High-Yield Waveguide Diplexer for Low-Cost E-band 5G Point-to-Point Radio Links

F. Teberio[1], I. Calero[1], I. Arregui[2,3], P. Martin-Iglesias [2,4], J. Teniente[2,3], M. A. G. Laso[2,3]
[1]Anteral S.L., Pamplona, Spain
[2]Electrical, Electronic and Communication Eng. Dept., Public University of Navarre, Pamplona, Spain
[3]Institute of Smart Cities, Public University of Navarre, Pamplona, 31006 Spain
[4]ESA/ESTEC, Noordwijk, The Netherlands
f.teberio@anteral.com

Abstract — **This paper presents the design and realization of a high-yield tuning-less waveguide diplexer and a high-gain lens horn antenna for 5G point-to-point fixed-beam communications at the frequency ranges of 71/76 GHz and 81/86 GHz (E-band). The diplexer is composed of two bandpass filters based on the combination of a low-pass filtering function and a high-pass structure. The diplexer provides very relaxed fabrication tolerances. A prototype has been fabricated and measured showing return loss better than 20 dB and attenuation levels higher than 60 dB. The insertion loss is better than 1 dB. A lens horn antenna which provides more than 38 dBi gain is utilized to provide high directivity at the same frequencies. The proposed sub-system combines the advantages of high-performance and simple mechanical assembly finding, it especially attractive for 5G applications due to the reduced fabrication cost.**

Keywords — **5G, diplexer, E-band, point-to-point radio-link, waveguide.**

I. INTRODUCTION

5G communications demand high-data rates as mobile data requirements increase for multimedia and online streaming. E-band backhaul point-to-point radio links at 71/76 GHz and 81/86 GHz can deliver up to 10 Gbps even in a dense urban radio environment [1]. To fulfil this requirement, high-gain antennas (above 38 dBi) with enough side-lobe suppression [2], and waveguide diplexers to separate the transmit and receive channels in the transceiver front-end have to be used [3]. The waveguide diplexers must feature high isolation between bands and low insertion loss. Furthermore, the additional requirements for 5G mm-wave backhaul are low-cost and compact size. In order to obtain more cost-effective devices, the manufacturing tolerances must be relaxed while preserving a high fabrication yield. Hence, the development of new E-band diplexers less sensitive to fabrication tolerances is in the spotlight [4].

During the last years, various types of E-band diplexers have been presented in the literature. A classical diplexer based on multiple coupled cavities was proposed in [5]. In this case, micromachining was needed to fabricate the prototype since it presents manufacturing tolerances significantly lower than a conventional milling process. Directional-coupler diplexers are one option but the geometry of this kind of structures is typically long and narrow due to the internal features of the filters and the directional couplers (or hybrids) [6]. More compact designs can be achieved using substrate integrated waveguides, which show a compact size and low weight but higher insertion loss and lower power in comparison with rectangular waveguide [7]. In rectangular waveguide, some ideas to increase the manufacturing yield in classical coupled resonant structures (with inductive and capacitive irises) have been proposed, such us using higher-order resonances of some waveguide cavities at the cost of increasing the length of the structure and the eventual appearance of spurious resonances between the passbands [8]. Besides, waveguide bandpass filters based on E-plane inserts requires the fabrication of three different parts and implies higher insertion loss [9].

In point-to-point fixed-beam communications at E-band, a high antenna gain is needed to provide large distance communications, up to several kilometres. Besides, a requirement for the side-lobe suppression must be accomplished following the European Telecommunication Standard Institute (ETSI) regulations (class 2/3) to minimize the interferences. A high-gain lens horn antenna can provide those characteristics with low-cost and compact size.

The paper is organized as follows. In section II, the design principles and the simulation results (S-parameters and high-power analysis) of the proposed tuning-less diplexer are shown. Moreover, the yield analysis of the final structure, considering a uniform function with a worst-case error of $\pm 20\mu$m, is presented. In section III, the experimental results of a fabricated prototype are given and discussed. Next, in section IV, the diplexer is integrated with a high-gain lens horn antenna to facilitate the use of this system in a fixed point-to-point radio link and the simulation results of the subsystem are presented. Finally, in section V some conclusions are outlined.

