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HIGH-ISOLATION AND WIDE-BAND 180° HYBRIDS BASED ON ELECTRONICALLY TUNABLE LUMPED-ELEMENT FILTERS

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Abstract—A new high isolation lumped-element 180° hybrid, using electronically adjustable filters with varactor diodes, are proposed. This design is very simple and based on only two configurable low order ($N = 2$) filters. Due to the limited tuning frequency range of varactor diodes, maximum near-octave frequency coverage of 2.5–5 GHz was planned in the high isolation hybrid. An impressive simulated typical isolation in the range of > 60 dB was achieved. One of the typical applications of developed hybrids could be the conversion of 70 MHz IF to microwave frequencies, with broadband mixers in single-conversion converters and very high LO rejection (> 60 dB).

1. INTRODUCTION

Various types of 180° hybrids based on transmission lines have been widely used on broadband mixer applications, because of their reduced cost and simplicity [1–4]. However, their limited isolation figure of 20 or 30 dB, generally narrow bandwidth operation, and large occupied surface in relatively low frequencies are a number of limitations to be overcome in ultra-broadband applications, such as UWB. The proposed 180° hybrids and baluns in [5–8] take advantage of the equivalence between transmission lines and lumped elements filters.

On the other hand, some investigations have been carried out in recent years on tunable devices, based on metamaterial transmission

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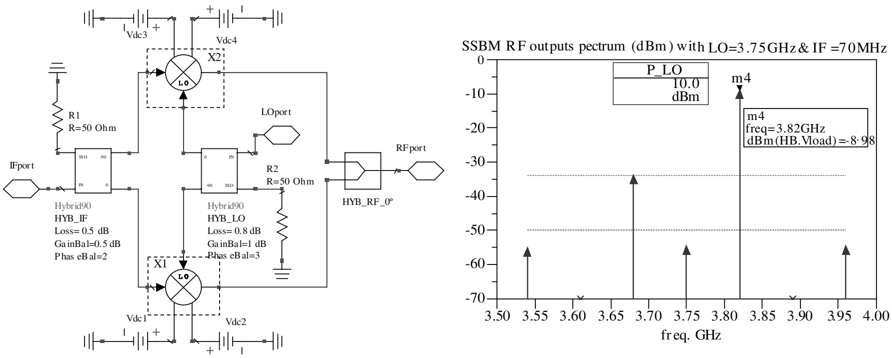


Figure 1. Microwave SSBM with more than 60 dB of LO suppression.

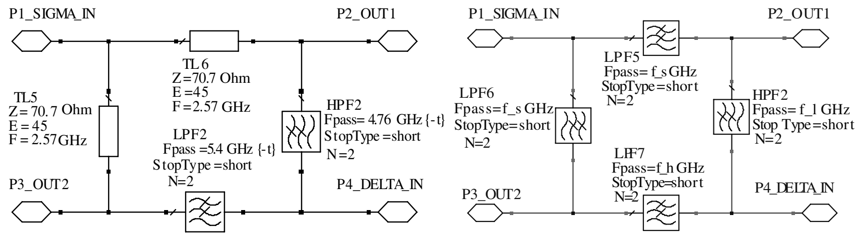
lines [4, 9, 10], which indicate feasible work of this kind of configurable devices. This article focuses on this line of tunable devices, delving into the very high isolation property, necessary for the use of designed hybrids on the single balanced mixers (SBM) of the typical DSBM (Double Side Band Modulator) or SSBM (Single Side Band Modulator) structures, in order to achieve a high rejection of the LO.

