Towards W-band self-biased circulators for next generation of VHTS payload

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INTRODUCTION

Circulators and isolators are non-reciprocal devices that are crucial components for satellite payloads as they make it possible to protect amplifiers from impedance mismatches or to ensure low reflection levels in electronically steerable antennas. Traditional circulators and isolators are made of soft ferrites that require more and more bulky permanent magnets as frequency increases. However, future very high throughput satellites (VHTS) will use W-band frequencies in order to provide very high data rates. In this context, the integration of circulators and isolators in satellite payloads will become a burning issue.

In order to be able to fabricate compact non-reciprocal devices, a solution consists in replacing soft ferrites (spinels or garnets) by pre-oriented hexaferrites. This solution makes it possible to fabricate magnetless components also called self-biased circulators and isolators. Several demonstrations were performed from Ku-band to Q-band. However, literature survey shows that no compact self-biased W-band components were either already mentioned in publications nor commercially available.

In this study, we designed and fabricated different W-band components based on pre-oriented strontium hexaferrites. At first, a self-biased WR-10 rectangular waveguide circulators was optimized for the 71-76 GHz frequency band. Measurements shows that such component could provide insertion losses lower than 1.06 dB and isolation levels better than 14.5 dB between 71 and 76 GHz. These preliminar results are especially promising knowing that calibration has to be optimized and that device assembling was manually performed.

Then, ultra-compact microstrip isolators were designed in the same frequency band. The size of the component is only 2 mm x 2 mm including coplanar waveguide-to-microstrip transitions that make it possible to measure the isolator using a probe station. In spite of a slight frequency shift, this planar isolator has insertion losses lower than 2.29 dB in the 71-76 GHz frequency band. The higher isolation level is 25.1 dB at 72.7 GHz and it remains higher than 11 dB in the frequency band of interest.

These promising results pave the way to the development of compact low-mass non-reciprocal devices for next generation of W-band satellite payload.

SELF-BIASED CIRCULATORS: CONCEPT AND MATERIALS

Non-reciprocal devices, such as circulators and isolators, require the use of magnetized ferrites to induce differences of transmission between forward and reverse travelling waves. This non-reciprocity arises from the anisotropy of magnetized ferrites. Standard circulators are using soft ferrites (spinels or garnets) that require using a permanent magnet to orientate magnetization perpendicular to the plane of the sample so that to fully saturate the ferrite disk and induces anisotropy of permeability (Fig. 1). To ensure high isolation over a wide bandwidth, ferrites with a high saturation magnetization (up to 5000 G) must be used at millimeter-wave frequencies. However, in such ferrites, field that opposes the applied field, known as the demagnetizing field, is created when a magnet is used to polarize the ferrite. As this field is proportional to magnetization, the size of the magnets used increases as the frequency increases. Indeed, at millimeter-wave frequencies, the thickness of the magnet can represent up to 80% of the total thickness of the component.

The use of pre-oriented hexaferrites in replacement of soft ferrites makes it possible to keep a strong magnetization without applying an external magnetic field, and thus, to remove the permanent magnet (Fig. 1).

