Reconfigurable RF-MEMS Circuits and Low Noise Amplifiers Fabricated Using a GaAs MMIC Foundry Process Technology

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Abstract. We present key building blocks for monolithically integrated (*i.e.* single-chip) RF-MEMS enabled reconfigurable low-noise amplifiers and RF front-ends that have been fabricated on a GaAs wafer using a MMIC foundry process technology. Measured results of a tunable (frequency-agile) 16-24 GHz GaAs MMIC based RF-MEMS impedance matching network show 0.4 dB of minimum in-band insertion loss and an on-chip integrated wideband (unmatched) LNA circuit present 15-20 dB of gain together with 2 dB of noise figure at 6-26 GHz, respectively. Simulated results of a GaAs MEMS-MMIC based 15-20 GHz tunable (dual-band) LNA circuit show 12-17 dB and 2.5- 5.5 dB of in-band gain and noise figure, respectively.

1. Introduction

Today, there is an increasing interest in making RF systems self-adjusting or "cognitive" [1]. Such a unique ability is expected to lead to very efficient RF systems with reduced complexity, power and cost. Frequency-agile (tunable) frontend architectures using RF Micro Electro Mechanical Systems (MEMS) is an enabling technology proposed to achieve those highly attractive benefits. Reconfigurable MEMS circuits could be utilised to implement tunable (multi-band) Low Noise/Power Amplifiers (LNA/PA) and filters that can be commercially very attractive since such devices could be useful for different frequency bands and applications. For example, today's wireless RF systems for point-to-point communication can operate at many different frequencies (sub-bands) within the

5 to 40 GHz range and a use of such highly adaptive (frequency-agile) front-end components could result in a reduced system complexity and cost savings due to component re-use. By monolithic integration of RF-MEMS and MMICs, a higher degree of functionality would be possible, e.g. in active reconfigurable multi-band front-ends. RF-MEMS together with active RF-circuitry have so far with a few notable exceptions mostly been realized as hybrid circuits and also mainly up to 5-10 GHz (see e.g. [2-6]) which still leaves room for significant improvements to be made with respect to RF-performance, frequency range, functionality as well as to achieve reduced complexity (higher level of integration) and lower costs. To the best of our knowledge, the X-band switched dual-path PAs and LNAs reported in [2-3] are the first and to this date only real example of a successful monolithic integration of active RF devices with MEMS switches in a GaAs MMIC process.

In this paper, we build on our previous work described in [7] that presented experimental s-parameter data of two (10-16 GHz and 15-23 GHz) Co-Planar Waveguide (CPW) type of loaded-line RF-MEMS matching networks implemented on a 600 µm thick GaAs substrate. Different types of MEMS circuits together with monolithically integrated (on-chip) active devices have recently been fabricated by the foundry OMMIC (within the EC FP7 ICT project MEMS-4-MMIC) on a 100 µm thick GaAs wafer with via holes. Here, we will present a GaAs MMIC based 16-24 GHz reconfigurable MEMS matching network together with an on-chip 6-26 GHz (unmatched) LNA circuit that both were implemented as micro-strip designs to facilitate the monolithic integration of a GaAs MEMS tunable (dual-band) LNA. Such MEMS based frequency-agile MMICs can be regarded as a first step towards realising highly integrated (potentially single-chip) reconfigurable active microwave/mm-wave circuits and frontends. Fig. 1 shows an exemplary circuit schematic of a tunable LNA architecture using on-chip GaAs MEMS based reconfigurable input/output impedance matching networks.

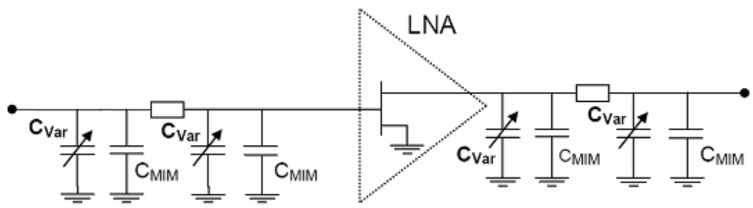

Fig. 1. Circuit schematic of a frequency-agile LNA architecture using on-chip GaAs RF-MEMS based reconfigurable impedance matching networks.

