Application of Additive Manufacturing Technologies for Realization of Multilayer Microstrip Directional Filter

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Abstract—**In this paper, an application of additive manufacturing technologies for realization of multilayer microwave circuits in microstrip transmission line technique is presented for the first time. An example of a second-order cascaded loops directional filter allowing to separate 2100 MHz LTE band was designed in suspended microstrip with three metal layers, manufactured using a combination of PolyJet 3D printing with UV cured VeroWhitePlus polymer material and magnetron sputtering of copper, and assembled out of two parts using a "lego-like" process. The obtained results for the manufactured circuit confirmed that the proposed approach is of potential use for circuits and systems operating within the microwave frequency range.**

Keywords-additive manufacturing; 3D printing; magnetron sputtering; multilayer suspended microstrip; directional filter.

I. INTRODUCTION

Rapid development of modern telecommunication systems very often requires multi-band operation using a single aperture along with multiplexing devices [1]-[2]. Moreover, small circuit size, flexible designs and low-cost of manufacturing are of particular interest. One of the approaches is utilization of UWB (ultra wideband) antennas or antenna arrays along with directional filter based multiplexers [3]. Broad operational band of the antenna allows to cover and integrate different systems such as e.g. GPS, GSM, WLAN while multiplexer circuits allow to separate those frequency bands for further usage. Moreover, application of directional filters as building blocks allows for very a flexible design of the multiplexer, since each band is separated by one filter connected in cascade, hence filtering characteristics and number of channels can be easily altered [3]-[6]. In addition, directional filters, hence multiplexers can be easily integrated with UWB antennas due to their structure and manufacturing compatibility. However, recent developments of additive manufacturing technologies including 3D printing allow for the realization of UWB antennas using alternative to laminate technology manufacturing schemes not constrained to 2.5D geometry [7]-[8]. Therefore, it would be beneficial to adopt additive manufacturing technologies for realization of multilayer microstrip-transmission line circuits including directional filters. Such an approach would allow reducing costs, weight and volume of the entire telecommunication system.

In this paper, a realization of multilayer microwave circuit in a microstrip transmission line technique using additive manufacturing technologies is proposed for the first time to the best of our knowledge. An example of a second-order cascaded loops directional filter allowing to separate the 2100 MHz LTE band was designed, manufactured and measured. A combination of PolyJet 3D printing with UV cured VeroWhitePlus polymer material and Magnetron sputtering of copper was utilized to realize the microstrip structure in which three metal layers were required. PolyJet 3D printer was used to print the two-part dielectric core: the top flat slab required to host the two-sided metallization and the shaped bottom slab required to provide ground plane surface on one side with half the thickness removed under the top metallization layers to reduce dielectric losses. Moreover, a recently developed lift-off technique [9] wasemployed to realize the two-sided board for the first time. On both sides of the top slab, masking layers realized as thin material layers bonded using support material have been added (all printed in one run) to allow realization of the conductive traces. Next, a layer of copper of appropriate thickness was sputtered on each side of the top printed part as well as on the bottom side of the bottom part. Following, masking layers have been lifted-off exposing circuit traces on the top flat dielectric slab. Finally, the top part was attached to the bottom one using "lego-like" positioning posts to create the complete circuit. In order to measure the circuits, SMA connectors were added and held in place using dedicated clips and glued to traces using silver epoxy. The obtained measurement results showed that the manufactured circuit exhibits bandpass, bandstop and isolate paths when the input port is fed with the desired frequency selective characteristics. The reflection coefficient at each port is below -6 dB, while the total insertion loss equals 6.5 dB at the center frequency, which is mainly due to the utilized relatively lossy VeroWhitePlus dielectric substrate. The obtained results for the manufactured circuit have confirmed that the proposed combination of additive manufacturing technologies are of potential use for realization of multilayer microwave circuits.