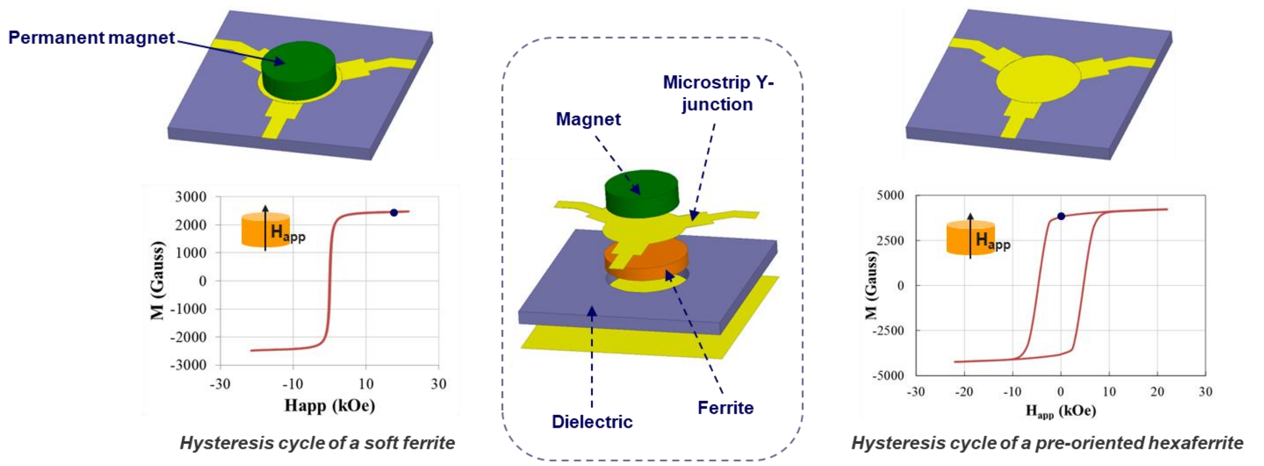

Fig. 1. Illustration of the structure of a standard circulator using a soft ferrite (on the left) and of a self-biased circulator using a pre-oriented hexaferrite (on the right).

Among hexaferrites, strontium hexagonal ferrites exhibit a high anisotropy field of about 18-20 kOe and a high remanence to saturation ratio, making it possible to realize mm-wave self-biased circulators. Moreover, their high coercive field makes them relatively robust to temperature and stray external magnetic fields. Such materials were previously used to realize demonstrators from Ku to V bands [1]-[12]. However, to our knowledge, there is only one attempt of W-band self-biased circulator in the literature in rectangular waveguide technology with a low bandwidth and moderate losses (1.1 dB at 73.5 GHz) [13] and no demonstrator in planar technology.
In this study, we used a substituted hexaferrite whose properties are detailed in Table 1.

Table 1. Ferrite properties

Material	ϵ_r	$tan\ \delta_e$	$4\pi Ms\ (G)$	M_r/M_s	$H_k\ (kOe)$	$\Delta H\ (Oe)$
SrM	21.3	5.10^{-4}	4800	0.85	17.5	200 @ 45 GHz

DESIGN AND CHARACTERIZATION OF W-BAND SELF-BIASED CIRCULATORS

Self-biased W-band rectangular waveguide circulators

The feasibility of W-band circulators was at first demonstrated in rectangular waveguide technology. General views of the Y-junction are available in Fig. 2. The component is built around WR-12 waveguides ($a \times b = 3.1 \times 1.55\ mm^2$). Impedance matching is ensured over a wide bandwidth using reduced height waveguide section of length l_t and height b_t. To help with the insertion of the ferrite disk into the Y junction, a $100\ \mu m$-tall step ($step_h$) has been added. The step extends $step_r = 100\ \mu m$ around the ferrite puck. The ferrite puck is fixed in the Y-junction with $100\ \mu m$-thick double-sided adhesive tape.

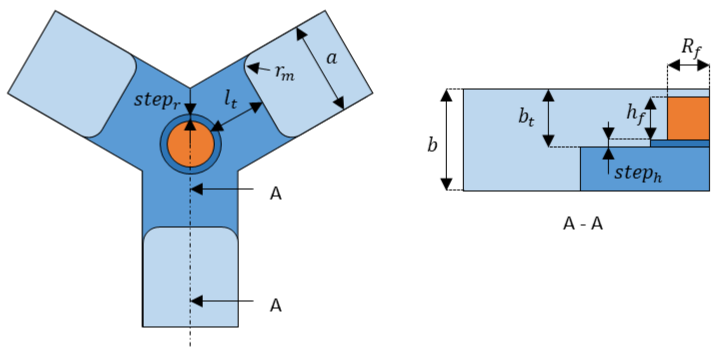

Fig. 2. Drawings of the rectangular waveguide Y-junction circulator.

The circulator enclosure is made as a split-block design. The two halves are machined in aluminum to create the waveguide Y-junction. The two parts are assembled with 5 CHC M2x12 screws. Alignment pins and holes are added to ensure good placement of the two half-shells. To guarantee good contact between the two parts where it is critical, the bottom side have rims right around the RF path. A thin layer of silver (σ = 61 MS/m, t ≥ 5 µm) is deposited onto the internal surface. Skin depth is in the order of 200 µm to 300 µm at W-band so the silver deposition thickness is sufficient to ensure low metallic loss. A complete description of the RF and mechanical designs is available in [14].

