Application of 3D Printing Technology for Realization of High-Performance Directional Couplers in Suspended Stripline Technique

Jakub Sorocki, Ilona Piekarz, Slawomir Gruszczynski, Krzysztof Wincza and John Papapolymerou

***Abstract*—In this paper, a novel approach for the realization of high-performance coupled-line directional couplers in suspended stripline technique is proposed taking advantage of recent development in 3D printing technology. A third degree of freedom is introduced to a 2.5D structure allowing to combine the advantages of strip-transmission-line techniques, for which the circuit can still be considered as a quasi-planar structure, with the 3D printing flexibility of air layer thickness variation limited only by technological constraints. It is shown, that the proposed approach is well suitable for the realization of low-loss circuits, where tight coupling and superior performance are required, as well as compactness. Moreover, it is shown that compensating elements, often required to improve couplers` performance, can easily be realized as a combination of a circuit mosaic and ground plane integrated 3D structures allowing for better circuit volume utilization. An example of a 3-dB coupled-line directional coupler operating within the ISM 5.8 GHz band is designed, manufactured and measured for experimental verification. The obtained results confirm the applicability of the proposed approach.**

***Index Terms*— additive manufacturing, compensation technique, coupled-line directional coupler, suspended stripline technique, 3D printing.**

I. Introduction

COUPLED-LINE directional couplers are widely-used components in microwave engineering due to their broadband operation and relatively small required area. Design of such type of directional couplers has been a subject of extensive studies over the past years [1]-[4]. Generally, coupled-line directional couplers can be designed in either symmetric stripline or asymmetric microstrip structures. However, when superior electrical performance of the circuits is of importance, the stripline technique is more favorable due to the homogeneity of the dielectric structure for which conditions for ideal coupled-line section realization [5], i.e. equal capacitive and inductive coupling coefficients, are always fulfilled. On the other hand, a suspended structure is preferred when insertion loss is of importance due to the lossless air layer in the dielectric stack-up reducing the total dielectric loss. Nevertheless, the utilization of a suspended stripline technique deteriorates the resulting coupler` performance, since the structure is no longer homogenous. For such a case, the equalization of coupling coefficients can be realized using various methods proposed in literature [6]-[8], among which the quasi-lumped compensation technique [8] allows for effective performance improvement while being straightforward in implementation.

Realization of directional couplers in a suspended stripline technique requires to address two main issues: ensuring high electrical performance and keeping mechanical integrity. For most cases, a two-part enclosure having conductive surfaces is required to serve two purposes: electrical to provide proper ground plane, and mechanical as a structural support for the middle thin laminate with the circuit mosaic to be elevated at an appropriate height over the ground plane. Most commonly, such an enclosure is made from metal that requires high-precision milling that is a time consuming and expensive process while the resulting piece is relatively heavy-weight. However, recent developments of additive manufacturing technologies, including 3D printing [9]-[10], allows for an alternative realization of the enclosure with a conductive surface for the suspended coupler lowering the overall time and cost of production while resulting in a strong and lightweight component at the same time.

In this paper, a novel approach for the realization of high-performance directional couplers in suspended stripline technique is proposed taking advantage of recent developments in 3D printing technology. A third degree of freedom is introduced to a 2.5D structure allowing to combine advantages of strip-transmission-line technique, for which the circuit can still be considered as a quasi-planar structure, with 3D printing allowing for flexible variation of the air layer thickness. It is shown that the proposed approach is well suited for the realization of tightly-coupled directional couplers where high performance, low loss and small size are of primary importance. An example of a 3-dB coupled-line directional coupler operating within the ISM 5.8 GHz band was designed and manufactured for experimental verification. A combination of additive manufacturing techniques, i.e. high-resolution polyjet 3D printing, and magnetron sputtering were used to manufacture the enclosure with the conductive surface having the additional benefit of being lightweight and

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self-enclosed. It is shown, that compensating elements, which were required to improve the couplers` performance can easily be realized as a hybrid of a circuit mosaic and ground plane integrated 3D structures allowing for better circuit volume utilization. The obtained measurement results confirm the applicability of the proposed approach.

