A Tunable Active MMIC Filter For On-Chip X-Band Radar Receiver Front-Ends

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Abstract **— A 7.9-9.7GHz tunable active monolithic microwave integrated circuit (MMIC) filter intended future on-chip X-band radar receiver front-ends is presented together with measured and simulated results. Typical measured filter data over the agile frequency band show a maximum gain of 11-16dB, a noise figure of 6dB, an input-referred third order intercept point of 0dBm and 20-23dB of out-of-band rejection at 2GHz below the filter center frequency.**

I. Introduction

A low vulnerability to jamming signals is of prime importance in modern radar systems. One possible way to achieve this could be to utilize frequency hopping phased array antennas that rely on adaptive methods and digital beamforming [1]. However, the number of microwave receiver modules required in such future adaptive radar array antennas can be as high as several hundreds. Hence, in order to be able to realize such multi-channel radar systems in a cost-effective way the size and cost of each receiver module should be minimized. As a consequence of this, increased interest has recently 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 [2]. A MMIC filter of this kind may reduce the number of down-converting stages required in an agile radar receiver by allowing a greater down-conversion step to be made. Reduction of receiver size and complexity must however be achieved without any serious impairment of the receiver performance. Rejection of interfering signals that, for example, may occur at the receiver image frequency (f_{image}) must be high enough to avoid the effect of jamming. That is, the total image rejection of the receiver should be in the same order as the required spurious-free dynamic range (SFDR) [1]. When the filter centre frequency (f_c) equals the radar frequency (f_{RF}), f_{image} can be expressed as f_c-$2f_{IF}$ where f_{IF} denotes the intermediate frequency of the receiver.

Tunable active bandpass filters must not only meet stringent requirements in terms of out-of-band rejection but also in terms of noise figure (*NF*) and input-referred third order intercept point (IIP_3). In this paper we focus on tunable active MMIC filters that can be used in receiver front-ends of future adaptive frequency hopping X-band (8-12GHz) radar antennas. Typical requirements for such filters can be found in [3] (see Table I). Note that an *SFDR* of 113dB/Hz$^{2/3}$ corresponds to an *SFDR* of 64dB when a noise bandwidth (*B*) of 20MHz is assumed.

TABLE I
TYPICAL REQUIREMENTS FOR ACTIVE FILTERS IF USED IN THE MICROWAVE RECEIVERS OF FUTURE ADAPTIVE X-BAND RADAR ANTENNAS [3].

Agile frequency range	≥20%
Centre frequency gain (*G*)	≥10 dB
Noise figure (*NF*)	<5 dB
Input third order intercept point (IIP_3)	≥0 dBm
Spurious-free dynamic range (*SFDR*)	≥113dB/Hz$^{2/3}$

In this paper we evaluate a novel design of a tunable active X-band MMIC filter previously presented in [4]. Starting from the filter specification described in Table I we also investigate the possibilities of using this filter in two different types of on-chip X-band radar front-ends.

II. A Tunable Active X-Band MMIC Filter

Recursive active microwave filters using hybrid circuit components were first proposed by Rauscher [5] as a way to realize small-sized broadband filter structures. Recursive active MMIC filters are even more compact. Such filters are also 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 [6]. A tunable recursive active X-band MMIC filter with a tuning range in the order of 20% is described in [7]. However, like many other presented tunable X-band MMIC filter designs it has either a relatively limited out-of-band rejection or a noise and large signal performance inadequate for our application in mind.

A frequency tunable active MMIC bandpass filter that according to simulations may achieve a sufficiently high out-of-band rejection while also being able to fulfil typical X-band radar receiver noise and large signal requirements is on the other hand presented in [4]. One purpose of the presented work in this paper is to further evaluate this filter design by comparing novel experimental data for the fabricated filter with corresponding simulated results (obtained using *HP EEsof* CAD-tool Libra v.6.0 together with foundry-provided circuit component libraries). The MMIC design of this tunable active filter is only shortly summarized below since important filter design issues have already been treated in [4]. The use of a cascaded (second order) recursive active filter was discussed in [4] as a possible approach to achieve a reasonable compromise between sufficient filter out-of-band rejection and adequate filter noise and large signal performance. It was proposed in [4] that such a second order filter could consist of a recursive active filter designed with a low value of *NF* (*Low-Noise filter*) in cascade with a recursive active filter that instead is designed with high value of IIP_3 (*High-*IP_3 *filter*). In order to maintain high filter selectivity together with adequate filter noise and large signal performance without severely deteriorating the filter input and output impedance matching a classic balanced configuration was used in [4]. The filter center frequency tuning was finally implemented using the novel concept of self-switched (three-bit) time shifters that enables (eight) discrete filter center frequency tuning states [7]. The balanced recursive active filter topology described above is depicted in Fig. 1. Figure 2 shows a photo of the corresponding MMIC filter that is based on this topology. The filter was fabricated by the *OMMIC* foundry using their 0.2μm GaAs/AlGaAs PHEMT MMIC process.

