Contribution of LTCC technology to the miniaturization of six-port networks

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***Abstract*—The six-port network has been identified in recent years as one of the best candidates to implement a Software Defined Radio (SDR). The main characteristic of the six-port architecture is its extremely large bandwidth, which involves multi-band and multi-mode capabilities. However, broadband six-port network designs lead to large size circuits. New technologies must be explored in order to achieve compact size and low-cost productions for configurable radio terminals. In this paper, the LTCC (*Low Temperature Co-fired Ceramic*) technology is proposed for implementing a six-port receiver. In the first place, we have developed an LTCC 90-degree hybrid coupler, which is the most critical component of the six-port network. Measurement results show a good performance over the frequency range from 1.5 to 6.5 GHz.**

Keywords- *Multiport networks; six-port technique; low temperature co-fired ceramic; tandem couplers; power dividers.*

I. Introduction

The search of a universal and reconfigurable RF front-end is still a key factor in a SDR implementation [1]-[3]. Two typical RF architectures for SDR are the zero-IF and low-IF architectures. These structures have many advantages suitable for SDR, such as flexibility, reconfigurability, low-cost, and high level of integration, but their main problems derive from the I-Q mod/demodulator devices. The trend towards high data rate services will require larger bandwidths, which become possible at high frequencies. I-Q mod/demodulators cannot operate in very large frequency ranges, so the use of zero-IF and low-IF architectures is limited by these devices.

Six-port network is an interesting architecture that is nowadays emerging as a promising alternative [4]-[5]. Active costly I-Q mixers are not necessary for the frequency conversion. Hence six-port networks can operate at very high frequencies, such us millimeter-wave frequencies or beyond 100 GHz. In addition, six-port networks have been demonstrated to perform high data rates (1.7 Gbit/s in [6]). The main advantage of the six-port architecture is its extremely large bandwidth, which involves multi-band and multi-mode capabilities. However, an important problem is the large dimensions of the passive six-port structure. The higher the frequency, the smaller the passive circuit and the easier the integration in a MMIC design. But for operating frequencies in the lower gigahertz region, a broadband design leads to large dimensions, which could be prohibitive, for example, for mobile communication applications.

Therefore, there is a need to explore new technologies in order to make the six-port network a viable and competitive solution for mobile terminals. The objective of this work is to analyze the contribution of the LTCC technology to the miniaturization of six-port networks.

II. Design Considerations on Six-Port Networks

The principle of operation of the six-port architecture is based on the measurement of four independent powers, when the radiofrequency (RF) and local oscillator (LO) signals are introduced into the remaining two ports. Six-port architecture consists of a linear and passive six-port network and four power detectors. The passive six-port circuit combines the input RF and LO signals with different phase relations. The q_i-points [7] characterize the relation between RF and LO at the six-port outputs. The design criterion of a six-port junction consists of achieving a good distribution of the q_i-points. In general, the closer the magnitudes of q_i, and the larger the differences between the arguments of q_i, the better will be the performance of the circuit.

Six-port configurations are based on the interconnection of several passive circuits, mainly couplers and power dividers. Several examples of six-port network topologies are presented in Fig.1. The design of the 90-degrees hybrid couplers is the most difficult part, as a tight coupling and proper phase shifts over very large bandwidths are required in a SDR. Branch-line and rate-race couplers are suitable for obtaining tight coupling values, such as 3 dB. However, these couplers are inherently narrowband circuits (<20% bandwidth). The use of 3-dB Lange couplers enhances the bandwidth, but only up to one octave. A tight coupler can also be obtained by connecting two couplers in tandem. In a tandem connection, the direct and coupled ports of the first coupler are connected to the isolated and input ports of the second one, respectively. The tandem connection of two 8.34-dB couplers leads to a 3-dB coupler. However, the bandwidth requirements of a RF front-end for SDR force to use multisection designs, which leads to large size circuits.

