AFSIW Y-junction Circulator Based on Full Height Ferrite Post for High-power Handling New Space Applications

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ABSTRACT

In this paper, a novel patent pending air-filled substrate integrated waveguide (AFSIW) Y-junction circulator topology intended for high-power handling space applications is presented. This new device has been developed to pave the way for future implementation of compact high-power microwave systems on substrate (SoS) based on the low-cost and high-performance AFSIW technological platform. This new circulator structure takes advantage of the AFSIW multilayer feature. It is not based on any impedance matching metal post or dielectric spacer. Instead, for matching purposes, the AFSIW top substrate material is used to load a full-height ferrite loaded Y-junction. This simple arrangement provides ease of manufacturing together with a high continuous wave (CW) and multipactor power handling capability, as the ferrite surface can be increased thank to sufficient design latitude and no gap is involved, respectively. For experimental validation, a demonstrator operating at 18.65 GHz, within the satellite downlink Ka-band, is designed and manufactured. It achieves a return loss, transmission loss, isolation and multipactor power handling in a fault short-circuited configuration of 20 dB, 0.68 dB, 21 dB and better than 200 W, respectively.

INTRODUCTION

The circulator is a crucial non-reciprocal device found in numerous telecommunication and radar systems. It is a key component used in the implementation of essential functions including isolators, duplexers and diplexers, especially in high-power microwave circuits and systems.
For the design of high-power handling circulators, the rectangular waveguide (RGW) technology is commonly used. However, the emerging new space applications are in demand for a technological alternative due to the RGW bulkiness and high cost. To provide a substitute technology, the low-cost substrate integrated waveguide (SIW) has been first considered for the design of compact circulators [1]. However, the conventional dielectric-filled SIW technology achieves relatively high loss and is therefore limited in terms of power handling. As a new alternative, the air-filled SIW (AFSIW) technological platform has been proposed [2]. It extends the printed circuit board (PCB) capabilities, especially in terms of power handling. Recently, in [3], an experimental evaluation reported a continuous wave power handling capability as high as 1340 W (61.27 dBm) at 20 GHz for this new substrate integrated technology. To the best of the authors' knowledge, an AFSIW circulator has not yet been reported in the literature. In this paper, a new circulator topology based on the AFSIW technology, intended for high-power space applications, is presented. For demonstration purpose, a prototype, operating in the satellite downlink Ka-band at 18.65 GHz, is designed, fabricated and measured. In section II, the proposed structure is described with a theoretical model allowing its pre-design and a multipactor power handling evaluation. Then, in section III, for validation purposes, a demonstrator is presented with simulation and experimental results.

CIRCULATOR TOPOLOGY

The Proposed Structure

Intensive efforts have been made to increase circulators power handling [4]. In this objective, the most used structure is the Okada resonator that is based on a partially filled Y-junction implementing two ferrites mounted on a top and a bottom metal post. In this topology, a gap is left between both ferrites in order to increase the ferrites base surface, to consequently increase the continuous wave power handling thanks to an improved thermal dissipation.