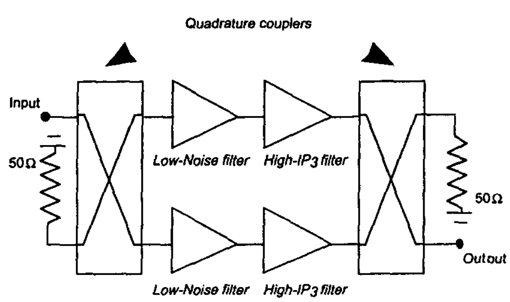

Fig. 1. A balanced recursive active filter topology composed of two identical second order filters placed between two quadrature couplers. The two (second order) filters consist in turn of two cascaded tunable recursive active filters (a *Low-Noise filter* in cascade with a *High-*IP_3 *filter*).

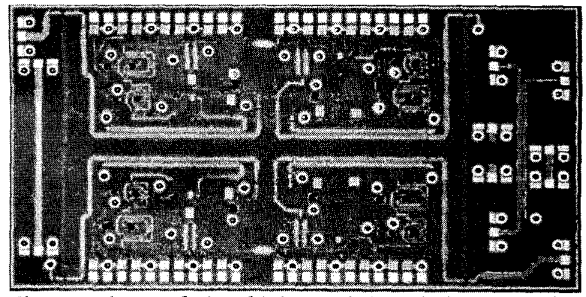

Fig. 2. Photo of the fabricated balanced (second order) tunable active X-band MMIC filter and some additional break out circuits for test purposes (chip dimensions: 3mm x 6mm).

III. RESULTS

Figure 3 shows simulated and measured s-parameters at one of the eight possible filter center frequency tuning states (f_c=7.9GHz). The biasing of the LNA's used in each filter section has been tuned to achieve maximum filter out-of-band rejection (drain bias V_{DD} is 3V and total bias current I_{DD} is 230mA). It can be noted from Fig. 3 that the input and output impedance matching is better than 10dB.

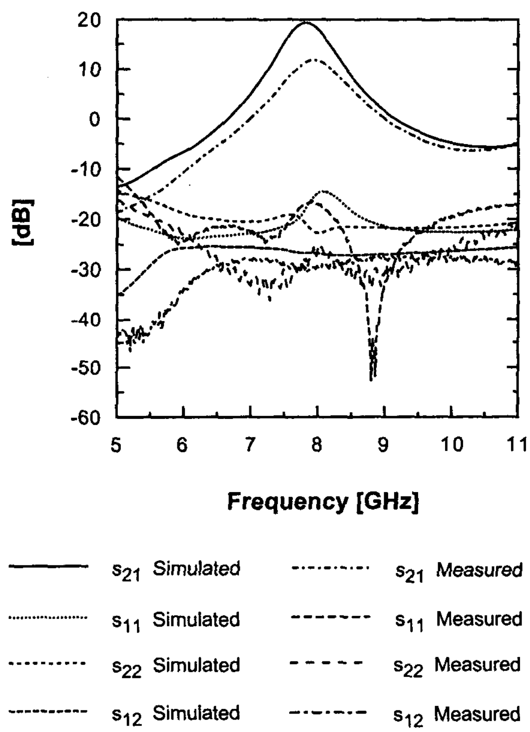

Fig. 3. Simulated and measured s-parameters at the filter center frequency tuning state that correspond to an f_c of 7.9GHz. The filter bias is tuned to achieve maximum possible out-of-band rejection (V_{DD}=3V and I_{DD}(total)=230mA).

TABLE II

SUMMARY OF RESULTS

Filter Results	Max out-of-band rejection [dB] (f_c-$2f_{IF}$)	Gain [dB] (f_c)	NF [dB] (f_c)	IIP_3 [dBm] (f_c)	SFDR* [dB] (f_c) *B=20MHz
Measured	7-9 (f_c-720MHz) 20-23 (f_c-2GHz)	11-16	6	≈0 (at three states)	≈63
Simulated	9-13 (f_c-720MHz) 23-28 (f_c-2GHz)	18-25	4	-9 to +4	59-67

Measured transmission gain (s_{21}) at all eight tuning states is shown in Fig. 4. The filter is tunable between 7.9 and 9.7GHz corresponding to a 20% relative tuning range.

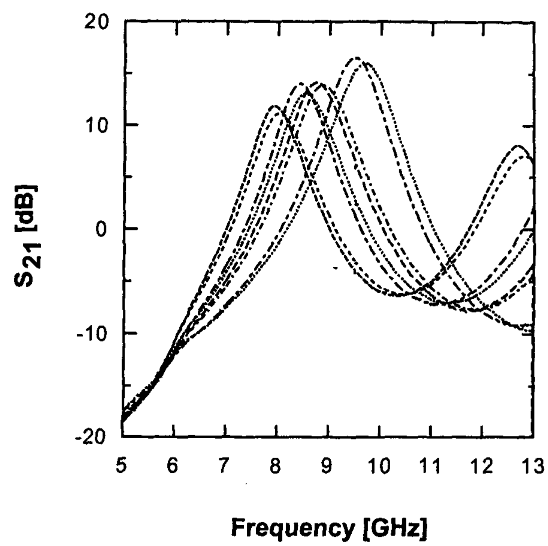

Fig. 4. Measured transmission gain (s_{21}) at all eight tuning states. The filter bias is tuned to achieve maximum possible filter out-of-band rejection (V_{DD}=3V and I_{DD}(total)=230mA).

