An Innovative Odd-Power Divider by means of a Triple FinLine Waveguide to Microstrip Transition

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ABSTRACT This paper outlines a novel approach to design a waveguide to microstrip finline transition that allows a division by three, of the *RF* power traveling inside a rectangular waveguide. The possibility of obtaining an odd power division of microwave and millimeter-wave signals with such finline transition is completely unexplored yet a harbinger of great opportunities. Starting from a 3D CAD model of the structure and continuing with electromagnetic simulations, the obtained results completely describe a transition able to achieve an almost perfect power splitting by three. Multyphisics simulations show an intrinsic resistance to vibrations of such transition, allowing it to be installed on aircraft or satellites modules. Thanks to this achievement, a totally new kind of power devices will come next, exploiting this odd power division. In fact, it will be possible to realize different types of microwave amplifiers, increasing the efficiency and decreasing the occupied size. To the author's best knowledge, it is the first time a divider by three finline transition is reported in the literature.

INDEX TERMS Power Dividers, Power Combiners, Finlines, Spatial Power Amplifiers, MMIC.

I. INTRODUCTION

STRUCTURES which allow the traveling wavefront RF power to convert, starting from a waveguide propagation and ending into a planar one, such as inside a microstrip, represent a key point in the microwave and millimeter-wave power applications. Furthermore, almost all power systems that operate over these bandwidths carry out the splitting and combing power operations through several binary steps, thus forcing the employment of a specific number of solid state power amplifiers. This number must be even and, more specifically, a power of two. If we consider a structure that performs the power splitting and the power recombination through n steps, on the final stage, we can find a total of 2^n paths, where an equivalent number of MMICs can be placed. This is the most common scenario for such applications, but it can lead to an exceeding level of available power, also introducing problems of sizing and heat dissipation. In this paper, an innovative waveguide to microstrip transition is outlined. Using the finline it allows a power division by three of the electromagnetic field traveling inside a waveguide, also ensuring the matching between the *quasi-TEM (qTEM)* circuits, microstrips in this case, and a rectangular waveguide. One of the most interesting applications for these transitions lies in the so-called wavefront amplifiers, more commonly known as SPAs (spatial power amplifiers) or SPCs (spatial power combiners) [1-8]. The basic working principle of a spatial amplifier system is that the power dividing/combining operation is performed in a single-stage parallel way; in the case of waveguide systems, this is done in the air, then with a very low dissipation factor. Several analytical models and topologies of SPCs have been studied in the last decade, all of them clearly show the immense potential of these architectures. In fact, structures as such can effectively replace high-power vacuum tubes, providing a low weight system, operating at low voltages with high reliability. The most interesting fact about the spatial power techniques is that the combination losses are independent of the number of solid-state amplifiers involved, further allowing for the combination of odd numbers of devices. The transition reported in this paper may be the first step towards a new kind of SPCs based on odd power divisions. A possible SPCs division into families is reported in Figure 1:

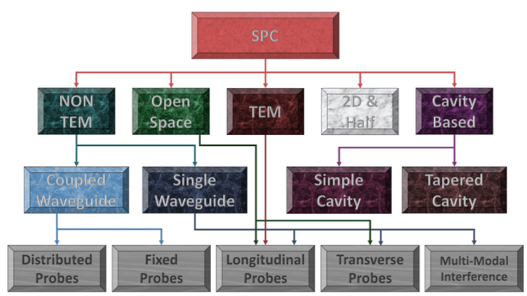


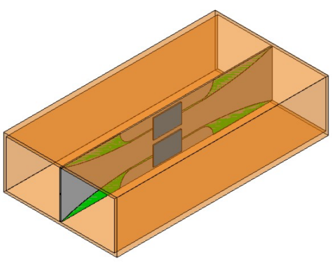
FIGURE 1. Spatial Power Combiners Family.

In this work, we will report the analysis and design of an innovative divider by three finline to microstrip transition (FLuS), working in Ka-Band.

This paper is organized as follows: in Section II, the difference between longitudinal and transverse probes is dealt with, in Section III the design rules adopted for the 3D drawing of the transition are reported, and in Sections IV and V, the results of the electromagnetic and multiphysics simulations are shown. Then, finally, the Conclusions of the present work are summarized.

