A Low-Cost Modular Transmit Front-End with Analog Beamforming Capability

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***Abstract*—In this paper, we present a radio frequency (RF) transmitter front-end that can be used in analog beamforming applications. The proposed system is modular and can be employed at different frequencies whereby C-band operation is shown. Using low-cost components and substrates, this design makes analog beamforming affordable also for commercial applications with unit costs below 130 € and expected overall gain of 11.1 dB. We demonstrate the system performance in terms of S-parameter measurements with frequency translation to 7.0 GHz. Reproducibility of the achieved results is shown by analyzing multiple front-end prototypes. The beamforming capability is verified by antenna pattern measurements with an eight-element array.**

I. Introduction

Analog beamforming techniques have long been employed in military applications like phased array radars for aircraft and ships [1]. With the advent of multiple input, multiple output (MIMO) communication in recent years, the demand for non-digital beamforming techniques has risen. While purely digital beamformers provide full control of signal amplitudes and phases, these systems require powerful digital circuits with one digital-to-analog converter (DAC) per antenna element. For applications with large antenna arrays, this leads to high system complexity and power consumption. Recent studies therefore investigate the use of hybrid or completely analog beamforming [2], [3].

In this paper, we propose a modular transmit front-end which performs analog beamforming by using digitally controlled variable gain amplifier (VGA) and phase shifter integrated circuits (ICs). The modular approach allows us to use the device for different transmit frequencies and thus makes the design very flexible. Distinctive features are low cost and power consumption as well as good reproducibility of performance.

II. Front-End Design and Implementation

A. Conceptual Design

The front-end is split into two parts: the beamforming and the upconverter units, whereby both should be connected in series. The block diagrams of both units are shown in Fig. 1. The beamforming unit takes a baseband or low frequency (LF) input and mixes it up to an intermediate frequency (IF) as can be seen in Fig. 1a. A bandpass filter limits the signal to the frequency range at which the subsequent phase shifter works with nominal performance. This shifter and also the subsequent VGA are digitally controlled and used to adjust amplitude and phase of the input signal.

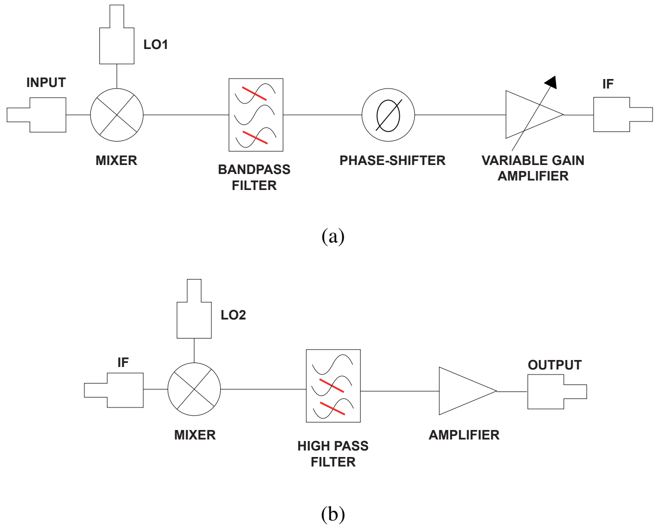

Fig. 1. Block diagrams of the two front-end modules: (a) Beamforming unit composed of a mixer, a bandpass filter, a phase shifter and a VGA; (b) Upconverter stage composed of mixer, highpass filter and amplifier.

As the operation frequency of phase shifters is usually limited, we use the upconverter module in Fig. 1b to achieve the desired transmit frequency. This circuit consists of another mixer stage, a highpass filter, and a radio frequency (RF) amplifier. The choice of components and local oscillator (LO) signal defines the transmit frequency of the whole front-end.