II. Directional Couplers with Introduced Third Dimension of Structure Control

Coupled-line directional couplers realized in the suspended stripline technique feature lower insertion losses, due to the lossless air layers in the dielectric stack-up placed in-between a thin laminate hosting the circuit mosaic. However, such a dielectric configuration is a non-homogenous medium that leads to a coupled-line section having unequal capacitive k_C and inductive k_L coupling coefficients, thus, deteriorating a circuit`s isolation and impedance match [5]. To obtain high-performance, coupling coefficients need to be equalized ($k_C = k_L = k$) by e.g., adding compensation quasi-lumped capacitances and inductances distributed along the coupler's length [8]. On the other hand, assuming fixed laminate parameters, the thickness of the air layers restricts the coupler's maximal available coupling coefficient as well as determines the width of the connecting transmission lines. The thicker the air layers the tighter the coupling between metal strips (being related to a ratio of mutual and self-capacitance of the coupled-line section) can be obtained. However, in such a case wider connecting lines are required to maintain a given impedance that may lead in an extreme case to a transmission line being non-realizable or too wide with respect to the wavelength. Moreover, when a thick air layer is used, physical realization of some compensating elements can be impossible or would require a surface area much greater than the coupled-line section itself. Therefore, the thickness of the air layers is chosen as a trade-off between the thickness required to obtain the desired coupling coefficient of the coupled lines and the thickness allowing for the realization of transmission lines and/or compensating elements. As a result, the realization of tightly coupled directional couplers in the suspended stripline technique is highly limited, when the same air layer thickness needs to be used for the realization of both the coupled-line section and connecting transmission lines.

Given the above stated limitations, we propose a novel approach to the design of coupled-line directional couplers in suspended stripline technique. A true third dimension of structure control is introduced by means of variable air layer thickness enabled by the development of 3D printing technology. The following design procedure for the directional coupler is proposed:

1. First, the required air layers thickness h_1 is established allowing to realize the required coupling k of the resulting coupled-line coupler with a small coupling margin (further compensation will lower the coupling coefficient slightly) considering the properties of the laminate that is going to be used to host the circuit mosaic, i.e. its permittivity ε_{rlam} and thickness h_{lam}.
2. Second, initial widths w of the coupled strips as well as offset o between them for the established in the first step dielectric stack-up and a given terminating impedance (typically 50 Ω) need to be found.
3. Next, the compensating elements required to equalize k_C and k_L (self and mutual capacitances as well as inductances) are calculated using [8] for a given number of subsections. The width w_1 of the thick air-layer cavity over which the coupled strips are suspended, as well as the air layer thickness h_2^{air} outside the cavity over which lumped compensating capacitors to ground are suspended are established based on EM calculations in an iterative procedure. The goal is to obtain the possible smallest elements to realize (lumped capacitors) on metal layers $m1$ and $m2$ without interfering with the coupled-strips self and mutual capacitance itself by too closely placed ground planes.
4. Subsequently, the width of the input transmission lines having a specified impedance (for most cases 50 Ω) is calculated assuming the dielectric structure from the first step. If the transmission lines are too wide, the thickness of the air layer h_3^{air} in the lines` region is set in such a way that the resulting line does not exceed a given limit.
5. Finally, transitions between coupled-line sections and connecting signal lines are designed. For the majority of cases, lumped capacitances [3]-[4] are required to compensate the discontinuity introduced by the transitions. The air layer thickness in the transition area can be varied from h_1^{air} to h_4^{air} to partially or fully eliminate the necessity of capacitor realization by means of increased metallization area within the circuit mosaic on the laminate.

The above described approach allows for significant simplification of the directional coupler design in the suspended stripline technique. Most importantly, limitations which lead to compromises between maximal coupling within the coupled section and general structure realizability for a given frequency range no longer hold. Moreover, the proposed hybrid of mosaic on the center laminate`s metal layers and ground plane integrated 3D structures, by means of air layer variable thickness, allows for partial or full realization of compensating elements. This is especially important at higher frequencies, where coupled line section becomes not long enough to accommodate any larger compensating elements limiting the compensation technique's frequency range of applicability.