II. DIRECTIONAL FILTER DESIGN

The general schematic diagram of a travelling-wave directional filter is presented in Fig. 1. Such a circuit is composed of n number of coupled wave-long resonators allowing for coupling the band of interest from input port #1 to bandpass port #2 while creating a bandstop at port #3. The order of the filter depends on the number of loop resonators and can be increased by adding resonators coupled in-between k_1 and k_k. The properties of the directional filter i.e., bandwidth, passband ripple and stopband rejection depend on coupling level between consecutive loop resonators, hence the directional coupler's coupling level is k_1 to k_k.

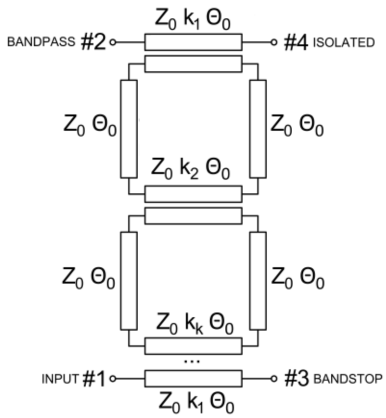


Figure 1. General schematic of a n^{th} order travelling-wave directional filter.

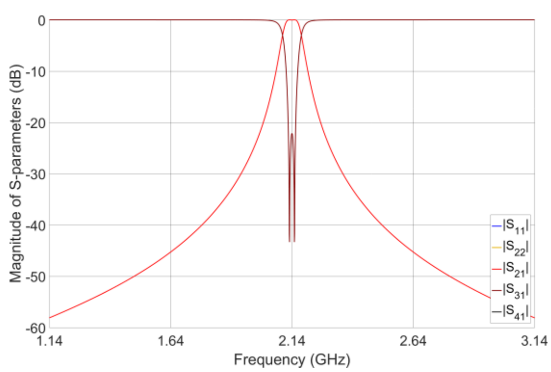


Figure 2. Frequency response of a 2nd order directional filter calculated for ideal-element circuit realizing equal-ripple Chebyshev response with a minimal stopband path in-band attenuation of 22 dB.

The above described directional filter is a well suitable circuit example to benchmark the proposed manufacturing approach. Since this is a circuit of a resonant nature, the utilized material parameters can be easily experimentally verified with respect to the designed ones by observing the quality factor and insertion loss. Moreover, realization of at least second-order filter requires to design two or more couplers of different coupling-levels (couplings are pair symmetrical towards the center loop) which can be broadside- or edge-coupled, hence both wide and narrow lines, fine features and narrow gaps as well as layers alignment are to be realized allowing assessment of the print and metallization quality in terms of the layer thickness and sharpness of line edges.

For the purpose of experimental investigation, a second-order directional filter was designed allowing to separate the 2100 MHz LTE band (2.1 – 2.18 GHz). A set of design parameters was found assuming an equal-ripple Chebyshev transfer function [10] providing minimal stopband path in-band attenuation of 22 dB and 80 MHz of bandwidth to be: $k_1 = 0.37$ ($Z_{0e} = 73.65\ \Omega$, $Z_{0o} = 33.95\ \Omega$), $k_2 = 0.08$ ($Z_{0e} = 54.12\ \Omega$, $Z_{0o} = 46.19\ \Omega$), whereas $Z_0 = 50\ \Omega$ and $\theta_0 = 90°$. The frequency response of such ideal-element directional filter is shown in Fig. 2.

The dielectric structure shown in Fig. 3 was selected for realization of the directional filter. Three dielectric layers are arranged in a suspended microstrip configuration. The VeroWhite polymer material was assumed to have a relative permittivity of $\varepsilon_r = 2.8$ and loss tangent $tan\delta = 0.01$ while metal layers are assumed to be 0.5 µm thick of copper. Such an arrangement was selected due to four main reasons:

- the 3D printed VeroWhite polymer layer is recommended in [9] to be of at least 0.5 mm thickness when used together with metal sputtering due to the thermo-mechanical properties of the material
- the air layer is introduced to reduce total dielectric losses due to VeroWhite being a relatively lossy material.
- at least three metallization layers are required to realize broadside-coupled couplers being a constitutive element of the filter.
- due to the 3D printing technology properties and because of microstrip arrangement, the dielectric stack-up can be conveniently manufactured as two separate pieces.

