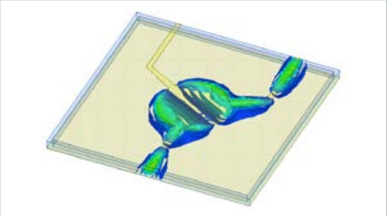

Q-band planar ultra-compact microwave circulators

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SPCD 2018

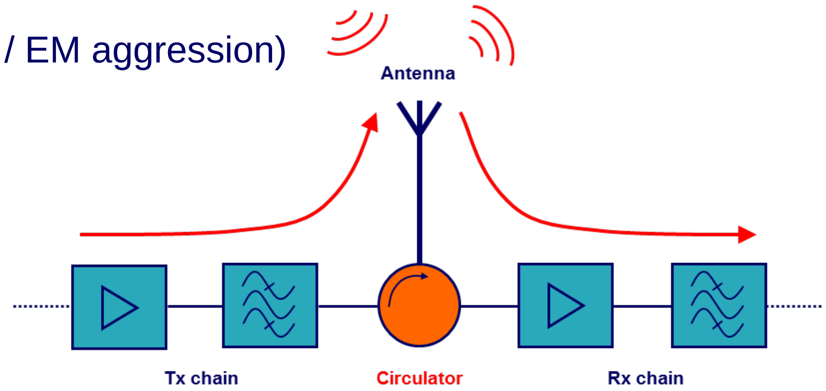
Outline

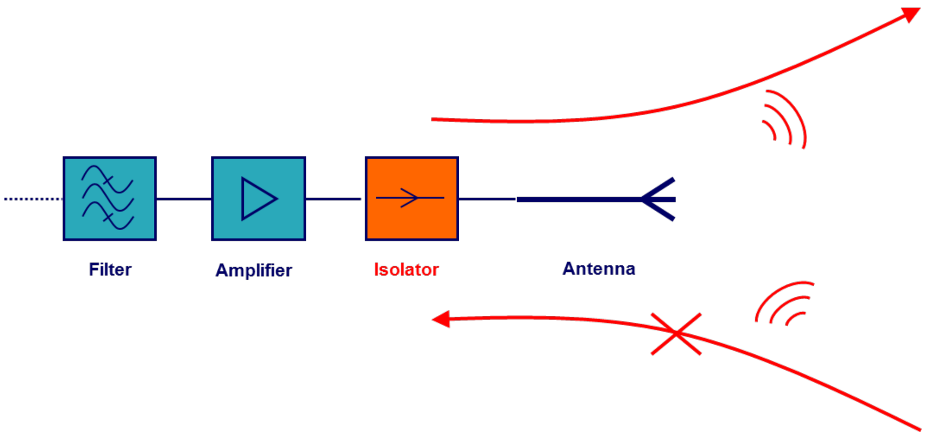
- ➲ **Concept and materials**
- ➲ **Demonstration in rectangular waveguide technology**
- ➲ **Ultra-compact planar circulators**
- ➲ **Conclusion and prospects**

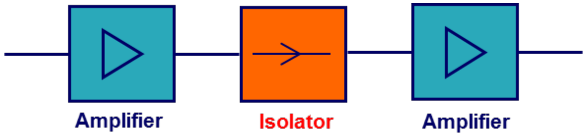
Concept and materials

➲ Microwave circulators and isolators

- ➲ Non-reciprocal devices
- ➲ Decoupling amplifiers
- ➲ Protection of RF systems (mismatched impedances / EM aggression)
- ➲ Full-Duplex systems
- ➲ …

