Dual-Mode Dielectric-Loaded Resonator for Satellite High-Power Filters

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***Abstract*—A novel resonator based on higher order dual-mode dielectric-loaded cavity is presented in this paper for compact high-power bandpass filters. The proposed doublet consists of a ceramic high-permittivity dielectric cylinder placed in the center of a circular metal cavity. The presence of the dielectric inside the cavity allows an excellent thermal stability. The dielectric material is based on BMT (Barium Magnesium Tantalum oxide) and it has been selected for its excellent performance in terms of losses. The presence of the dielectric results in a noticeable resonator shrink. In order to guarantee thermal sink capabilities suitable for the high power requirements, the dielectric cylinder cannot be too small. For this reason a higher order resonant mode has been selected. A pair of shaped irises placed on top and bottom surfaces of the cavity allows the control of the coupling to the adjacent cavities. Each doublet can provide a transmission zero above or below the passband. Its position is controlled by the rotation angle of the irises. The feasibility of proposed solution has been demonstrated through the measurement of a preliminary second-order Ku-band filter prototype, which shows very promising results. This doublet can be used as building block for higher order filters.**

***Keywords*—ceramics, compact filter, dielectric resonator, bandpass filter, elliptic filter.**

I. Introduction

The miniaturization of microwave devices is a hot topic for the modern telecommunication satellite systems. Due to the growing amount of data that needs to be processed, payload architectures are becoming very complex. The mass and size reduction of devices on board is essential for decreasing the costs of a specific satellite program. In the modern multi-beam systems, a single High-Power-Amplifier (HPA) can be shared between several beams in order to reduce the number of high-power amplifiers embarked on the satellite. To do this, a high number of Output De-Multiplexer (ODEMUX) is required after the HPA to separate the signals destined for each beam. This highlights how smaller and lighter microwave filters are favourite for reducing their volume occupation in the next generation of satellites.

Conventional solutions based on rectangular or circular waveguide cavities allow for obtaining high performing filter solutions, especially in terms of Q-factor and power-handling. Despite this, such technology generally provides bulky and heavy geometries. In [1], [2] a general overview of the technologies and techniques concerning the filters development is presented. Several solutions have been proposed in the literature to mitigate mass and volume problems. Dielectric-loaded resonators (DRs) based on high permittivity (ε_r) materials represent an effective alternative to standard filters with the advantage of size reduction [3]. Numerous resonator concepts based on this technology have been proposed and studied in the years: TM_{010}, $TE_{01\delta}$ or $TM_{01\delta}$ mode dielectric resonators are some of the most favourite solutions [4], [5].

Each DR topology presents both advantages and disadvantages; thus, the best choice mainly depends on application. Whatever the solution, the use of the fundamental mode typically provides excellent Q-factor, but the shrinking of the structure can become hardly manageable in terms of manufacturing tolerances and assembly when the operating frequency increases. As a consequence, also the high-power performance in space environment (e.g. power-handling and multipactor) can be affected. The employment of higher order modes is a good solution when larger size is necessary for a suitable thermal sink and/or when manufacturing tolerance may represent a problem. In this paper a novel dual-mode dielectric-loaded resonator is presented for high-power bandpass filters. The proposed structure presents excellent performance in terms of thermal stability. The measured Q-factor is about 6000 and this represents a very good result considering the small size of the cavity. In order to validate the proposed solution a preliminary second-order filter has been designed and tested in the frame of the European Space Agency (ESA) ARTES AT project called DOMUK ("Dielectric-loaded high-power Output de-Multiplexer at Ku/Ka-band", ESA Contract Number: 4000125645/19/NL/NR), which requirements have been considered as a benchmark.

II. Proposed Resonator

The 3D model of the proposed doublet is presented in Fig. 1. A high permittivity (ε_r=24, Qxf=250000) dielectric cylinder based on BMT (Barium Magnesium Tantalum oxide) is placed in the centre of a metal circular cavity. Low-permittivity dielectric supports hold the ceramic cylinder inside the case avoiding any direct contact between the dielectric and metal parts. Small housings on the supports allow the correct alignment of dielectric load.