III. Design of a High-Performance 3dB Directional Coupler

To experimentally verify the benefits of the proposed approach, a 3dB coupled-line directional coupler was designed in a suspended stripline technique to operate at the center frequency of 5.8 GHz. A 7 mil Rogers LCP laminate having ε_{rlam} = 3.14 was used as a center suspended dielectric with metal layers $m1$ and $m2$ on both sides. A cross-sectional view of the proposed dielectric structure is shown in Fig. 1. The height of each of the air layers is a multiple of the 3D printer's printing resolution (in this study 30 μm) to ensure dimensional accuracy of the printed parts. The height of the air layer in the coupled-line section region was set to be h_1 = 1.2 mm as it allows to realize maximal coupling of k_{max} = 0.84 (Z_0 = 50 Ω, k_{max} = 0.5(k_{Lmax} + k_{Cmax})). The initial width and offset of the coupled-line section strips were found for broadside coupled section using *Linpar* software [11], to be w = 0.7 mm and o = 0.14 mm (modal impedances Z_{0e} = 210.6 Ω and Z_{0o} = 22.3 Ω, terminating impedance Z_T = 68.6 Ω (Z_T > $(k_C/k_L)Z_0^2$), coupling coefficients k_L = 0.73, k_C = 0.87).

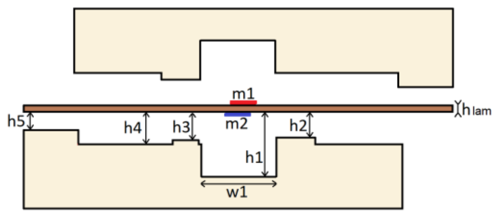


Fig. 1. Cross-sectional view of dielectric structure utilized for the design of a 3-dB coupled-line directional coupler. Different air layer thicknesses are used to obtain a more compact circuit and realize compensating elements as well as fixed stripline coupled-line width and microstrip connecting transmission lines. Dimensions: h_1 = 1.2 mm, w_1 = 2.38 mm, h_2 = 0.51 mm, h_3 = 0.3 mm, h_4 = 0.51 mm, h_5 = 0.3 mm, h_{lam} = 0.18 mm.

In the selected dielectric stack-up where a thin laminate is suspended over a thick air layer k_C > k_L and to equalize the coupling coefficients k_C needs be lowered [8] resulting in k = k_L. This can be done by adding quasi-lumped capacitances i.e., self C_1, C_2 and mutual C_m as shown in Fig. 2. Values of compensating elements were calculated according to [8] assuming that the coupled-line section is divided into n = 4 subsections. For the designed coupler, the additional compensating lumped capacitances are equal C_1 = C_2 = 0.06 pF and C_m = 0.03 pF. Realization of the mutual capacitance is straightforward requiring to locally increase the overlap between the strips. However, the value of self-capacitances is relatively large and their realization on air layer thickness of h_1 would require a metal surface area drastically exceeding the size of the coupled strips. To counteract that, a thinner air layer having h_2 = 0.51 mm was used outside the cavity over which the coupled strips are suspended (see Fig. 1). The width of the cavity has been found to be w_1 = 2.38 mm based on EM calculations in an iterative procedure aimed at size minimization of the capacitors surface while keeping the coupled strips unaffected by the closely placed vertical and horizontal ground planes (see Fig. 3). Finally, transitions between the coupled-line section and the connecting stripline transmission lines were designed. The thickness of the air layer in the signal lines\` region was set to be h_4 = 0.51 mm resulting in a 50 Ω transmission line having a width of w_{TLsl} = 1.46 mm (being a trade-off between minimal insertion loss and a maximal usable trace width compared to the wavelength). Moreover, to improve return losses, a lumped capacitance needed to be added in the transition region. To obtain a more compact layout, the capacitances were realized by means of a locally decreased air layer height to h_3 = 0.3 mm instead of additional metallization pads. As a result, in the coupled-line section\`s region a cavity is created where ground planes are more distant from the metal strips to allow for reducing the capacitance to ground and the realization of the required strong coupling. On the other hand, the remaining elements are realized on various thinner air layers, reducing the size of the compensating capacitances for the coupled-line section and transition region as well as signal line widths.