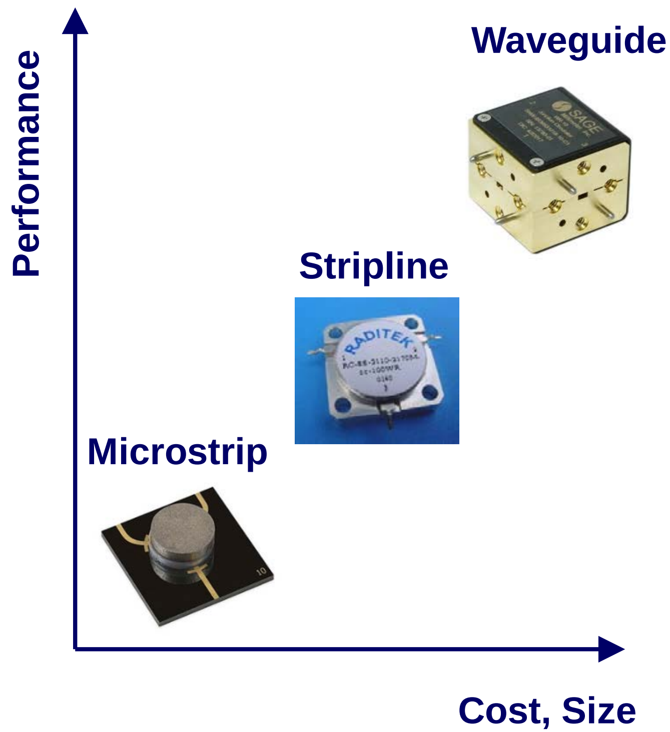






Concept and materials

➲ Technology



➲ Ferrites

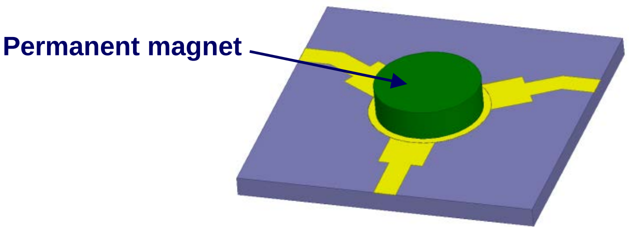
- ➲ Garnet ferrites
  - ➲ YIG and substituted YIG (Gadolinium, Vanadium, Aluminum, Cobalt…)
  - ➲ up to X-Ku bands
- ➲ Spinel ferrites
  - ➲ ex. $NiFe_2O_4$, $Li_{0.5}Fe_{0.5}Fe_2O_4$…
  - ➲ up to E-W bands
- ➲ Hexaferrites
  - ➲ SrM ($SrFe_{12}O_{19}$) and BaM ($BaFe_{12}O_{19}$)
  - ➲ Ka to Q/V bands (and more?)

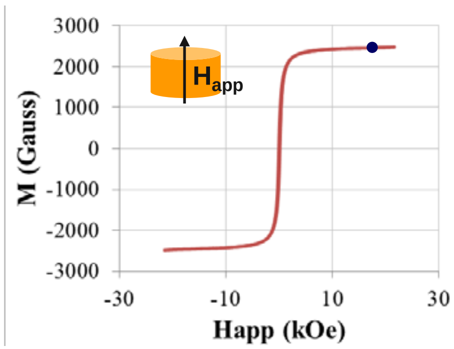
- ➢ Expensive and bulky devices / RF designers tend to remove it from front-ends
- ➢ **New technologies and materials have to be developped**

Concept and materials

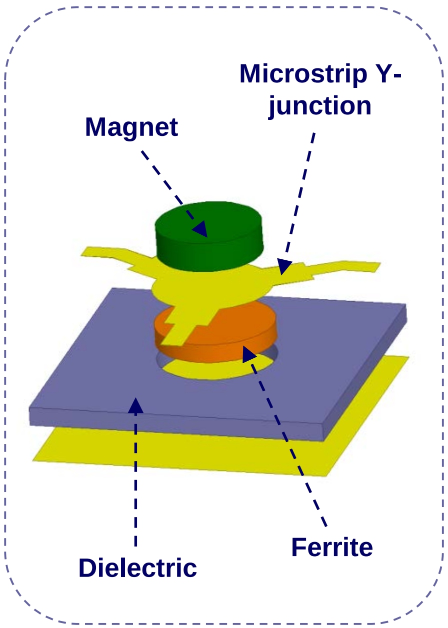
Classical circulator

ferrite or dielectric/ferrite

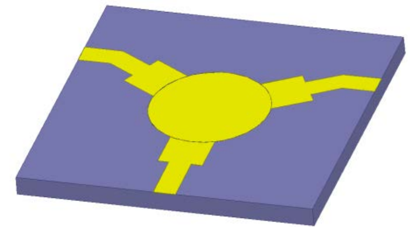


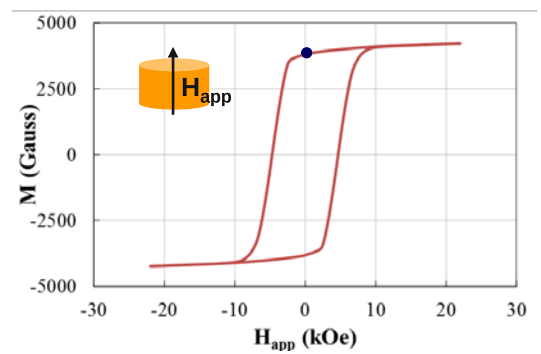


Hysteresis cycle of a soft ferrite



Self-biased circulator





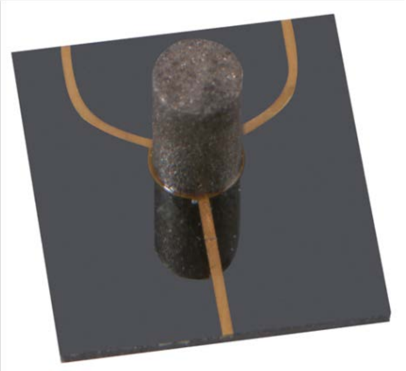
Hysteresis cycle of a pre-oriented hexaferrite

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

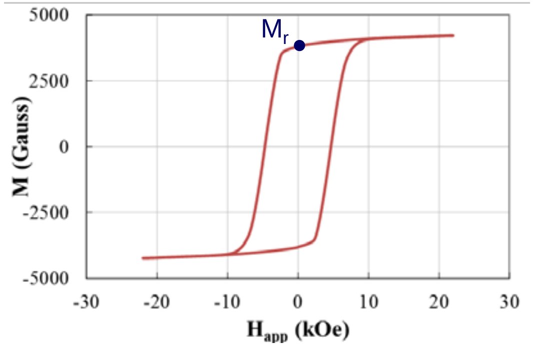
- Pre-oriented hexaferrite
- Magnetization state: remanence
- No permanent magnet
- Easier integration