The proposed design concept offers distinct advantages. Through the use of two separate units, the frequency plan is very flexible. The beamforming unit is quite generic and can be used in combination with different upconverter units. The upconverter on the other hand can be designed to suit the desired transmit frequency and necessary output power. Additionally, having the steerable components on the IF makes the printed circuit board (PCB) design easier. The lower frequencies are less susceptible to impedance mismatch and

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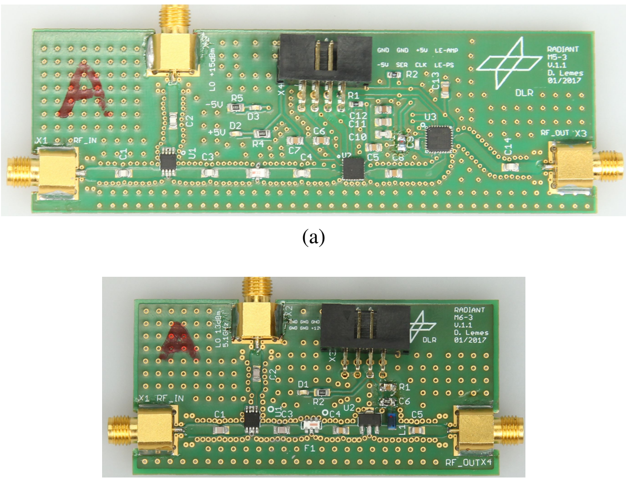
TABLE I
COMBINED LINK BUDGET

Component	Type	Gain / dB	Budget / dB	Price / €
HMC-316 [4]	Mixer	−7.5	−7.5	6.07
BFCN-1945+ [5]	Bandpass	−1.8	−9.3	4.35
MAPS-010163 [6]	Phase shifter	−5.0	−14.3	49.87
ADL-5240 [7]	VGA	19.7	5.4	7.39
HMC-218 [8]	Mixer	−7	−1.6	5.71
HFCN-6010+ [9]	Highpass	−1.3	−2.9	3.29
GALI-2+ [10]	Amplifier	14	11.1	1.27



(a)

(b)

Fig. 2. Assembled beamforming (a) and upconverter (b) PCBs. The dimensions are 110 mm × 36 mm and 74 mm × 36 mm, respectively.

ground plane interruptions. These occur due to the necessary control lines that have to be implemented for the steerable components. When designing the upconverter unit, one can focus on good RF design practice.

B. Fabricated Prototypes

The RF components used in this work are listed in Table I along with the expected link budget of the combined front-end. In our case, a C-band output signal around 7.0 GHz was generated from a 500 MHz input signal. Thus, the LO signals were chosen to be 1.4 and 5.1 GHz, respectively. The presented design shows an overall gain of 11.1 dB. If higher output power is needed, it can be achieved by drop-in amplifiers or replacing the upconverter unit with a more powerful one.

The front-end PCBs were fabricated using two-layer FR-4 substrate with standard thickness of 1.55 mm. The cost for ten units, i.e. 20 PCBs is currently around 180 €. The assembled circuits are shown in Fig. 2. Table I lists the price per piece for the RF components, Table II shows the prices of the additional parts of the front-end. The prices are based on the assumption that a total of ten front-ends is fabricated.

The total price of one front-end consisting of beamforming and upconverter unit is thus 127.75 €. As can be seen from Table I, this number is dominated by the cost for the phase shifter. However, to obtain the phase resolution necessary for beamforming, a cheaper device could not be chosen.

TABLE II
PRICES OF ADDITIONAL PARTS

Part	Price / €
PCBs	18.00
SMA connectors	15.00
Passive RCL components + LEDs	15.60
DC connectors	1.20

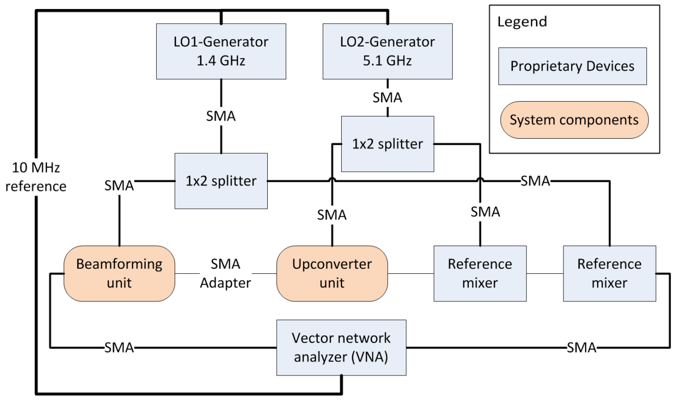


Fig. 3. Setup to measure the whole front-end directly with a VNA. Two reference mixers are used after the front-end to ensure equal input and output frequencies at the VNA.

