7.6-8.6GHZ AGILE IMAGE REJECT ON-CHIP RECEIVER FRONT-END FOR ADAPTIVE X-BAND SMART SKIN ARRAY ANTENNAS

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SUMMARY

In this paper, we evaluate a new design of a previously presented agile single-chip receiver front-end intended for a digital beamforming X-band smart skin array antenna. Firstly, by using a two-stage low noise amplifier in each filter section of the tunable active filter used in the front-end, a higher filter gain and selectivity as well as a lower filter noise figure can be achieved at the expense of a smaller filter tuning range. Secondly, the 1GHz-IF double balanced mixer also utilized in the front-end has been re-optimized to achieve higher image rejection and lower conversion loss. As a result of the filter and mixer RF performance improvements achieved the re-designed front-end can exhibit at least 50-85dB of image rejection, up to 13dB of conversion gain, a 6.4dB minimum value noise figure and 60-65dB of spurious-free dynamic range over the 7.6-8.6GHz agile receiver bandwidth, respectively.

INTRODUCTION

A low vulnerability to jamming signals due to electronic warfare or electromagnetic interference, for example, is essential in modern radar systems. One way to achieve this is to use a frequency hopping radar where the transmitter and the receiver jump in a pseudo-random like way between different selected frequencies. To further reduce the vulnerability to jamming signals adaptive methods and digital beamforming can be adopted [1]. Frequency hopping adaptive radar systems may in the future also rely on compact conformal phased array antennas that can be confined inside the metallic surface of a vessel or an aircraft, for example, so called "smart skin" antennas [2]. In such multi-channel adaptive array antennas the number of transmit/receive (T/R) modules required is anticipated to be as high as several hundreds or more. To minimize size and cost of each T/R-module is therefore becoming increasingly important. As a consequence of this, increased interest has been focused on the possibility of using tunable narrow-band active monolithic microwave integrated circuit (MMIC) filters to reduce the vulnerable bandwidth of frequency hopping radar receivers [3]. Compared with using a fixed frequency bandpass filter, a tunable filter may also reduce the number of down-converting stages required in an agile receiver by allowing a greater down-conversion step to be made. Rejection of interfering signals that, for example, may occur at the receiver image frequency ($f_{image}=f_{RF}\pm 2f_{IF}$ where f_{RF} and f_{IF} denote the radar frequency and the intermediate frequency of the receiver, respectively) should be high enough to minimize the effect of jamming. Typical requirements for receiver front-ends of adaptive X-band (8-12GHz) antennas are summarized in Table 1. The specification is based on our experience in the area and on assumed radar system requirements. To the best of our knowledge, relatively few papers have been published on fully monolithically integrated agile image reject front-ends at X-band and above. Zelley [4] presented a 12-18GHz single-chip transceiver with 20dB of image rejection. In this paper, we evaluate a re-design of an agile image reject filter/mixer single-chip X-band receiver front-end that was first presented in [3]. Compared with results obtained in [3], measurements on the re-designed front-end show an improved RF performance in terms of higher image rejection and conversion gain as well as lower noise figure, respectively.

Conversion gain (G)	≥ 10dB
Noise figure (NF)	< 5 dB
Input third order intercept point (IIP_3)	≥ -6 dBm
Spurious-free dynamic range (SFDR)	≥ 109 dB/Hz$^{2/3}$ (≥ 60dB for a noise bandwidth B= 20MHz)

Table 1: Typical receiver front-end requirements in future adaptive X-band radar antennas.