Concept and materials

➲ Self-biased technology for Q-band applications



36-38 GHz soft ferrite-based planar circulator



M(H) cycle of a pre-oriented hexaferrite

- **Interest of self-biased technology:**
  - Soft ferrite: thickness mainly dependent on magnet size
  - Ex. 36-38 GHz planar circulator: magnet = 3.8 mm, ferrite = 0.2 mm
- **Materials requirement:**
  - High remanent-to-saturation ratio (M_r/M_S)
  - Low magnetic losses (ΔH)
  - High anisotropy field (H_k)
  - Properties of SrM BUT H_k too low for Q-band operation
- **Selected material:**
  - Substituted strontium hexaferrite

Concept and materials

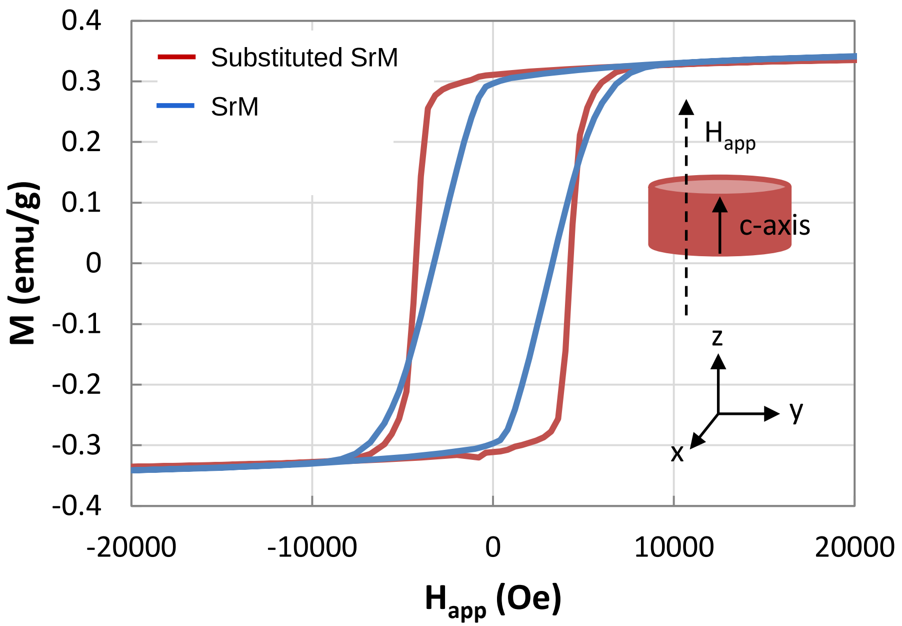
➲ Substituted strontium hexaferrites

❑ 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 substituted SrM hysteresis cycles measured using a SQUID

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Concept and materials

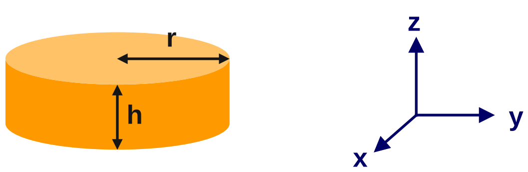
➲ Dynamic properties modeling

- Use of Ansys HFSS (Polder’s model => only valid for fully saturated ferrites)
- Use of Polder’s model for highly pre-oriented hexaferrites:

$$H_{int\ Polder} = \cancel{H_{app}} + H_k - \underbrace{N_z \times M_r}_{\text{Demagnetizing field}}$$

$$M_{Polder} = M_r$$

Demagnetizing field



- **N_z (h/r) integrated into EM simulators**
- **Shape-dependant magnetic properties: taken into account during the simulations**

Polder’s model

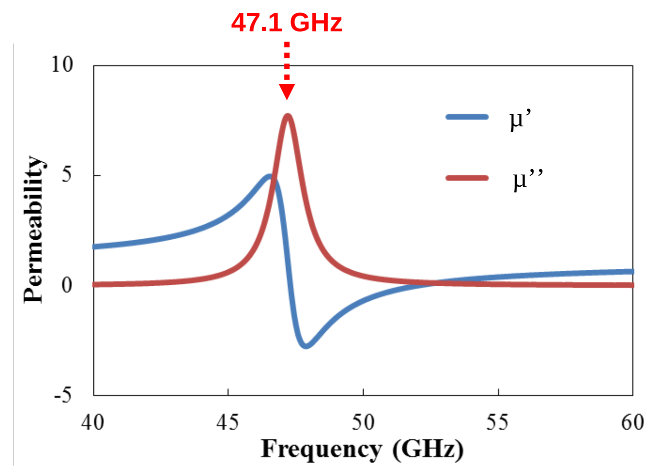
$$\mu = 1 + \frac{\omega_H \omega_M}{\omega_H^2 - \omega^2}$$