II. LONGITUDINAL AND TRANSVERSE PROBES

An electromagnetic probe is a very useful component for microwave and millimeter-wave electronics; through this tool, in fact, it is possible to sample a specific amount of EM power that is traveling in a particular area of the system, also allowing the transition from one type of propagation to another. For instance, inside an SPC device, probes are used to convert into a planar propagation structure, the power coming from a waveguide or a coaxial infrastructure. Of course, a probe is a 3D object, and the electromagnetic field propagates in a specific direction while its components assume specific orientations in space. It is simple to understand that a probe cannot have an arbitrary shape and cannot be placed in a random spot, especially when the system works at high frequencies. Two major categories of probes are used in this part of the spectrum: longitudinal probes [9-11] and transverse probes [12-15]. Although they could have different shapes, as the names suggest, the difference between these two kinds of probes mainly lies in the positioning of those with respect to the propagation direction of the EM field. Using longitudinal probes allows to develop the system in a singular direction, the propagation one, also providing the broadest possible bandwidth; transverse probes instead, are placed perpendicular and from the point of power sampling onwards, the majority of the EM power propagates in a perpendicular direction with respect to the previous one. All the uncollected power which is not captured by the probe must be appropriately treated. To do so, generally, a metallic plate is placed at a specific distance from the probe, distance which is of course $\lambda/4$, with λ representing the wavelength of the centre band frequency. As it's easy to guess, the introduction of a length-dependent portion of transmission line, implies a reduction in the useful bandwidth.



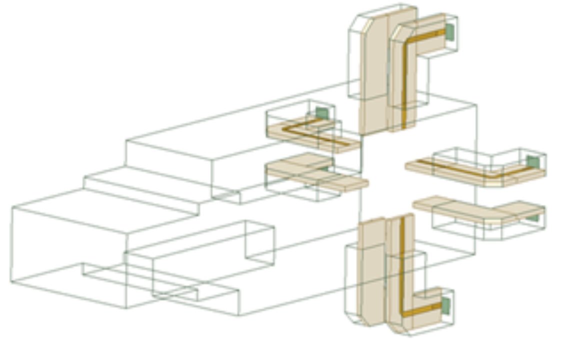


FIGURE 2. Longitudinal and Transverse Probes.

One of the most efficient longitudinal probes is the so-called finline [16], which exploits a 90° degree rotation of the traveling field to capture and confine within a microstrip, most of the useful RF signal propagated inside a waveguide. The most significant feature of a FLuS transition is the operative bandwidth which does not introduce restrictions whatsoever. Therefore, the entirety of the waveguide bandwidth can be exploited appropriately, as presented in the electromagnetic results section.

The finline transition is generally considered as an impedance transformer. It allows to match the impedance of the fundamental mode traveling inside the square waveguide, with the impedance of the field propagating in a microstrip. In this frequency range, the impedance of the fundamental TE_{10} mode presents a mean value of about 320 Ω, while the impedance of the microstrip is always 50 Ω. Furthermore, the finline performs a 90 ° rotation of the electric field.

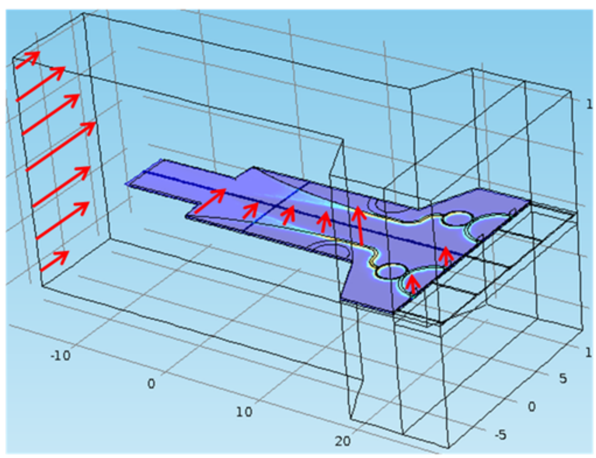


FIGURE 3. Electric Field Rotation performed by Finline.

