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COMPACT FULL KU-BAND TRIPLEXER WITH IMPROVED E-PLANE POWER DIVIDER

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Abstract—An improved E-plane power divider for compact waveguide triplexers with large separation between channels is presented. The configuration of the divider aims to exploit the different behavior of the device for frequency bands with large separation, leading to a very asymmetric E-plane junction. H-plane filters with inductive windows are used for each channel, in order to obtain reduced insertion losses and lower sensitivity than in metal-insert E-plane filters. The resultant triplexer configuration is very compact, and its design is analyzed and optimized by Mode-Matching. The experimental results of a full Ku-band prototype for communications satellite systems show a very good agreement with the expected simulated response.

1. INTRODUCTION

A waveguide triplexer is a device used in communication systems to perform the frequency discrimination between three different signal channels [1]. It can be used to split the signal incoming by the waveguide common port into three different channel ports, each one associated to a different frequency band. Other common use is to combine the signals from each channel port into a signal with a broader frequency range in the common port attached to the antenna. In these cases, the frequency discrimination facility of the triplexers allows the use of the same antenna for different frequency bands, achieving an important reduction of mass and volume in the hardware equipment. This is a very important feature in communications satellite systems.

The electrical requirements of a triplexer are also very diverse. A general theory for the synthesis of multiplexers can be found in [2, 3]. The main features to control are the selectivity of the channels, their bandwidth and separation, the insertion losses and the power handling capability [4]. These aspects determine the selection of a triplexer configuration. In addition, a very accurate Computer-Aided Design (CAD) is necessary in order to find a circuit model and a suitable set of dimensions for the physical configuration of the triplexer. Nowadays, the CAD combines circuit synthesis with full-wave analysis of the waveguide structure, and it is helped by numeric optimization in the computer [5, 6].

This approach has many benefits in comparison with a procedure based on experimental adjustments, since the use of tuning screws reduces the power handling capability, generate Passive InterModulation (PIM) products and increase the multipaction risk, raising the cost of the device [4]. However, if the CAD is accurate, the experimental tuning or adjustments are reduced or even avoided, provided that the mechanical tolerances in the manufacture of the component are small enough.

In this paper, the design of a compact full Ku-band triplexer with a modified E-plane power divider is presented. The main advantages of the proposed structure arise from their the wide band electrical performance and, thus, for applications with large separation between channels. The configuration of the power divider and the filters will be discussed. The expected simulated results, obtained by an efficient and accurate CAD tool based on the Mode-Matching method, will be compared with the experimental measurements of a prototype manufactured for a leading European satellite operator.

2. TRIPLEXER CONFIGURATION AND DESIGN

2.1. Triplexer Configuration

There have been many contributions to the design of multiplexers in the past, providing different configurations based on hybrid couplers, circulators, directional filters or manifold structures [1, 4–7].

The selection of a particular topology is mainly determined by the electrical requirements (channel bandwidths and separation, isolation, selectivity and out off-band rejection, return and insertion losses in the pass-band, etc.). Nevertheless, the interfaces with the antenna and the other components of its feed system must be also taken into account, since the compactness or volume constrain is another usual specification.

The main blocks which make up a triplexer (or multiplexer) are the channel filters and the power divider (the junction connecting the filters to the common port). From the geometrical point of view, there is a wide variety of possibilities to select them (see for instance the classification in [5]). Filters with E-plane metal inserts [8], H-plane cavities with inductive windows [9], and T-septum [10] or ridge [11] waveguides are some examples of channel filters, which could be also used to synthesize elliptic function responses [2]. Power dividers can be done with E- or H-plane T-junctions [9, 12–14]. The manifold configuration is a very usual choice for contiguous bands multiplexers [15–17]. Y-junctions are used for narrow to medium bandwidth applications [18]. E- or H-plane n-furcations (divider-type) are preferred for applications with broadband channels or with large frequency separation between channels [8, 19, 20]. Other considerations in the design [21] are the frequency band [22, 23] or the possibility of substrate integration [24].

