Design and Validation of Quasi Ideal Ultra-Wideband 3dB/180° Couplers for High Precision Spherical Near-Field Probes

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***Abstract*—Spherical Near Field (SNF) measurement systems are primarily limited in usable bandwidth by the probe frequency coverage. This limitation mainly arises from the presence of higher-order azimuthal modes in the probe pattern [1]. In case of electrically large or offset AUTs, such a limitation may be overcome by a full probe correction algorithm for the NF/FF transformation [2]. However, probes approximating first order performance over the full bandwidth are generally preferred. Traditionally, first-order probes based on geometrically symmetric Ortho-Mode Junctions (OMJ) with externally balanced feeding have been widely accepted. These probe designs rely on couplers that provide equal amplitude and opposite phase distribution at their output ports [3]. In this paper, the design and validation of a novel 3dB/180° coupler is presented. The concept is based on the natural anti-symmetric properties of the electric field within the component, providing a quasi-perfect amplitude and opposite phase distribution. To achieve these properties, an architecture based on slot coupling is selected. The design has been implemented in several frequency bands, from UHF to Ku-band, as stand-alone cased components. Experimental data at L/S-band is presented in this paper, showing excellent performance in terms of matching, balance, and isolation between output ports, well in-line with full-wave electromagnetic predictions. In addition, the impact of the coupler accuracy is also assessed on a relevant SNF test case [1].**

I. INTRODUCTION

Hybrid couplers providing at their output ports equal amplitude and opposite phase distribution (i.e. 3dB/180° couplers) are a recurrent need in many antenna applications, where precision feeding is required. For dual polarized probes used in SNF measurement systems, this type of couplers is a crucial component. Effectively, to obtain high quality radiation patterns with excellent symmetry, low cross-polarization, and reduced content of higher-order azimuthal modes in the radiated pattern, these probes need an external balanced feeding circuit. This allows to avoid the excitation of high order modes in the ortho-mode junction (OMJ), susceptible to appear when wideband operation is required. It is known that overmoding in the OMJ generally deteriorates the probe pattern characteristics and increases the radiated higher-order azimuthal modes. Precision mechanical manufacturing can ensure excellent accuracy in the radiating parts of these probes, therefore annihilating the excitation of high order modes from this section. The achievable quality of the radiation pattern is therefore directly correlated to the quality of the components generating the balanced feeding. Amplitude and phase errors in these components induce excitation of high order modes and consequently radiation pattern degradation.

Most of the commercially available couplers are based on coupling techniques which do not provide inherent anti-symmetric distribution over frequency. The concept proposed in this paper is based on the natural anti-symmetric properties of the electric field within the component, obtained thanks to the anti-symmetric geometrical structure of the selected coupling technique, which provides a quasi-ideal amplitude and opposite phase distribution over frequency. For this purpose, a coupling technique based on slot coupling is selected.

This paper is organized as follows: Section II describes the general architecture of the coupler, Section III the detailed design, Section IV the manufacturing and validation, Section V the advantages deriving by the use of this coupler technology in a SNF measurement test case.

II. GENERAL CONCEPT AND ARCHITECTURE

The proposed couplers are conceived in the microwave frequency range, typically from UHF to Ku-band. The core of the coupler is a double dielectric layer printed circuit board (Figure 1.).

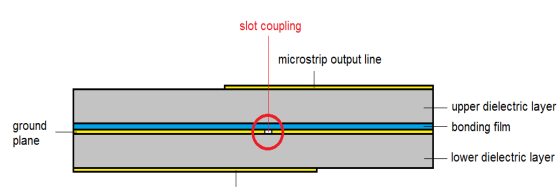

Figure 1. Description of the slot coupling mechanism between two microstrip lines.

The printed circuit technology provides a simple and compact solution, well suited for slot coupling techniques. A coupler printed circuit contains three copper layers. The central layer is a ground plane, in which the slots are etched away. The lower copper layer contains the input microstrip lines while the upper copper layer contains the output microstrip lines. The electric field carried by the input microstrip lines is transferred through the slots to the output microstrip lines. A phase inversion of 180° is obtained by reversing the direction of one output line compared to the other output line (Figure 2.), while the equal amplitude distribution is preserved.