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

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

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

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



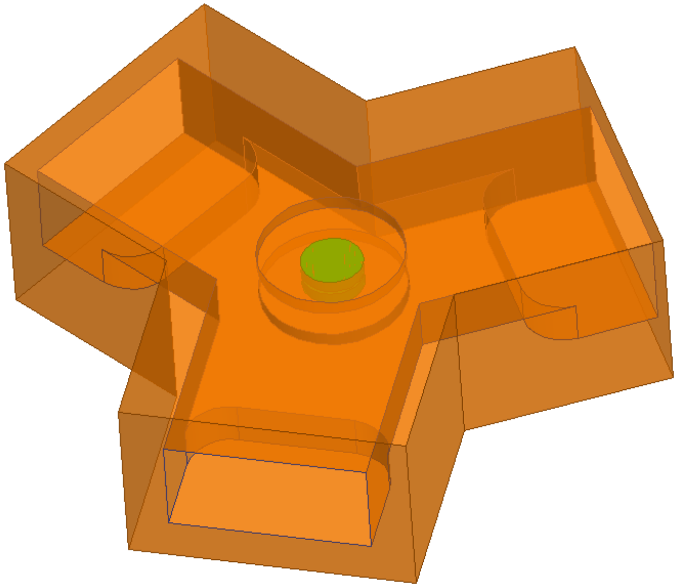
Permeability spectra of substituted SrM puck calculated using Polder’s model

Rectangular waveguide technology

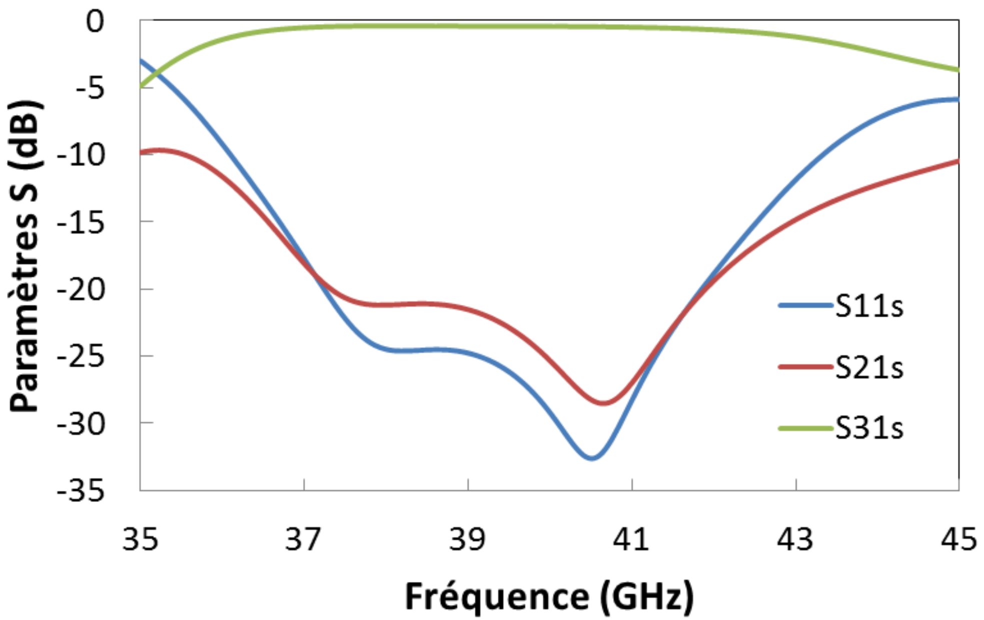
➲ **Ferrite properties:**

M_S (G)	H_k (kOe)	M_r/M_S	ΔH (Oe)	ε_r
4140	19.75	0.88	**400**	21

➲ **Y-junction optimization:**



Optimized structure



Simulated optimized performances of SrM-2-based circulator

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

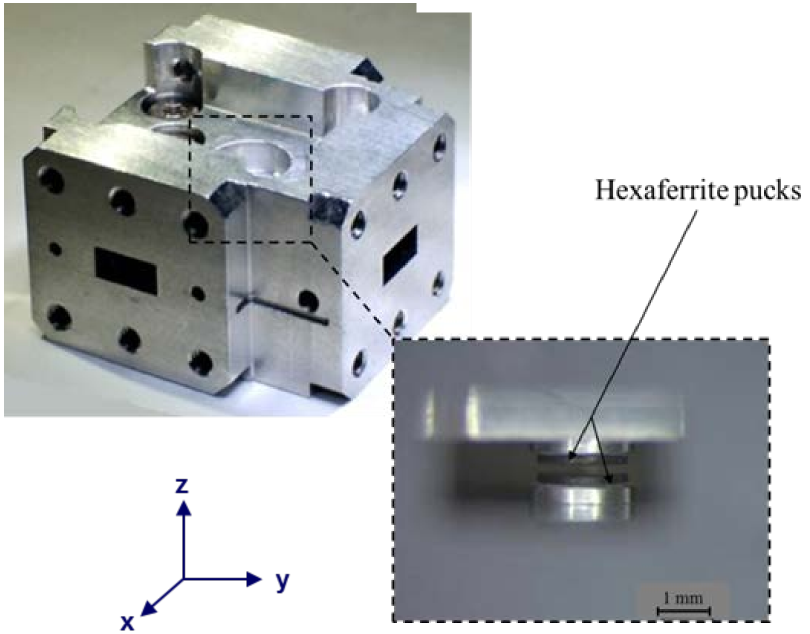
Rectangular waveguide technology

➲ 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 35-45 GHz
- TRL calibration
- Measurement in isolator mode (load connected to one of the port)