7.6-8.6GHZ AGILE IMAGE REJECT SINGLE-CHIP RECEIVER FRONT-END

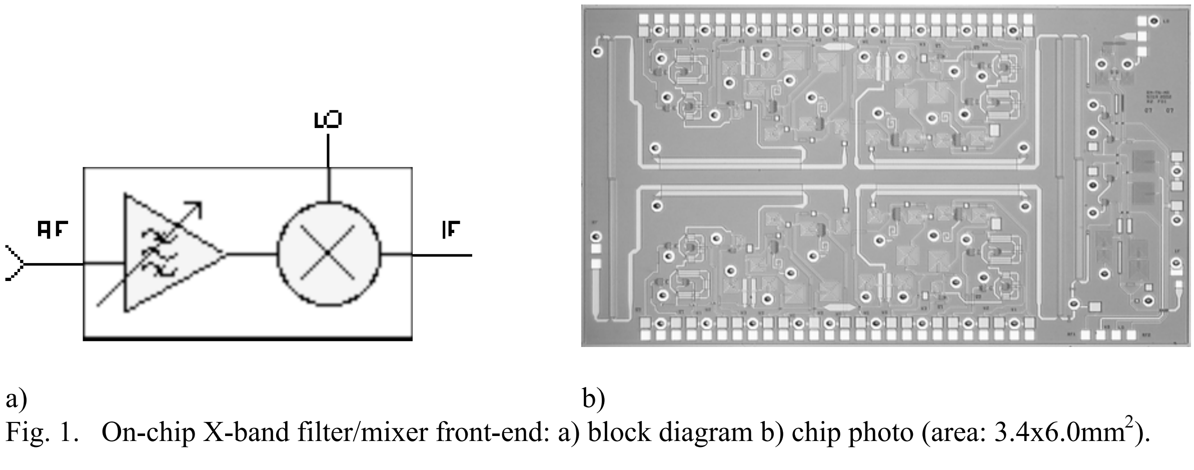
In this section, we shortly describe some new design improvements that have been carried out in a re-design of an agile single-chip X-band receiver front-end originally presented in [3]. This front-end is based on two recently developed X-band circuits: a tunable active MMIC filter [5] and a 1GHz-IF image rejection MMIC mixer [6]. The front-end presented in [3] was demonstrated to exhibit a relatively good RF performance in terms of maximum values of SFDR and image rejection obtained (around 60dB, respectively) over its agile bandwidth (7.9-9.7GHz). Measured values of front-end conversion gain were reported in [3] to be not much higher than 0dB. The noise figure of the front-end in [3] was estimated to be at least 7dB (front-end noise figure was later measured to 8-9dB over the agile bandwidth). With the aim to improve front-end performance, we have re-designed the filter and the mixer circuits used in the first version of the front-end. Design improvements of these two MMIC's and the combined re-designed single-chip front-end are described below.

Tunable active filter and image rejection mixer

In [3] and [5] a filter implementation was chosen that consists of two identical (second order) recursive active filters placed in a balanced configuration between two quadrature couplers. Recursive active MMIC filters have been shown to be promising for narrow-band and low-noise applications since high-Q filters of this type can be designed with high gain in combination with a noise figure approaching that of the low-noise amplifier (LNA) used in the filters [7]. Such filters could potentially replace the more traditional cascade of an LNA and a passive filter (that often can be rather bulky). Filter frequency tuning was implemented in [3, 5] using the concept of self-switched (three-bit) time shifters that enables (eight) discrete center frequency (f_c) tuning states (i.e. 000-111). A close to adequate filter noise and large signal performance (NF=6dB and $IIP_3\approx$0dBm) together with a tuning range in the order of 20% (7.9-9.7GHz) were obtained in [5]. Measured values of filter gain and out-of-band rejection were, however, found in [5] to be typically 7-9dB and 3-5dB lower than expected, respectively. It is shown in [8] that the use of a cascaded two-stage LNA in each filter section of the balanced active filter enables a higher filter gain and selectivity as well as a lower filter noise figure to be achieved, respectively. Finally, we have re-designed the 1GHz-IF mixer circuit used in [3]. Firstly, the use of larger transistor sizes in the mixing stages of this double balanced mixer improves linearity. Secondly, by improving the mixer phase and amplitude balance as well as the internal impedance matching in the mixer output stage, higher values of image rejection and lower values of conversion loss are obtained, respectively.