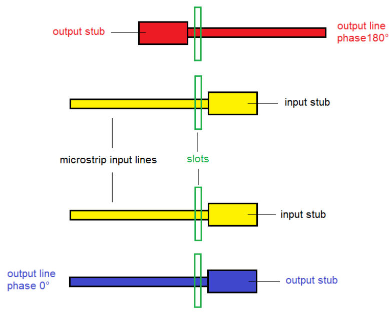

Figure 2. Description of the 180°phase reversal mechanism obtained thanks to slot coupling between microstrip lines.

Based on the described slot coupling technique, two possible architectures for the 3dB/180° coupler have been defined, both having one input port and two output ports delivering the same amplitude and opposite phase.

In the first architecture, the input line is divided into two branches through a power divider (Figure 3.). On each branch, a slot coupler is inserted to transfer the input signal to a corresponding output line. The phase reversal is applied to one of these lines to obtain the 180° phase shift between outputs. This architecture allows independent stubs on each input and output branch, which facilitates the matching of the slot couplers. Moreover, a relevant advantage of this architecture resides in the possibility to use a multiple section Wilkinson divider allowing to obtain a good isolation (better than 20 dB) between the two outputs of the divider. This parameter is important to immunize the amplitude and phase distribution of the coupler against the residual mismatch and matching asymmetries of the probe OMJ ports.

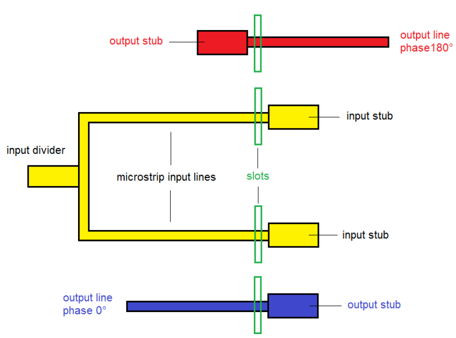

Figure 3. Schematic of the architecture of a coupler based on two separated slot couplings.

A second possible architecture has been defined for this type of coupler (Figure 4.). A unique slot coupler is inserted between the input line and a unique output line terminated by the two output ports. This solution has the advantage of being very compact. However, it provides less freedom to optimize the slot coupler. Moreover, the isolation between output ports is limited by the architecture.

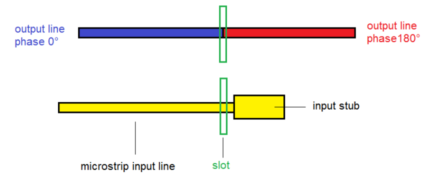

Figure 4. Schematic of the architecture of a coupler based on a common slot coupling.

Consequently, it has been decided to proceed with the first architecture for the coupler. It must be pointed out that the key component of these couplers is the ultra-wideband slot couplers that, thanks to their specific design, are able to provide a good matching (better than 20 dB) over frequency ratio of 1 to 4, when coupling through conventional slots is narrower band.

III. Coupler Detailed Design

The architecture retained for detailed design of the coupler (Figure 3.) contains essentially three ultra-wideband components: two slot couplers and a power divider. Each of these elements is first optimized individually using electromagnetic simulations to achieve superior RF performance, particularly for matching. These components are then connected with well matched lines to minimize the overall mismatch of the entire coupler. Fine tuning of the entire coupler as an assembly is then performed also using electromagnetic simulations.

A. Slot coupler design and performance

A slot coupler consists of an input and an output 50 Ohms microstrip line sharing the same ground plane. A slot etched away in this ground plane ensures the coupling between the input and the output line. By appropriately selecting the dielectric substrate, the layout of the slot and the matching stubs, a well matched slot coupler with low transmission loss can be obtained (Figure 5.).

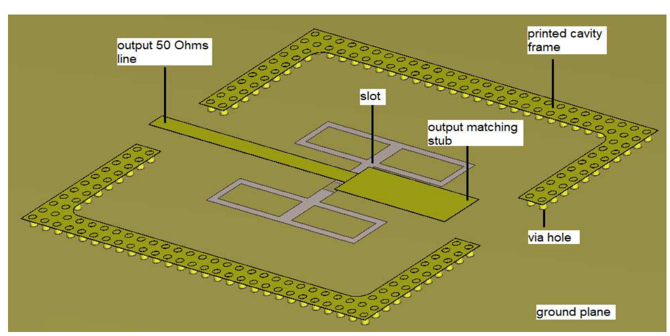

Figure 5. Metallic printed structure of a slot coupler.