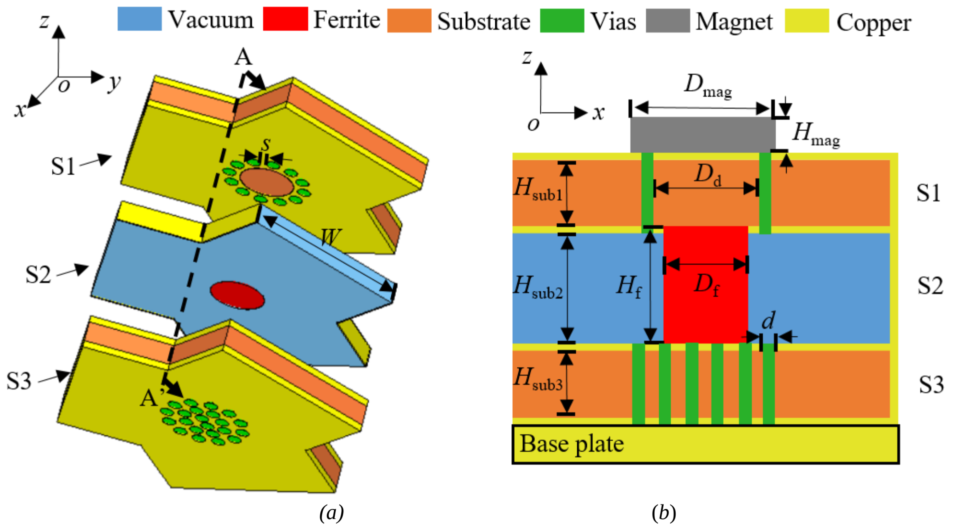

Fig. 1. (a) 3D and (b) AA' cross-section views of the AFSIW circulator.

However, the gap between the ferrites drastically reduces the multipactor power handling [5]. Alternatively, dielectric spacers can be used between the two ferrites to avoid gaps [6]. Inspired by this topology to provide a high-power handling capability, the proposed AFSIW circulator is illustrated in Fig. 1. AFSIW can be considered as a reduced-height waveguide for which the matching of Y-junction is difficult. To provide design freedom, the use of ferrite pedestal is commonly used. But, as the AFSIW technology is intended for medium to high volumes, simple designs are desired, and therefore the use of metal posts must be avoided. Instead, additionally to allow a gapless design, dielectric spacers can be used to provide design flexibility allowing the matching of the resonators together with an increased contact surface allowing better thermal dissipation. Though, resonator arrangements with dielectric spacers are not desired due to the manufacturing complexity. As a substitute, the proposed design takes advantage of the AFSIW multilayer structure. The top substrate is used to provide a dielectric loading of a full-height ferrite post, resulting in an original and very simple design. Additionally, this single ferrite arrangement allows the use of a single magnet that can be surface mounted on the top substrate. Furthermore, as in [3], the bottom substrate can implement a via farm (that can optimally consist of copper-filled vias) to offer an optimal heat sink providing high continuous wave power handling (see Fig. 1).

The Proposed Structure

The proposed gapless structure allows loading the full-height ferrite post with a dielectric disk implemented within the S1 top substrate material. This arrangement allows reducing the junction effective permittivity εeff that is obtained considering the conservation of the series capacitance from:

$$\frac{H_{sub1}+H_f}{\varepsilon_{eff}}=\frac{H_{sub1}}{\varepsilon_d}+\frac{H_f}{\varepsilon_f}\,, \tag{1}$$

where H_{sub1} and H_f are the S1 substrate and ferrite post height, respectively, and ε_d and ε_f are the S1 substrate material and ferrite relative permitivities, respectively.
Then, the diameter of the ferrite post is given by [8]:

$$D_f=\frac{1.84}{k_0\sqrt{\varepsilon_{eff}}}, \tag{2}$$

where k_0 is the wavenumber in vacuum.
The resonator size can be determined using (1) and (2) while maximizing D_f to achieve a large thermal dissipation surface to optimize the continuous wave power handling.

Multipactor Power Handling Evaluation

The multipactor power handling limitation of the proposed gapless resonator Y-junction structure is given by the AFSIW S2 inner substrate height H_{sub2}. Using the Spark 3D simulation software the multipactor threshold can be evaluated. The copper secondary emission was taken into account during this evaluation. Fig. 2 reports the simulation result versus H_{sub2} at 18.65 GHz. It can be observed that using a 1.524 mm (60 mil) standard thickness S2 substrate, a multipactor threshold of 24 kW (43.8 dBW) is achieved. This value provides sufficient margin to consider using the AFSIW and proposed circulator for high-power space applications. Considering a commonly used 12 dB acceptance margin for circulators and ferrite devices [9], space applications requiring peak power as high as 1514 W can be targeted.