2. RF-MEMS Matching Networks and LNAS Fabricated Using a GaAs MMIC Foundry Process

Fig. 2 shows a photograph of a 1-bit loaded-line type of RFMEMS impedance matching network (top) and a wideband two-stage (unmatched) LNA circuit (bottom) with dimensions of 700 μm × 1100 μm and 1300 μm × 700 μm, respectively (incl. RF and DC pads). The ohmic contact type of MEMS switch used here was developed by OMMIC using a GaAs MMIC foundry process technology [8]. For the MEMS switches on the fabricated GaAs MMIC wafer that were used here the actuation voltage typically was found to vary between 20-40 V.

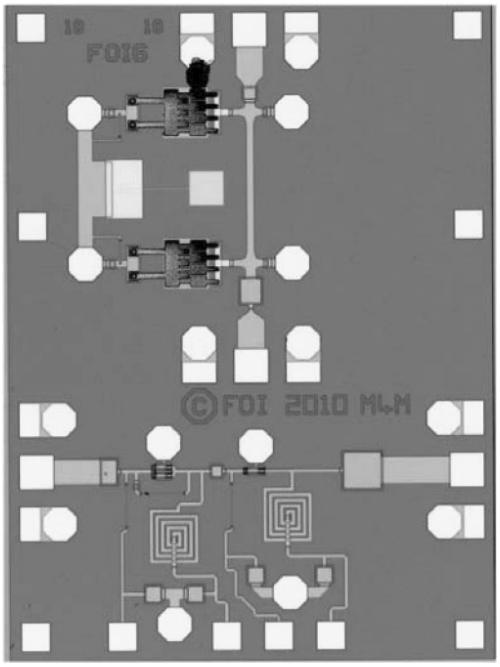

Fig. 2. Photograph of an RF-MEMS reconfigurable matching network (top) and a wideband (unmatched) LNA circuit (bottom) that have been fabricated on the same GaAs wafer using an MMIC foundry process technology.

Fig. 3 shows measured transmission (S_{21}) and input reflection (S_{11}) of the GaAs MMIC based 1-bit RF-MEMS input matching network shown in Fig. 2 when the two MEMS switches used were both switched ON (Down state) and OFF (Up state), respectively. The two possible tuning states shown here correspond to a centre frequency (f_c) for the input impedance matching that is equal to 16.2 GHz and 24.1 GHz, respectively (*i.e.* 40% tuning range). At the two frequencies, s_{11} and s_{21} are equal to -12.8 dB and -4.5 dB and -22.2 dB and -0.4 dB, respectively. The measured results of the reconfigurable matching network also compare relatively well with the corresponding EM-simulated data if we assume a contact resistance (R_{on}) of 4 Ω for the two MEMS switched used in parallel (the MEMS switch capacitance in the Up state Cup equal 10 fF). Simulations further indicate that it should be possible to achieve a low transmission loss for the MEMS matching network also within the Down state (*i.e.* when both switches are ON) if R_{on} would be reduced to 1-2 Ω (*i.e*. by obtaining an improved contact). This would then also result in a higher in-band small-signal gain and lower in-band Noise Figure (NF) of a tunable LNA that were using such types of RF-MEMS matching networks.

The experimental s-parameter data presented here were measured between 5-40 GHz due to the RF probes and the onchip calibration standard that were used in this case. Furthermore, the s-parameters of the GaAs RF-MEMS matching network were measured at two different RF input power levels (-25 dBm and 9 dBm, respectively). As is shown in Fig. 3, the measured RF performance of the GaAs MEMS matching network is largely the same at these two power levels thus indicating the relatively highly linear properties of this type of reconfigurable MEMS matching network.