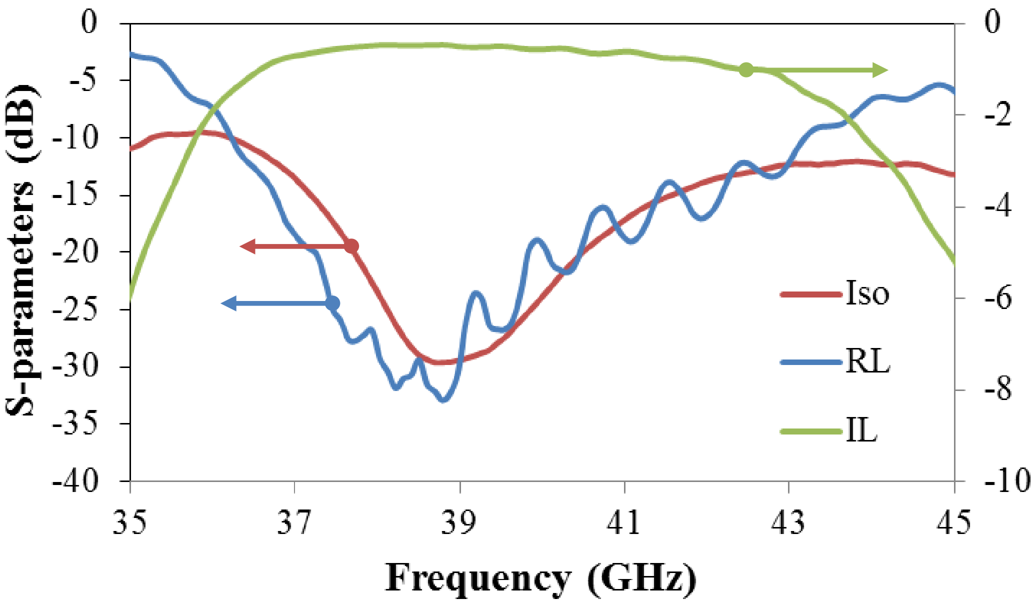


Photograph of the circulator in rectangular waveguide technology (Insert: hexaferrite pucks placed in the middle of the Y-junction)

Rectangular waveguide technology

➲ Microwave measurement

COBHAM



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**

- **Promising results**
- **Hexaferrites: competitive / spinel ferrites**

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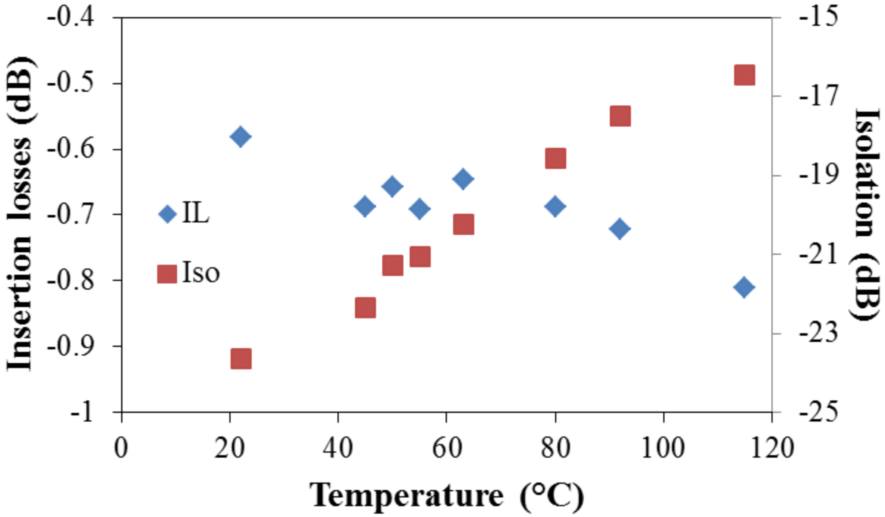
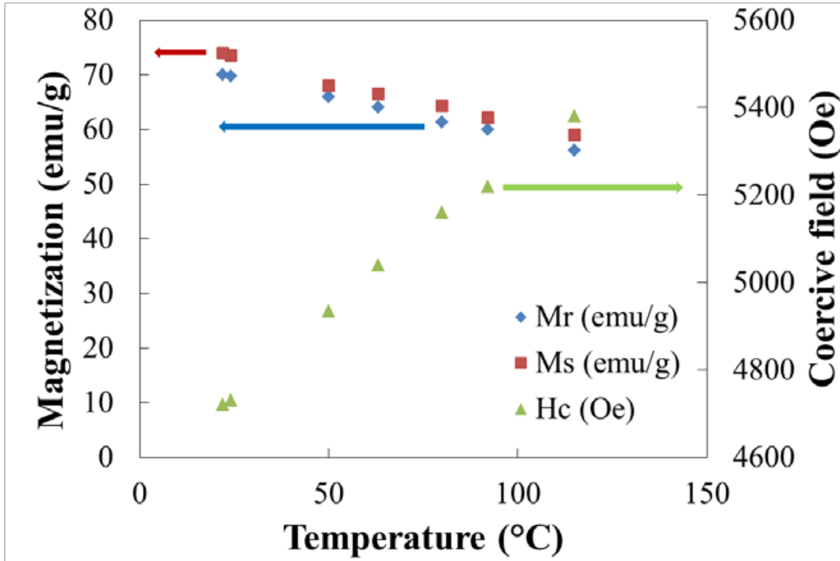
Rectangular waveguide technology