That is the case reported in [8], where a three-octave (698-5850 MHz) six-port network is presented. The six-port network topology is that shown in Fig. 1(c), and it is implemented in

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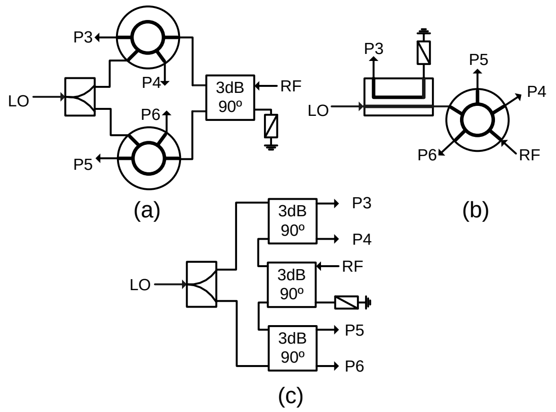

Figure 1. Examples of six-port network topologies

conventional planar technology. The three-octave 90-degree 3-dB couplers are obtained from the tandem connection of two seven section 8.34-dB couplers. The high coupling level of the central section requires the use of broadside-coupled lines and a low dielectric constant substrate, which increases the size of the circuits even more. The dimensions of the constructed coupler are 130x17x2.6 mm, and consequently the size of the overall six-port network is not inconsiderable. The six-port demodulation of high-speed signals has been satisfactorily proved [9], but some efforts must be made in order to reduce the size.

LTCC is a cost-effective substrate technology which enables to develop compact microwave and millimeter wave modules. It makes possible to integrate passive and active microwave circuits, antenna structures, low-frequency electronics, and digital components on one multilayer substrate. Our objective is to study the contribution of LTCC to the miniaturization of the six-port architecture.

III. LTCC Six-Port Network

Continuing our previous work [8]-[9], we are going to develop a new version of the six-port network based on LTCC technology. The LTCC layer structure, represented in Fig. 2, is composed of eight DuPont-951 substrate layers (ε_r=7.8, tgδ=0.006 @3GHz). The description of the different designed circuits is presented below.

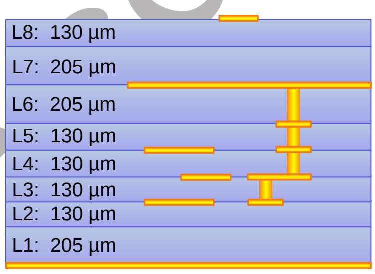

Figure 2. LTCC layer structure

A. 90-degree hybrid coupler

The 90-degree hybrid coupler will be implemented by the tandem connection of two symmetrical multisection 8.34-dB couplers, according to [8]. The highest coupling level required in a multisection coupler design, which corresponds to the central section coupling level, will limit the bandwidth. From the design tables [10], for a 0.05-dB ripple, 8.34-dB coupler, the central section coupling level is 6.28 dB for three λ/4-sections, 5.18 dB for five sections, and 4.47 dB for seven sections. Higher ripple levels provide wider bandwidths, but it leads to higher coupling levels. Considering a 930 µm substrate height, the theoretical coupling level achieved with two 50 Ω λ/4 broadside-coupled striplines with a 130 µm separation is 5.89 dB. This reduces the possibilities to use a three-section design, with a stripline structure composed of layers L1-L6 (930 µm). The ripple could be increased until 0.2 dB, achieving a theoretical bandwidth of $B=f_2/f_1=3.18211$, which means that the 1838.4-5850 MHz frequency range could be covered. If a larger bandwidth is required, coupling can be maximized by reducing the separation of the inner conductors, and increasing the distance to the ground planes. A low dielectric constant substrate also maximizes the highest coupling, as the ground plane separation will be large relative to the overlay separation, although this increases the circuit dimension. However, our design has to adapt to the fixed layer structure, and no modifications can be realized to increase the bandwidth.