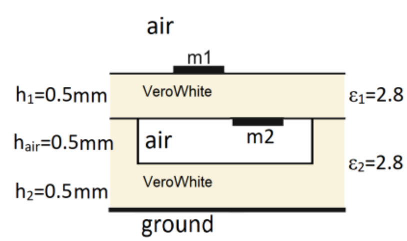


Figure 3. Cross-sectional view of the dielectric structure utilized for the circuit design. The stack-up in suspended microstrip configuration consists of two relatively lossy VeroWite 3D printed polymer layers and lossless air layer in the middle to allow for reducing the overall dielectric losses and three metallization layers.

Having established the substrate properties, the geometry of each main component of the filter was determined to allow for physical layout design. The selected structure allows only for very weak coupling to be realized on a single metal layer, hence coupling k_1 was realized in broadside-coupled configuration while k_2 in edge-coupled configuration. The geometry for both couplers was found using the *Linpar* software [11] together with the widths of 50 Ω transmission lines on metal layers $m1$ and $m2$. Subsequently, the physical lengths for quarter-wave long couplers and uncoupled line sections composing wave-long loop resonator were found. The final layout of the circuit was designed using the *NI AWR Design Environment* software and is shown in Fig. 4 along with the annotated dimensions. To match the lengths of couplers, sections of transmission lines were appropriately bended while maintaining continuity of impedance and electrical length. Moreover, transitions from coupled to uncoupled lines were appropriately designed to minimize the negative influence of the discontinuity. It has to be noted that directional couplers realized in suspended structure feature deteriorated performance due to unequal capacitive and inductive coupling coefficients [12] which is then reflected in the performance of the resulting filter. However, to keep the feature size relatively large as the manufacturing technique is experimental, and considering this negative influence is less visible for looser couplings, the couplers were not compensated.

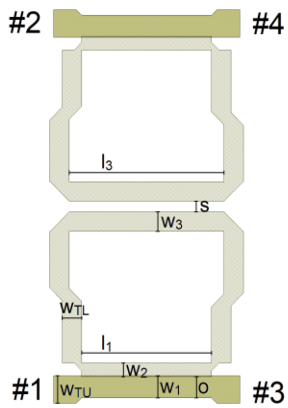


Figure 4. Layout of the designed 2nd order travelling wave directional filter: w_1 = 4.15 mm, w_2 = 2.6 mm, o = 3.95 mm, l_1 = 25.3 mm, w_3 = 3.7 mm, s = 2.0 mm, l_3 = 30.2 mm, w_{TL} = 3.8 mm, w_{TU} = 5.2 mm. Connecting transmission lines are placed on metal $m1$ while center edge-coupled coupler is placed on metal $m2$. The total area of the filter equals 37.8 x 74.4 mm.

III. Multilayer Circuit Realization using Combination of Additive manufacturing Technologies

In order to physically realize the travelling wave directional filter described in the previous section it is proposed to utilize a combination of 3D printing and selective metal sputtering to manufacture the dielectric substrate and metallization layers, respectively. For the purpose of this research, a commercially available Objet Connex350 Multi Material Poly Jet 3D Printing System utilizing UV cured photo-polymer resin was used together with a Denton Desk Top Pro Sputtering System, both shown in Fig. 5. The 3D printer allows for fine feature resolution required for the realization of microwave circuits 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. Moreover, a support material can be printed being uncured resin. A recently developed manufacturing technique shown in [9] was employed and extended on the realization of multilayer circuits. To realize a conductive circuit mosaic on top and/or bottom of the core dielectric, additional sacrificial masking layers are 3D printed together with the core being loosely bonded with support material. An expanded view of such prepared model is shown in Fig. 6. The masking layers allow for selective metallization of the core dielectric by sputtering the whole part and lifting-off the sacrificial layers with the excessive metal. The imposed limitation of such manufacturing approach is the minimum thickness of the core and maximal thickness of the metal being related to the thermo-mechanical properties of the material. For this research, the minimal core thickness was assumed to be 0.5 mm as indicated in the previous section; the masking layer and support material layers were assumed to be 0.2 mm while the maximum thickness of the sputtered copper was assumed to be 0.5 µm with a 50 nm thick intermediate layer of Titanium ensuring proper adhesion of the copper being sputtered beforehand. However, when a thicker metallization is required, the electroplating process can be used.