III. TRIPLE FINLINE DESIGN RULES

The Transition analyzed in this paper can be placed inside a WR28 waveguide, so all the signals with frequencies between 26 and 40 GHz can be processed correctly. A relatively smooth conversion of the fundamental TE_{10} mode into a *qTEM* propagation microstrip can be done. Despite the bandwidth chosen for this paper, the following design rules are also applicable to any waveguide size, but, of course, going up in frequency means shortening the wavelength, then the practical realization of the transition gets more complicated. The triple FLuS is realized on an Al_2O_3 substrate with a thickness of 254 μm while the ground and the "hot" plates are made of gold. This is a standard technology of construction for such devices, but different materials with different thicknesses could be used for various reasons. Duroid substrates, for instance, present very small losses either because of the small $\tan\delta$ of the substrate, but mainly because in that case, the hot plate is very large, then the ohmic resistance is very low; on the other hand, though, the substrate is relatively soft and even a moderated power can thermally deform it [3,5]. Ceramic substrates are more reliable in that sense, also being tolerant to mechanic vibrations, as it is shown in section IV. On the front of the golden plates, they represent the actual FLuS, and they have a specific shape, called taper, to rotate and convey the waveguide field into a planar microstrip one. The finline taper acts as a broad-band impedance transformer between the waveguide and the microstrip ports since they have different characteristic impedances. The minimum of combining losses can be achieved with a proper choice of the taper. A finline taper can be made following several profiles, there are in fact exponential, parabolic, sine and cosine tapers, and for this design, an inverted exponential profile, that we call "logarithmic", has been chosen and implemented with the following equations:

$$w(z) = w_0\left(\exp\left(\frac{z}{L}\ln(w_f)\right) - 1\right)$$

$$w_0 = \frac{w_{50} + w_{sub}}{2 \cdot (1 - w_f)}$$

Where $\boldsymbol{w_0}$ represents the initial width of the taper, $\boldsymbol{w_f}$ defines the curvature, and $\boldsymbol{L}$ is the total length of the fin; $\boldsymbol{w_0}$ is composed by $\boldsymbol{w_{50}}$, the microstrip width, and $\boldsymbol{w_{sub}}$, the width of the substrate.

In terms of optimization, the most significant parameter is $\boldsymbol{L}$, since the others ($\boldsymbol{w_{50}}$, $\boldsymbol{w_{sub}}$) are constrained by the type of substrate involved. The parameter $\boldsymbol{w_f}$ can assume all values between 0 and 1 and it affects the curvature of the taper, then it is less significant in terms of optimization. $\boldsymbol{L}$ instead is a much more sensitive parameter and must assume a value close to $\lambda/2$, with λ the wavelength associated to the central frequency of the bandwidth considered. For this project the central frequency is 33 GHz and the corresponding wavelength is 9 mm, then the length of $\boldsymbol{L}$ is 4.5 *mm*.

To perform the impedance matching, it is possible to study the reflection coefficient of the finline. In case of a logarithmic taper, the reflection coefficient varies according to the law:

$$\Gamma = \frac{1}{2} e^{-j\beta L} \ln(\bar{Z}_L) \frac{\sin(\beta L)}{\beta L}$$

Where $\boldsymbol{\bar{Z}_L}$ is the characteristic impedance of the taper at point $\boldsymbol{L}$ while $\boldsymbol{\beta}$ is the constant of propagation and it is assumed to be constant along the entire stretch of the transmission line. The reflection coefficient graph shows a typical sync trend of the function.

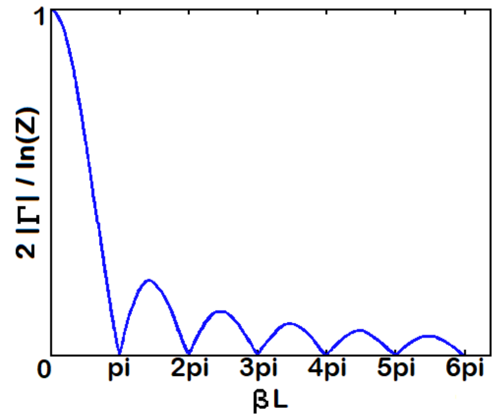


FIGURE 4. Reflection Coefficient of a Logarithmic Taper.

Following these equations, it is possible to realize any kind of logarithmic taper finline and from now on, becomes crucial the choice of the number of power divisions demanded. In this work, an innovative triple finline has been studied and simulated. Therefore, a power division by three has been achieved and, to the author's best knowledge, there are no other examples in the literature of a structure as such. Having to realize three tapers along the whole short side of the waveguide (b = *3.556 mm* in case of WR28), two mirroring operations must be done with respect to the vertical lengths of $b/3$ and $2b/3$.