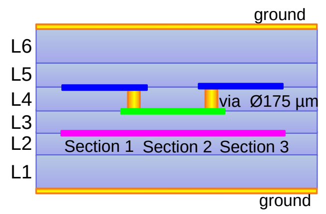

Figure 3. Cross section of the 8.34-dB coupler

TABLE I. 3-Section 8.34-dB Coupler Characteristics

Parameter	Section1	Section2
Z_{oe} (Ω)	54.32	87.43
Z_{oo} (Ω)	46.02	28.59
Line width (µm)	210	150
Line spacing (µm)	618	0

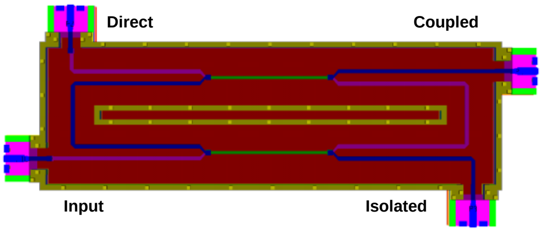

Figure 4. Top view of the LTCC 3-dB tandem coupler

The even and odd impedances for a symmetrical 3-section, 0.2-dB ripple, 8.34-dB coupler are shown in Table I. Central section coupled lines will be placed on top of layers L2 and L3. Sections 1 and 3 will be synthesized with offset-broadside-coupled lines over layers L2 and L4. They will be interconnected to the central section by means of vias. The cross section of the 3-section 8.34-dB coupler is presented in Fig. 3. The coupler dimensions are given in Table I.

Two 8.34-dB couplers are connected in tandem to form the 3-dB coupler. Fig. 4 shows the top view of the LTCC 3-dB tandem coupler, where the top ground on layer L6 appears in semi-transparent gray color. The 3dB coupler dimensions are

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TABLE II. 3-SECTION WILKINSON POWER DIVIDER PARAMETERS

Design Parameters	Section1	Section2	Section3
Z_o (Ω)	57.77	70.71	86.54
R (Ω)	371.41	207.66	108.64
Implementation	**Section1**	**Section2**	**Section3**
Line width (μm)	285	185	100
R (Ω)	360	200	110

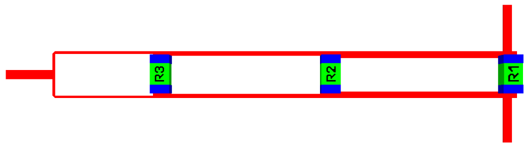

Figure 5. Layout of the Wilkinson power divider

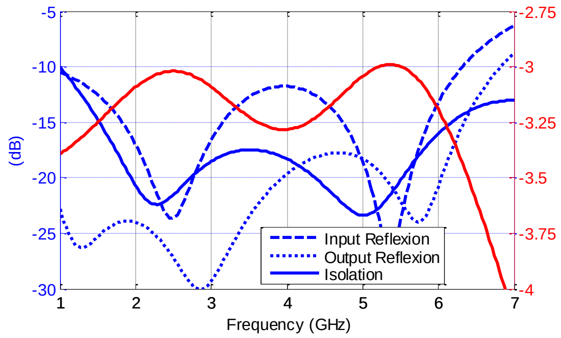

Figure 6. Simulated frequency response of the Wilkinson power divider

20x4.7 mm. The simulated frequency response will be presented in section IV, together with the measurement results. All the simulations have been realized using the EMPIRE XCel 3D-EM field simulator.

B. Wilkinson Power Divider

A multisection Wilkinson divider design is needed to cover the design frequency range of the 3-dB coupler (1838.4-5850 MHz). From the design equations [11], and setting an input return loss better than 20 dB, we obtain that three sections are required to cover the operating frequency range. The Wilkinson divider will be implemented in microstrip using layers L7-L8. The parameters of the 3-section Wilkinson power divider are given in Table II. The layout of the circuit and the EM simulated response with EMPIRE are presented in Fig. 5 and Fig.6, respectively.