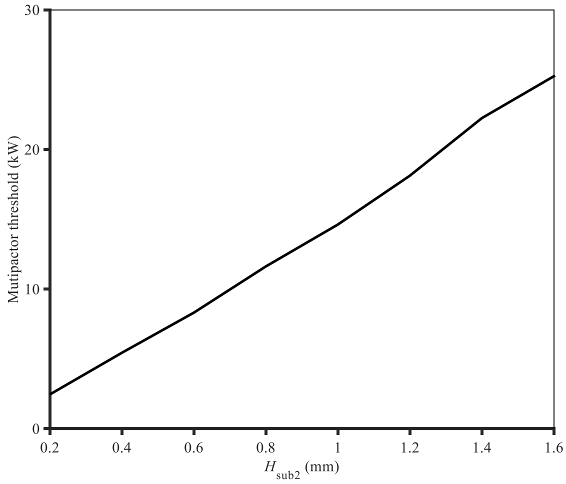

Fig. 2. Simulated multipactor threshold versus the inner substrate height H_{sub2} at 18.65 GHz.

EXPERIMENTAL VALIDATION

Demonstrator Design

To evaluate a low-cost design, a multilayer PCB stack consisting of three FR-4 substrates having a relative permittivity $\varepsilon_d = 4$ is considered. Standard substrate thicknesses of $H_{sub1} = H_{sub3} = 0.508$ mm and $H_{sub2} = 1.524$ mm are used. Substrate S2 height has been selected to maximize the multipactor margin. Substrate S1 height has been selected as low as possible to minimize the distance between the magnet and the ferrite. Finally, substrate S3 height has been selected as low as possible to minimize the distance between the ferrite and the base plate and also to achieve a symmetric PCB stack. The full-height ferrite post is $H_f = 1.524$ mm. The ferrite implemented in this demonstrator is a spinel lithium ferrite material with relative permittivity $\varepsilon_f = 16$ and saturation magnetization $4\pi Ms = 3700$ Gauss. It is magnetized using a SM-CO5 magnet with a residual magnetic field of $B_r = 0.92$ T, diameter $D_{mag} = 3$ mm and height $H_{mag} = 1$ mm. Solving (1) and (2), a pre-design ferrite post diameter $D_f = 2.4$ mm is obtained. S1 bottom copper layer is etched above the ferrite to obtain a S1 dielectric material disk of diameter $D_d = D_f$. A dielectric cavity is formed above the ferrite in S1 using metallic vias of diameter $d = 0.8$ mm with a spacing of $s = 0.4$ mm to guarantee the self-shielding of the structure. The Y-junction is interconnected using AFSIW transmission lines of width $W = 12.954$ mm. Furthermore, inductive iris of width W_{self} and length l_{self} at a distance L_{self} from the Y-junction are implemented on the three access for matching purposes. Finally, an optimization is achieved using the CST microwave studio electromagnetic (EM) simulator. Table 1 reports the demonstrator dimensions after optimization.

Table 1. Demonstrator dimensions obtained after optimization.

Parameters	W	H_{sub1}	H_{sub2}	H_{sub3}	D_f	D_d	L_{self}	l_{self}	W_{self}
(mm)	12.954	0.508	1.524	0.508	3.12	3.87	2	5	9.554

Fabrication

The AFSIW Y-junction circulator demonstrator was manufactured using a multilayer PCB process. Photographs of the substrates before assembly are shown in Fig. 3. The ferrite post has been mounted manually on top of S3 and fixed using a thermal conductive glue.

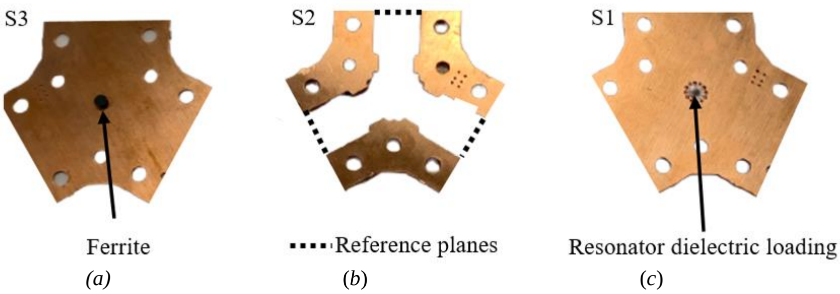

Fig. 3. Photographs of the fabricated AFSIW circulator substrates before assembly: (*a*) substrate 1, (*b*) substrate 2, and (*c*) substrate 3.