To avoid spurious radiation, the slot coupler is enclosed in a metallic cavity (Figure 6.). Each half of this cavity is positioned against the corresponding printed cavity frame (Figure 5.). The continuity of the shielding provided by the cavity through the dielectric substrates is realized with metallic via holes connecting the lower and upper printed cavity frames. The metallic cavity is made sufficiently small to avoid the excitation of resonances over the frequency band of operation.

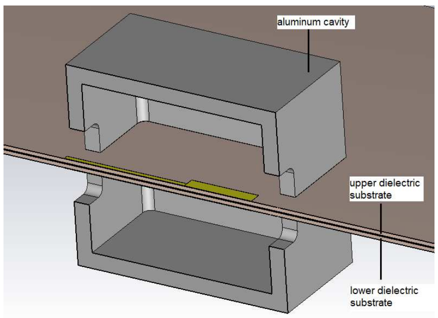

Figure 6. Side cut view of the slot coupler enclosed in its metallic cavity.

Due to the small dimensions of the cavity, it is difficult to obtain satisfactory matching performance with a conventional slot (Figure 7. -a), especially on a wide frequency band. The performance is improved by using an H-shaped slot (Figure 7. -b), that leads to a more compact structure with more tuning parameters. This type of slot structure helps concentrating the electric field between the input and output lines, improving the coupling between these lines. This type of slot structure is also less affected by the short-circuiting effect of the cavity that tends to reduce the bandwidth. The H-shaped slot can be made furthermore compact by enlarging its branches parallel to the lines (Figure 7. -c). This modification is also beneficial to the bandwidth. Finally, this last modification also offers the opportunity of adding printed elements inside these branches, (Figure 7. -d). These printed elements allow controlling a second coupling mode that permits to further improve matching and operational bandwidth, achieving a two-octave frequency coverage (1:4).

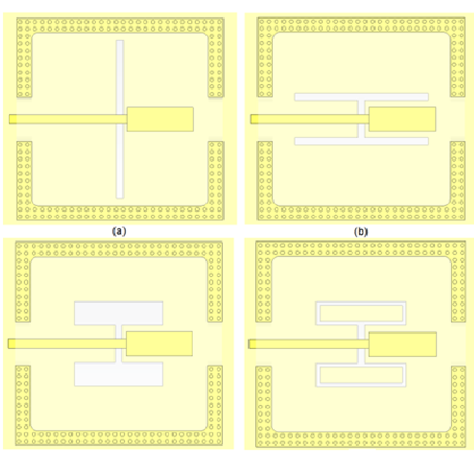

Figure 7. Evolution of the slot layout to improve performance (matching and bandwidth).

Using the different parameters previously described and following the architecture previously introduced (Figure 5.), a slot coupler implemented on RO4350B dielectric substrates has been optimized over the 1.4-4.2 GHz frequency band. Over this bandwidth, the slot coupler has a good matching over its input (S11) and output (S22) ports (Figure 8.). Matching remains quite acceptable even on an extended bandwidth. The maximum transmission loss over 1.4-4.2 GHz does not exceed 0.23 dB. This type of slot coupler is also quite compact in dimensions, since the inner section of the cavity is in the order of 0.11 wavelength at 1.4 GHz.

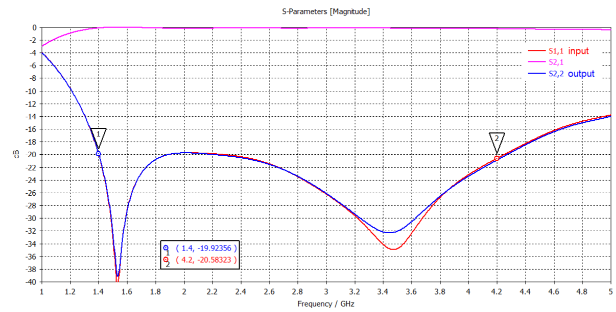

Figure 8. S-parameters of the slot coupler enclosed in its metallic cavity.