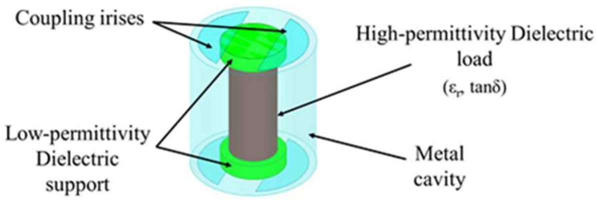

Fig. 1. 3D model of proposed higher order mode dielectric-loaded doublet.

Two degenerate higher order modes are adopted as operating modes. These are mixed TE and TM mode, which electric (E) and magnetic (H) field distributions are shown in Fig. 2.

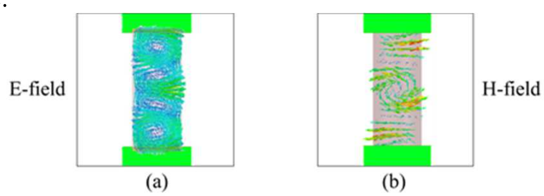

Fig. 2. EM field distribution of dual-mode dielectric-loaded doublet: (a) E-field and (b) H-field.

The topology scheme of transversal doublet and the basic coupling mechanism are presented in Fig. 3. The coupling with adjacent cavities is obtained by a pair of irises on the top and bottom surfaces of the cavity. Varying the rotation angle (θ) of the irises, each doublet can provide a transmission zero (TZ) which can be moved above or below the passband.

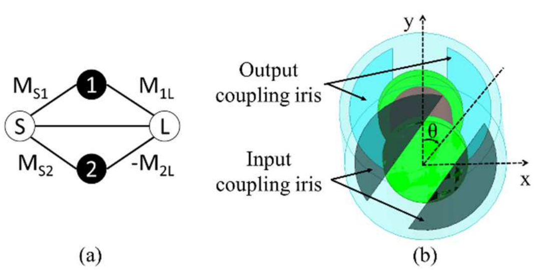

Fig. 3. Topology scheme of dielectric-loaded transversal doublet (a) and 3D view of the doublet with rotation angle of input coupling irises (b).

The full-wave response of a Ku-band doublet is presented in Fig. 4, where the S-parameters are plotted for different rotation angles of input irises with respect to the output ones.

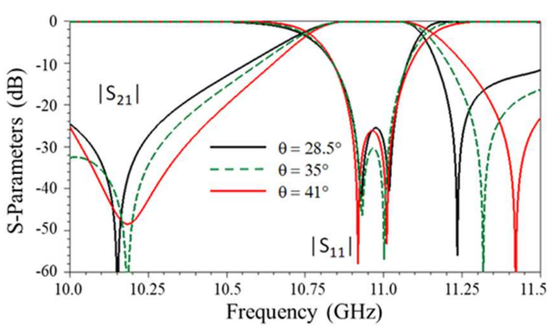

Fig. 4. Simulated response of the doublet with respect to different rotation angles of the input irises.

By changing the ratio of the coupling to the two resonant modes (M_{S1}/M_{S2}), the doublet allows control over the frequency position of only one TZ, while the second transmission zero cannot be controlled because it is not possible to control the source to load direct coupling.

Geometries and materials have been carefully chosen in order to improve the robustness of the structure from mechanical and thermal points of view. The use of higher order resonant modes allowed to obtain large enough high-permittivity loads to ensure proper thermal sink capabilities for the high power requirements while high Q-factor values are kept despite small size of the structure. Particular attention has been focused on the supports, which represent key elements for the correct behaviour of the filter, especially when high-power level (e.g. 150 W continuous wave (CW)) have to be handled in space environment. From the electro-magnetic (EM) point of view, the best materials for the supports should have a dielectric permittivity close to 1, in order to minimize the interaction of the resonant mode with the lossy metal cavity. From the thermal point of view, the material used for the supports has to be a good thermal conductor in order to ease the thermal flow. Numerous options have been evaluated: Rexolite, Teflon, Quartz glass, Alumina. Rexolite and Teflon are almost equivalent. They are very good from the point of view of ε_r, but they are very poor concerning the thermal conductivity aspect. Alumina is characterized by a higher thermal conductivity; however, the radius of the support has to be reduced due to the higher ε_r, with consequent issue on the assembly process. Concerning the Quartz, it presents intermediate characteristic for both thermal conductivity and dielectric constant, but it is fragile.

