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Novel Ridged Waveguide Differential Phase Shifter for Satellite Application

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Abstract- **A compact differential phase shifter structure that exhibits both full-band operation and easy mechanical manufacture is presented. It consists of a rectangular waveguide loaded with single ridge sections terminated by a unique H-plane step widening to standard waveguide dimensions. Two prototypes of 90º and 180º differential phase shifters with reference to an empty waveguide of the same length were designed and tested for the WR75 waveguide band. In both cases the differential phase shifter exhibits a maximum measured phase error of ±2.5º and ±3.5º respectively, with return losses better than 24 dB and insertion losses lower than 0.06 dB over a >40% bandwidth, which represents state-of-the-art achievement for non-dielectric loaded waveguide circuits. Furthermore, this structure is well suited for H-plane millimetre-wave integration.**

Index Terms— **Phase shifters, waveguide components, antenna feed subsystems.**

I. INTRODUCTION

Differential phase shifters (DPS) are of considerable importance for subsb systems requiring a relative phase difference in th hee electromagnetic signal between two different loc acations within the circuit. DPSs are generally useedd to introduce a phase shift of 90º or 180º, butt any other value may be needed for accomplishinng the function of the microwave subsystem. Ammong its current applications, phase discriminatoorrs, beam forming networks, frequency translators,s, power dividers and phase array antenna can be a appointed. Many structures have been proposed i inn the literature to fulfill different requirements: broad bandwidth, power handling capabilities, low losses, low cost, reduced physical size and easy mechanical manufacturability [1]-[4]. Furthermore, most of the designs given in the literature do not look for a physical equality between the phase-shift structure and the empty reference waveguide, which imposes a further constraint that decreases in a natural way the bandwidth of application.

The design of some DPSs based on waveguides loaded with dielectric slabs, with the aim of increasing the frequency bandwidth, may be found in [1], but they did not exceed 15% of fractional bandwidth. Subsequent DPSs based on ferrite materials are presented in [2] in order to broaden the frequency bandwidth and improve non-reciprocity of the DPSs, but the use of slot lines and dielectric layers increases the losses and limits the bandwidth application. In [3] the design of waveguide DPSs using a series of discontinuities in the form of E-plane stubs, with respect to an empty waveguide having different length, obtains a 17% bandwidth with excellent phase performances.

In [4] a DPS was proposed to achieve 30% bandwidth by using a ridged waveguide section together with a series of capacitive inserted posts that complicate the design and fabrication, thus deteriorating the electrical performances of the practical device. The use of hollow waveguides

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loaded with capacitive irises, ridged sections or fins [5] provides a constant phase shift of 90º, with respect to an empty waveguide of the same length, in a 20% bandwidth. This philosophy results in small size designs ($L = 1.5\lambda_0$, being λ_0 the wavelength at the central frequency) when compared with previous designs. To increase the instantaneous bandwidth a great number of discontinuities must be introduced and therefore the design becomes bulky, lossy and critical against the mechanic tolerances. Recently a broadband waveguide 90º-DPS filled by a longitudinally inhomogeneous dielectric is described in [6]. This structure provides a return loss limited to 13 dB with phase error of ±4º for a 40% bandwidth. Unfortunately most of the previous cited DPSs are not fully satisfactory due to their intrinsic frequency bandwidth limitations, losses or maximum phase errors.Other unsatisfied DPS configurations can be found in [7]-[8].

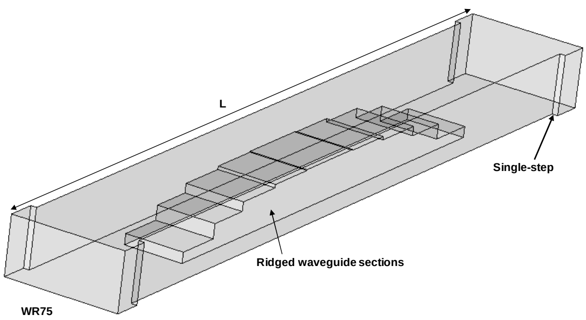

Fig. 1.Internal view of the differential phase shifter. The filled ridged waveguide is delayed by 90º or 180º with respect to an empty waveguide of the same length L.