Small-signal Results

The prototype was measured in small signals using a dedicated three-port test fixture. An AFSIW TRL calibration kit was used to de-embed cables and interconnection effects. The reference planes are shown in Fig. 3(b). Fig. 4 compares the simulated and experimental small-signal results. A very good agreement between simulation and measurement is obtained. In this figure, the E-filed magnitude, obtained feeding port 1, illustrates the proper operation of the circulator. At 18.65 GHz, a return loss, transmission loss and isolation of 20 dB, 0.68 dB and 21 dB is achieved in measurement. Obviously, a better transmission loss could be obtained using a lower loss top substrate, but at the expense of a higher cost.

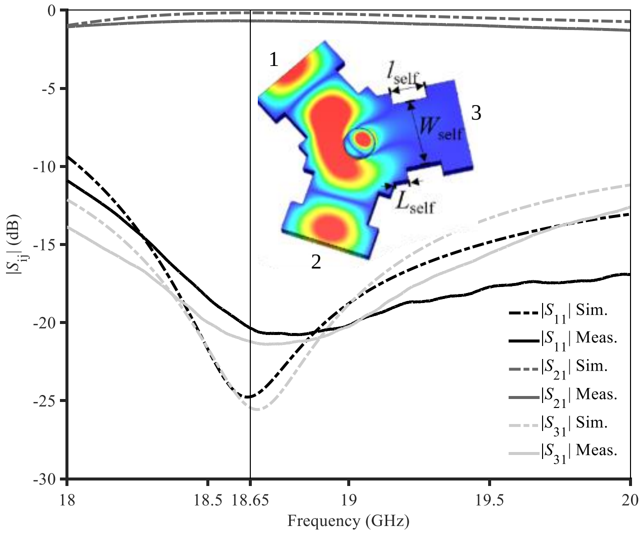

Fig. 4. Simulated and measured S-parameters of the demonstrator with simulated E-field magnitude distribution at 18.65 GHz.

Multipactor Power Handling Test Results

A multipactor power handling test was carried out to verify the capability of the demonstrator. A picture of the test set-up is illustrated in Fig. 5. Surface mounted WR51-to-AFSIW transitions are used in this set-up.

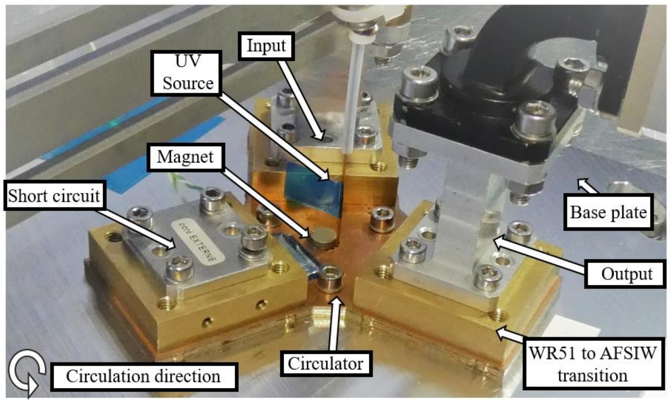

Fig. 5. Photographs of the assembled circulator during the multipactor test.

The power test was carried out according to the European Cooperation for Space Standardization (ECSS) procedure [9] using a pulsed power generator. The device was placed in a vacuum chamber under a chamber pressure as low as 5 nBar. Electrons' excitation in the Y-junction was achieved using an ultraviolet spectrum fiber penetrating through the S1 metallic vias. Two multipactor detection methods were implemented: the first based on the phase nulling principle and the second on the third harmonic technic. During this test, the circulator port 2 was short-circuited to evaluate the worst-case fault mode. Fig. 6 reports the measurement results including the power, return loss and chamber pressure over time. There was no multipactor, neither outgassing, detected during this experimentation. The input power was increased by steps of 50 W every 30 minutes, up to the maximum power available in the test facility in this frequency range: 200 W (which is a power level commonly found in satellite Ka-band downlink transmitters). The return loss stayed over 18 dB during the overall test.