For this 1.4-4.2 GHz frequency band application, the rectangular printed elements inside the side branches of the slot have been cut in two parts (Figure 5.), to avoid the use of a second coupling mode. The slot is then equivalent to the H-shaped slot with enlarged branches (Figure 7. -c). When connecting the two halves of each printed elements to form two solid printed rectangular elements (Figure 7. -d), the second coupling mode is activated and the reflection coefficient above 3.8 GHz is strongly improved (Figure 9. –red curve). This type of slot structure can then be further tuned, and a matching better than -20 dB can be achieved over at least a 1 to 4 frequency ratio (Figure 9. –green curve).

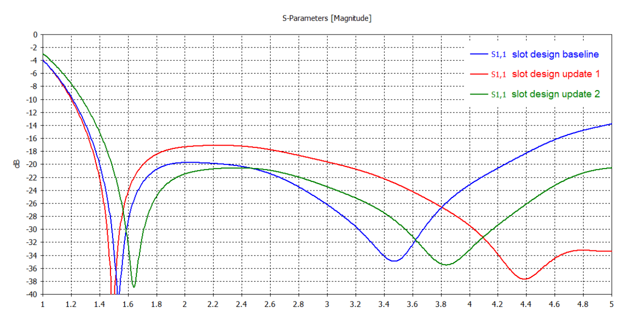

Figure 9. Matching optimization of the slot coupler versus the layout of the slot.

B. *Wilkinson power divider design and performance*

As previously explained, the architecture of the coupler has been selected such as to allow the use of a Wilkinson divider at its input, to provide good isolation between the output ports of the entire coupler (Figure 3.). A Wilkinson divider can be made ultra-wideband using a multiple section architecture. Each section is approximately a quarter of effective wavelength long. After several design iterations and trade-offs, a three sections Wilkinson divider has been considered sufficient for the required bandwidth, achieving a relatively compact structure (Figure 10.).

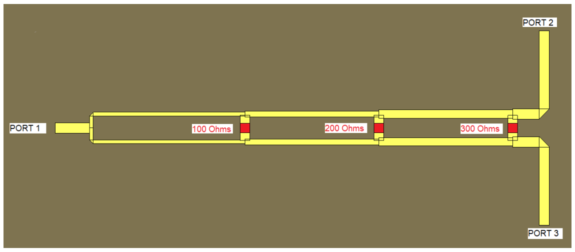

Figure 10. Layout of the three sections Wilkinson divider.

The Wilkinson divider is etched on the lower face of the same microstrip circuit as the one containing the slot couplers. The adjustment of the width and length of each section allows obtaining satisfactory performance over the 1.4-4.2 GHz frequency band (Figure 11.). The matching and the isolation remain better than -20 dB, while the transmission loss do not exceed 0.3 dB in the upper part of the frequency band.

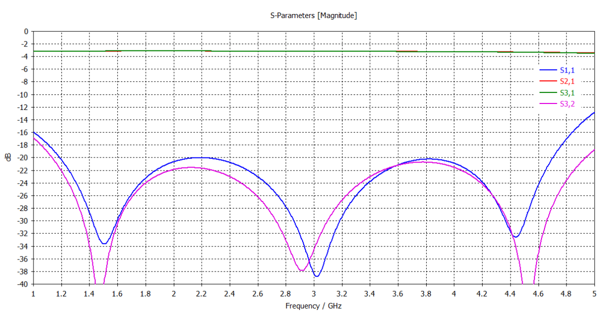

Figure 11. S-parameters of the three sections printed Wilkinson divider.

C. Complete coupler design and performance

The entire coupler is then conceived using the key elements previously described connected with optimized printed lines. The input port 1 is connected to a printed input 50 Ohms line etched on the lower face of the multi-layer printed circuit (Figure 12.). The output ports 2 and 3 are connected to output 50 Ohms line etched on the upper face of the multi-layer printed circuit (Figure 13.).

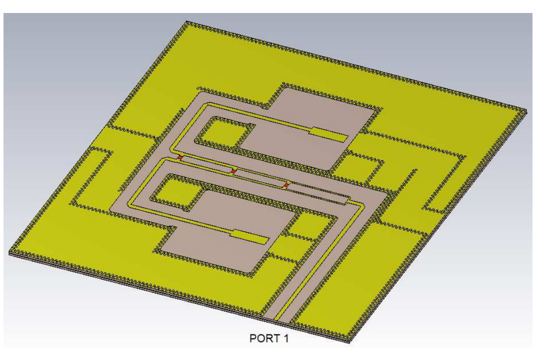

Figure 12. View of the lower face of the printed circuit of the complete coupler.