The above described directional coupler was designed and electromagnetically (EM) analyzed using *NI AWR Design Enviroment* software with AXIEM 2.5D solver. Calculated S-parameters for the final layout shown in Fig. 3 are provided in Fig. 4. The calculated coupling equals C = 3 ± 0.14 dB, the phase difference equals 90º while return losses and isolation are better than 45 dB within the band of operation. As seen, the proposed design approach allows for the realization of a high-performance circuit while having the benefit of a more efficient volume utilization of the component and extended frequency range of the compensation technique applicability while keeping the advantage of low insertion losses.

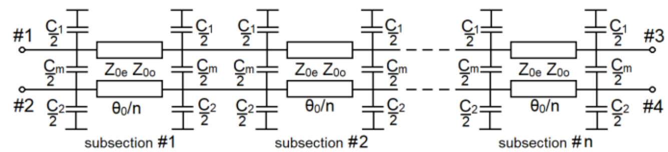


Fig. 2. Schematic diagram of the compensated coupler for case of k_C > k_L, where self-capacitances C_1, C_2 and mutual capacitances C_m have been utilized to equalize the coupling coefficients as shown in [8].

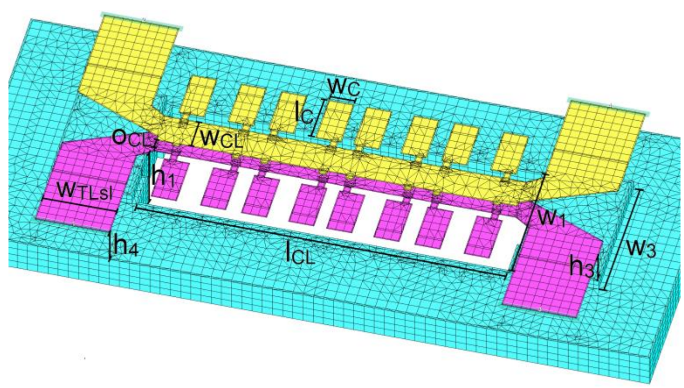


Fig. 3. Plane view on the EM model of the designed directional coupler with top ground removed. The cavity with thicker air layer can be seen in the coupled-line section area allowing to obtain tight coupling while thinner air layers outside the cavity allow to reduce the surface area of the compensating elements and connecting transmission lines. Moreover, four identical subsections can be seen, as for the application of the compensation technique. Dimensions: w_{CL} = 0.66 mm, o_{CL} = 0.12 mm, l_{CL} = 7.04 mm, w_1 = 2.38 mm, w_C = 0.5, l_C = 1.02 mm (distanced by 0.14 mm from the CL), w_3 = 2.7 mm, w_{TLsl} = 1.46 mm. The total area occupied by the directional coupler equals 10.56 mm x 3.1 mm including transitions to strip transmission line.

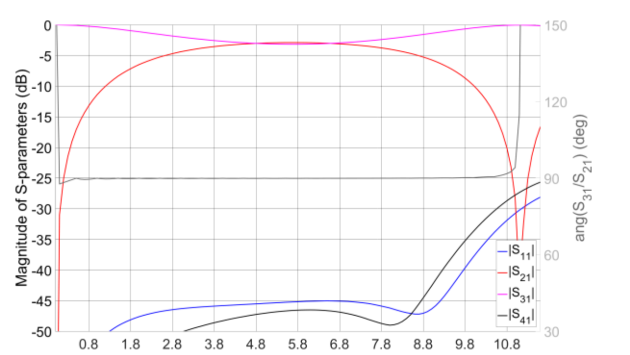


Fig. 4. EM calculated S-parameters of the designed 3-dB directional coupler with suspended stripline output transmission lines.