II. DIPLEXER SIMULATION RESULTS

A. Design and Simulation

The proposed solution consists of two bandpass filters designed according to the methodology described in [10]. Both filters are joined with a H-plane T-junction with a septum in the middle to improve the return loss in both passbands. The filters are based on a combination of a high-pass and a low-pass response. The high-pass filtering function is achieved through a constant (simple to fabricate) width reduction while the low-pass filtering function is accomplished using quarter-wave step-shaped bandstop elements of different heights. The most interesting advantage of this kind of structure is that the transmission zeros can be placed at the required upper rejection band achieving very high attenuation levels with just a few elements. Furthermore, the diplexers designed following the technique in [10] will be more compact and less sensitive to manufacturing tolerances in comparison with classical diplexers based on two inductive-iris filters to fulfill the same frequency specifications. Finally, two mitred bends are added to have the output ports of both channels in the same plane and opposite to the common port.

The frequency requirements for a tuning-less E-band diplexer are given in Table 1. All ports comply with the WR-12 waveguide standard (3.099 mm × 1.549 mm). Both filters have 7 elements, and their minimum width is 2.21 mm for the low-channel filter and 1.90 mm for the high-channel filter. A stepwise design approach has been followed. First, the bandpass filters were designed as stand-alone components to fulfil the required specifications following the technique described in [10]. The filters were aimed at accomplishing a return loss of 28 dB in both passbands, increasing the bandwidth in ±1 GHz (70 to 77 GHz and 80 to 87 GHz) to further enhance the manufacturing yield of the structure. Then, the filters are joined directly to the T-junction with the septum by waveguide sections whose lengths, as well as the dimensions of the septa, are optimized. After that, the dimensions of the waveguide sections close to the junction are also optimized and, finally, once the frequency response is very close to the required performance, all dimensions are finely adjusted. All the waveguide sections between the step-shaped bandstop elements and septum have a thickness higher than 0.5 mm. Besides, the radius of all internal features is 0.4 mm to ensure a fabrication with minimum vibrations. The simulated frequency response (carried out with MWS) for the proposed diplexer is shown in Fig. 1.

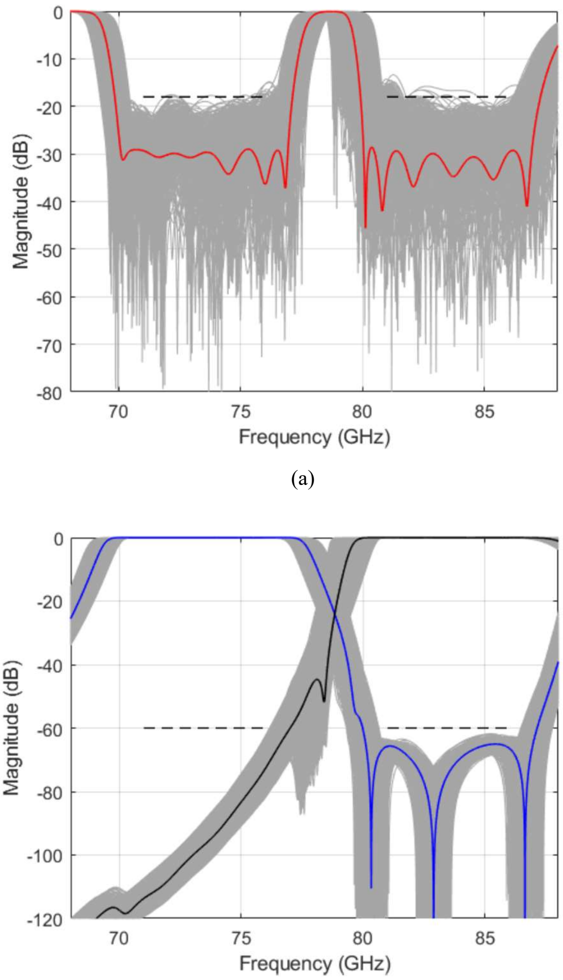
B. *Yield Analysis*

The yield analysis to manufacturing tolerances has been performed to prove the advantage in terms of fabrication robustness of the proposed diplexer in industrial applications.