In this work a very simple and compact structure for DPSs, Fig.1 and Fig.2, suitable for millimetre wave applications is proposed. It consists of a hollow waveguide that is longitudinally filled by a continuously stepped ridge waveguide section and terminated by single H-plane widening steps towards the standard WR75 waveguides. The advantages of the architecture presented here are ultra-wideband operation for extremely low insertion losses and differential phase errors, ease manufacture and integration, simple scaling properties, and a high degree of stability against the inherent mechanical tolerances. In the present design neither dielectric slabs nor ferrite materials are used, that can be sensitive to the temperature changes although in the majority of designs in order to improve the frequency bandwidth they use dielectric slabs or ferrite materials. The novel DPS brought a very important improvement compared with the previous designs providing a broad useful bandwidth, low cost, compactness, easier manufacture, and improved electromagnetic features.And that no severe problems may arise to meet the power specifications as no dielectric or ferrite materials are necessary.

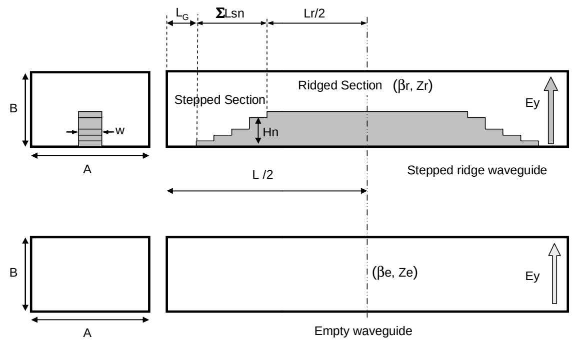

Fig.2.Geometry of the proposed stepped ridge DPS.

II. DPS DESIGN AND SIMULATION

A schematic view of the complete DPS is shown in Fig.2. The idea of using ridge waveguides to guarantee broader monomode bandwidth is not new. In these structures the cutoff frequency of the fundamental mode is reduced, while the available bandwidth up to the second propagating mode is proportionally increased [9]-[10]. Furthermore, unlike the above mentioned designs where the differential phase shift curve exhibits a limited quadratic shape, the proposed stepped ridged DPS has a rather cubic shape, thus allowing wideband operation with very low phase errors. This is because the ridged steps, not more than four in most of cases, behave at the same time as impedance transformers (for matching purposes) and semi-lumped phase

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shifters (for differential phase purposes).It is evident that ridged waveguides provide a bandwidth considerably greater than those designed with irises or with stubs. This because, while the transversal irises or stubs do not change the cutoff frequency of the fundamental mode or the higher-order modes at all, the use of ridges reduces the cutoff frequency of the fundamental mode and increase proportionally the cutoff frequency of the higher-order modes.

In order to meet the design specifications, we have proceeded as follows. An initial design method based on monomode equivalent circuit for the discontinuities and waveguide sections has been used. According this model, each step discontinuity can be modeled by a shunt susceptance whose value is determined from the generalized scattering matrix associated to this discontinuity by using the modal scattering analysis developed in [11], and by extracting the values corresponding to the fundamental mode from the generalized scattering matrix. The mathematic arrangement for a rigorous treatment of such phase shift structures should take into account the higher order mode coupling effects at all the discontinuities instead of a classical monomode equivalent circuit representation of each sub-structure. This second solution could be viewed as a good starting point for the subsequent optimization step.

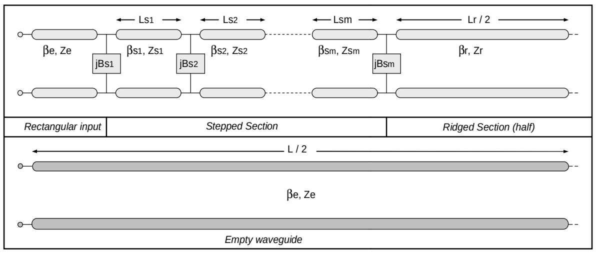

Fig.3. Monomode electrical equivalent circuit for one half DPS.

Furthermore, rectangular and ridged waveguide sections can be modeled in the monomode approach by a simple dispersive transmission line where the characteristic admittances and propagation constants can be calculated from [12]. Fig.3 shows this representation for one half of the complete DSP, where the different step susceptances, B_{si}, propagation constants, β_{si} and β_r, and waveguide impedances, Z_{si} and Z_r, are the geometry-related design parameters with respect to an empty waveguide of the same length L defined by β_e and Z_e.