Single-chip filter and mixer front-end

The re-designed filter and mixer circuits described above have been utilized in a new version of our previously proposed on-chip X-band receiver front-end. Block diagram and chip photo of the re-designed front-end are shown in Figs. 1 a and b, respectively. The front-end is fabricated in a 0.2μm GaAs PHEMT MMIC process from the OMMIC foundry.

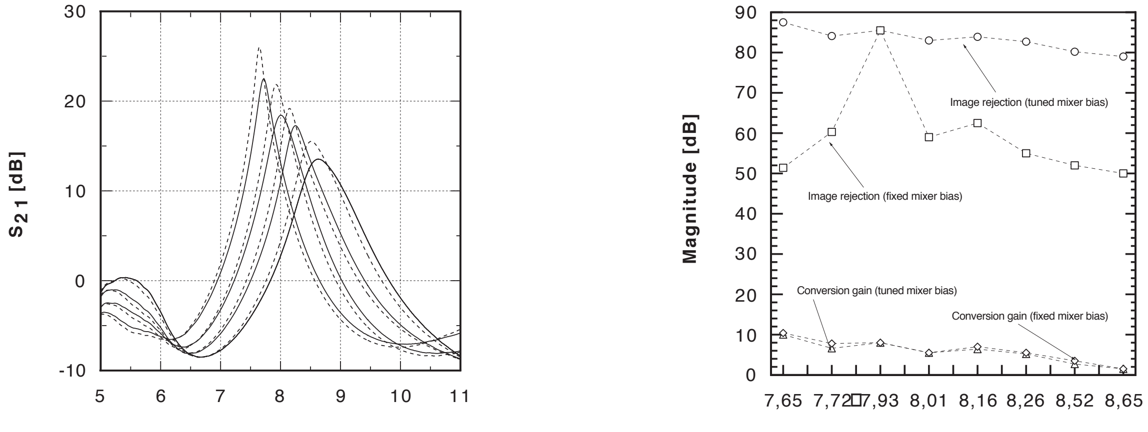


a) b)

Fig. 1. On-chip X-band filter/mixer front-end: a) block diagram b) chip photo (area: 3.4x6.0mm^2).

RESULTS

We have performed RF measurements on break out circuits containing the re-designed filter and mixer as well as on the combined single-chip filter/mixer front-end. Figure 2a shows measured maximum transmission gain (s_{21}) of the active filter used in the front-end at all eight possible filter center frequency tuning states (i.e. 000-111). As can be seen, the filter is discretely tunable to eight different frequencies between 7.6-8.6GHz corresponding to a relative tuning range of 13%. According to simulations the filter is tunable between 7.3-8.4GHz. The discrepancy may be explained by the fact that two off-chip resistance networks have been bonded to the re-designed filter in an attempt to compensate for a layout error [8]. Measured values of maximum s_{21} vary between 13.5-26.0dB over the agile bandwidth. Filter DC current $I_{DD}(filter)$ drawn from a drain bias (V_{DD}) of 3V equals in this case 250mA. According to simulations, maximum s_{21} is obtained when $I_{DD}(filter)$=68mA. Figure 2b shows measured front-end image rejection (2GHz below f_c) and conversion gain at the eight center frequencies in the case of fixed and tuned mixer bias, respectively. A front-end image rejection that varies between 50-85dB over the agile bandwidth is achieved when a fixed mixer bias (V_{DD}=5V and $I_{DD}(mixer)$=56mA) is used at all eight center frequencies. Re-tuning of mixer bias to obtain maximum possible mixer image rejection at each center frequency results in a front-end image rejection of 79-87dB from 7.65 to 8.65GHz. $I_{DD}(mixer)$ varies in this case between 51-58mA. Measured values of front-end conversion gain across the agile frequency band are essentially the same (around 1-10dB) regardless if fixed or tuned mixer bias is used (see Fig. 2b). In both cases, $I_{DD}(filter)$ is set to 160mA. Front-end conversion gain increases to 2-13dB over the agile bandwidth when $I_{DD}(filter)$ is raised to 250mA. An RF input power of –20dBm and an LO power of 9dBm were used during measurements.



a) b)

Fig. 2. a) Measured maximum gain (s_{21}) of the filter used in the front-end at all eight different center frequencies. b) Measured front-end image rejection and conversion gain over the agile bandwidth.