➲ 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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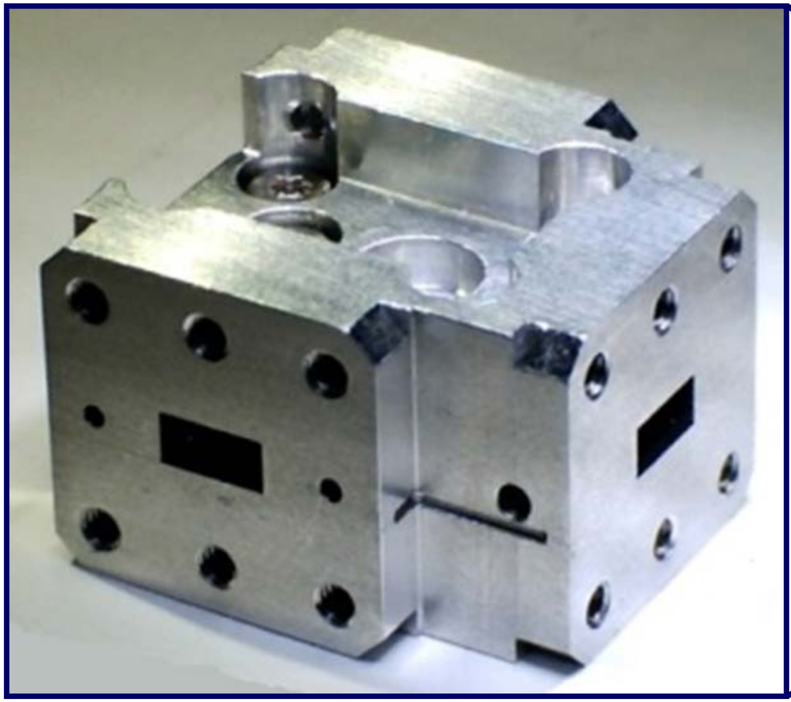
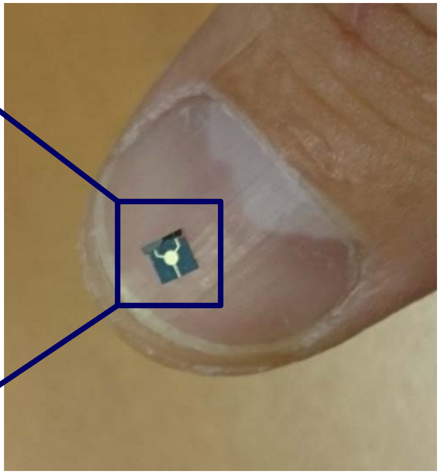
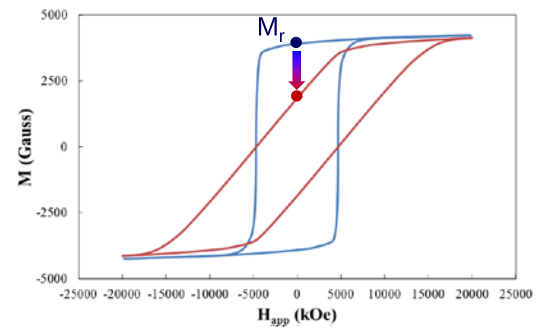
Ultra-compact circulators

➲ **Transfer to planar technology (microstrip)**



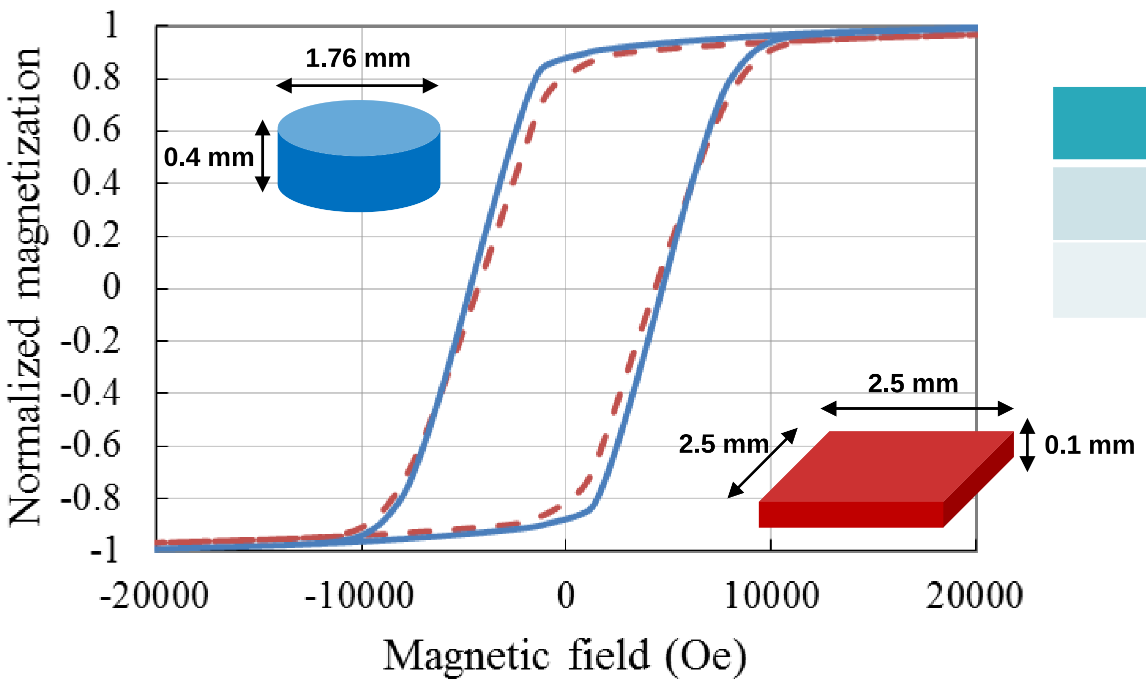


- **Not obvious: static magnetic properties / shape effect**
- **Possible decrease of cycle squareness**