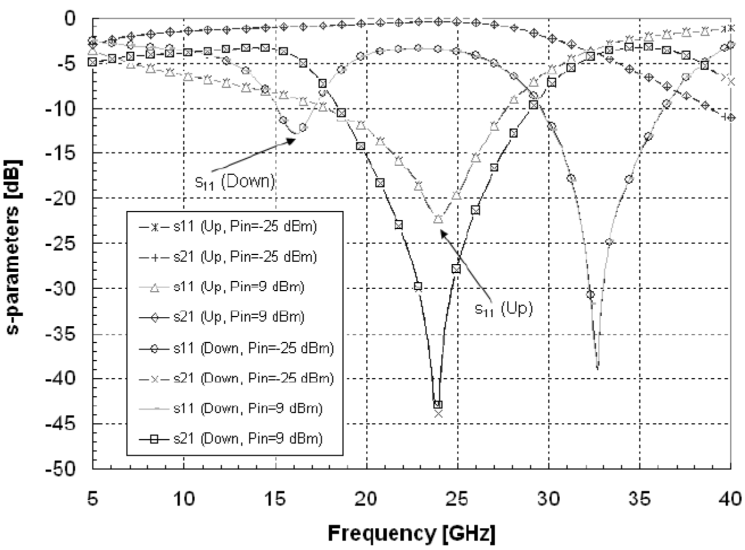

Fig. 3. Measured transmission S_{21} and input reflection S_{11} of a GaAs MMIC based 1-bit RF-MEMS input matching network when the two MEMS switches used were both switched ON (Down state) and OFF (Up state), respectively.

Fig. 4 shows measured s-parameter data and noise figure of the two-stage wideband (unmatched) LNA MMIC shown in Fig. 2. The LNA presents a gain of 15-20 dB at 6-26 GHz and NF=2 dB within this frequency range (NF could be measured up to 26.5 GHz due to a limitation with respect to the noise figure measurement equipment used). The (fixed) wideband LNA MMIC was intentionally made without any input and output impedance matching networks which explains the quite moderate values obtained for the LNA input and output return losses (S_{11} and S_{22} above of -8 dB at 5-40 GHz, respectively). The P_{DC} of the unmatched GaAs LNA MMIC was in this case equal to 60 mW. The measured results of the GaAs 1-bit MEMS matching network and unmatched LNA (see Fig. 3-4) have further been used in simulations to be able to predict the expected RF performance of a corresponding GaAs RF-MEMS based (single-chip) tunable LNA MMIC design.

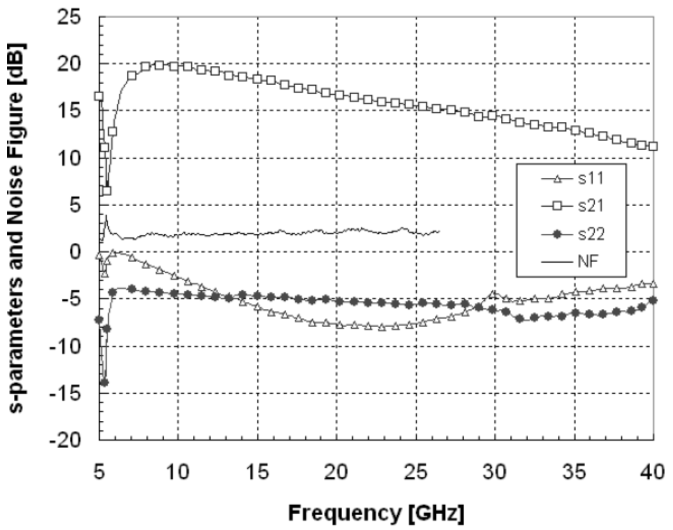

Fig. 4. Measured s-parameters and noise figure of a two-stage wideband (unmatched) LNA MMIC fabricated on the same GaAs wafer as a 1-bit RFMEMS matching network (see Fig. 2).

Fig. 5 shows simulated small-signal results of a tunable dualband LNA design based on the measured s-parameter data of a 1-bit GaAs MEMS input/output matching network and a wideband (unmatched) LNA circuit (both shown in Fig. 2). The two centre frequencies obtained for the tunable LNA correspond to when the two MEMS switches used within each MEMS matching network are either in the Up state or in the Down state, respectively (corresponding to the two tuning states shown in Fig. 3). The results show that it can be possible to achieve a high in-band tunable LNA gain (12-17 dB) together with relatively low values of return losses within the two frequency bands at 15 GHz and 20 GHz, respectively (corresponding to a tuning range of 29%). Measured data of a 1-bit GaAs MEMS matching network and a 6-26 GHz wideband (unmatched) LNA together with corresponding simulated results of a tunable dual-band LNA design are summarized in Table 1. Compared with simulated tunable LNA gain and NF at f_c=20 GHz, the in-band gain and NF is 5 dB lower and 3 dB higher at f_c=15 GHz which can be explained by the 3 dB higher measured losses of the GaAs MEMS matching network at this frequency when the two MEMS were activated (Down state). Simulations further indicate it should be possible to obtain a similar high in-band gain and low NF for a GaAs MEMS based tunable LNA circuit if the MEMS switch contact resistance could be made sufficiently small (R_{on}=1-2 Ω).