After a preliminary design, the device was optimized using Ansys HFSS software. In simulation, minimum insertion loss of 0.26 dB at 76.3 GHz is achieved (Fig. 3). Maximum isolation level is 22.8 dB at 76.4 GHz. In the frequency band of interest (71 – 76 GHz), isolation level and return loss are above 20 dB and insertion loss is below 0.3 dB.
The component has been measured using Rohde & Schwartz ZVA67 with ZVA-110 W-band (75 – 110 GHz) frequency converters. The test bench has only 2 ports, so the third port is terminated with the waveguide load from the calibration kit, see Fig. 7. WR-10 to WR-12 waveguide transitions are added to fit the component onto the converters and onto the termination. A Thru-Reflect-Line (TRL) calibration is done with WR-10 waveguide calibration kit due to the lack of WR-12 waveguide calibration kit. There is a fairly good agreement between the simulation and the measurement. Minimum insertion loss is 0.37 dB at 71.6 GHz. Maximum isolation level is 17.8 dB at 71.6 GHz. In the frequency band of interest (71 – 76 GHz), isolation level and return loss are above 14.3 dB and insertion loss is below 1.45 dB. High insertion loss between 71 GHz and 76 GHz is due to a shift of the circulator response towards low frequencies. Better performance can be noticed between 68.4 GHz and 74.2 GHz with an isolation level above 15 dB and insertion loss below 0.83 dB. This shift in frequency could be explained by technological tolerances on the ferrite placement and/or an inaccurate estimation of the ferrite properties.

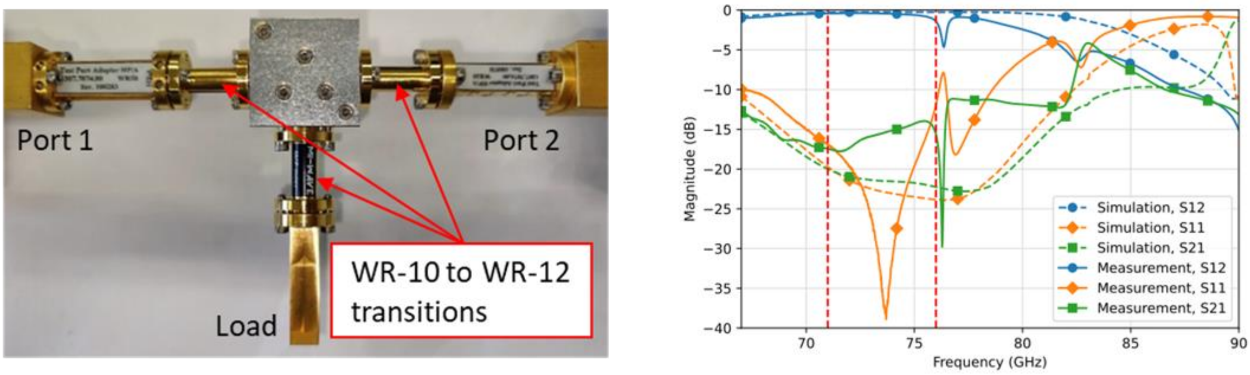

Fig. 3. Measurement setup (on the left) and comparison of simulated and measured S-parameters (on the right).

This first step allowed us to demonstrate that this self-biased technology can be used up to W-band with competitive performance compared to technologies using soft ferrites. However, self-biased circulators are of greater interest in planar technology, as the absence of a magnet in a waveguide circulator does not significantly reduce its size.