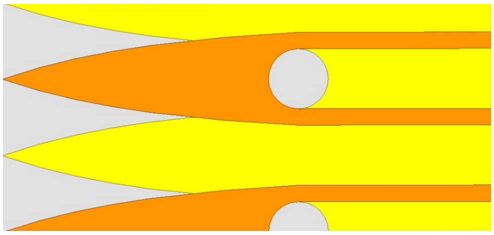


FIGURE 5. Triple Finline in Antipodal Configuration.

A very attractive configuration, especially regarding the integration, is the well-known "Antipodal Configuration". This construction technique implies two metal finline transitions plates arranged on both sides of a dielectric substrate to obtain hot and ground planes and their profiles are dual mirrored. This transition is currently very easily manufactured using sputtering or, more commonly known, printed circuit board techniques. A view of this configuration is reported in *figure 5*, where the orange lines represent the hot plates while the yellow lines show the pattern of the ground planes.

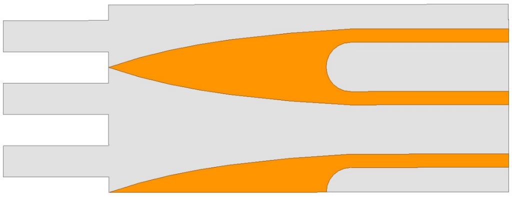


FIGURE 6. The innovative Triple Finline, complete with QWTs.

At this point, it might be possible to insert the triple FLuS transition inside a rectangular waveguide and proceed with the EM simulations but, further optimization of the structure can be made, allowing an important reduction of the return loss measured on the face of the waveguide where the input signal is applied. Usually, a dielectric quarter wave transformer (QWT) is adopted, and since the power division is different from the canonical division by two, a "parallel QWT" (P-QWT) has been implemented. This design choice is crucial to equalize the power transiting on each microstrip, as it will show in the next section, and the reason for this behavior is justified by the symmetrization of the flowing currents [7]. As the name suggests, a quarter wave transfmorer has a longitudinal length of a quarter of wavelength and for this project, the length of all the QWTs is 2.25 *mm.*

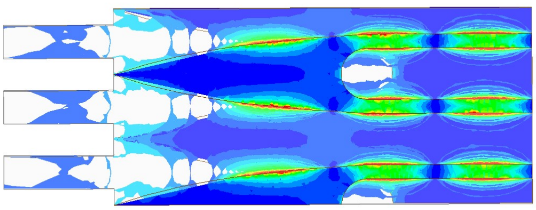


FIGURE 7. The Symmetry of the currents inside the Triple Finline, induced by P-QWT.

The impact of the P-QWTs, as well as all the electromagnetic performance of the transition is reported and fully detailed in the next section, where the simulated results entirely describe the characteristics of this innovative transition.

As already mentioned, a fundamental aspect of this transition is achieving an odd power division of the electromagnetic front wave. Up to now, there is no other transition capable of such. The vast majority of power divisions in the microwave and millimeter-wave applications are carried out following schemes of even power division, either for a planar or a waveguide structure. The only odd power divisions that are possible to find in the literature are made by means of waveguide systems, which don't allow to follow a planar propagation of the system, but require a three-dimensional development to perform the odd divisions [17,18]. Then the transit power must be converted into a solid-state transmission line anyway. Implementing the FLuS reported in this paper, it is possible to achieve the odd power division, as well as the transition waveguide to microstrip, just in one shot, also saving space and gaining in terms of compactness, since there is only one direction that the system follows. This aspect represents a milestone in the world of microwave amplifiers, because it offers the possibility to reach the amount of total power required without being forced to implement a classic even power divider structure. For example, if we must reach a relatively high power inside an amplifier operating in Ka-Band, which exploits the SPA technology, the use of dual finline transition is often not sufficient to success, because combining the power of only 2 MMICs might be not enough. In almost every power system operating in these bandwidths, the next step is to implement a power divider by four, since even combinations are the only available until now. Still, the combined power of four MMICs may be excessive, and the system's total efficiency would fall drastically, both in terms of energy and size. Moreover, a quadruple finline transition for a WR28 waveguide is challenging to realize, since there must be four microstrip lines in the height of *3.556 mm* and, in fact, a quadruple Ka-Band FLuS shows very poor values of isolation between the microstrips ports. A triple finline instead, is the perfect solution to reach decent amounts of power, while ensuring excellent values of isolation between the three MMICs involved and not making the system grow too much in terms of occupied space. Regarding transitions that allow higher power divisions, such as hexa-finlines [11], they are not realizable in small a waveguide like a WR28 because of the short height (the rule of three times the substrate height between lines cannot be satisfied [18]). This aspect increases the value of this triple transition which allows reaching the maximum power division, preserving the isolation between ports inside this range of waveguides.