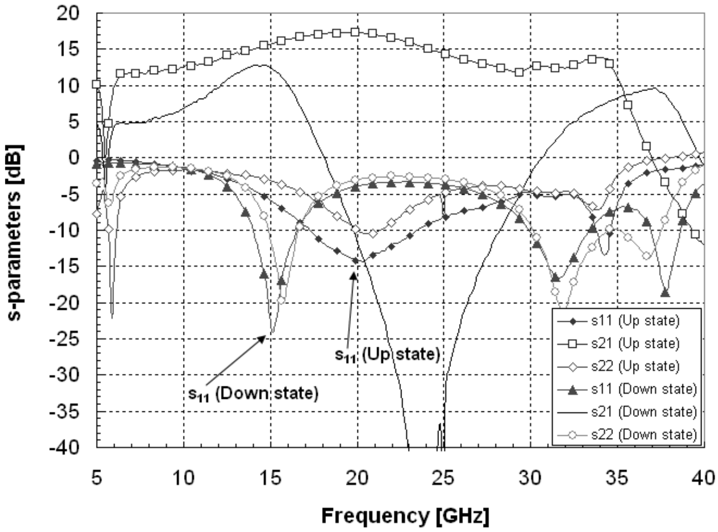

Fig. 5. Simulated s-parameters of a tunable dual-band LNA design based on the measured data of a 1-bit GaAs RF-MEMS (input/output) matching network and an unmatched LNA circuit (both shown in Fig. 2).

Table 1. Results of RF-MEMS and LNA circuits made on GaAs

Circuits	**Gain [dB]**	**Imput matching [dB]**	**NF [dB]**
MEMS matching network	-3.5(@ 15GHz) -0.6(@ 20GHz)	-10.0(@ 15GHz) -12.3(@ 15GHz)	N/A N/A
Wideband LNA	-18.3(@ 15GHz) -16.6(@ 20GHz)	-5.9(@ 15GHz) -7.7(@ 20GHz)	-1.9(@ 15GHz) -1.9(@ 20GHz)
Tunable LNA (sim.)	-12.3(@ 15GHz) -17.3(@ 15GHz)	-24.0(@ 15GHz) -14.8(@ 20GHz)	-5.5(@ 15GHz) -2.5(@ 20GHz)

3. Conclusion

We presented a frequency-agile 16-24 GHz 1-bit RF-MEMS matching network and a wideband (unmatched) LNA circuit that have been fabricated on the same GaAs substrate using a MMIC foundry process technology. The GaAs MEMS based matching network and unmatched LNA are both implemented as micro-strip designs to facilitate the monolithic integration of an RF-MEMS enabled tunable (dual-band) LNA MMIC. The 1-bit GaAs MEMS matching network has 0.4 dB of minimum in-band transmission loss (in the up state) and the on-chip integrated unmatched LNA design shows 15-20 dB of gain together with 2 dB of noise figure at 6-26 GHz, respectively.

Simulated results of a 15-20 GHz tunable dual-band LNA design (based on the measured data of the 1-bit GaAs MEMS input/output matching network and the unmatched LNA) show that it can be possible to achieve a high in-band gain of 12-17 dB and low values of return losses within the two frequency bands (corresponding to a tuning range of 29%). Simulations further indicate that the tunable LNA gain and noise figure at the lower frequency band (i.e. when all the MEMS switches used are in the down-state) are primarily limited by the MEMS switch contact resistance. The initial prototypes of GaAs RFMEMS based tunable MMICs presented in this paper can be regarded as a first step towards realising highly integrated (potentially single-chip) reconfigurable active microwave/mmwave circuits and front-ends.

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