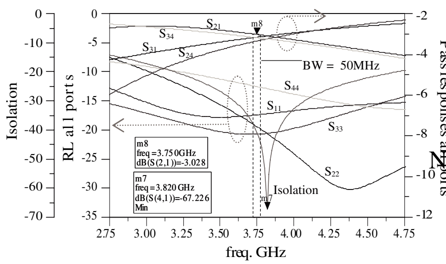
As seen in Figure 1, the adjustable high isolation SBM mixers — X1 & X2 — are inserted on a typical Hartley type phase-shift SSBM [11], in order to achieve higher suppression level of carrier than classical approaches [12]. Four DC voltages (independent between them on first approximation) are the key to achieve a carrier-rejection of > 60 dB. Moreover, sideband suppression was implemented by the input and LO 90° hybrids, with the balance parameters on the state-of-the-art range.

Furthermore, the high-isolation hybrids designed in Section 2 have a significant bandwidth, on the range of the octave. One of the devices is an all-lumped variant, with only concentrated components, and therefore minimum occupied surface. The designs have been developed with the aid of commercial software ADS from Agilent$^{\text{TM}}$, v.2009A, and their electromagnetic planar simulator, MOMENTUM, was extensively used.

2. HYBRID DESIGN AND DEVELOPMENT

The classical approaches of lumped-element 180° hybrids [5–7, 12], were based on the direct substitution of three 90° lines of the Rat-Race by low-pass filter sections (LPF), and the 270° line by high-pass filter (HPF). Several combinations of order (N) and open-type or short-





Fc (GHz)		2.5	3.75	5
f_h (GHz)		2.74	4.07	5.4
f_l (GHz)		2.41	3.58	4.76
Compact	dBpp BW=50 MHz	<1	<0.4	<0.25
Note 1 Ultra-Compact	dBpp BW=50 MHz	<1.7	<0.7	<1.4
Compact	Isolation (dB)	74	67	66
Ultra-Compact	Isolation (dB)	74	66	68

(a) Compact Version Note 1 (b) Ultra-compact Version Note 2

Figure 2. Ideal block diagrams of compact & ultra-compact hybrids, simulation plots of compact version and resuming table. (a) The length of the transmission lines on the schematic diagram was minimised to maintain the performance. The result was a 45° length line lower limit of operating frequency of hybrid (2.5 GHz). (b) The fixed corner frequency (f_s) of the LPF-s between ports P1 & P2 and P1 & P3 of the schematic diagram was optimised on ADS to 4.5 GHz.

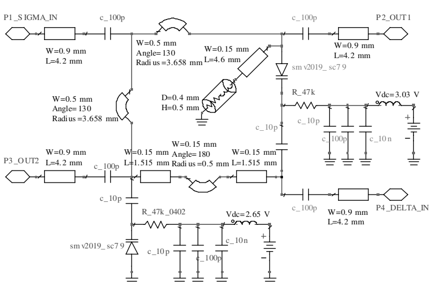
type stop band configuration were possible, but low order filters are preferred because of their simplicity when adjustable filters are used to tune the characteristics on frequency [9, 10]. This approach gives a minimum 3-varactor hybrid because all 3 LPF-s are converted to tuneable filters substituting the capacitors by varactors. Furthermore, this approximation results in two different varactor models on the hybrid, because of the combination of two capacitors in parallel with the basic third order filters.

Figure 2 shows how to achieve the simplest configurable hybrid, with only two equal varactors, and consequently, the way for a more compact device, maintaining the high-isolation aim: the cancelation of two signals on the 180° hybrid is based on the equality of amplitude and the 180° phase relations between the paths P1 → P2 → P4, and P1 → P3 → P4. Then the ideal infinite isolation ($S_{41} = 0$) could be achieved if one of these two options are implemented between 1 & 2 and 1 & 3 accesses: a) Two equal-length transmission lines, resulting in a compact version of hybrid, and b) two equal LPF-s between ports P1 & P2 and P1 & P3, with fixed cut-off frequencies, resulting in an ultra-compact all-lumped-element version. Modifying the ratio between cut-off frequencies of P3-P4 LPF (f_h) and P2-P4 HPF (f_l), high isolation could be achieved on a narrow-band margin (i.e., LO frequency on up-converters), maintaining a quasi-constant pass-response between ports P1 & P2, P1 & P3, P4 & P2 and P4 & P3.