IV. Manufacturing of The Directional Coupler and Experimental Results

Before manufacturing the directional coupler, additional circuitry was designed to allow for convenient circuit measurement and reliable mounting of SMA connectors while showcasing additional benefits of the proposed technique. First, a transition from the suspended stripline to a suspended microstrip transmission line was designed. The height of the air layer was reduced from h_4 to $h_5 = 0.3$ mm in the microstrip region allowing to keep uniform 50 Ω transmission line width. Such a realization reduces the influence of top and bottom enclosure misalignments increasing circuit robustness. Moreover, the discontinuity in the transition region was compensated by adding a pseudo-lumped capacitor realized by shifting the air-layer thickness step (h_4 stripline to h_5 microstrip) into the stripline region by 0.26 mm to locally lower the line` impedance. Next, to allow for a reliable ground plane connection between the SMA connector and couplers` enclosure without the need of soldering to the 3D printed elements, a suspended microstrip to conductor backed coplanar waveguide was designed. Such a configuration allows also for pre-assembly of the circuit reducing the number of assembly failure points since both center pin as well as outer conductor of the SMA connectors can be directly soldered to the CPW metal on the laminate. The discontinuity in the transition region was capacitively compensated by gradually increasing the distance between the center conductor and the ground pads. To ensure proper connection between the CPW ground planes and the metalized surface of the 3D enclosure, a metal skirt around the circuit on the *m*1 and *m*2 metal layers was added creating a large surface for pressure contact. A photograph of the manufactured circuit mosaic on the LCP laminate is shown in Fig. 5a-b, where each of the above described parts of the circuit can be clearly seen.

On the other hand, the 3D printed enclosure was designed to create, together with the inner laminate, a self-enclosed circuit. For that reason, the enclosure was designed in such a way that mechanical and electrical properties are complementary to each other. To ensure mechanical strength and mounting points for the top and bottom halves of the enclosure as well as to provide a low-inductance connection between top and bottom ground planes, large surface area pads were designed together with a set of tightly-fitted post and hole elements (see Fig. 5). Moreover, brackets for SMA connectors were added to allow for reduction of peeling force on the laminate while coaxial cables are connected during measurements.

For the realization of the 3D case with conductive surface a combination of polyjet 3D printer and magnetron sputtering system shown in Fig. 6 were employed. A commercially available Objet Connex350 Multi Material 3D Printing System utilizing photo-polymer resin was used to print the enclosure shown in Fig. 5b-c out of VeroWhitePlus material. The 3D printer allows for fine feature resolution required for the realization of substrate integrated 3D structures with build resolution of X-axis: 600 dpi; Y-axis: 600 dpi; Z-axis: 1600 dpi as well as high quality surface finish with fast and clean prototyping at the same time. Following, the 3D printed material was covered with 1μm of copper as seen in Fig. 5e-f using a Denton Desk Top Pro Sputtering system. To ensure proper adhesion of copper, a 50-nm thick intermediate layer of Titanium was sputtered beforehand. Instead of sputtering, copper plating techniques could also be used.

After manufacturing all the parts, the circuit was assembled. At first, the laminate layer was pre-assembled by soldering all SMA connectors. After that, two halves of the enclosure were connected using a lego-like process and an additional set of screws to tighten the contacts. A photograph of the fully assembled circuit is shown in Fig. 7.