The triplexer presented in this paper is made up of a modified E-plane power divider as seen in Fig. 1. The objective is to take

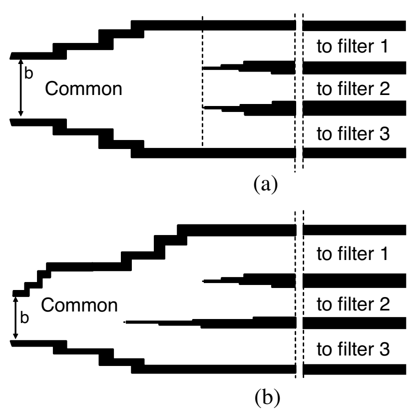

Figure 1. (a) Symmetric E-plane power divider. (b) Alternative asymmetric topology with enough degrees of freedom for triplexers with large separation between channels.

into account that the junction is going to operate in very different frequencies and, thus, the structure must include enough degrees of freedom with respect to a symmetric junction.

Moreover, the filters of the triplexer will be made in H-plane configuration with inductive windows. Although E-plane metal-insert filters are very well suited to the junction, they provide high insertion losses and the filters are very sensitive with respect to any tolerance in the manufacture of the metal septum.

Table 1. Main specifications (nominal) for the Ku-band waveguide triplexer.

	Band (GHz)	Return Loss	Interfaces
Channel 1	12.95–13.25	≥ 23 dB	WR75
Channel 2	13.75–14.50	≥ 23 dB	WR75
Channel 3	18.10–18.40	≥ 23 dB	WR51
	Rejections (dB)		
Band (GHz)	Filter 1	Filter 2	Filter 3
11.7–12.5	75	90	90
12.5–12.75	30	90	90
12.9–13.0	-	70	90
13.0–13.25	-	50	80
13.75–14.5	50	-	70
17.3–17.7	60	60	30
17.7–18.1	60	70	-
18.1–18.4	70	70	-
19.0–20	40	40	40
Isolation between channels: 1–2 ≥ 60 dB, 1–3, 2–3 ≥ 100 dB			
Group delay variation (peak to peak) ≤ 3 ns			
Insertion loss for each channel ≤ 0.3 dB			
Interface common port: WR62			

The selected configuration will be illustrated with the design of a prototype, whose final aspect ratio is anticipated in Fig. 2. Its main specifications are shown in Table 1. The channels (2.3%, 5.3%

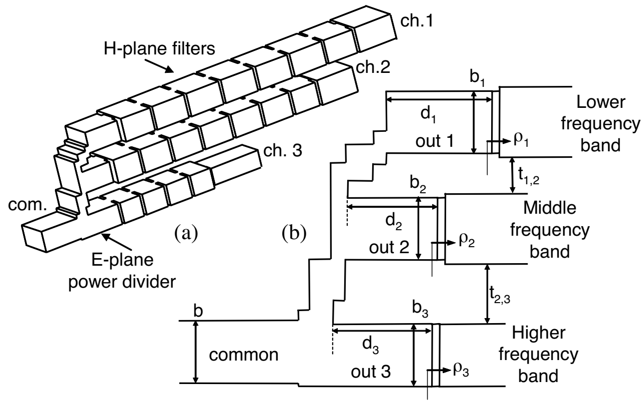

Figure 2. (a) General view of the triplexer with the power divider and the H-plane filters with inductive windows. (b) Detail of the layout of the improved E-plane power divider (Aspect ratios of the final optimized prototype).

and 1.6% of fractional bandwidth) are centered in 13.10, 14.12 and 18.25 GHz, respectively (frequencies which later on are compensated for the operating temperature range). The insertion loss must be better than 0.3 dB, while the return loss should be better than 23 dB. In addition, the component must be very compact to fit in the antenna feed system.

2.2. Design of the Channel Filters

The channel filters provide the frequency selectivity to the triplexer. Two main aspects in the design are the choice of the resonant mode and its quality factor Q, which will determine the insertion losses of the filter. The TE_{101} resonant mode in inductive window H-plane filters can provide enough Q for this application (at least $Q = 6700$ is required for the requirements in insertion loss). The Q of the TE_{101} mode can be increased by enlarging the heights of the cavities, at the expense of reducing the frequency band without spurious resonant modes.

In order to fulfill the specifications, filters 1 and 2 will have seven cavities. Filter 1 is designed with a fractional bandwidth of 3.1% to reduce the insertion losses in the nominal 2.3% channel bandwidth. Channel filter 3 requires only a four order design, since its frequency band is well separated from the other two. On the other hand, it is the filter at the highest frequency, which means that it will be more sensitive and with high losses. In the three cases, the filters are designed as standard all-pole Chebychev filters with a return loss of 25 dB, although the final requirements are 23 dB, in order to anticipate degradations in the complete structure.