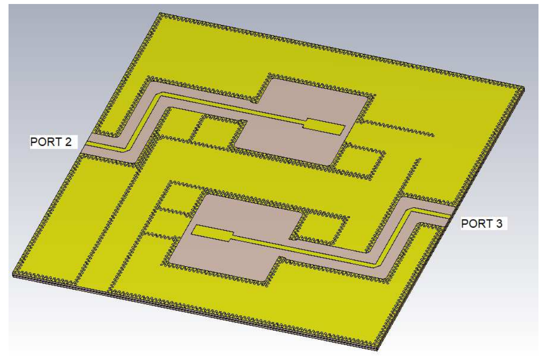

Figure 13. View of the upper face of the printed circuit of the complete coupler.

The lower and upper faces of the printed circuit are covered for a large part by printed metallic areas forming a lower and an upper ground plane, connected to the central ground plane containing the slots through metallized via holes. These via holes act as a shield preventing the propagation of spurious electric fields inside the printed circuit. The lower and upper ground planes also facilitate the entire shielding of the circuit by simply enclosing it between an upper and lower aluminum shell to control the electric field radiated by the feed lines (Figure 14.).

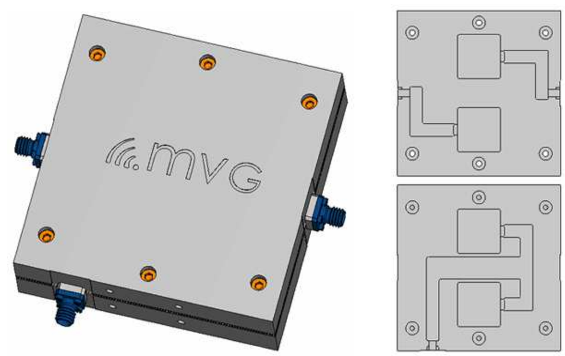

Figure 14. CAD view of the cased 3dB/180° coupler (left), view of the inner layout of the aluminum shells (right).

The designed coupler provides a very satisfactory matching over the 1.4-4.2 GHz frequency band (S11, Figure 15.) and the interest of using a Wilkinson divider in order to obtain a good isolation between output ports is clearly demonstrated (S32, Figure 15.).

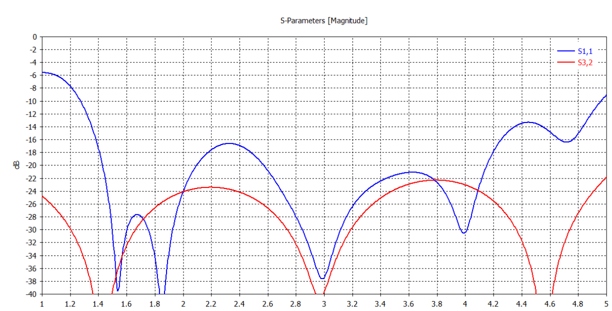

Figure 15. Matching and output ports isolation of the coupler.

The major characteristic of the proposed design resides in the quality of the amplitude and phase distribution that it generates at the output ports. The difference of amplitude between the output ports is negligible over the entire frequency band of use 1.4-4.2 GHz and do not exceed 0.02 dB over the upper part of the band (Figure 16.). The transmission losses for the complete coupler structure remain around 0.8 dB over the most critical part of the frequency band (4.2 GHz). The difference of phase between the output ports is almost exactly 180° over the entire bandwidth 1.4-4.2 GHz, the maximum phase error is in the order of 0.5° (Figure 17.).

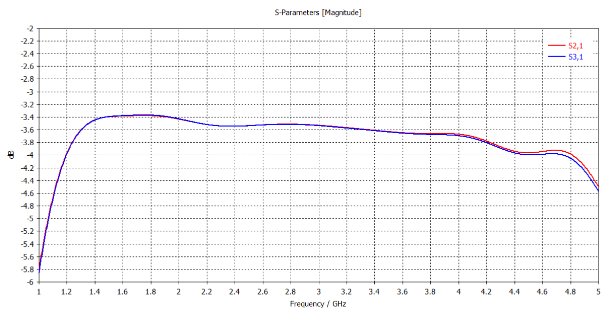

Figure 16. Amplitude distribution over the output ports of the coupler (0.02 dB max deviation in nominal band).