Self-biased W-band planar circulators

Promising performance of rectangular waveguide circulator led us to design a planar self-biased device for the W-band space downlink band (71-76 GHz). Due to measurement limitations (only two port measurement available in the laboratory), the study focused on the design of an isolator based on a three-port Y-junction circulator with a 50Ω load connected to one port. The simulation model is shown on Fig. 4. The Y-junction was designed in microstrip technology and includes quarter-wavelength impedance transformers. Coplanar waveguide to microstrip transitions were designed to be able to measure the device using a standard probe station. The 50Ω load was designed as a patch of Ta_2N resistive material. The load was optimized separately to provide a reflection coefficient lower than -30 dB over 71-76 GHz frequency band. The total size of the device is only 1.2 mm x 1.2 mm.
In simulation, insertion losses between 71 and 76 GHz remain lower than 2.22 dB with a minimum value of 1.33 dB at 71.7 GHz (Fig. 5). Impedance matching is satisfying over the frequency band of interest with a reflection level below -23.7 dB on both ports. Then, a good isolation level is ensured with a maximum value of 22.8 dB at 73.5 dB and a minimum value of 13.5 dB over the 71-76 GHz frequency band.
The fabrication followed a standard process for ceramics-based microwave devices. Ferrite substrates were at first polished. Then, a Ta_2N and gold plating was realized before a selective etching using standard photolithography process. Devices were finally magnetized using a vibrating sample magnetometer under a magnetic field amplitude of 23 kOe.
Microwave measurements were performed using a Microtest probe station with Picoprobe 110H-GSG-250-P probes (Fig. 4). S-parameters were measured with a ZVA67 Rohde & Schwarz vector network analyzer equipped with ZVA-110 frequency converters.
In the frequency band of interest, measured insertion losses remain lower than 2.29 dB. Due to a slight shift in frequency, isolation and reflection levels are slightly degraded compared to simulation. However, S12 reaches a minimum value of -25.1 dB at 72.7 GHz and remains lower than -10.9 dB between 71-76 GHz.
Taking into account technological and measurement difficulties, these measured results are in quite good agreement with simulated ones and demonstrate that very compact and efficient non-reciprocal devices can be designed up to W-band.

Fig. 4. Simulation model (on the left) and measurement setup (on the right) of the W-band planar self-biased isolator.

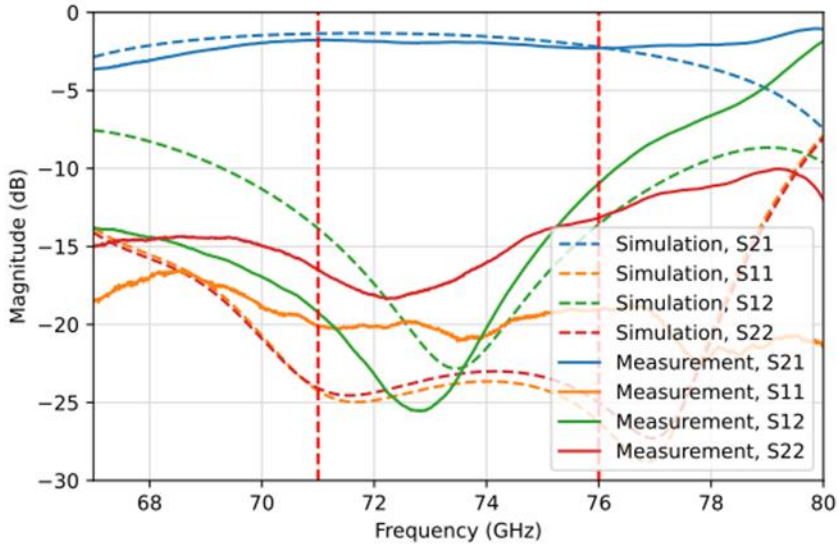

Fig. 5. Comparison between simulated (short dash) and measured (full line) S-parameters of the W-band planar isolator.

CONCLUSION

In this study, state-of-the-art performance of self-biased W-band circulator/isolator was demonstrated in both rectangular waveguide and planar technologies. It was shown that rectangular waveguide self-biased circulators can provide insertion losses and isolation levels competitive with standard spinel's-based devices but without applied field (no magnet). In planar technology, we realized, to our knowledge, the first self-biased isolator in W-band. Its quite promising performance in a very compact size (less than 1.5 mm^2) seems to make it possible to integrate such devices in future generation of W-band VHTS payloads.

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