The full-wave analysis of the filters is carried out by means of a rigorous Mode-Matching (MM) method. The analysis by MM provides the Generalized Scattering Matrices (GSMs) of the discontinuities between the different sections of rectangular waveguide which make up the filter (see for instance [8, 12, 25]). These GSMs are cascaded consecutively in order to get the complete response of the filter in a very efficient and accurate way.

The same MM formulation can be applied to bifurcations, trifurcations and T-junctions. Therefore, the GSM of the power divider and the whole triplexer can also be obtained by this method. This is an interesting feature of the selected triplexer topology, since the computation time and accuracy of the simulations is strongly dependent on the physical structure. With the selected configuration, the analysis can be performed in a very efficient way by MM. Moreover, the design approach for the junction operating as power divider is discussed now.

2.3. Design of the Power Divider

The topology for the power divider is shown in Fig. 2(b). It is important to remark that the physical position of the channel filters with respect to the output ports of the junction is very important for frequency bands with large separation.

At high frequencies, obstacles and discontinuities in the signal path influence very significatively the propagation. This effect shown in [25] for E-plane structures (at quasi-optical frequencies the beaming effect is commonly used) suggests to connect the highest frequency channel with the output port of the power divider with less obstacles. In this way, the higher frequency channel finds a small number of discontinuities and is placed in the most direct path between the input and the output. The lowest channel is located in the upper part and the remaining filter in the middle. Previously to the optimization, the distances between the channels $t_{1,2}$ and $t_{2,3}$ (see Fig. 2(b)) are fixed in advance for mechanical considerations.

The output ports of the power divider (see Fig. 2(b)) are loaded with the reflection coefficient of the fundamental mode of each filter $\rho_j, j = 1, \ldots, 3$. The responses ρ_j are modelled using the fictitious reactive load concept [17]. For a given geometry, the GSM of the power divider is obtained by MM and cascaded with the ρ_j. In this way, the lengths d_j connecting the filters with the junction and the internal dimensions of the power divider (lengths and heights of the waveguide sections) are optimized in order to achieve the required matching at the common port in the channel bands.

A typical cost function combines the reflection coefficient in N_f frequencies f_i distributed in the specified bands for each channel:

$$C = \sum_{i=1}^{N_f} |S_{com,com}^{(MM)} - S_{com,com}^{(cir)}|^2 \rfloor_{f=f_i}. \quad (1)$$

The cost function compares the result obtained by the MM code developed for the waveguide triplexer and the ideal circuit response.

The process to obtain the dimensions of the power divider is almost finished with the previous optimization. Nevertheless, the lengths d_j require a final refinement, which is carried out by considering more interacting modes in the waveguides connecting the filters with the power divider. In other multiplexer designs, for instance in contiguous channel applications, this last refinement may additionally involve changes in the dimensions of the filters (usually the closest to the junction, first coupling iris and cavity). For the triplexer under analysis, the final optimization is only used to adjust the lengths d_j. In any case, the sequential and incremental design process reduces the computational load of the optimizations.

3. NUMERICAL AND EXPERIMENTAL RESULTS

The design process shown above has been used to design a triplexer for satellite applications, whose main specifications have already been given in Table 1. The topology of the optimized power divider has became very asymmetric, as it can be seen in Fig. 2(b), in order to operate in this application with large separation between channels. The largest path in the junction is from the common port to the channel 1, while the most direct is to the channel 3.

The final configuration, with its actual aspect ratio is shown in Fig. 3. The structure fits in the volume constrain required by the application. Two E-plane bends are attached to the final structure in the lower and upper channel, in order to connect the structure to the remaining part of the antenna feed system. A photograph of the built component is shown in Fig. 4.

Figure 5 shows the response for the three channel filters, including the experimental measurements and the expected simulations. The isolation exceeds 60 dB between channel 1 and 2 and 100 dB for the other channels. All the waveguide modes with a cutoff frequency under 60 GHz has been used in the MM analysis, which have a good agreement with the measurements.