Another distinctive feature of the triple FLuS is the phase difference between the three microstrip ports. All the classic finline structures perform an even power division; then, the phase difference is always of 180° between two adjacent ports. This relation still remains in the triple finline, but since there is an odd number of planar ports it results in a couple of ports that share the same phase and an unpaired port (the central one), which is in phase opposition.

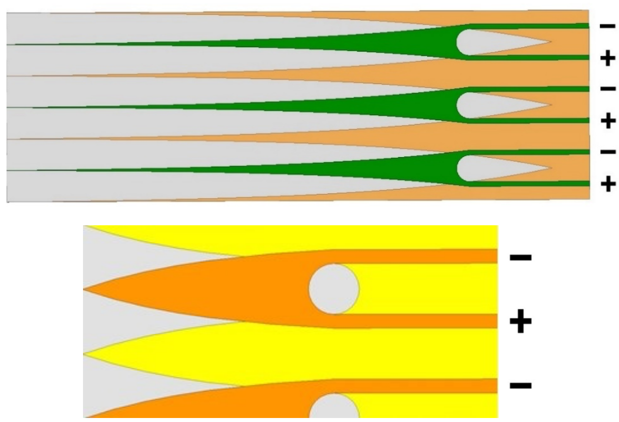


FIGURE 8. Phase Difference distribution inside a WR90 Hexa-FLuS and a Triple FLuS.

To better visualize the mutual phase difference on the microstrip side, the following figure depicts the pattern of the signal phases on the middle and the lower port with respect to the upper port and, as expected, phase differences of 180° and 0° occur.

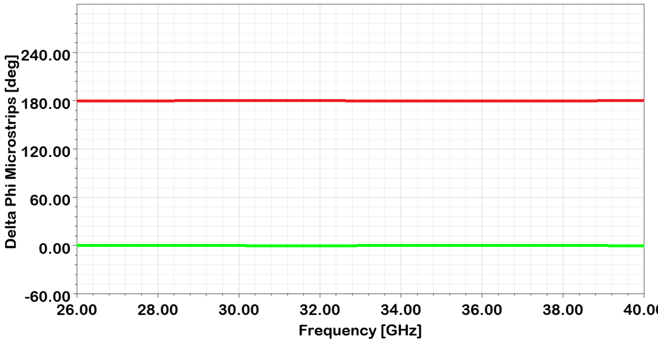


FIGURE 9. Phase difference of the central (red) and lower (green) port with respect to the upper microstrip port.

Another important difference between any even FLuS, so as the hexa fin shown in *figure 8*, and the innovative triple FLuS described in this work, is the connection among the FLuS conductors and the short waveguide wall. In fact, even FLuSes have a common ground layer that connects top and bottom waveguide walls at the same longitudinal coordinate so that the external microstrips are always in phase reversal; conversely, in the triple FLuS the common ground does not connect the top and bottom waveguide walls at the same longitudinal coordinate but with a difference of path of nearly half wavelength, so that external microstrips are always with the same phase.

IV. ELECTROMAGNETIC SIMULATIONS

The first simulations were carried out on a triple FLuS without QWTs, noting that already this configuration shows satisfactory results in terms of return loss and insertion loss, remarking the inherently excellent behavior of the FLuS transitions across relatively large bandwidths. The simulation setup used in this section is shown below, and all the following results were obtained using the well-known software *HFSS* [19].

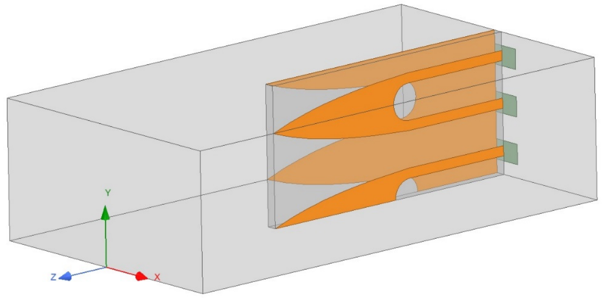


FIGURE 10. Triple Finline with NO QWT inside a WR28 Waveguide, ready for simulations.