(a) (b)

Figure 5. Objet Connex350 Multi Material PolyJet 3D Printing System (a) and Denton Desk Top Pro Sputtering System (b) setups at Michigan State University, MI, USA.

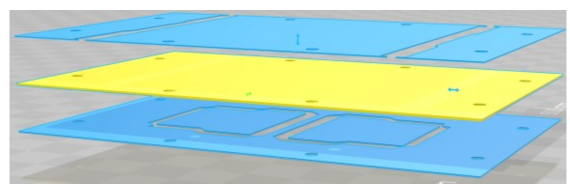
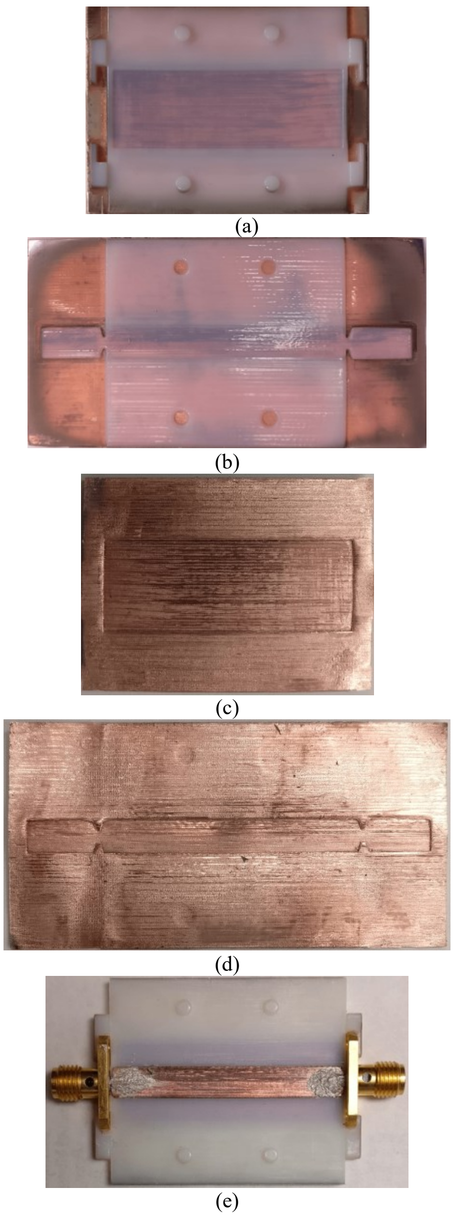


Figure 6. Exploded view of the layer setup for manufacturing of two-sided board using the lift-off technique. Two sacrificial masking layers (blue) are bonded using the support material to the center core dielectric substrate (yellow) and printed all at once. After metal sputtering, the masking layers are peeled-off exposing desired mosaic of metal traces.

A. Test transmission line section

A test transmission line was designed beforehand to test-run the proposed manufacturing scheme and to determine the properties of the utilized materials and their suitability for realization of the designed directional filter. The structure was designed as a two-part "lego-like" assembly with a single-sided metallization. The lower part having a thickness of 1 mm with half the thickness removed in the transmission line region provides the metalized ground plane on the bottom side. Realization of the air layer as a cavity is required from the mechanical perspective to help maintain the desired thickness. To prevent bending of the core material due to a large metal surface of different thermal contraction coefficients, the ground plane area was appropriately reduced. Additionally, dedicated brackets were added to hold the SMA connectors and reduce the peeling force during measurements. On the other hand, the top part is 0.5 mm thick on top of which the 40 mm long, 5.2 mm wide metal trace was realized. Additionally, snap-off tabs were added to provide a large connection surface for optional electroplating. Photographs of the circuit at different stages of manufacturing are provided in Fig. 7. Finally, the circuit was assembled by connecting the top and bottom pieces of the VeroWhite. Moreover, SMA connectors were attached and glued using silver epoxy to ensure a galvanic contact.