III. TEST AND MEASUREMENT METHODOLOGY

To assess the performance of the front-ends, we used two measurement techniques. First, standard vector-mixer calibration (VMC) using a vector network analyzer (VNA), an external LO, and a pair of calibration mixers is considered. This method is well suited to obtain the conversion gain of a single converter stage. However, the whole front-end could not be measured with this method as it has two upconverter stages and the required hardware for a VMC was not available.

Therefore we used the measurement setup depicted in Fig. 3 to assess the relative amplitudes and phases between all front-ends. The front-end input is thereby connected to the VNA port 1. The upmixed output signal is fed to two commercial mixers in downconverter configuration [11]. The output of the second mixer is connected to VNA port 2. Two signal generators create the necessary LO signals which are split and fed to the respective front-end module and downmixer. Thus, the VNA can perform a normal S-parameter measurement whereby only S11 and S21 are of interest. All measurement devices are synchronized with a 10 MHz reference. The proposed setup can be used to calibrate the front-ends.

It should be noted that this configuration can only be used to assess the relative gain and phase values of the front-ends, not the absolute ones. This is due to the reference mixers in the signal paths. This should be kept in mind when regarding the measurements obtained with the setup in Fig. 3.

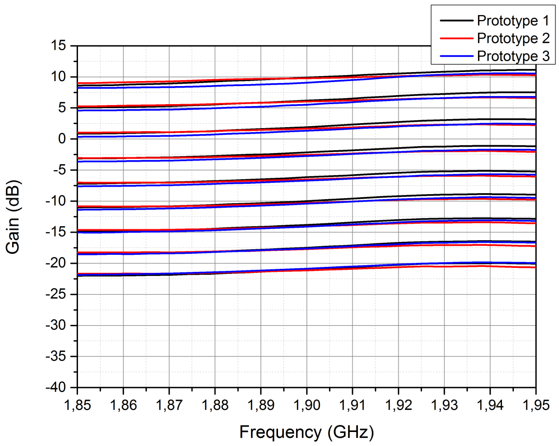


Fig. 4. Upconverter gain (VC21) for selected VGA states and three prototypes of the beamforming module. It can be seen that the curves of the three units are nearly overlapping, proving the reproducibility of the design.

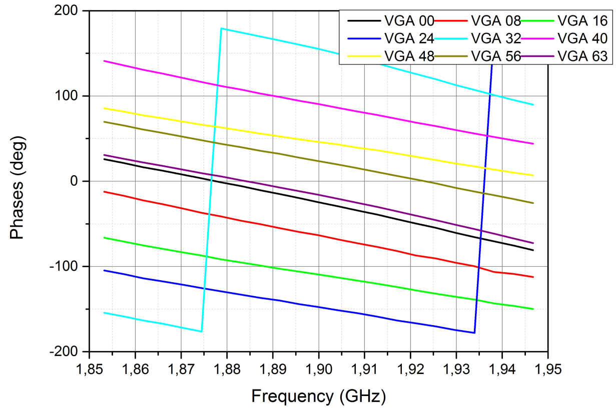


Fig. 5. Measured phase values for one beamforming module.

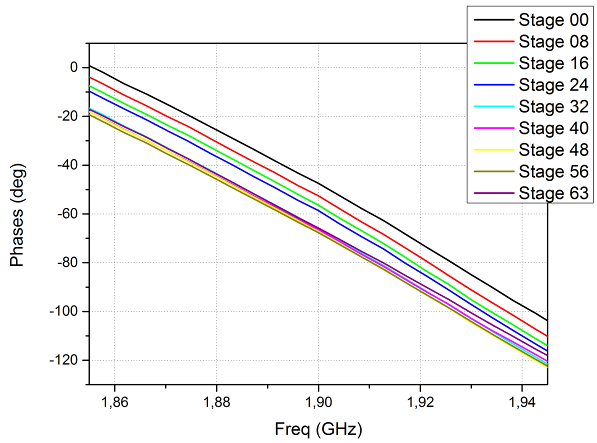


Fig. 6. Phase shift introduced by the VGA for different gain values.

IV. Measurement Results and Performance

The VGA and phase shifter are both accepting 6-bit control words, i.e. they have 64 possible states. In order to preserve the visibility of the plots, only nine of these are shown in each figure. We used the following control words to illustrate the available dynamic range: 0, 8, 16, 24, 32, 40, 48, 56, 63.