Notes 1 & 2: 1) The length of the transmission lines on the schematic diagram was minimised to maintain the performance. The result was a 45° length line lower limit of operating frequency of hybrid (2.5 GHz). 2) The fixed corner frequency (f_s) of the LPF-s between ports P1 & P2 and P1 & P3 of the schematic diagram was optimised on ADS to 4.5 GHz.

70 MHz IF up-converter, with 50 MHz BW, and approximately 2.5 ÷ 5 GHz RF output, was used as an application example: cut-off frequencies are ideally synthesized and tuned with ADS system filters, to achieve a maximum figure of isolation between 1 and 4 accesses 70 MHz up from 50 MHz pass-band. Obviously, a trade-off between pass responses and isolation level exists: the crossing point of both is on the same point ideally, and then, 70 MHz down on frequency there is a dBpp maximum error, which is quantified on the contiguous table.

As seen in the graphs and table, the ultra-compact all-lumped hybrid of Figure 2 has worse pass & return loss (RL) responses,



Fc (GHz)	2.5	3.75	5
V_HPF (V)	3.03	9.32	18.01
V_LPF (V)	2.65	8.88	17.66
dBpp (BW = 50 MHz)	<1.2	<0.5	<0.3
Isolation (dB)	69	75	78

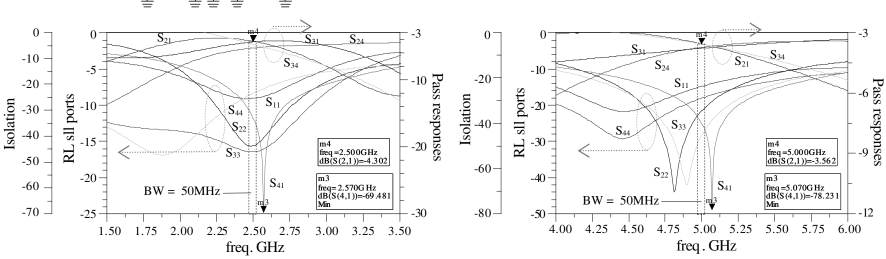
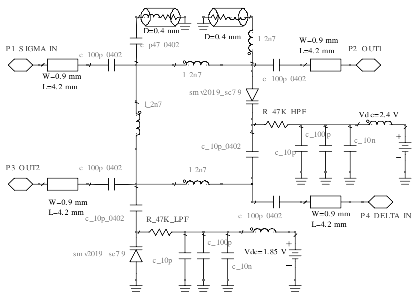


Figure 3. Schematic & quasi-realistic simulations of compact hybrid.



Fc (GHz)	2.5	3.75	5
V_HPF (V)	2.4	8.5	17.75
V_LPF (V)	1.85	7.6	16.36
dBpp (BW = 50 MHz)	<1.5	<0.55	<0.5
Isolation (dB)	69	74	89

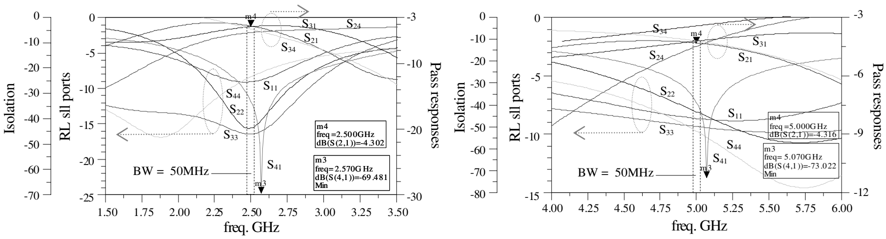


Figure 4. Schematic & quasi-realistic simulations of ultra-compact hybrid.