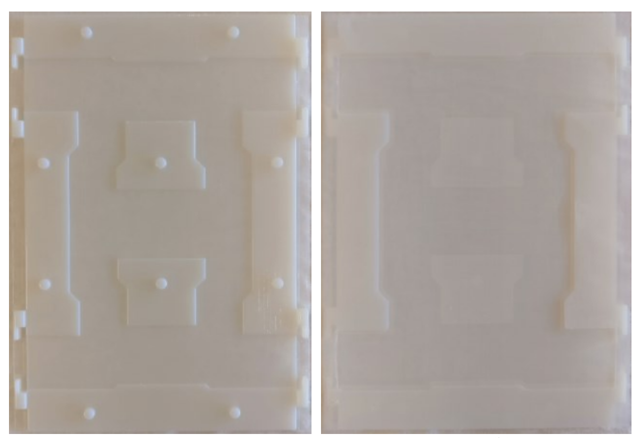


(a) (b) (c) (d) (e)

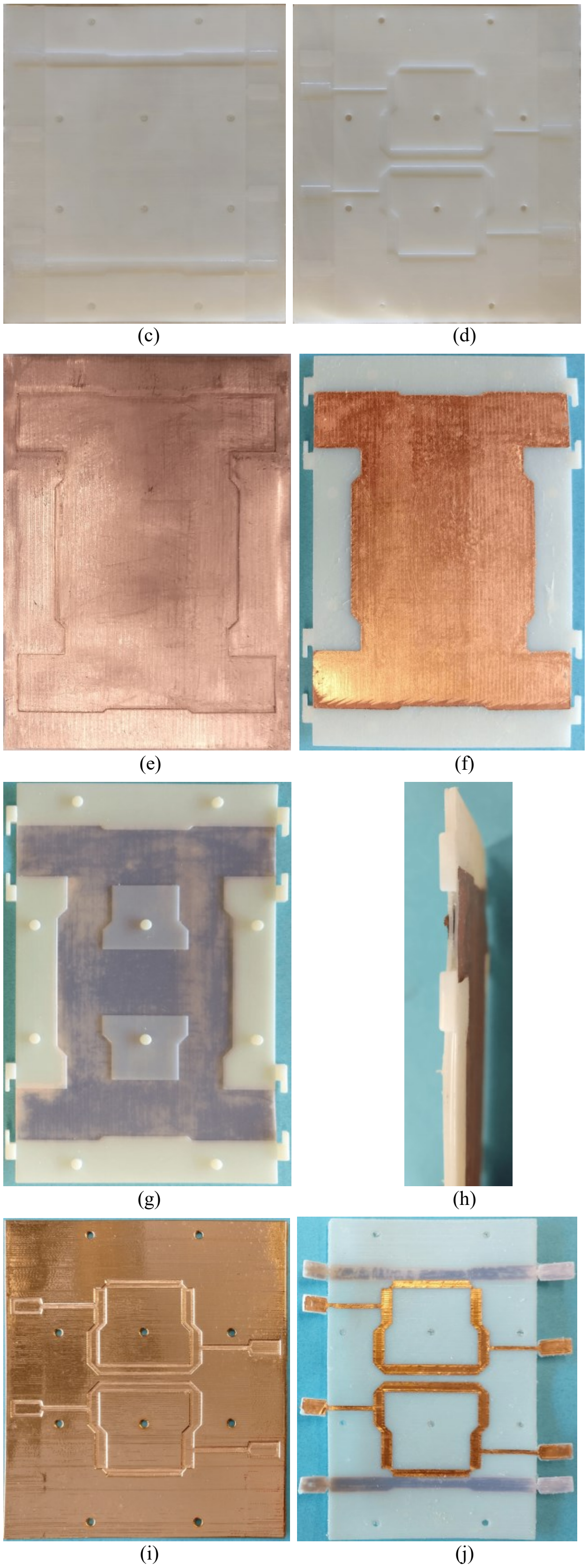
Figure 7. Photographs of the test transmission line at different stages of manufacturing: 3D printed VeroWhite bottom (a) and top (b) parts were one-sided sputtered with 0.5µm of copper (c), (d) and then sacrificial masking layers were removed. Fully assembled circuit (e) with SMA connectors attached using silver epoxy. Overall size of the circuit equals 40 x 35.2 mm.