C. Six-Port Network

For the design of the six-port network, three 3dB tandem couplers and a Wilkinson divider have been connected following the topology of Fig. 1(c). The 3D view of the LTCC six-port network is presented in Fig. 8 (the ground metal on layer L6 has been removed in the figure). The design of a microstrip-to-stripline transition has been required to connect the couplers with the Wilkinson divider. The dimensions of the six-port network are 25x28x1.27 mm. Nevertheless, these dimensions can be optimized further, for example, the sections of the divider and the couplers can be folded. In any case, our purpose is to take advantage of the LTCC possibilities to develop a complete LTCC six-port receiver. The free area over the three couplers can be used to locate the four power detectors and other low frequency components, such us low-pass filters or video amplifiers. The central free space under the Wilkinson divider can be also used, for example, to locate a RF filter, a low-noise amplifier, or digital components indeed.

The simulated response of the six-port network is presented in Fig. 8 and Fig. 9. The RF-LO isolation is better than 18 dB from 1-6 GHz, and better than 25 dB up to 4 GHz. The return loss at RF port is better than 20 dB up to 4.4 GHz, and better than 14 dB from that frequency. The match at LO port, which is conditioned by the Wilkinson input reflexion, is below 10 dB from 1GHz to 6 GHz. Ideally, in this six-port topology the magnitudes of q_i-points are equal to 1, and the arguments differ 90 degrees. The simulated q_i-points of the developed six-port network, given in Fig. 9, satisfactorily fulfill these requirements. The magnitudes of q_i are in the range of 0.6 to 1.5 from 1.2 GHz to 7 GHz, and the maximum error in the relative phase differences is 9º over the theoretical 90º.