From the half-circuit ABCD matrix (1), we easily determine the overall input impedance and the voltage transfer ratio for which the amplitude must be equal to one and the phase must be delayed by a constant value with respect to the reference waveguide. Using conventional mathematic tools shunt susceptances as well as characteristic impedances and propagation constants are adjusted in a classical electrical circuit format. Then the obtained values are translated back to physical dimensions by using the monomode generalized scattering matrix method.

$$\begin{bmatrix} Ah & Bh \\ Ch & Dh \end{bmatrix} = \begin{bmatrix} \cos\theta e & j\,Ze.\sin\theta e \\ j\,Ye.\sin\theta e & \cos\theta e \end{bmatrix} \begin{bmatrix} 1 & 0 \\ jBs1 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta s1 & j\,Zs1.\sin\theta s1 \\ j\,Ys1.\sin\theta s1 & \cos\theta s1 \end{bmatrix} \cdot$$

$$\cdot \begin{bmatrix} 1 & 0 \\ jBs2 & 1 \end{bmatrix} \cdots\cdots \begin{bmatrix} 1 & 0 \\ jBsm & 1 \end{bmatrix} \begin{bmatrix} \cos(\theta r/2) & j\,Zr.\sin(\theta r/2) \\ j\,Yr.\sin(\theta r/2) & \cos(\theta r/2) \end{bmatrix} \quad (1)$$

Finally, these values are used as initial guess for a mode matching simulator μWave-Wizard [11]. Minor optimization of the geometric dimensions is sufficient to meet the required specifications. According to the Fig.2, the geometrical dimensions of the 90º and 180º DPSs are depicted in Table 1.

Table 1: Differential phase shifter dimensions

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Parameter	90º DPS (mm)	180º DPS (mm)
a	17.1	17.11
b	9.5	9.5
L_G	19.17	15.37
w	9.71	10.36
H_{s1}	1.73	2.04
H_{s2}	4.05	5.61
H_{s3}	5.53	7.83
H_{s4}	6.05	8.24
H_{s5}	6.17	8.54
L_{s1}	7.93	6.48
L_{s2}	7.3	5.38
L_{s3}	8.54	7.58
L_{s4}	8.53	7.9
Lr/2	6.22	10.68
L/2	57.69	53.39

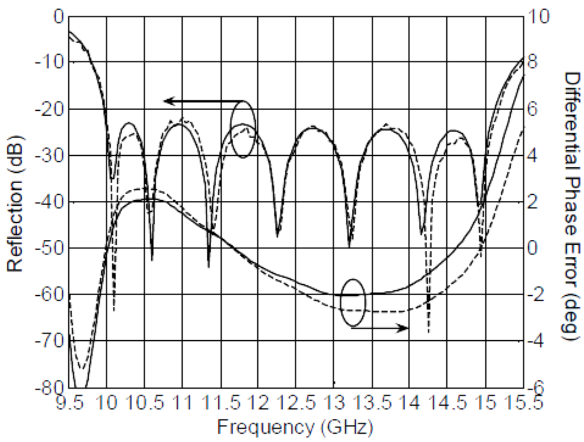
III. EXPERIMENTAL RESULTS

In order to validate the previous concepts, two prototypes for the Ku-band corresponding to Table I have been fabricated, on Aluminum 6061 as the body material for its availability, excellent mechanical properties and ease of surface treatment (σ = 3.5 .10^7 S/m: data supplied by the manufacturer), by using standard milling techniques. After conventional waveguide TRL (Thru-Reflect-Line) calibration, both DSPs were tested with respect to a WR75 empty waveguide section of the same length L. Fig.4 and Fig.5 show the measured reflection and transmission coefficients as well as the differential phase shift error for both cases together with their respective simulation generated by the mode matching tool [13]. Return losses better than 24 dB can be observed over the full Ku-band (40% bandwidth), whereas the insertion losses are less than 0.06 dB. The measured cubic-shape differential phase shift remains in the range of 90º±2.5º and 180º±3.5º for the two DPSs. These performances are key specifications for array antennas or feed systems and, define the today's state-of-the-art for non dielectric loaded DSPs.