A. Beamforming Module

To prove the reproducibility, a comparison between three prototypes of the beamforming module is shown in Fig. 4. These results were obtained with the standard VMC measurement setup and thus show the upconverter gain of the circuits. The line groups correspond to the nine VGA states mentioned above. Only small discrepancy between the prototypes is observed. It is mainly due to tolerances of soldering and the intrinsic variability of the electrical properties of the components. The observed maximum gain is slightly higher than estimated in our link budget in Table I.

The phase variation capability of the beamforming module is shown in Fig. 5, using nine of the 63 available states of the phase shifter. For better readability, we provide the results for a single beamforming module only. Combining the phase shifter functionality with the gain adjustment by the VGA, it is possible to generate nearly arbitrary beamforming coefficients. It can be seen that the resulting phase values in Fig. 5 do not have exactly equal spacing. This introduces an error to the beamforming coefficients and may deteriorate the resulting beam pattern in comparison to the theoretical result.

Additionally, a phase variation due to the operation of the VGA could be observed. Varying the gain level introduces different phase shifts because of the varying number of attenuators switched into the signal path by the VGA, which produces a variation of the electrical path length. Fig. 6 shows the measured phase for different VGA settings, i.e. without changing the phase shifter. We observed phase differences in a range of 18.24°. In order to increase the beamforming accuracy, this effect needs to be taken into account during calibration of the front-ends and when setting coefficients.

B. Upconverter Module

Using again the standard VMC setup, the parameters S11 and VC21 have been measured and are shown in Fig. 7. As before, we compare three units to show the reproducibility of the results. The upper group of curves represents the upconverter gain (VC21), while the lower group shows the measured input matching (S11). The obeserved S11 of <-8 dB is acceptable and corresponds well to the expectation from the mixer datasheet. The measured gain around 6 to 7.5 dB is in accordance with the link budget from Table I.

C. Combined Front-End

Having analyzed the two modules individually, we shall now evaluate the performance of the whole front-end with beamforming and upconverter modules connected in series. Since we do not have the possibility to perform a VMC with two upconverter stages, the measurement setup shown in Fig. 3

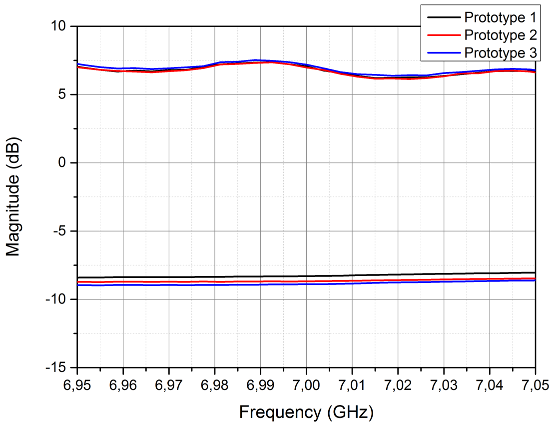


Fig. 7. Measured S11 (lower curves) and VC21 (upper curves) for three prototypes of the upconverter module. Reproducibility of the results can be clearly seen.

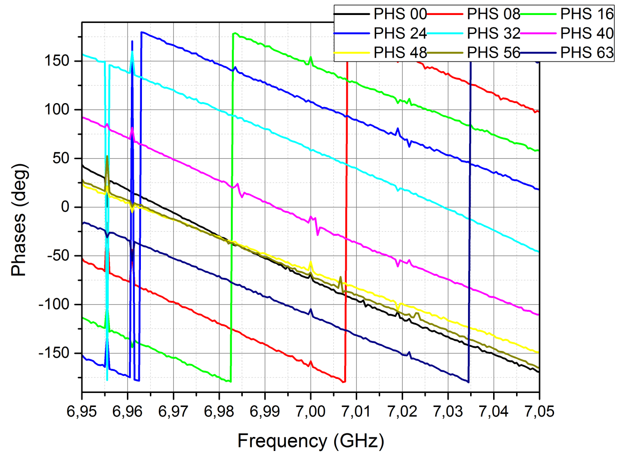


Fig. 9. Total phase shift for the complete front-end controlled by the phase-shifter.