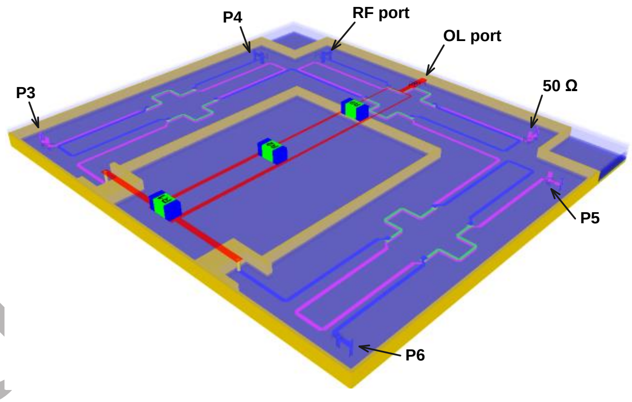

Figure 7. 3D view of the LTCC six-port network

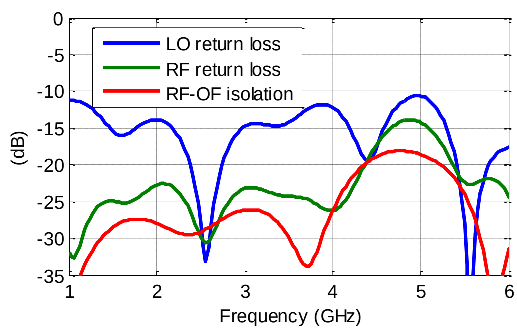

Figure 8. Simulated return losses and isolation of the LTCC six-port network

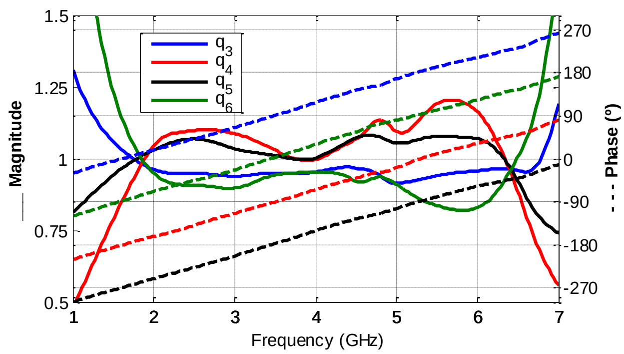

Figure 9. Simulated q_i-points of the LTCC six-port network

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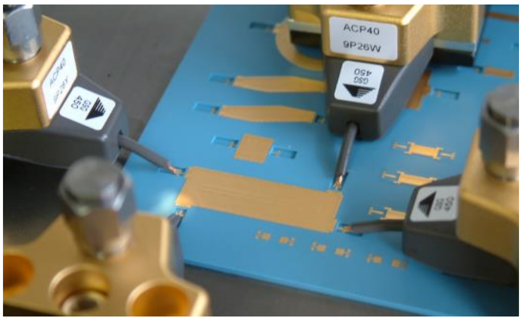

Figure 10. Fabricated LTCC 3-dB tandem coupler

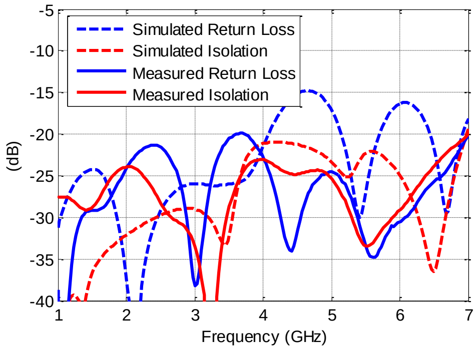

Figure 11. Input return loss and isolation of the LTCC 3-dB tandem coupler

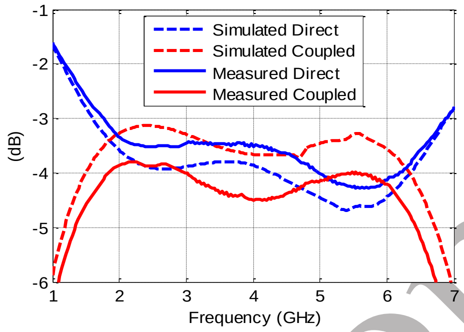

Figure 12. Insertion losses of the LTCC 3-dB tandem coupler

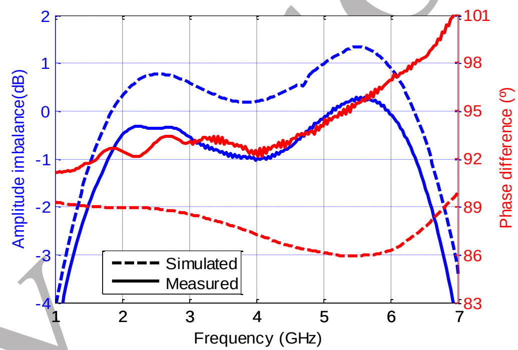

Figure 13. Amplitude and phase imbalances of the LTCC tandem coupler

IV. Measurements Results

The critical element of the six-port network is the 90-degree hybrid coupler, as it determines the system bandwidth. Consequently, in order to prove the viability and performance of the LTCC technology, we have firstly fabricated the 3-dB tandem coupler. The photograph of the constructed LTCC 3-dB tandem coupler is shown in Fig. 10. The circuit has been measured with good performance, as it can be seen in Fig. 11-13. Return loss and isolation are better than 20 dB from 1 to 7 GHz. Simulated and measured insertion losses are quite similar, excepting for an additional 0.8 dB loss in the coupling level. Amplitude imbalance is below 2 dB from 1.5 to 6.5 GHz. Phase difference between direct and coupled ports varies from 91º to 98 between 1.5-6.5 GHz.

V. Conclusions

This paper shows the possibilities of the LTCC technology to reduce the six-port architecture dimensions. The design of an LTCC six-port network is described. It presents a good performance from 1.5-6.5 GHz, and its size is 25x28x1.27 mm. Firstly, the LTCC 90-degree 3 dB coupler has been fabricated, as this circuit is the most critical element of the six-port network. Measurement results show a good response over the frequency range from 1.5 to 6.5 GHz. These first results prepare the ground for developing a complete LTCC six-port receiver, which is our objective at present.

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