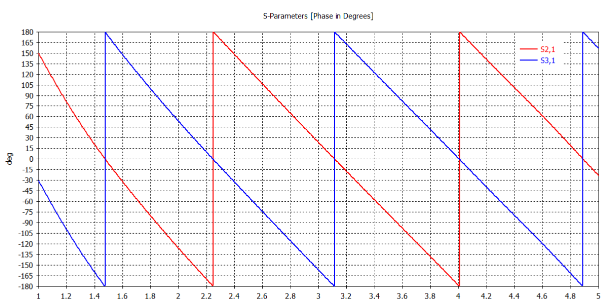

Figure 17. Phase distribution over the output ports of the coupler (0.5° max deviation in nominal band).

IV. COUPLER MANUFACTURING AND VALIDATION

The coupler, referenced as FN140, has been manufactured in several units to cover the nominal 1.4-4.2 GHz frequency band and to be integrated into a SNF measurement probe. The resulting component is a cased three ports device with connectorized RF interfaces (Figure 18.).

Figure 18. Manufactured coupler covering 1.4-4.2 GHz nominal band.

The printed circuit is manufactured in RO4350B [4] as a double layer circuit bonded with an intermediate adhesive film, having dielectric constant matched to the bulk material. Silver plating is used for the surface finish to improve the conductivity and ensure galvanic compatibility with the metallic parts (Figure 19.). The clamshells are manufactured from Aluminum by precision milling. The resulting assembly is quite compact (90x90x25 mm), which makes it suitable for an integration with measurement probes.

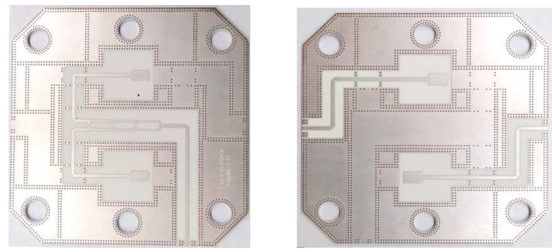

Figure 19. Printed circuit board: lower face (left) and top face (right).

Within the batch of four manufactured units, two serial numbers have been selected. The conducted measurement of these two couplers is reported in the following. The input reflection coefficient shows excellent results with a reflection coefficient of -20 dB in average and a -25 dB isolation between output ports (Figure 20.). Good repeatability between the components is also experienced.

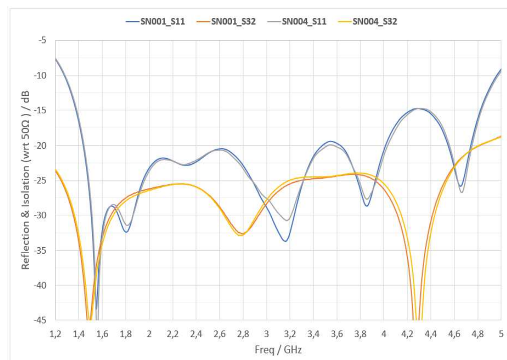

Figure 20. Input reflection coefficient and isolation between output ports (referenced to 50 Ω).

The amplitude and phase balance between output ports has also been computed as the complex ratio between the transmission parameters from the Input to the Output ports (Figure 21.). The phase unbalance should be intended as the deviation from the theoretical 180° phase offset.

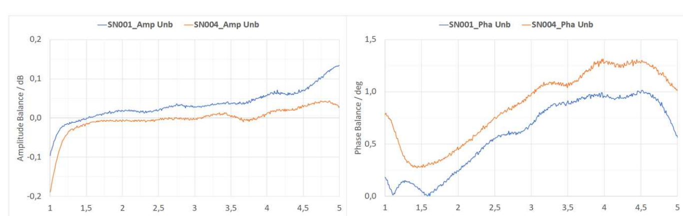

Figure 21. Unbalance between output ports: amplitude (left) and phase (right).