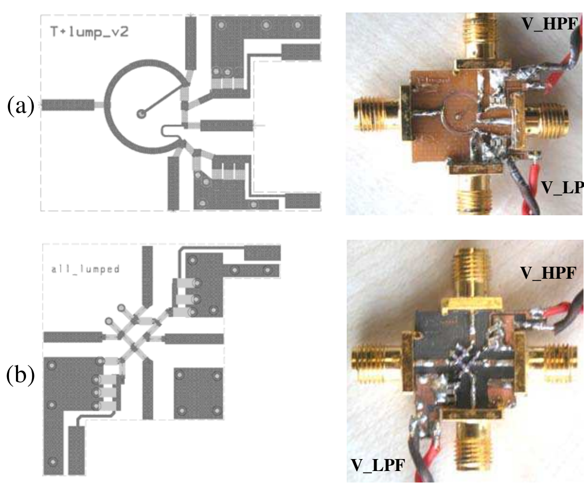


Figure 5. (a) Compact and (b) ultra-compact 180° hybrids layouts & photos.

but their advantage is, obviously, the compactness. Both cases have less dBpp on higher frequencies, which is better to optimise the up-converter behaviour.

The filter blocks were implemented using standard 0402 surface mounting (SMD) components, and the varactors are also standard type, SMV2019 model on SC-79 case, from Skyworks Solutions Inc [13]. It is important to remark that improving the state-of-the-art solutions [9, 10], in this case, both varactors could be the same model.

Schematic diagrams of both hybrids and the results of the quasi-realistic simulations are presented in Figures 3 and 4. The data in the tables, summarize the implementations, with an acceptable error on pass losses — less than 1.5 dBpp worst case — and a very high isolation of > 60 dB.

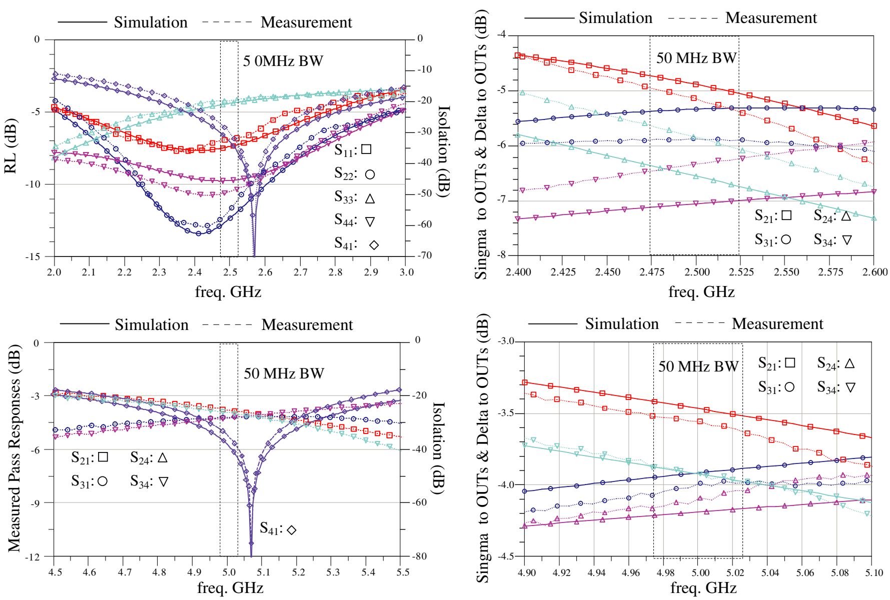
The filters with fixed corners in Figure 4 were designed using the same inductance as the adjustable LPF and HPF, in order to minimize the number of different components.

3. IMPLEMENTED HYBRIDS AND MEASUREMENT RESULTS

Two hybrids, presented in Figure 5, were mounted on a FR-4 substrate to verify the validity of high isolation in real conditions. Two independent polarization voltages were used on varactor biasing, in order to compensate the devices impairments and easily achieve the high isolation point.