Typical measured filter, mixer and front-end data are summarized in Table 2. As a comparison, simulated filter, mixer and front-end results are also shown in this table. All simulated results are obtained using *HP EEsof* CAD-tool Libra v.6.0 together with foundry-provided circuit component libraries. As can be seen in Table 2, measured filter data are generally in an over-all agreement with corresponding simulated results. However, measured values of front-end conversion gain and *NF* are typically 7-8dB lower and up to 2dB higher than expected, respectively. These discrepancies could (at least partially) be explained by a 4dB higher mixer conversion loss and a 1dB higher filter *NF*, respectively, compared with simulations (see Table 2). The 9-10dB higher measured values of front-end IIP_3 (compared with corresponding simulated values) could almost entirely be explained by the 7-8dB lower measured values of front-end conversion gain (also compared with simulations). Compared with the front-end in [3], the front-end evaluated in this paper can obtain at least 20dB higher values of image rejection together with up to an order of magnitude higher conversion gain and up to 2dB lower *NF* at the expense of an 800MHz smaller tuning range. A comparison with typical requirements given in Table 1 further imply that our re-designed front-end can achieve a close to adequate noise and large signal performance for the receivers of future adaptive X-band antennas. It could here be argued that the requirements on receiver *NF* and conversion gain quite easily may be met if we use an LNA with sufficiently high gain and low *NF* in front of the front-end. This approach will, however, also result in an impairment of receiver IIP_3 by an amount that, at least, is given by the gain of the LNA used. It means our front-end, in that case, should be re-optimized to achieve an IIP_3 that is sufficiently high (also when an LNA is used in front of it) to enable the requirement on receiver IIP_3 to be met.

Results	**Image rejection [dB]** (f_{RF}-2f_{IF})	**Conversion gain [dB]** (f_c)	**NF [dB]** (f_c)	**IIP3 [dBm]** (f_c)	**SFDR* [dB]** (f_c) *B=20MHz
Filter (meas.) [8] (f_c=7.6-8.6GHz)	22-32	13-26	4.4-5.2	-8 to +5	58-67
Filter (sim.) [8] (f_c=7.3-8.4GHz)	21-31	13-22	3.5-4.2	-9 to +3	58-67
Mixer (meas.) (f_{RF}=8-12GHz)	25-50 (without tuning) >60 (with tuning)	-6 to –2	12-14	N/A	N/A
Mixer (sim.) (f_{RF}=8-12GHz)	27-37 (without tuning) >50 (with tuning)	-2 to 2	8-12	14-19	71-72
Receiver (meas.) (f_{RF}=7.6-8.6GHz)	50-85 (without tuning) 79-87 (with tuning)	2-13	6.4-6.9	-5 to 5	60-66
Receiver (sim.) (f_{RF}=7.3-8.4GHz)	50-63 (without tuning)	10-20	4.8-5.8$^{(\dagger)}$	-15 to -4	54-61$^{(\dagger)}$

Table 2: Summary of results (†estimated based on measured filter and mixer data).

CONCLUSION

A new design of a previously presented single-chip receiver front-end (composed of a tunable active X-band filter and a 1GHz-IF image rejection mixer) has been evaluated. Compared with the original design, at least 20dB higher image rejection together with up to an order of magnitude higher conversion gain and up to 2dB lower noise figure can be obtained when using this 7.6-8.6GHz agile front-end. The over-all RF front-end performance achieved is also close to what could be considered adequate for future adaptive X-band radar systems. The use of agile on-chip front-ends as the one presented in this paper could potentially result in a significant reduction of receiver size and complexity in digital beamforming X-band smart skin array antennas, for example.

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