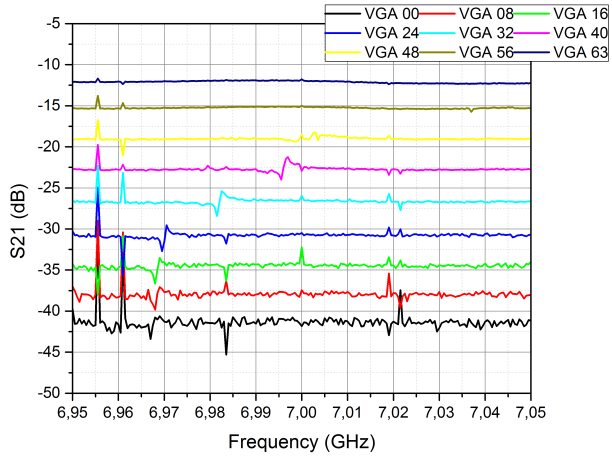


Fig. 8. Total gain for the complete front-end controlled by the VGA.

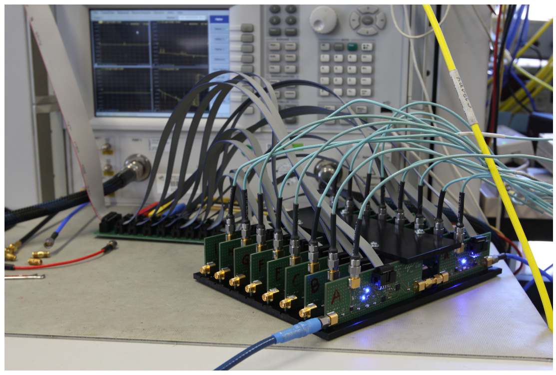


Fig. 10. Measurement and calibration of eight front-ends using the proposed VNA setup.

is now employed. As mentioned above, it should be noted that the obtained gain values include the insertion loss of the reference mixers. Thus, it is only used to compare the output power between front-ends.

Fig. 8 and Fig. 9 show respectively the magnitude and phase of the VNA measurement for one front-end when VGA and phase shifter are actuated. The spikes which can be observed in both curves are due to spurious frequencies in the setup created by the subsequent up and down conversion. We can observe that amplitude and phase steering also works with the complete front-end. Moreover, by sequentially measuring all front-ends, calibration and beamforming coefficients can be adjusted. This shall be used in the following.

D. Beam Steering Application

The proposed front-ends were applied to steer an eight-element linear microstrip antenna array. For this purpose, eight boards were prototyped. Fig. 10 shows the front-ends rigged for S-parameter measurements for calibration using the previously described technique. Using the depicted setup we obtained coefficients for 0°, 30°, and 45° phased array type beam steering

The PCBs were then connected to the antenna array and the complete setup was installed in an anechoic chamber. The hardware on the positioner is shown in Fig. 11: In the back, we see the antenna array with the front-ends. The ribbon cables are used to actuate VGAs and phase shifters and to distribute the supply voltages. Two RF amplifiers are used to enhance the signal level of the LO signals.

In Fig. 12, we see the measured radiation patterns for the three beam steering scenarios mentioned above. Successful steering of the main beam to the desired directions can be clearly observed. The side-lobe levels are slightly higher than one would expect from theory. However, this is due to the discretization of the beamforming coefficients which cannot exactly match the calculated amplitude and phase values. From these patterns, we can conclude that the proposed front-ends

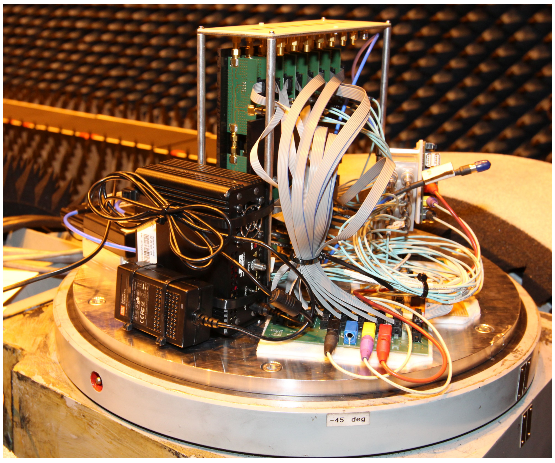


Fig. 11. Eight-element antenna array with front-ends installed on the positioner in an anechoic chamber. This setup was used to measure the antenna patterns with beamforming.