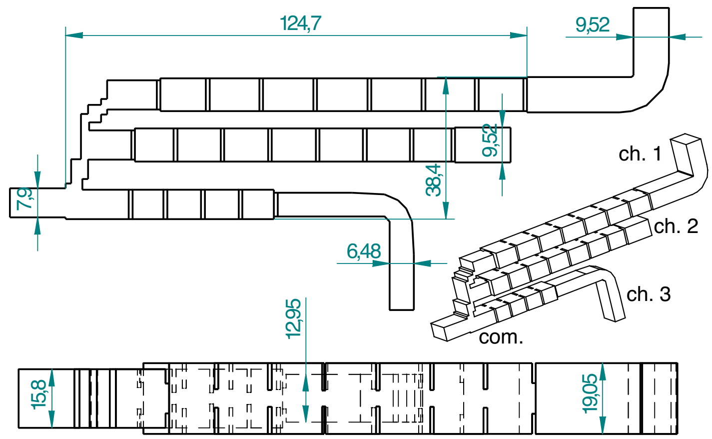

Figure 3. Final layout of the waveguide triplexer (actual manufactured structure and aspect ratio).

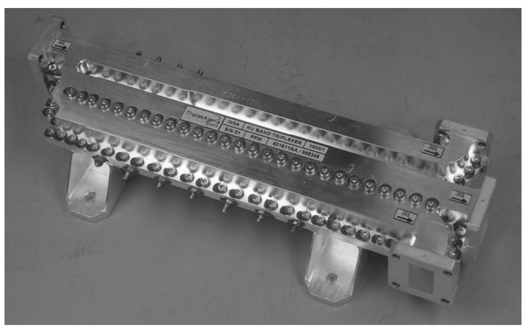

Figure 4. Photograph of the manufactured Ku-band waveguide triplexer for communications satellite systems (Courtesy of Thales Alenia Space España).

The transmission and reflection coefficients detailed in the frequency band of the channels are shown in Fig. 6. The measurements are within the specifications, with a response very similar to the theoretical design by MM.

Figure 7 shows the detail of the insertion losses for each channel. The circuit simulations with a $Q = 6700$ for the resonators is also given in the same graph. This value has been enough to fulfill the requirements. Finally, the group delay for all the channels are shown in Fig. 8.

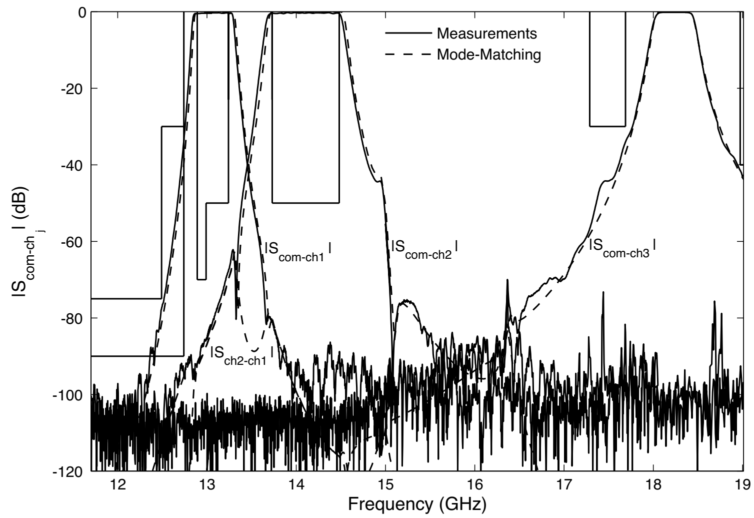

Figure 5. Comparison between the measured transmission coefficients of the triplexer and the simulated responses from Mode-Matching (specification mask from Table 1).