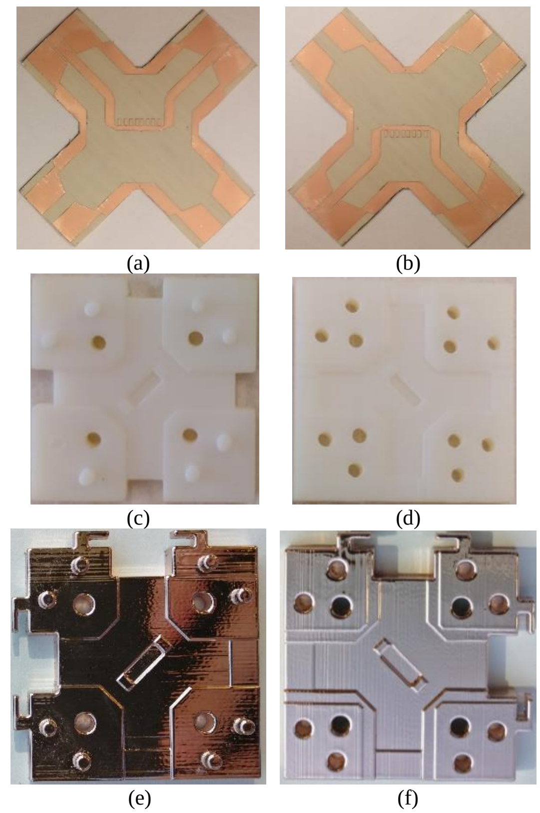
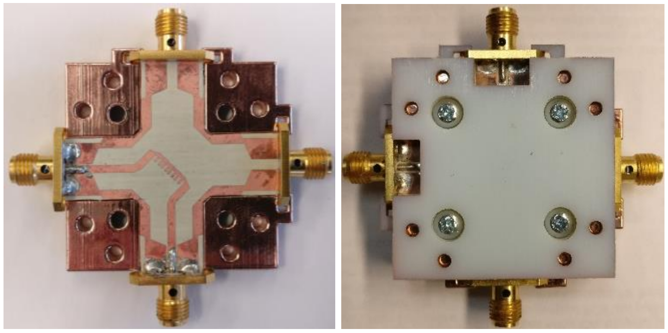


Fig. 5. Photograph of the top (a) and bottom (b) sides of thin inner laminate on which copper directional coupler traces are etched. A full-metal skirt around is realized to connect SMA outer conductor with the CPW ground planes and with the top and bottom enclosure conductor. Photograph of the inner side of the 3D printed out of VeroWhitePlus material top (c) and bottom (d) halves of the enclosure with sputtered 1 μm of copper afterward (e), (f). 3D objects with different air layer heights can be clearly visible together with lego-like post and hole ensuring galvanic connection of the top and bottom ground planes.

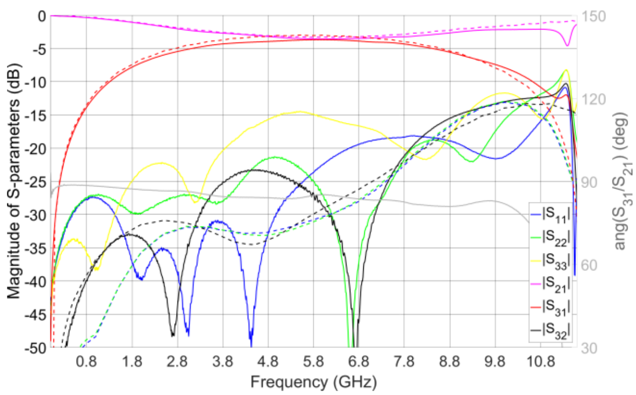
(a) (b)

Fig. 6. Objet Connex350 Multi Material PolyJet 3D Printing System (a) and Denton Desk Top Pro Sputtering System (b) setups at Michigan State University, MI, USA.

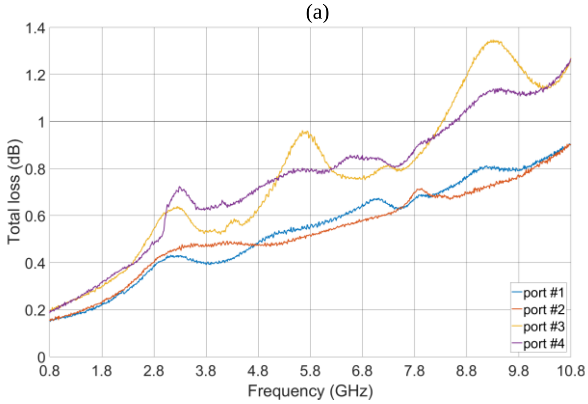


(a) (b)

Fig. 7. Photograph of the manufactured bottom half of the case with pre-assembled suspended laminate (a) and fully assembled directional coupler circuit (b) where CPW lines with attached SMA connectors are visible. The overall dimensions of each half are 40 mm x 40 mm x 4.5 mm.



