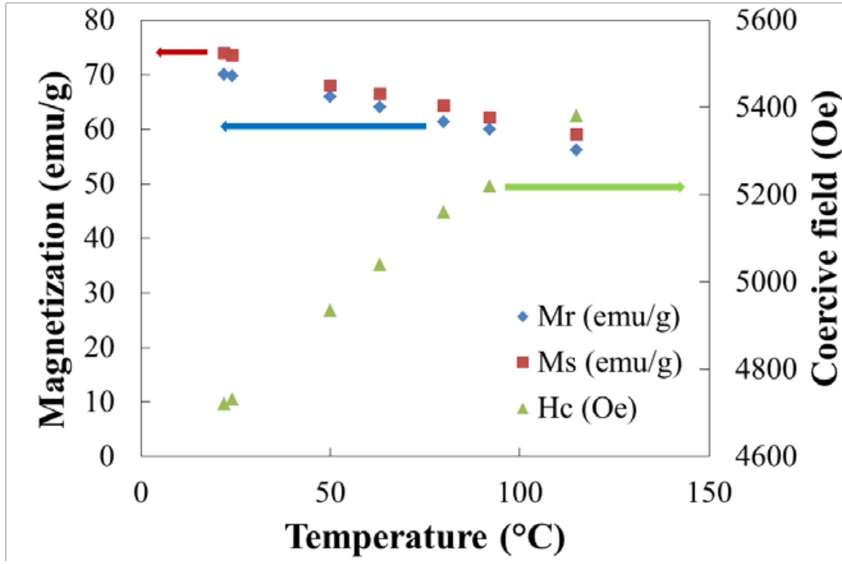
Self-biased circulators: 2nd run

➲ Effect of temperature



Isolation and insertion losses at 40 GHz as a function of temperature



Magnetization and coercive field as a function of temperature

- @ 40 GHz & 115°C: ΔIL = 0.23 dB, Δiso = 7 dB
- Isolation remains > 15 dB up to 115°C

- Decrease of M_s and M_r = 20%
- Increase of H_c = 14%

- **Retro-simulations: linear increase of ΔH as a function of temperature ($\Delta H_{22°C}$ = 400 Oe and $\Delta H_{115°C}$ = 760 Oe)**

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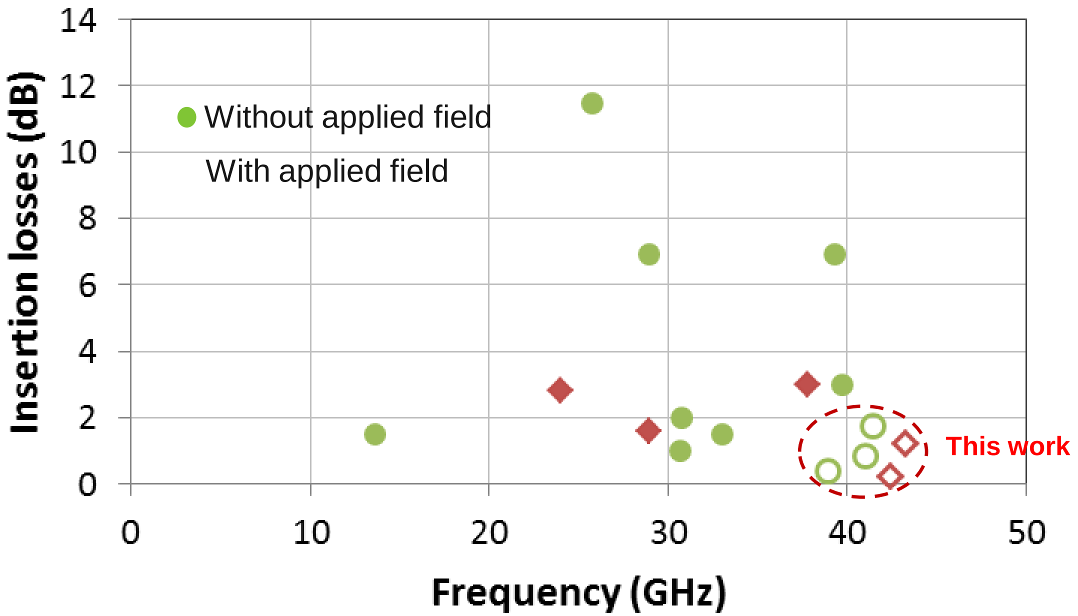
Conclusions and prospects

➲ **Selection of a lanthanum-cobalt substituted strontium hexaferrite for mm-wave applications**

➲ **Best performances without applied field: IL = 0.41 dB @ 38.9 GHz, RBW = 10.4% (4 GHz)**

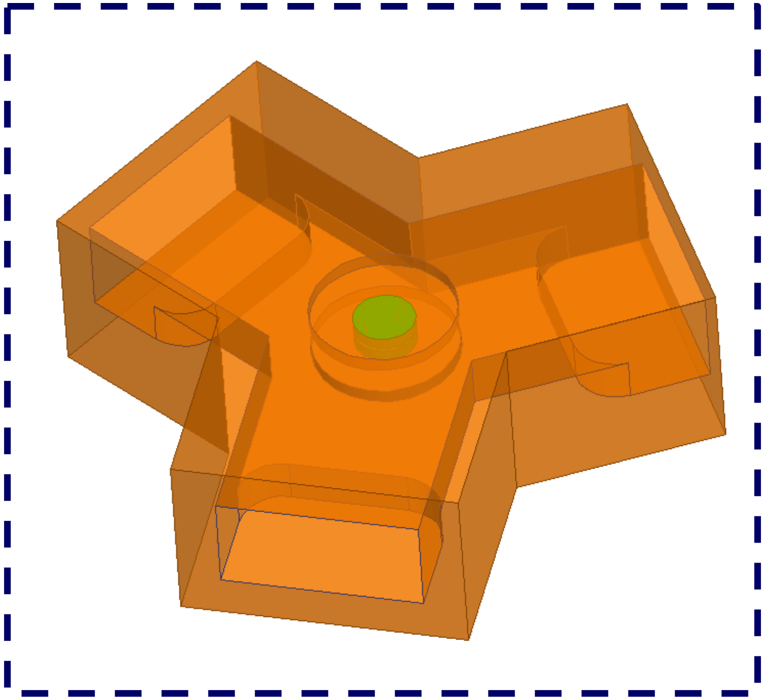
➲ **Measurements vs temperature: quite good stability**

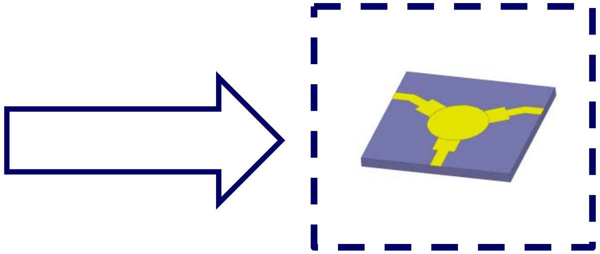


Insertion losses as a function of frequency measured on hexaferrite-based circulators

Conclusions and prospects

➲ **Realization of integrated mm-wave self-biased circulators and isolators**





- **Measured performances at a next SPCD…**

Acknowledgements

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direction générale de la compétitivité de l'industrie et des services

Thank you for your attention