The thickness of the supports is another critical parameter. A thick spacer increases the distance between the ceramic load and the metal walls, thus reducing the interaction of the field with the metal and resulting in an increased Q-factor. On the other hand, a larger thickness of the support, reduces the thermal flow from the ceramic to the metal surfaces. In the design here presented, Teflon has been selected mainly for its low relative permittivity, and also considering its 'softness' that allows an easier manufacturing and assembly.

The spurious free range is another aspect which has to be considered since the closest spurious resonant modes can affect both lower and upper stopbands. The unloaded Q-factor (Q_{UL}), the resonant frequency of the operating mode and the frequency of the closest spurious modes have been analysed with respect to the most critical design parameters. In Fig. 5 their variation as a function of supports thickness is presented.

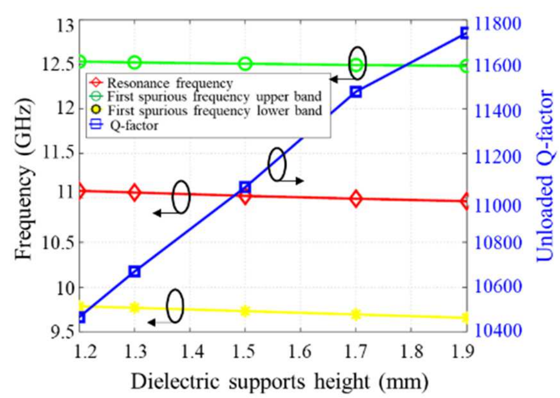

Fig. 5. Resonant frequencies and Q_{UL} variation by changing the thickness of support spacers.

If one changes the support thickness between 1 and 2 mm, the unloaded Q-factor can always be above 10000, and the spurious-free range of roughly 1 GHz can be achieved in both upper and lower stop-bands. In order to improve thermal flow as much as possible, a thickness of 1.2 mm has been selected.

III. Second-Order Filter Prototype

The feasibility of proposed design concept has been demonstrated through the preliminary measurements of a second-order filter which is centred at 11 GHz with a bandwidth (BW) of 240 MHz. The 3D model of the doublet is shown in Fig. 6 where the input and output couplings have been designed by considering the standard waveguide WR75 interface.

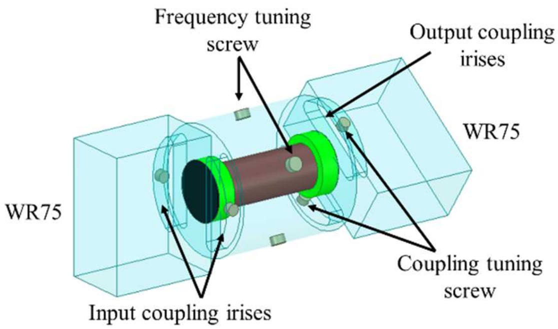

Fig. 6. 3D model of second-order Ku-band filter based on proposed higher order mode dielectric-loaded doublet.

Tuning screws have been added to compensate the measured response variation of the filter due to the manufacturing tolerances. Frequency tuning screws have been placed in the centre of the cavity since the E-field has a maximum at the centre of the ceramic cylinder.

Regarding the tuning screws for couplings, a trade-off between maximum coupling (i.e. fractional bandwidth (FBW)) and tuning range has been found. The screw diameter must be smaller than the wall thickness of the irises. An increasing of the thickness results in the possibility of using larger screw, thus incrementing the tuning range, but, on the other hand, the maximum achievable FBW will be smaller, because thicker irises imply smaller couplings. The goal was to achieve a BW of 240 MHz at 11 GHz and the thickness of the iris has been set to 2.2 mm. The screw diameter is 1.4 mm.

The 3D mechanical and manufactured models of the filter are shown in Fig. 7. The filter is composed by three main silver-plated aluminium parts. The overall size (L x W x H) is 52.7 mm x 50 mm x 50 mm with a mass of 118g.

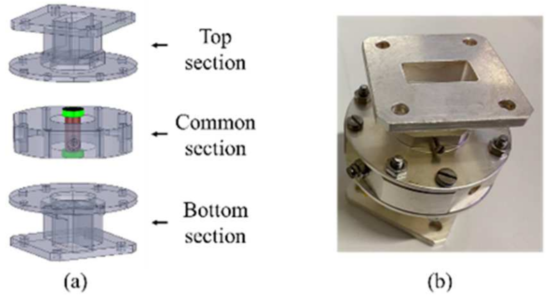

Fig. 7. 3D mechanical (a) and manufactured (b) models of second-order Ku-band filter based on higher order mode dielectric-loaded doublet.