Five hundred iterations varying all dimensions of the final structure (considering rounded corners) have been performed using CST MWS. The different physical dimensions are randomly generated using a uniform function with a worst-case error of ± 20µm (consistent with a conventional low-cost fabrication procedure). As can be seen in Fig. 1, the curves show very good fitting with the ideal frequency response. The resulting manufacturing yield is more than 97% for the S_{22}, 83% for the S_{33} and 100% for the S_{21} and S_{31}, resulting in more than 80% for all parameters. Using the same frequency specifications and the same error distribution, a diplexer based on classical inductive iris filters would show a much worse performance (see for instance Figs. 5 and 6 in [10]).

Table 1. Diplexer frequency requirements.

Parameter	**Low Channel**	**High Channel**
Passband (GHz)	71-76	81-86
Return loss (dB)	> 18	> 18
Attenuation (dB) at 81 GHz	> 60 dB	< 1 dB
Attenuation (dB) at 76 GHz	< 1 dB	> 60 dB



(a)

(b)

Fig. 1. Sensitivity analysis to fabrication tolerances (±20 µm) performed with CST MWS in the (a) $|S_{11}|$- (red line) and (b) $|S_{21}|$- (blue line) and $|S_{31}|$- (black line) parameters of the proposed E-band diplexer, varying the physical dimensions of the structure. Grey lines are the 500 simulation trials. Frequency specifications are represented by dashed lines.

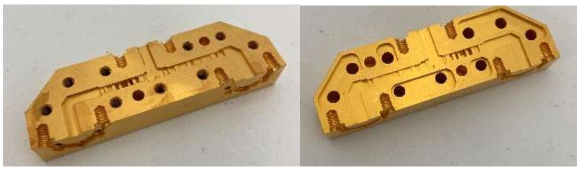


Fig. 2. Photograph of the two halves of the fabricated prototype.

C. *High-Power Analysis*

The high-power behaviour of the diplexer has been estimated with SPARK3D. A corona discharge analysis has been performed to compute the corona breakdown power threshold considering room temperature (293 K), air, and a fixed pressure of 1013 mbar. The electromagnetic fields have been previously simulated and imported from CST MWS. The minimum breakdown power supported by the diplexer is 1400 W. Last but not least, W-band frequency range for satellite communications are identical to the E-band for ground networks. This diplexer could be used in W-band feeders for ground or space segment. Additional analysis regarding thermal management and multipactor will be required due to the high-power Tx signals used in this application.

III. DIPLEXER FABRICATION AND MEASUREMENT

A gold coated aluminium prototype has been fabricated using conventional computer-controlled milling in two halves cut by the H-plane (see Fig. 2).

The fabricated prototype has been measured using a PNA-X and WR-10 VDI (Virginia Diodes)™ extenders, WR10 to WR12 waveguide tapers and a WR-12 calibration kit. The measured result (Fig. 3) shows, as required, a rejection better than 60 dB in both bands. Moreover, the return loss of the diplexer is kept better than 20 dB and the insertion loss is kept below 1 dB for the lower and higher channel. The results in Fig. 3 are within the yield analysis results shown in Fig. 1.

IV. ANTENNA FIXED-BEAM SYSTEM

According to the current European Telecommunication Standard Institute (ETSI) regulations [11], the point-to-point wireless link antenna should have a minimum gain of 38 dBi and meet class 2 or 3 radiation pattern envelope criteria (RPE). The proposed antenna (HGLHA-WR12) is a hyperbolic lens horn antenna whose design is based on the Fermat's principle of equality of electrical path lengths, see Fig. 4 [12]. The lens is optimized to reduce aberration to the minimum while it applies phase correction and achieves superior performance with minimum size. The lens includes a mounting layer, and the dielectric material employed in the lens is PTFE with relative permittivity of 2.1. The HGLHA-WR12 total diameter is 205 mm and its length is 205 mm making a very compact solution for point-to-point 5G communication networks. Besides, the horn antenna is prepared for outdoor operation and a pair of antennas of this type can establish a radio link of above 1-km LoS and above 99.9% reliability in most climates.

The frequency response of the HGLHA-WR12 and the presented diplexer has been simulated with CST Microwave Studio. The realized gain and the cross-polar level are plotted in Fig. 5. The ETSI E-band class 2 RPE is also provided to verify the antenna plus diplexer compliance. As it can be seen, the sub-system is completely compliant with the ETSI requirements. The simulated gain is higher than 38 dBi, the return loss is above 14 dB and the boresight cross-polar level is below -40 dB.