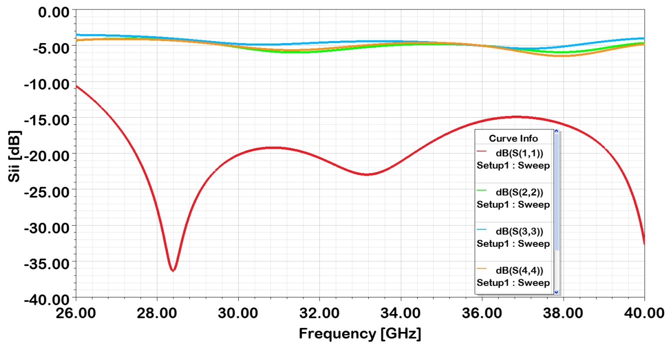


FIGURE 11. Matching on all the four ports of the system without QWT.

As expected, the matching on the microstrip ports is not comparable with the input matching on the waveguide section, which is very good across the whole band. The reason for this is the absence of an isolated port where all the unwanted reflections can be extinguished [20], such as in the case of a Wilkinson divider [21]. Nevertheless, the pattern of these scattering parameters is quite flat.

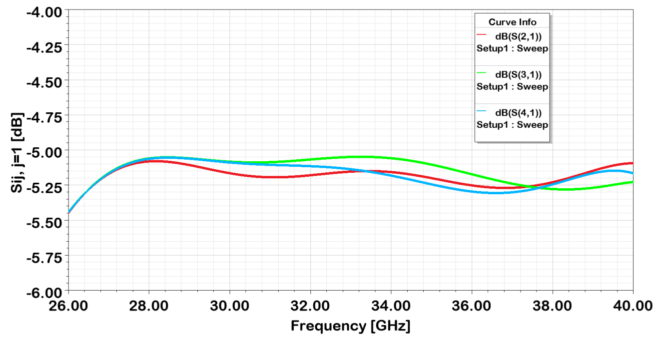


FIGURE 12. Insertion Losses of the system without QWT.

A lossless splitting by three, corresponds to a value of 4.77 dB and since the mean value of the insertion losses hovers around 5.1 dB, this structure introduces an average of 0.4 dB of losses over the whole Ka-Band.

Instead, the configuration with three parallel QWTs, which is the best and the more optimized one, is going to be reported, also for the multiphysics simulations. Two significant improvements occurred, related to the quantities just shown above.

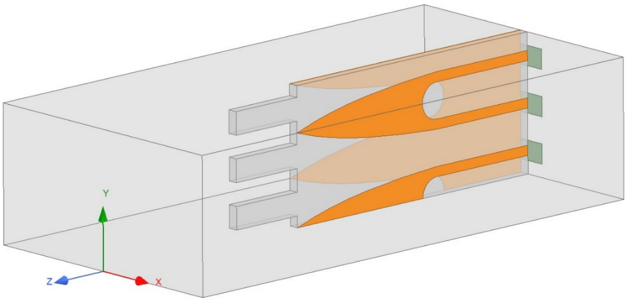


FIGURE 13. Triple Finline with triple P-QWT inside a WR28 Waveguide, ready for simulations.

The realization of a QWT with the shape shown in the previous figure is relatively simple and using a laser technique, a very small resolution (about 0.15 *mm*) can be reached. The use of laser processing technologies is also recommended since the Al_2O_3 is a relatively hard substrate. It stands to reason that since there are three hot and three ground metal lines, the fundamental TE_{10} mode must be divided into three parts so that each line can be equal excited, and that explains the particular shape of the P-QWT in the previous figure.

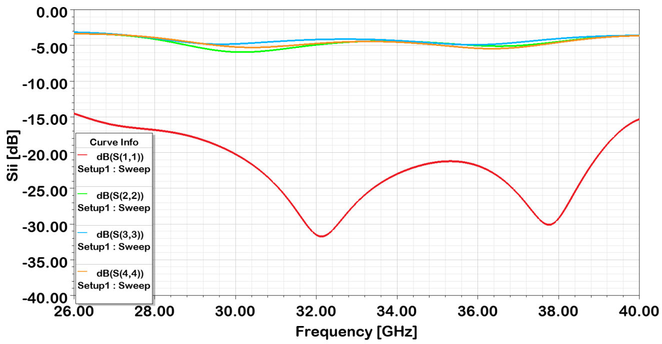


FIGURE 14. Matching on all the four ports of the system with a triple P-QWT.