B. *Second-order directional filter*

After successfully manufacturing the test transmission line, the designed directional filter was manufactured. The structure was designed as a two-part "lego-like" assembly with a single-sided metallization on the bottom part and two sided metallization on the top part. Similarly to the previous circuit, the lower part having a thickness of 1 mm with half the thickness removed in the metal strips region provides the metalized ground plane on the bottom side. Also the ground plane area is appropriately reduced to prevent bending of the core material. Identical brackets were added at each port to hold the SMA connectors and reduce the peeling force during measurements. On the other hand, the top part is 0.5 mm thick with the top and bottom side metallization providing metal layers $m1$ and $m2$. To connect the directional filter, 20 mm long 50 Ω transmission line sections were added to each port. Similarly as for the test line, snap-off tabs with narrow lines connecting to each metal trace were added to provide a large connection surface for optional electroplating. In the case of the directional filter, an additional layer of copper was grown using the electroplating process to a final thickness of 2 µm as the measurements of the test line have shown relatively large metal resistivity. It has to be noted however that the maximal thickness of such a metal layer is limited due to the limited adhesion between the printed dielectric and sputtered metal. Photographs of the circuit at different stages of manufacturing are provided in Fig. 8. Finally, the circuit was assembled by connecting the top and bottom pieces of VeroWhite. Moreover, SMA connectors were attached and glued using silver epoxy to ensure galvanic contact.



(a) (b)



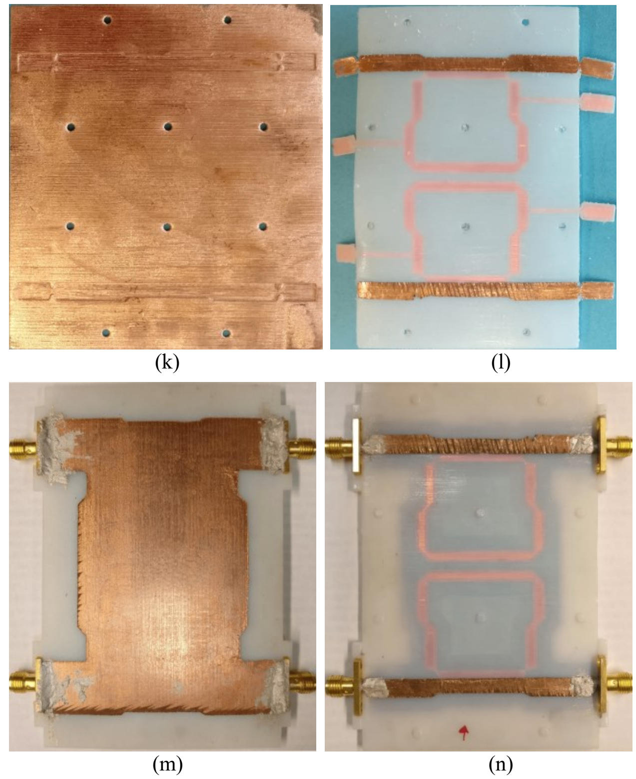


Figure 8. Photographs of the designed directional filter at different stages of manufacturing: 3D printed VeroWhite two-sided bottom (a), (b) and top (c)(d) parts were one-sided (e), (g) and two-sided (i), (k) sputtered with 0.5µm of copper and electroplated to obtain 2 µm thick metal. Following, the sacrificial masking layers were removed (f), (j), (l). Fully assembled circuit using lego-like process (h) with SMA connectors attached using silver epoxy (m), (n). Overall size of the circuit equals 104 x 67.8 mm.