Ultra-compact circulators

➲ Magnetic properties



Shape factor	
Disk	Plate
0,23	0,04

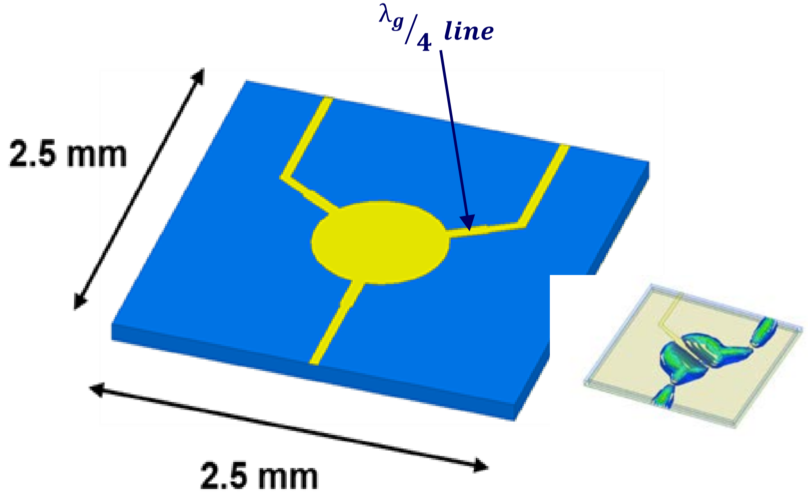
- Slight decrease of Mr/Ms (disk = 0.88 / plate = 0.83)
- Compatible with the realization of planar self-biased circulators

Ultra-compact circulators

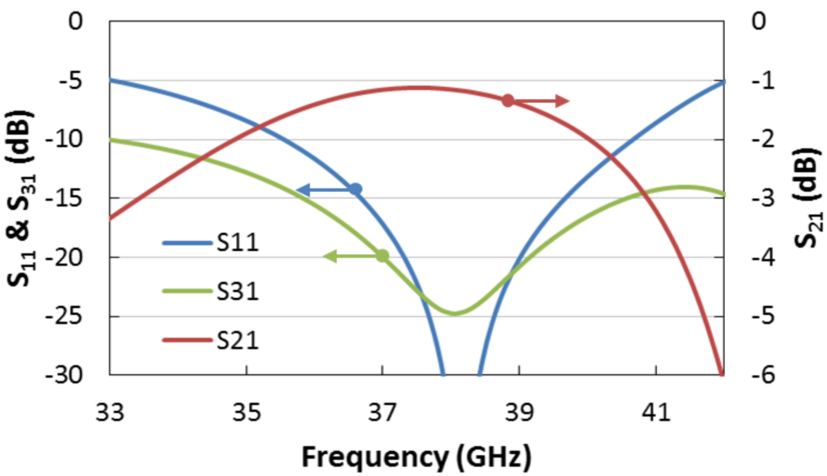
➲ Circulator design

- ➢ Bosma model (pre-design)
- ➢ Optimization Ansys HFSS

M_s (G)	H_k (Oe)	M_r/M_s	ΔH (Oe)	ε_r
4140	19750	**0.83**	400	21



Simulation model



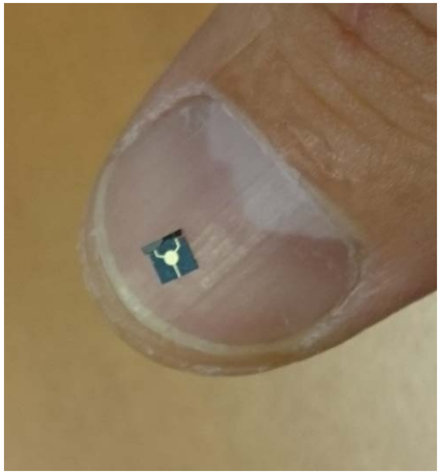
Simulated S-parameters

- ➢ **Very compact device: 2.5 mm x 2.5 mm x 0.1 mm**
- ➢ **Simulated performance: IL_{min} = 1.13 dB @37.8 GHz, RBW_{-15dB} = 7.7%**

Ultra-compact circulators

➲ **Fabrication**

- Machining and polishing of ferrite substrates
- Metallization: standard thin film process