(a)



(b)

Fig. 8. Measured S-parameters of the manufactured 3-dB directional coupler (solid lines) in comparison to EM calculated ones for the full circuit including stripline to microstrip to CPW transitions (a) and measured total loss calculated from each port (b).

The assembled directional coupler was measured using a Keysight PNA Network Analyzer N5227A calibrated using SOLT standards with the reference plane set at the SMA connector plane. The measured S-parameters are shown in Fig. 8a along with EM calculated ones for the entire structure. Moreover, total loss calculated from each port (as a difference between total power delivered to a port and powers transmitted and reflected from the port) is provided in Fig. 8b. As seen, the manufactured circuit features high-performance while keeping total loss very low. Center frequency of operation is slightly shifted by 200 MHz from the designed one to f_0 = 6 GHz. Coupling and transmission at f_0 equals C_{max} = -3.658 dB and T_{min} = -3.573 dB, respectively, which is a slight undercoupling compared to the design while the phase difference equals 84.2° ± 1°. Moreover, total loss incorporating the coupler itself as well as the connecting transmission lines is as low as 0.55 dB at the center frequency. Return losses are better than 15 dB, while isolation is better than 20 dB within the operational band. Considering that the manufacturing capabilities of the equipment are tested to their limits in this study and accounting limited assembly process accuracy, the obtained results are very satisfactory and match closely with the EM predicted results confirming the applicability of the proposed design approach. Moreover, the proposed approach allows for obtaining superior or comparable performance with respect to the circuits shown in literature as it can be seen in Table I while featuring the above presented advantages.

TABLE I

PERFORMANCE COMPARISON OF THE PROPOSED DIRECTIONAL COUPLER WITH OTHER SUSPENDED COUPLED-LINE COUPLERS

Reference	[12]	[13]	[14]	**This work**
Coupler type	single-section 3dB coupler in stripline	single-section 3dB tandem in stripline	single-section 3dB coupler in microstrip	single-section 3dB coupler in stripline
Enclosure	milled metal	PCB	milled metal	metal coated 3D print
Air layer vs max coupling	fixed height/ limited C_{max}	fixed height/ limited C_{max}	fixed height/ limited C_{max}	var. height/ unlimited C_{max}
Area (mm^2)	N.A.	22.3 x 15.5	76.7 x 41.1	10.56 x 3.1
f_0 (GHz)	2.5	2.25	0.89	6
Ret. loss (dB)	> 26	> 20	> 20	> 15
Isolation (dB)	> 28	> 20	>24	> 20
Phase diff.	N.A.	90.5 ± 2.5°	90.5 ± 3.5°	84.2° ± 1°.
Total loss at f_0	0.1* dB	0.45$^+$ dB	0.07* dB	0.55* dB

* includes directional coupler and all the connecting transmission lines
$^+$ directional coupler only

V. CONCLUSION

A novel approach for the realization of high-performance and low-loss directional couplers in suspended stripline technique was proposed taking advantage of recent development in 3D printing technology. By introducing a third degree of freedom, an air layer thickness variable circuit is obtained. It was shown that the proposed approach is well suited for the realization of circuits where tight coupling is required, as well as small size. Moreover, it was shown that compensating elements often required to improve the couplers` performance can easily be realized as a hybrid of a circuit mosaic and ground plane integrated 3D structures allowing for better circuit volume utilization. An example of a 3-dB coupled-line directional coupler operating within ISM 5.8 GHz band was designed and measured. The obtained results confirm the applicational potential of the proposed approach.

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