IV. Experimental Results

Experimental verification of the proposed manufacturing scheme was conducted by means of electrical performance measurement of the realized section of the test transmission line and directional filter. The Keysight PNA Network Analyzer N5227A calibrated using SOLT standards with the reference plane set at the SMA connector plane was used. The measured frequency response along with the total power loss (calculated as a difference between power delivered to the port and sum of reflected and transmitted powers) is provided in each case.

A. Transmission Line Section

First, the 3D printed transmission line was measured and respective data is provided in Fig. 9 and Fig. 10 along with results of electromagnetic (EM) simulations using *NI AWR Design Environment* software. As seen, similar reflection coefficient is obtained to the predicted one meaning the line is well matched; however, higher insertion loss is observed. Moreover, it can be seen from Fig. 7e that the top trace features sharp edges and consistent width while the layer thicknesses, including the air layer, are consistent in thickness. It can be concluded that the assumed dielectric permittivity of VeroWhite material is close to being correct while the assumed loss tangent is too small and for the manufactured circuit is of order of magnitude higher. The predicted total loss at 2.14 GHz which is center frequency of operation of the designed directional filter equals ≈ 0.003 dB/mm while measurements show ≈ 0.020 dB/mm.

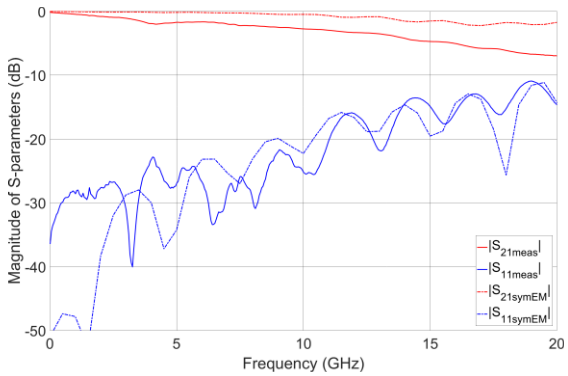


Figure 9. Measured S-parameters of the manufactured sections of transmission lines in comparison with EM simulated data.

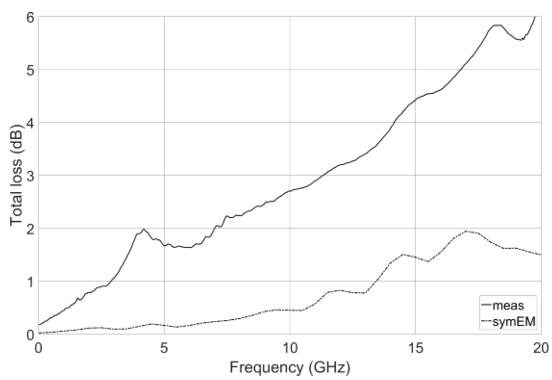
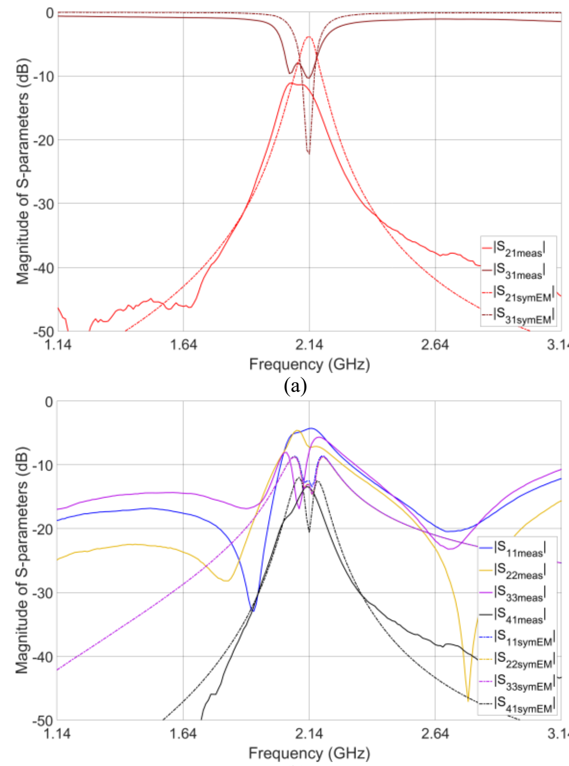