The comparison between measured (solid lines) and simulated (dotted lines) responses is plotted in Fig. 8, where very promising results are observed. The tuning process allows for an easy recovering of the manufacturing errors for both mechanical and ceramic permittivity tolerances. The response shows a narrower bandwidth with respect to the simulation. An unloaded Q-factor of roughly 6000 has been measured, in agreement with the expectations.

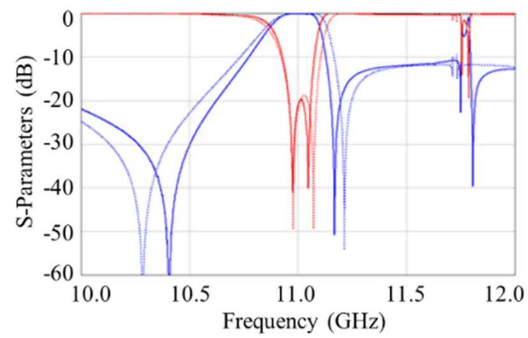

Fig. 8. Comparison between measurement (solid lines) and full-wave simulation (dotted lines) of second-order Ku-band filter based on higher order mode dielectric-loaded doublet.

In Fig. 9, a very stable measured filter response is shows with respect to the temperature variation. A maximum frequency shift of the response of roughly 3 MHz is observed in the range -35 °C ÷ +70 °C. The equivalent τ_f (relative frequency shift per °C) is below 3 ppm/°C.

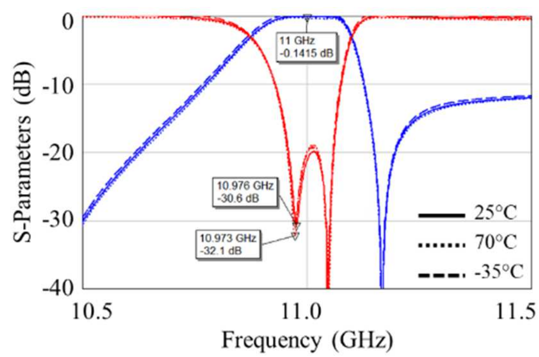

Fig. 9. Measured responses of second-order Ku-band filter with respect to the temperature variation.

About the high-power performance, multipactor analysis in Spark-3D shows no discharges above 1 KW; while power handling analysis in Ansys exhibits that the filter can handle up to 150 W CW in space environment.

IV. Conclusion

In this paper a novel doublet resonator based on higher order dual-mode dielectric-loaded cavity has been presented as an alternative solution for compact high-power filters. The proposed resonator can provide a transmission zero above or below the passband by changing the rotation angle of the coupling irises. The feasibility of proposed solution have been demonstrated through the measurement of a preliminary second-order Ku-band filter, which highlights the good thermal stability of the architecture. An equivalent τ_f below 3 ppm/°C has been achieved in the frequency range -35 °C ÷ +70 °C. Power analysis shows that the filter can handle up to 150 W CW in space environment. Thanks to the reduced number of physical cavities, compact higher order filter architectures can be realized by cascading multiple doublets.

ACKNOWLEDGMENT

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REFERENCES

[1] R. V. Snyder, G. Macchiarella, S. Bastioli and C. Tomassoni, "Emerging Trends in Techniques and Technology as Applied to Filter Design", IEEE Journal of Microwaves, vol. 1, no. 1, pp. 317-344, winter 2021.

[2] R. V. Snyder, A. Mortazawi, I. Hunter, S. Bastioli, G. Macchiarella and K. Wu, "Present and Future Trends in Filters and Multiplexers", IEEE Transactions on Microwave Theory and Techniques, vol. 63, n. 10, 2015.

[3] S. B. Cohn, "Microwave bandpass filters containing high- dielectric resonators," IEEE Transactions on Microwave Theory and Techniques, vol. 16, no. 4, pp. 218–227, Apr. 1968.

[4] S. J. Fiedziuszko and S. Holmes, "Dielectric resonators raise your high-Q," IEEE Microwave Magazine, vol. 2, no. 3, pp. 50-60, 2001.

[5] X. C. Wang and K. A. Zaki, "Dielectric Resonators and Filters," IEEE Microwave Magazine, pp. 115-127, Oct. 2007.