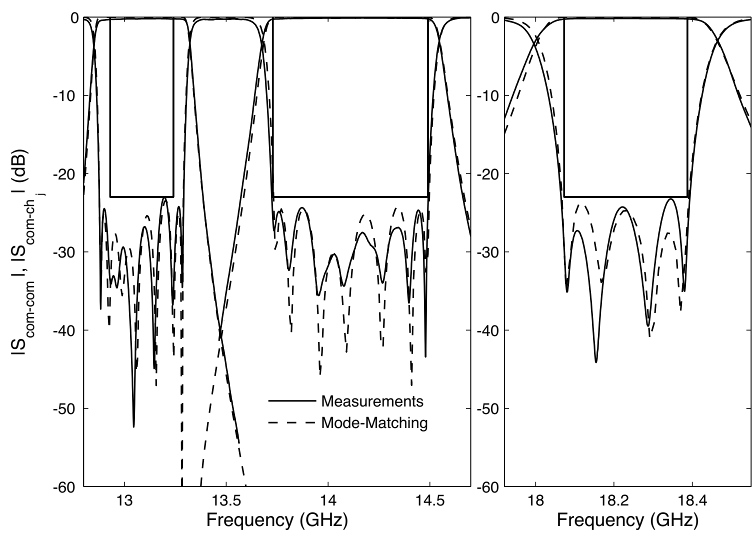

Figure 6. Comparison between the simulated return and insertion losses and the measurements for the three channels of the triplexer.

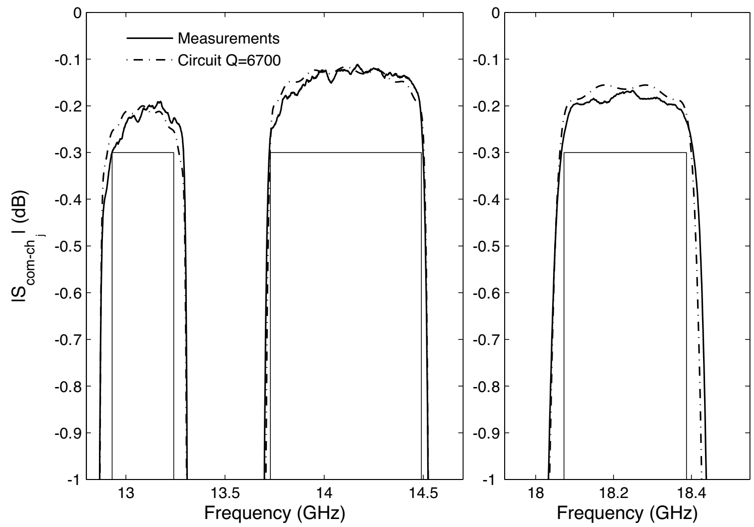

Figure 7. Measured insertion loss for the three channels of the triplexer. Comparison with the simulated circuital response assuming resonators of quality factor $Q = 6700$.

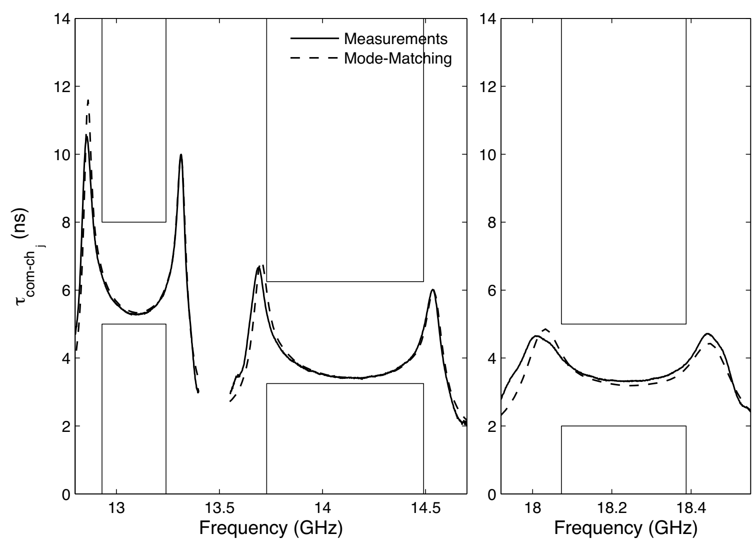

Figure 8. Comparison between the simulated group delay variation and the measurements for the three channels of the triplexer.

4. CONCLUSIONS

The full-wave design of a Ku-band triplexer has been presented, focused on achieving a compact structure with low insertion losses and sensitivity. The selection of the power divider is an essential design part when the channel separations are broad. The filter locations should take into account the different behavior of the frequencies involved in the device. Moreover, the power divider needs enough degrees of freedom to operate in the broad bandwidth, leading to a very asymmetric junction.

These features have been illustrated with the design of a triplexer for communications satellite systems, operating in the full Ku-band. The triplexer is optimized with an ad-hoc CAD tool based on MM. The experimental results fulfill the specifications and are in good agreement with the theoretical simulations.

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