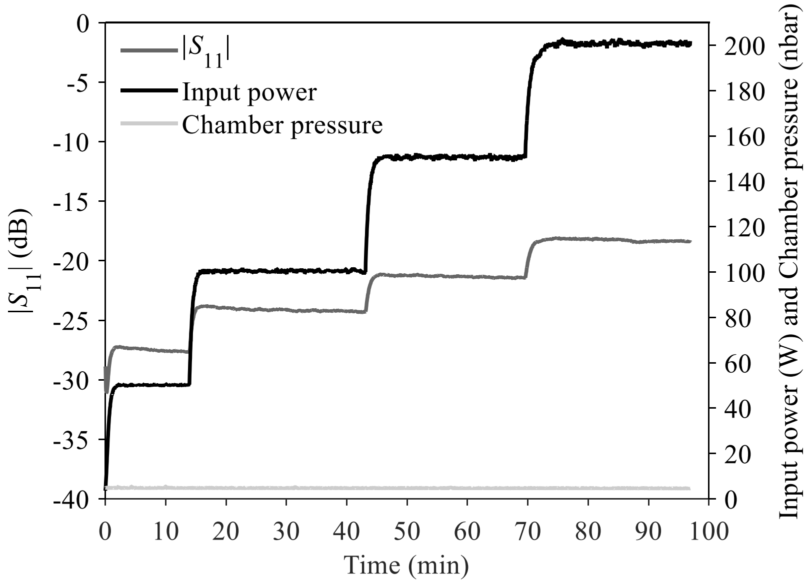

Fig. 6. Measured return loss, input power and chamber pressure over time of the demonstrator at 18.65 GHz during the multipactor test.

CONCLUSION

A novel AFSIW Y-junction circulator with a high continuous wave and multipactor power handling capability has been presented in this paper. This new topology extends the PCB capabilities, and opens the door for the substrate integration of high-power microwave circuits and systems envisioned by the authors to be deployed by the industry, particularly for the new space applications.

References

[1] W. D'Orazio and K. Wu, “Substrate-integrated-waveguide circulators suitable for millimeter-wave integration,” IEEE Trans. Microw. Theory Techn., vol. 54, no. 10, pp. 3675-3680, Oct. 2006.

[2] F. Parment et al., “Air-filled substrate integrated waveguide for low-loss and high power-handling millimeter-wave substrate integrated circuits,” IEEE Trans. Microw. Theory Techn., vol. 63, no. 4, pp. 1228-1238, Apr. 2015.

[3] T. Martin et al., “Configurable perforated air-filled substrate integrated waveguide (AFSIW) for generic high-performance systems on substrate,” IEEE Trans. Microw. Theory Techn., vol. 67, no. 11, pp. 4308 - 4321, Sep. 2019.

[4] F. Okada and K. Ohwi, “Design of a high-power CW Y-junction waveguide circulator,” IEEE Trans. Microw. Theory Techn., vol. 26, no. 5, pp. 364-369, May 1978.

[5] M. Yu, “Power-handling capability for RF filters,” in IEEE Microwave Magazine, vol. 8, no. 5, pp. 88-97, Oct. 2007.

[6] J. Helszajn and J. Sharp, “Verification of first circulation conditions of turnstile waveguide circulators using a finite-element solver,” IEEE Trans. Microw. Theory Techn., vol. 53, no. 7, pp. 2309-2316, July 2005.

[7] R. Roveda et al., “Dissipative parameters in ferrites and insertion losses in waveguide Y-circulators below resonance,” IEEE Trans. Microw. Theory Techn., vol. 20, no. 2, pp. 89-96.

[8] E. J. Denlinger, “Design of partial height ferrite waveguide circulators (Short Papers),” IEEE Trans. Microw. Theory Techn., vol. 22, no. 8, pp. 810-813, Aug. 1974.

[9] Multipactor Design and Test, ECSS-E-ST-20-01C, 15 June 2020.