Figure 10. Measured total loss of the manufactured 40 mm long transmission line section in comparison with the EM simulated data.

B. *Second-Order Directional Filter*

Finally, the manufactured directional filter was measured and the measurement results are provided in Fig. 11 and Fig. 12 along with results of EM simulations. It can be observed that the center frequency of operation is close to the design value being shifted downwards only by 50 MHz (2.3 %) while the bandwidth of operation is 60 MHz which is wider than the design value. The very uneven and jagged edges (especially on $m1$ layer) as seen in Fig. 8n being a result of the electroplating process are especially reflected in the measured reflection and isolation response, since the directional filter circuit is very sensitive on the impedance of the loop resonators. Similarly, as for the transmission line section, much higher loss is observed compared to the EM simulations. However, loss per mm outside the band of operation is lower compared to the test transmission line due to thicker metal layer. As seen in Fig 12, the total loss (including connecting transmission lines) reaches up to 6 dB at the center frequency and is very inconsistent from port to port. It can be concluded that this is due to uneven quality of metal layers m1 and m2, as well as the inconsistent thickness of the air layer. It has to be noted, however, that the directional filter is five times the area of the test line and some material shrinkage due to heat treatment during the sputtering process is more visible.



(a)

(b)

Figure 11. Measured S-parameters of the manufactured directional filter (solid lines): bandpass and bandstop paths response (a) isolated path response and reflection coefficients (b) in comparison with the EM simulated data (dash-dot lines).

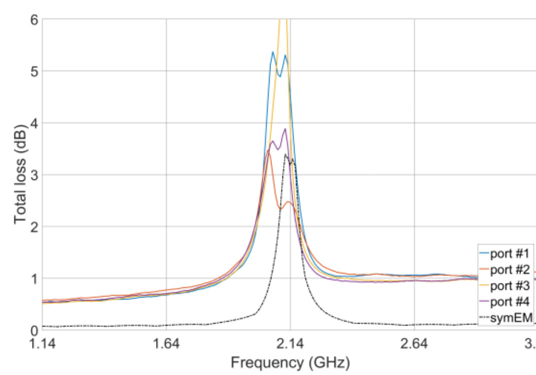


Figure 12. Measured total loss of the manufactured directional filter including 20 mm long connecting lines at each port in comparison with EM simulated data.

Based on the above presented measurement results we conclude that the proposed manufacturing process and material choice is suited for microwave circuit applications. The total power losses which are of main challenge for now can be reduced by further optimizing the manufacturing process which may be a subject of further studies.

V. Conclusion

An application of additive manufacturing technologies for realization of multilayer microwave circuits in microstrip transmission line technique was presented for the first time. An exemple of a second-order cascaded loops directional filter allowing to separate the 2100 MHz LTE band was designed in suspended microstrip with three metal layers, manufactured using a combination of PolyJet 3D printing with UV cured VeroWhitePlus polymer material and magnetron sputtering of copper and assembled out of two parts using a “lego-like” process. The obtained measurement results for the manufactured circuit demonstrated that the proposed manufacturing scheme has application potential as a low-cost and fast process not limited to planar structures, making it a suitable alternative for realization of microwave circuits.

Acknowledgment

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