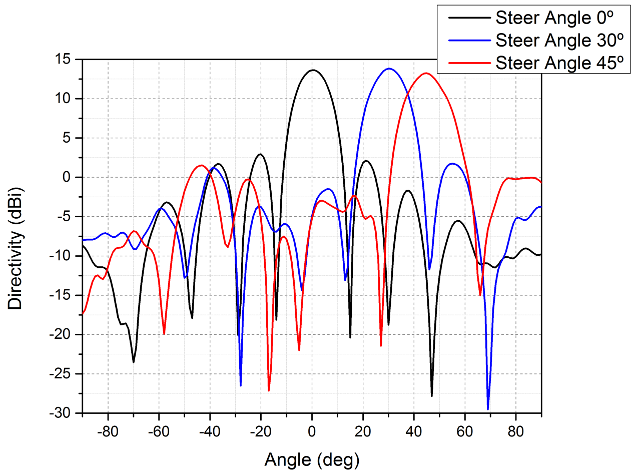


Fig. 12. Measured radiation patterns obtained with the realized front-ends and the eight-element array.

are suitable for application in analog beamforming.

V. Conclusion

In this work, we have proposed a design scheme for a transmitter front-end with analog beamforming capability. The use of a modular architecture with independent beamforming and upconverter units allows a flexible configuration in terms of transmit frequency and power. Additionally, we have demonstrated an implementation of the proposed system operating in C-band, whereby good performance and reproducibility have been verified. By using standard components and two-layer FR-4 laminates, the front-ends could be fabricated for under 130 € per piece.

A special setup was presented which allowed S-parameter measurements of the combined front-ends and thus calibration and adjustment of the beamforming coefficients. Finally, we have proven the applicability of the proposed front-end topology by radiation pattern measurements with an eight-element linear array in an anechoic chamber. We thereby operated the system in phased array fashion and could demonstrate its analog beam steering ability.

References

[1] W. J. Fontana and K. H. Krueger, "An/spy-3: the navy's next-generation force protection radar system," in *IEEE International Symposium on Phased Array Systems and Technology, 2003.*, Oct 2003, pp. 594–603.

[2] J. Nsenga, A. Bourdoux, and F. Horlin, "Mixed analog/digital beamforming for 60 ghz mimo frequency selective channels," in *2010 IEEE International Conference on Communications*, May 2010, pp. 1–6.

[3] V. Venkateswaran and A. J. van der Veen, "Analog beamforming in mimo communications with phase shift networks and online channel estimation," *IEEE Transactions on Signal Processing*, vol. 58, no. 8, pp. 4131–4143, Aug 2010.

[4] *HMC316MS8 / 316MS8E GaAs MMIC High IP3 Double-Balanced Mixer, 1.5 - 3.8 GHz*, Analog Devices Inc., One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, v02.0505.

[5] *BFCN-1945+ Data Sheet – LTCC Bandpass Filter*, Mini-Circuits, P.O. Box 350166, Brooklyn, NY 11235-0003, rev. D.

[6] *MAPS-010163 – Digital Phase Shifter 6-Bit, 1.4 -2.4 GHz*, MACOM Technology Solutions Inc., 100 Chelmsford Street, Lowell, MA 01851, rev. V5.

[7] *ADL5240 Data Sheet – 100 MHz to 4000 MHz RF/IF Digitally Controlled VGA*, Analog Devices Inc., One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, rev. A.

[8] *HMC218AMS8E – GaAs MMIC SMT Double-Balanced Mixer, 4.5 - 6 GHz*, Hittite Microwave Corporation, 20 Alpha Road, Chelmsford, MA 01824, v00.0411.

[9] *HFCN-6010+ Data Sheet – Ceramic High Pass Filter*, Mini-Circuits, P.O. Box 350166, Brooklyn, NY 11235-0003, rev. C.

[10] *GALI 2+ Data Sheet – Surface Mount Monolithic Amplifier DC-8 GHz*, Mini-Circuits, P.O. Box 350166, Brooklyn, NY 11235-0003, rev. D.

[11] *Double Balanced Mixers M1-0008*, Marki Microwave, 215 Vineyard Court, Morgan Hill, CA 95037, Nov. 2013.