Additionally, to the amplitude and phase unbalance, the Equivalent Error associated to the couplers is calculated according to [1]. This parameter is an effective metric to quantify the defects induced by the un-idealities of an external 3dB/180° coupler when an OMJ with balanced feeding is used in the probe design. The achieved values of Equivalent Error show outstanding performance over frequency (Figure 22.).

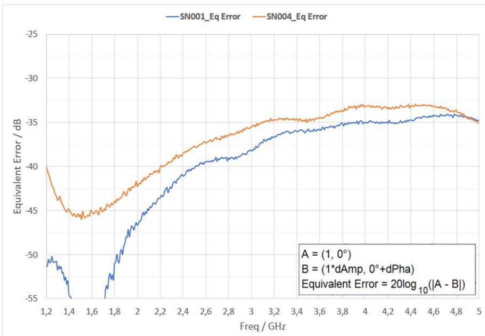

Figure 22. Equivalent error of the manufactured couplers.

As a last figure of merit, the insertion loss of the couplers has been measured. The performance is not presented in the paper, but the data show a value of 0.55 dB at the low end of the band, gently increasing with frequency and reaching a maximum of 1.2 dB loss at high end.

V. Coupler Implemented with Probe

After validation of the stand-alone components, the couplers have been integrated in a near field dual polarized probe (SP1400). To verify the effectiveness of the newly developed components and demonstrate the impact on measurement accuracy, a validation campaign has been conducted. A reference dual ridge horn antenna (SH400) has been measured in a SNF system, in extreme offset conditions and several pointing directions [1].

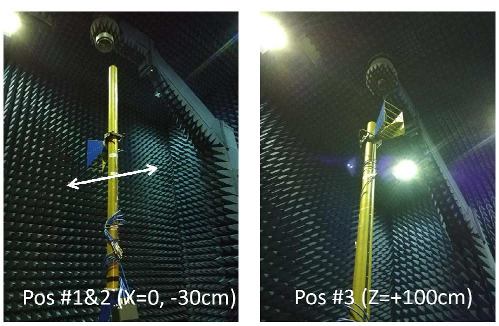

Figure 23. Test campaign in SNF with offset AUT (SH400).

Three different positions of the AUT have been considered: onset; vertically offset; offset in the direction of propagation (Figure 23.). It is well-known that different positions of the AUT in the range generate different probe effects, and hence different measured patterns, unless probe correction (PC) is properly applied. Indeed, the objective of this test has been to verify that the variation of the pattern, measured with the AUT in different positions, was sufficiently small. The peak directivity variation is chosen as indicator for the overall pattern variation and evaluated when different schemes of PC are applied (Figure 24.). As expected, the highest variations (uncertainty) are obtained when PC is not applied at all (up to ±0.3dB, blue trace). By applying the First Order PC (FOPC, orange trace) such variations significantly drop to less than ±0.1dB. The full PC is also applied considering the whole spherical spectrum of the probe obtained from the calibration (green trace). The obtained variation is basically the same as the one achieved with the FOPC, remarking the excellent first order behavior of the SP1400 equipped with the newly designed couplers.

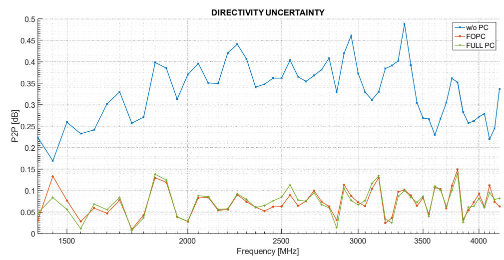

Figure 24. Max directivity variation of the SH400 measured in three different positions and different levels of PC.

VI. Conclusion

A novel 3dB/180° coupler with quasi-ideal amplitude and opposite phase distribution at its output ports is presented. The concept is based on the natural anti-symmetric properties of the electric field within the component and implemented in printed circuit technology with slot coupling. Such couplers have been manufactured in several frequency bands, ranging from UHF to Ku-band (i.e. 0.8–20 GHz), as stand-alone cased components. Experimental data at L/S-band (1.4-4.2 GHz) is here reported, showing excellent performance in terms of matching, balance, and isolation between output ports, well in-line with full-wave electromagnetic predictions. When used in ortho-mode junctions with balanced feeding schemes, this coupler has the advantage to provide a highly electrical symmetry of the feeding, minimizing the higher-order azimuthal modes contained in the probe pattern.

References

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