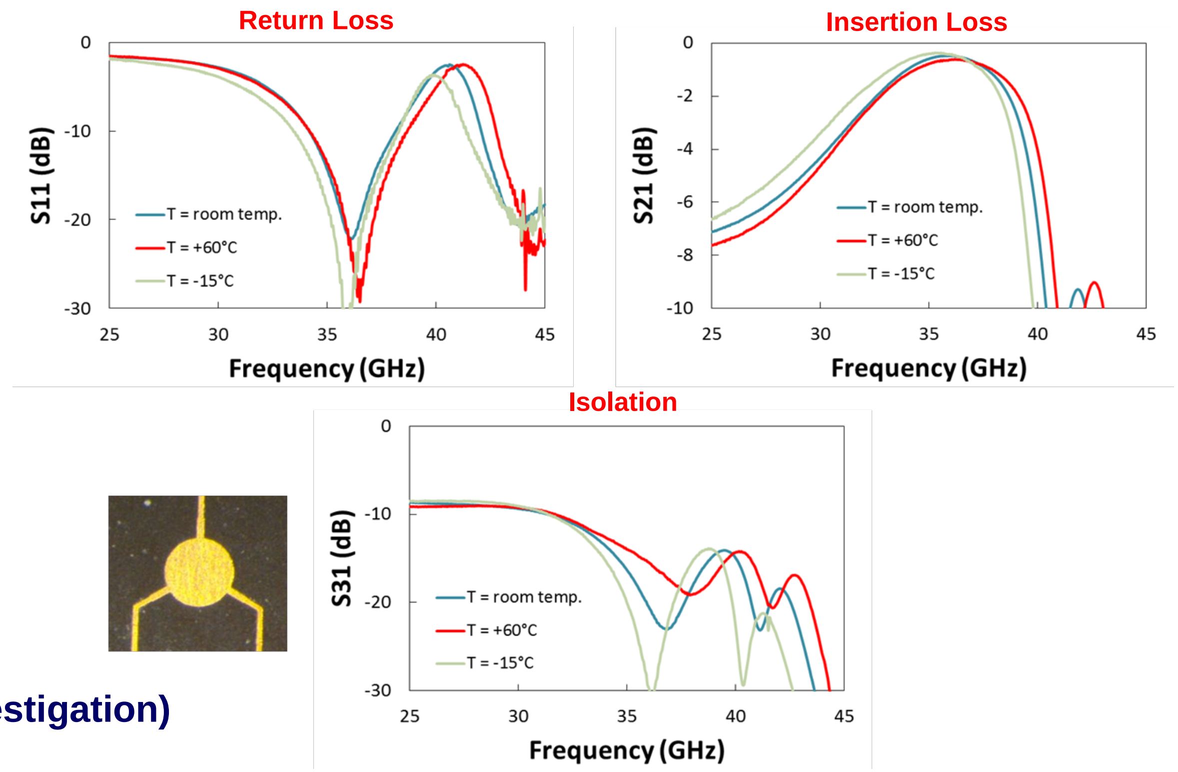
➲ **Microwave measurements**

- Dedicated microstrip probes
- VNA 25-45 GHz frequency band
- Temperature -15°C to +60°C

Ultra-compact circulators

➲ Measured performance

@ 35.8 GHz / Room temp.	
IL (dB)	0.45
RL (dB)	27
Iso (dB)	17
RBW (%)	4.5



Measured S-parameters (room temp., -15°C, +60°C)

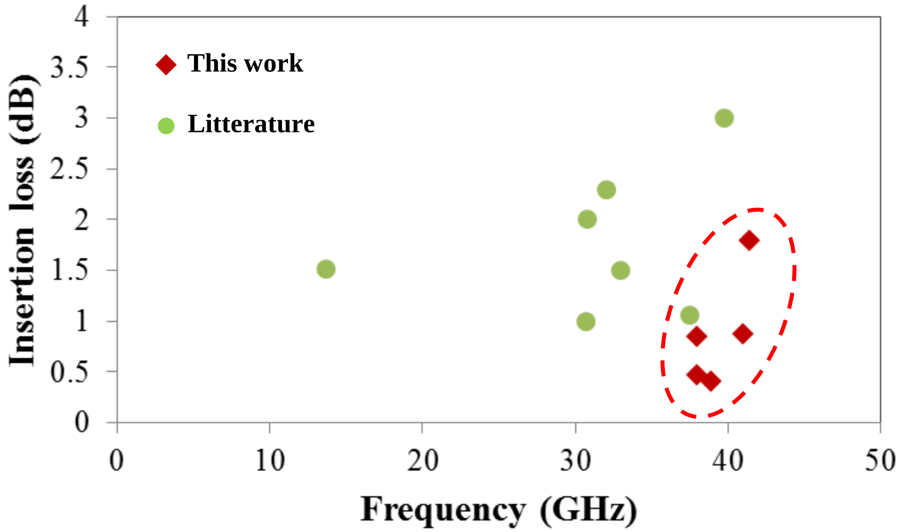
- **Slight shift in frequency (under investigation)**
- **Good temperature stability**
  - Increase of IL: +0.15 dB at +60°C
  - RL & Iso higher than 15 dB from -15°C to +60°C

Conclusions and prospects

➲ Substituted strontium hexaferrites: promising technology for Q-band compact circulators and isolators

➲ State of the art: Low insertion loss (0.45 dB) for a very compact low-weight circulators (~3 mg)

➲ Standard thin film process



➲ Investigation of measurement/simulation frequency shifts

➲ Correlation of temperature evolution (static magnetic properties)

➲ Design and fabrication of Ka-band circulators and isolators (dedicated hexaferrites)

Acknowledgements

MM_WIN

EURIPIDES

Eureka Initiative for Packaging & Integration of µDevices & Smart Systems

Integrated isolators

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Thank you for your attention

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