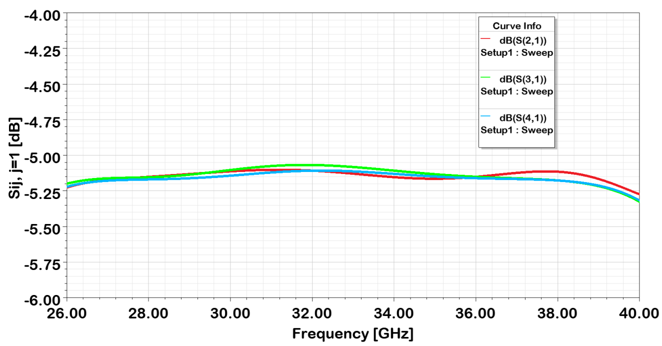


FIGURE 15. Insertion Losses of the system with a triple P-QWT.

On the matching side, the introduction of this triple parallel QWT leads to a general flattening of the scattering parameters, especially regarding the S_{11} that lies below the value of -15 dB over the entire band, whereas generally, the maximum target to not exceed in a microwave project is -10 dB. But the most important improvement introduced by the triple QWT concerns the power splitting; in fact, an almost perfect division has been achieved, with a maximum power difference between a microstrip port and another one of 0.05 dB. It is possible to consider that all the traveling RF power coming from the rectangular waveguide and properly converted inside the FLuS transition, is split almost equally within the three microstrip lines. For instance, this is a crucial feature in SPA applications, where a perfect power division is obsessively demanded to excite and lead to the saturation of all the MMICs implied.

The final scattering parameters to report to completely describe the triple FLuS transition are the isolation parameters between the microstrip ports. Since the three microstrips are relatively distant from each other, certainly more than three times the substrate height (which is a general rule of thumb), the isolation values exhibit a flat trend with a -9 dB of average power.

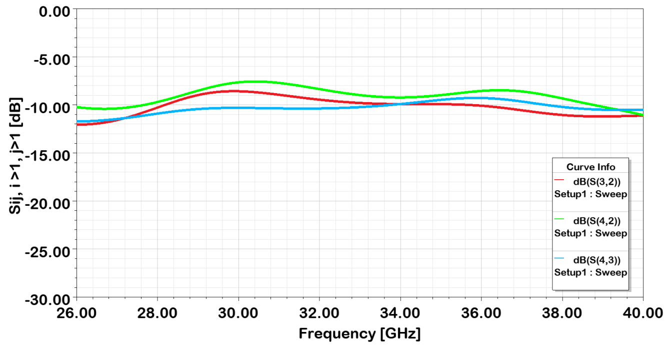


FIGURE 16. Isolation Losses of the system with a triple P-QWT.

This ends the section about the complete EM characterization of the triple FLuS which, of course, is the most important one but, since the possible applications of this structure require other constraints besides the electromagnetic ones, a multiphysics analysis of this structure were carried to draw up a comprehensive report. These results are shown in the next section.

V. STRUCTURAL MECHANICAL SIMULATIONS

Space, avionic and naval applications; these and many others are the possible environments where a finline transition is demanded, within a spatial power amplifier, for instance. The only EM characterization is not sufficient to certify that these devices can properly work on a satellite or inside an aircraft because, in these environments, a mechanical force capable of damaging the transition could occur, or the mechanical frame could not be designed for properly thermal dissipation. To fully describe from an engineering point of view the triple FLuS, structural simulations were undertaken with *COMSOL Multyphysics* version IV [22] (such analysis has never been done on a Hexa-FLuS). With the addition of these results, a virtual prototype, ready to be realized, of a triple FLuS transition has been presented and evaluated.

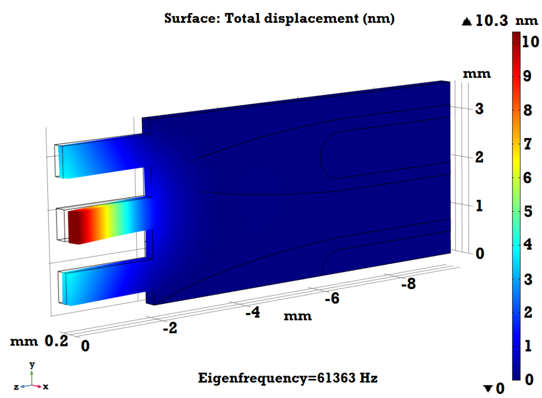


FIGURE 17. Mechanical Deformation (nm) at First Mechanical Eigenfrequency.