The compendium of measurements of both hybrids is presented in Figures 6 and 7, with RL & Isolation, and Pass responses, presented in separated graphics. Due to a board fabrication and components tolerances, and specially the varactors impairments, the DC controls, V_HPF and V_LPF presented in the tables in Figures 6 and 7, are slightly different from quasi-realistic simulations in Figures 3 and 4. This causes different cross-points between configurable HPF & LPF-s of the hybrid, and appreciable differences (especially at 2.5 GHz) between simulation and measurements on RL and Pass responses. However, the utility of both high-isolation hybrids to reject high level signal, such as LO on SBM mixer with a valid pass responses dBpp, is guaranteed. To demonstrate it, the great similarity between simulated and measured high isolation (S_{41}) and simulated and measured pass responses are remarked.

The high frequency limit of the devices is also affected by parasitic effects between lumped-components metalized terminals and ground: therefore, the frequency-range of the hybrids lowers. These parasites were introduced in the ADS simulations, resulting in a great similarity with measurement results. As shown in the table of Figure 6, the achieved frequency ratio ($r = 2$) is just higher than an octave, because the margin of the varactors could go up to 20 V DC.



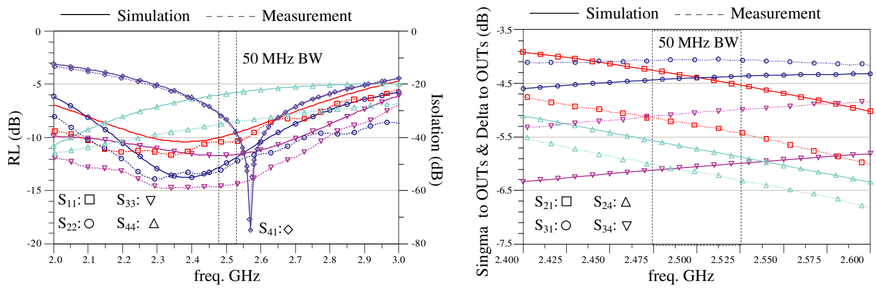
	Measu rements			Realistic Simulation		
Fc (GHz)	**2.5**	**3.75**	**5**	**2.5**	**3.75**	**5**
V_HPF (V)	1.29	5.62	15.32	1.3	6.79	14.72
V_LPF (V)	0.85	6.76	16.9	0.82	6.13	14.14
dBpp (BW=50 MHz)	<1.53	<0.6	<0.6	<2.4	<1.2	<0.85
Isolation (dB)	70	80	75	72	75	84

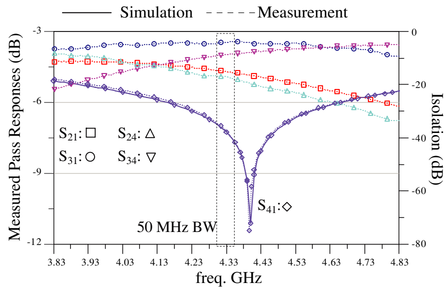
Figure 6. Compact 180° hybrid RL & isolation, and pass responses measurements & octave-range compendium table.

In the all-lumped ultra-compact hybrid, the parasites are greater, because of higher amount of lumped components, and the higher coupling between them (e.g., lumped-inductors that have an inductive coupling because of proximity). Thus, the differences between simulated pass responses and measured ones are higher than compact version, and the range of the hybrid is less than an octave: the actual frequency range extends from 2.5 to 4.33 GHz (1.7 ratio).

Comparison between simulation and measurement is presented only on the low part of frequency range (2.5 GHz), and the high isolation property is highlighted. The table in the figure remarks the utility of hybrid to reject high level signal like LO on SBM mixer with a valid pass responses dBpp.

The last measurement is the comparison between "*low-level*" *and*





Summary Table	Measurements		
Fc (GHz)	2.5	3.75	4.33
V_HPF (V)	1.89	7.55	12.36
V_LPF (V)	2.12	9.34	16.9
dBpp (BW=50 MHz)	<2.3	<2.2	<1.6
Isolation (dB)	>70	>63	>74

Figure 7. Ultra-compact 180° hybrid RL & isolation, pass responses, & quasi-octave range compendium table.