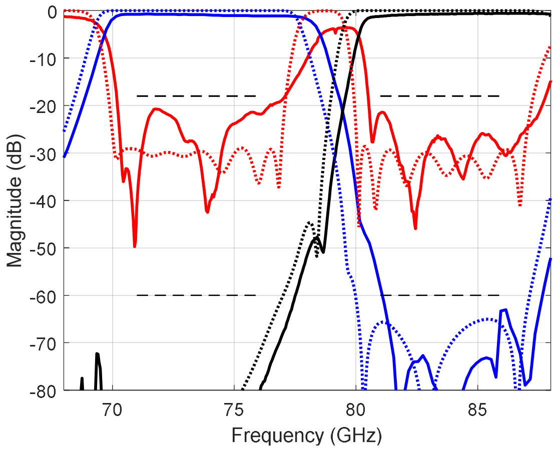
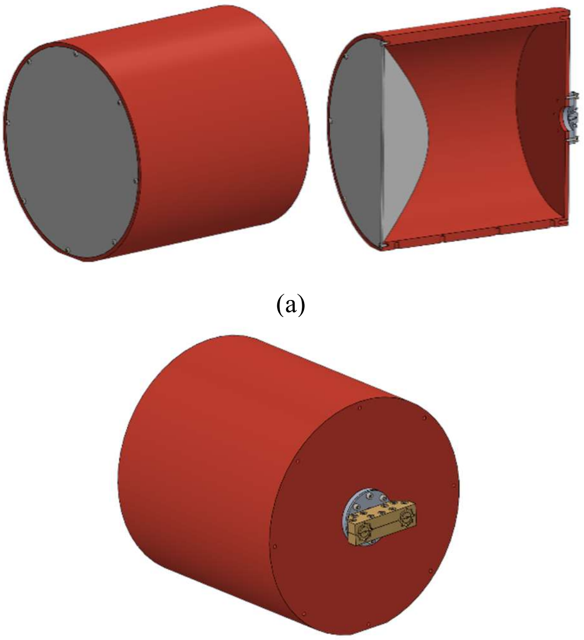


Fig. 3. Comparison between the CST MWS simulated frequency response (dotted lines) of the tuneless final diplexer with rounded corners and measurements of the fabricated prototype (solid lines). $|S_{11}|$ represented in red line, $|S_{21}|$ represented in blue solid line, and $|S_{31}|$ represented in black line. Frequency specifications are represented by dashed lines.



(a)

(b)

Fig. 4. 3D-view of the (a) HGLHA-WR12 and (b) the proposed waveguide diplexer joined to the antenna.

V. CONCLUSION

In this paper, low-cost components for an E-band radio-link and 5G millimetre-wave communications have been presented. The diplexer is composed of two bandpass filters based on quarter-wave step-shaped bandstop elements with a width reduction separated with a H-plane T-junction with a septum. This technique allows the design of a high-yield structure, making it especially attractive for mass production. The diplexer has been combined with a low-cost lens horn antenna which provides more than 38-dBi gain and the sub-system is compliant with the ETSI requirements. A prototype of the diplexer has been fabricated and measured, fully validating the diplexer configuration proposed in this paper. Simulations of the diplexer plus antenna subsystem have been also provided.

ACKNOWLEDGMENT

This work was supported by the Spanish Ministerio de Ciencia, Innovación y Universidades–Agencia Estatal de Investigación under Project TEC2017-85529-C3-2-R (AEI, FEDER-EU).

REFERENCES

[1] A. V. Raisanen, J. Zheng, J. Ala-Laurinaho, S. Karki and V. Viikari, "Millimeter-Wave Antennas for 5G," *2018 11th Global Symposium on Millimeter Waves (GSMM)*, Boulder, CO, USA, 2018, pp. 1-4.

[2] P. Kadera, T. Mikulasek, J. Hruska and J. Lacik, "Hyperbolic Lens Horn Antenna for Fixed-Beam E-Band Communication," 2020 30th International Conference Radioelektronika (RADIOELEKTRONIKA), Bratislava, Slovakia, 2020.

[3] S. M. Dilek, R. Henneberger and I. Kallfass, "Performance Analysis of E-Band Duplex Transceiver Based on Waveguide Diplexer Filters," *2018 48th European Microwave Conference (EuMC)*, Madrid, 2018, pp. 1069-1072.