The structural analysis allows us to find the mechanical eigenfrequencies that occur when the transition is bounded inside a rectangular waveguide, as seen in *figure 10* and *figure 13,* and the system is subject to vibration. For this structure, the first eigenfrequency appears for vibration of 61 kHz, and it causes a maximum mechanical displacement of 10 *nm* of the Al_2O_3 substrate, then a very negligible deformation. This result shows the space qualification of this structure, since the fundamental mechanical eigenfrequency lies much above the value of 10 kHz, also causing almost imperceptible deformations. 10 kHz is the value of the maximum vibration frequency tested during a qualification test phase on a satellite module and, in particular, during the so-called "pyrotechnic shock test" in which the module must resist shock waves caused by explosives in the launch phase.
Another effect that can be evaluated with a structural analysis regards the mechanical stress suffered when these eigenfrequencies occur. Among all the types of stress, the Von Mises stress has been considered, since it refers to the maximum distortion criterion in the case of ductile materials.

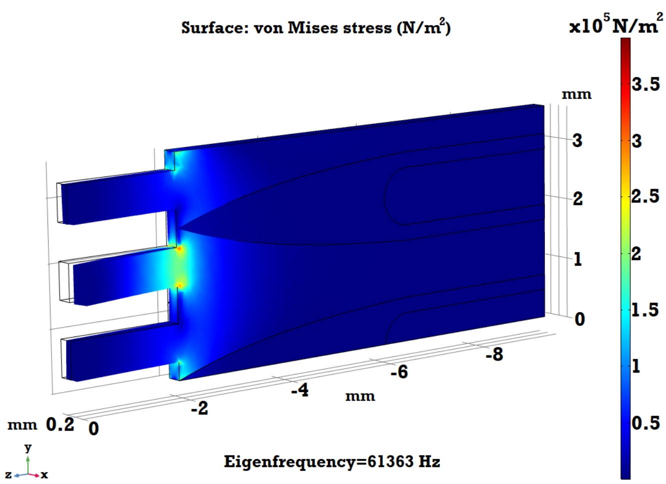


FIGURE 18. Stress at First Mechanical Eigenfrequency.

Evaluating both stress and mechanical displacement over an integration line extending along the z axis and placed in the middle of the height on the *y* axis i.e., where the deformation at the fundamental eigenfrequency is maximum, the graph shown in the next figure is obtained.

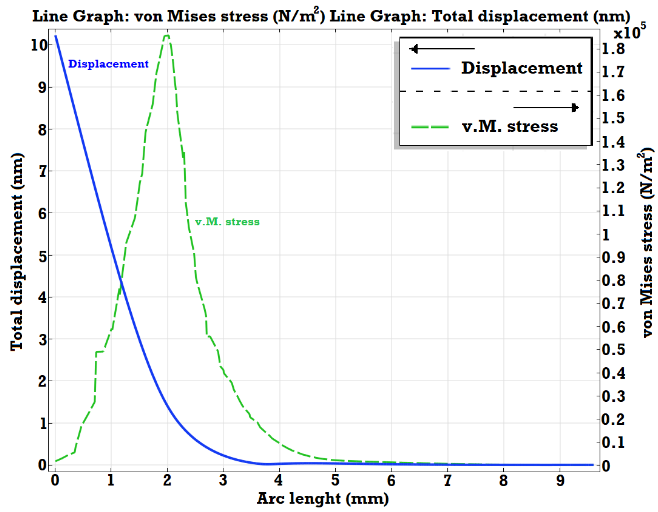


FIGURE 19. Stress and Displacement at First Mechanical Eigenfrequency (61kHz).

VI. CONCLUSIONS

This work has designed and reported a complete novel RF power dividing-combining structure. Using the well-established finline technology, it has been possible to achieve a power division by three over the entire bandwidth of a rectangular waveguide (in this case, a WR28), thus releasing from the obligation of realizing a power of two combination system. Based on the results of electromagnetic and Multypishics simulations, emerges a virtual prototype ready to be realized and installed on space and military platforms. Usually, the natural application for these transitions is inside a spatial power amplifier, but it can be placed in many other different electromagnetic structures. This innovative transition will allow combining active or passive devices in odd combinations, increasing the degrees of freedom for microwave and millimeter-wave designers. To the author's best knowledge, this is the first waveguide to microstrip transition able to realize an odd division of the *RF* power.

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