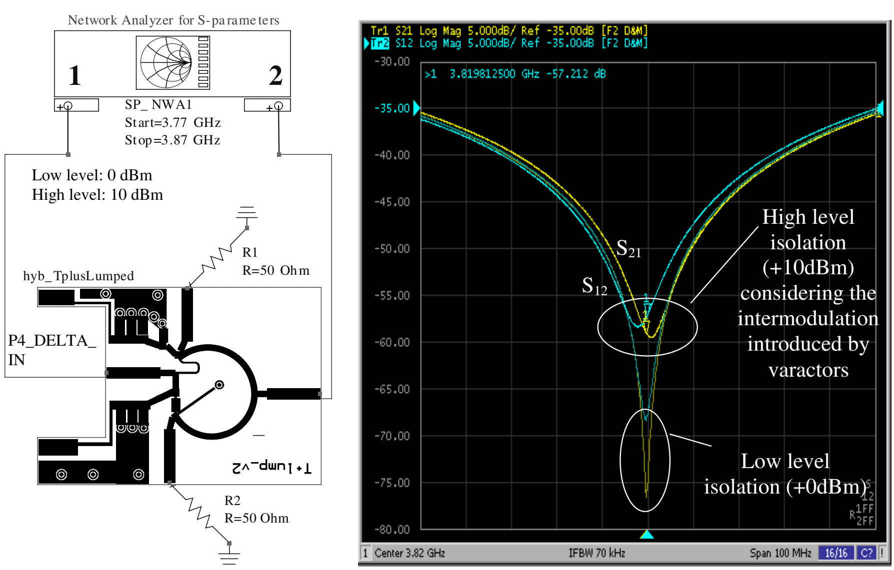


Figure 8. Compact Hybrid: measurement set, and comparison between high-level and low-level maximum isolation.

"*high-level*" *isolation* of the hybrid: in other words, it is a measurement related to the intermodulation generated by the varactors non-linearity, which would affect the actual isolation when a high-level signal like LO is injected to the hybrid of the SBM mixer on the converter scheme (see Figure 1).

The plot of Figure 8 is a measurement of parameter S_{41} of a compact hybrid, i.e., isolation, and was extracted with Agilent Network Analyzer E5071A, using two levels of power source: 0 dBm low-level, and +10 dBm high-level. In both cases, the two varactor polarisations were varied (V_HPF and V_LPF in Figures 3 & 4 & 5) to search the point of maximum isolation.

As seen in the figure, the isolation is slightly degraded, but still useful: i.e., for a typical single balanced mixer application, LO level would be in the range of +10 dBm, and then a high practical rejection would be possible, despite the contribution of varactor non-linearity.

This result proves the capability of this kind of high-rejection hybrids to form a part of the microwave frequency agile converters. The difference between S_{21} and S_{12} traces also indicates that intermodulation on varactors causes a slight non-reciprocal effect on the hybrid's behaviour.

4. CONCLUSIONS

Two versions of compact lumped-element 180° hybrids, with very high and configurable isolation, were presented: one is based on a mix solution, with a pair of transmission lines and a pair of LPF and HPF; the other is fully-lumped and results in an ultra-compact design. The use of one single varactor model to cover an octave performance is quite remarkable, and the high level of practical isolation achieved is very useful for up-converter applications from 70 MHz IF to the UWB microwave band. Also, this property could be useful for direct-conversion very low-noise receivers, that need a high LO blocking, as well as many other applications.

Compared to state-of-the-art configurations [9, 10], the volume reduction is more than 70% in compact version, and 85% in ultra-compact all-lumped version, both cases with less number of lumped components and only two varactors, both of the same model. The ultra-compact hybrid is the first all-lumped configurable 180° hybrid that the authors know. Also, the frequency bandwidth reported for the compact version is higher than state-of-the-art designs. Finally, it is highlighted that manufacturing board was in standard processes and that the components are also standard and economical.

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