[4] A. Vosoogh, A. A. Brazález, Y. Li and Z. S. He, "A Compact Mass-producible E-band Bandpass Filter Based on Multi-layer Waveguide Technology," 2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020, pp. 1-5.

[5] V. Nocella, L. Pelliccia, P. Farinelli, R. Sorrentino, M. Costa, D. Yufeng, and Z. Yanzhao, "E-band cavity diplexer based on micromachined technology," *International Journal of Microwave and Wireless Technologies*, vol. 8, no. 2, pp. 179–184, 2016.

[6] John Ross Aitken, Jiasheng Hong, "Design of millimetre wave diplexers with relaxed fabrication tolerances", *Microwaves Antennas & Propagation IET*, vol. 9, no. 8, pp. 802-807, 2015.

[7] Y. Uemichi, O. Nukaga, X. Han, S. Amakawa and N. Guan, "Highly Configurable Cylindrical-Resonator-Based Bandpass Filter Built of Silica-Based Post-Wall Waveguide and Its Application to Compact E-Band Hybrid-Coupled Diplexer," *2019 IEEE MTT-S International Microwave Symposium (IMS)*, Boston, MA, USA, 2019, pp. 726-729As

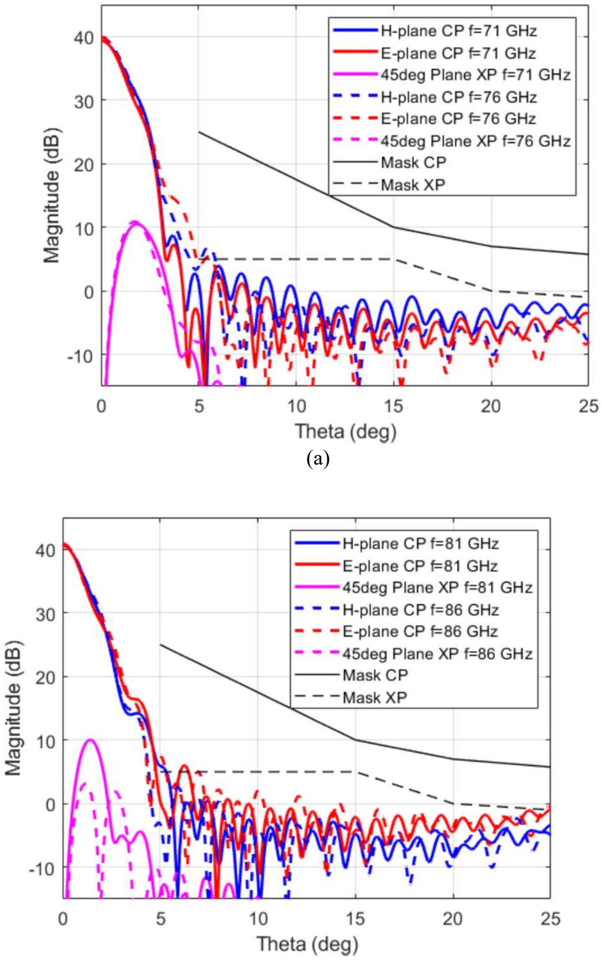
[8] G. Cannone and M. Oldoni, "High-yield E-band diplexer for fixed radio point-to-point equipment," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 24, no. 4, pp. 508–512, Dec. 2013.

[9] J. Dittloff and F. Arndt, "Computer-aided design of slit-coupled H-plane T-junction diplexers with E-plane metal-insert filters," *IEEE Trans. Microw. Theory Techn.*, vol. 36, no. 12, pp. 1833–1840, Dec. 1988.

[10] F. Teberio, I. Arregui, P. Soto, M. A. G. Laso, V. E. Boria and M. Guglielmi, "High-Performance Compact Diplexers for Ku/K-Band Satellite Applications," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 10, pp. 3866-3876, Oct. 2017.

[11] ETSI EN 302 217-4 (V2.1.1) (05-2017): "Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas; Part 4: Antennas".

[12] Online available: www.anteral.com



(a)

(b)

Fig. 5. Simulated realized gain and cross polar level of the HGLHA-WR12 and the waveguide diplexer. (a) Low channel, (b) High Channel.