Measured and simulated data for the evaluated MMIC filter at all eight tuning states are summarized in Table II. Measured values of maximum filter out-of-band rejection at 720MHz and 2GHz below f_c are compared respectively with the corresponding simulated results. This comparison shows that measured values of maximum filter out-of-band rejection are 4-5 dB lower than what is expected according to simulations. Table II further reveals that the measured values of filter gain are 7-9dB lower when compared with simulated data. A reasonable explanation to these discrepancies could be that (compared with simulations) a lower filter loop-gain is achieved for the different filter sections in the fabricated MMIC filter. Measurements on a break out circuit that contain the type of LNA that is used in each filter section show 1dB lower gain than expected. Also, measurements on break out circuits that contain the type of couplers used in each filter section show slightly higher coupler losses than predicted by simulations. In fact, if we take all the above mentioned deviations into account during simulation we instead obtain simulated values of filter gain and filter out-of-band rejection that are much more closer to the corresponding measured values.

For all eight tuning states, measured values of *NF* are 2dB higher than the corresponding simulated data (see Table II). This discrepancy can in turn to a large extent be explained by a deviation between measured and simulated values of *NF* for the break out circuit that contain the type of LNA used in each filter section. Measured values of *NF* for the LNA were more than 1dB higher than expected something that could possibly be explained by inaccurate transistor noise models [6]. Table II further shows that the measured values of IIP_3 are in a relatively close agreement with the corresponding simulated values. A comparison with the typical requirements given in Table I finally implies that the filter noise and large signal performance is close to what should be adequate for the microwave receivers of future adaptive X-band radar antennas.

IV. POSSIBILITIES OF UTILIZING THE MMIC FILTER IN ON-CHIP X-BAND RADAR RECEIVER FRONT-ENDS

If an MMIC bandpass filter is combined with a MMIC image rejection mixer, an on-chip front-end that combines the attractive feature of small size at low cost with a good ability to reject unwanted signals may potentially be realized. As mentioned previously in this paper the total image rejection of a radar receiver should be in the same order as the required *SFDR* value (64dB when *B*=20MHz). An X-band MMIC image rejection mixer that may help to ease the requirement on filter out-of-band rejection has recently been presented [7]-[8]. This mixer has been designed in two versions with an IF of 1GHz and 360MHz respectively. Measured results for these two mixer circuits show that it is possible to obtain an image rejection of 40-50dB [7]-[8]. Thus, if an image rejection mixer of that kind is used in an on-chip radar receiver front-end the requirement on filter out-of-band rejection at f_{image} can be reduced to 15-25dB. According to measured results presented in Table II the tunable active MMIC filter can achieve an out-of-band rejection of 20-23dB at 2GHz below f_c. This corresponds to an equally high image rejection when an IF of 1GHz is assumed.

In addition to the results presented so far in this paper we have designed a 7.9-9.7GHz on-chip receiver front-end simply by cascading the evaluated tunable active MMIC filter and the 1GHz-IF mixer described in [8]. The front-end (that is presented and experimentally evaluated in another paper [9]) has a maximum image rejection of 60dB over the agile bandwidth. Estimations presented in [9] (based on measured data of the filter and of the mixer) indicate a noise and large signal performance of the front-end that is close to that of the filter.

In the receivers of a digital beamforming antenna AD-converters with 10-14 bits are normally required [2]. The relatively high IF of 1GHz for the front-end in [9] implies that a second down-converting stage will be needed since an IF of that order is too high for today's standard ADC's when such a high number of bits are required. Even so, compared with conventional microwave receivers that are fabricated using hybrid circuit components the front-end in [9] is much smaller in size. Hence, such a front-end could enable a significant reduction of the microwave receiver size and complexity in adaptive X-band radar antennas.

Compared with a two-stage RF down-converter solution an even more simplified front-end architecture would of course be to realize an on-chip single-stage down-converter by using a tunable filter and a mixer with an IF that is sufficiently low for 10-14 bits standard ADC's. It is believed than an IF in the order of 300MHz could in a near future be considered low enough for under-sampling ADC's with 10-14 bits. The maximum possible image rejection that can be achieved for the filter evaluated in this paper when we assume an IF of 360MHz is however too low (7-9dB) compared with what typically would be required (15-25dB). Hence, in case this filter is to be used to realize an on-chip single-stage down-converter the remaining 55dB of additional image rejection typically needed should be provided by the image rejection mixer.

V. Conclusion

A 7.9-9.7GHz tunable active MMIC filter design has been experimentally evaluated. The measured filter performance deviate somewhat compared with the corresponding simulated results but is yet close to what should be adequate for the microwave receivers of future adaptive X-band radar systems. Finally, we have also addressed the issue of using the evaluated MMIC filter to realize on-chip X-band down-converters. To exemplify the feasibility of such a concept, a 1GHz-IF X-band on-chip front-end that is partly based on this MMIC filter has been developed and evaluated.

Acknowledgement

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