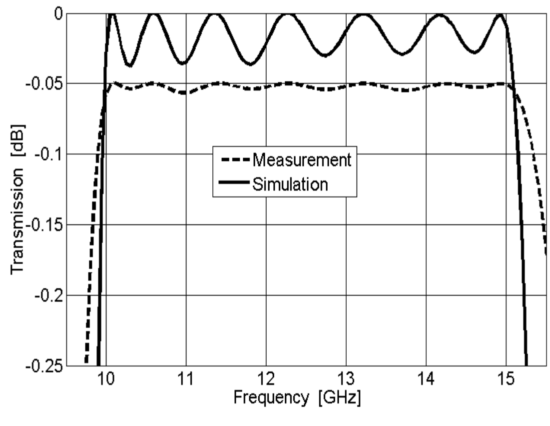
Finally a yield analysis was performed on the previous designs regarding the physical parameters of the circuits. It can be pointed out that the return losses and the differential phase shift were highly robust against the geometry variations. The return losses and the difference phase shift with reference to all dimensions were measured. The fig.6 shows the return losses variation due to the tolerance of all device dimensions in the case of 90º DPS.

In the worst case scenario with a dimension tolerance of 0.05 mm the return losses are better than 21 dB while the differential phase shift error is ±3º and ±4º for the 90º and 180º DSP respectively.

Photographs of the assembled prototypes phase shifters are shown in Fig. 7.



(a)



(b)

Fig.4. a) Measured (dashed) and simulated (solid) reflection coefficient and differential phase error of the 90º-DPS. b) Measured (dashed) and simulated (solid) transmission coefficient of the 90º-DPS.

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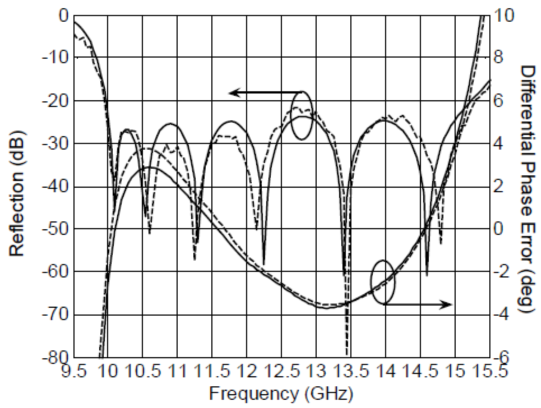
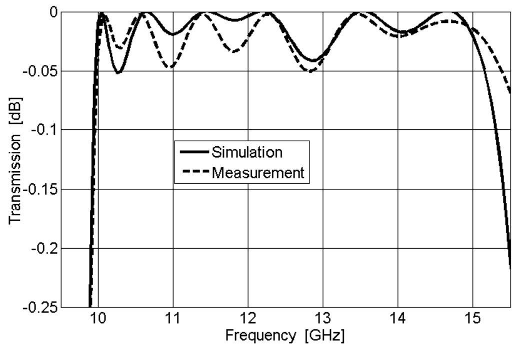


(a)



(b)

Fig.5. a) Measured (dashed) and simulated (solid) reflection coefficient and differential phase error of the 180º-DPS. b) Measured (dashed) and simulated (solid) transmission coefficient of the 180º-DPS.

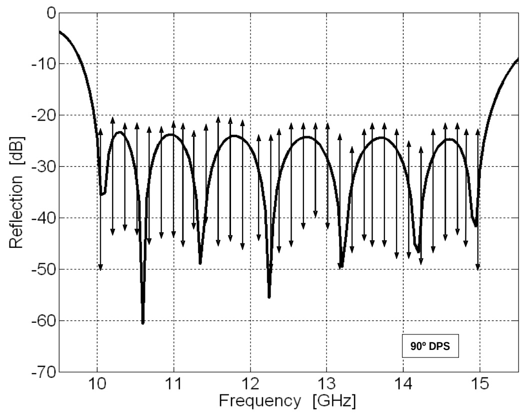


Fig.6. Return loss yield analysis with ± 0.05mm tolerance in the case of 90º DPS.

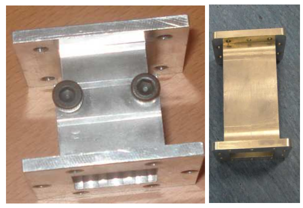


Fig.7. View of the assembled prototypes of both types of the differential phase shifter

IV. CONCLUSIONS

Two 90º and 180º stepped ridged waveguide differential phase shifters have been designed with the method of modal analysis by using simple electrical equivalent circuits that only consider the fundamental propagating mode. They were designed, constructed and tested with dimensional constraints for easy and low-cost production. The prototypes were fabricated using conventional milling techniques. Ultra wideband operation >40% for extremely low losses and differential phase errors, ease manufacture and integration, simple scaling properties, and a high degree of stability against the inherent mechanical tolerances has been obtained. These differential phase shifters define the today's state-of-the-art for non-dielectric loaded waveguide circuits.

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