Wideband variable gain amplifier with noise cancellation

A.M. El-Gabaly and C.E. Saavedra

A 1–5 GHz noise-cancelling variable gain amplifier is presented in 0.18 µm CMOS technology that achieves a low noise figure (NF) below 4.8 dB over an 11 dB gain range. Its NF is as low as 3.2 dB for the gain range of 5.5 to 11 dB, while its input return loss is better than 13 dB over the entire gain range of −5 to 11 dB. The measured input-referred two-tone third-order intercept point (IIP3) at 2.4 GHz is better than 0 and −4.5 dBm at minimum and maximum gain, respectively. The circuit occupies an area of only 0.067 mm^2 and consumes less than 19 mW of power from a 1.8 V supply.

Introduction: Variable gain amplifiers (VGAs) are very useful components in RF frontends because they serve as general-purpose gain blocks that can be used to precisely adjust the overall gain of a transceiver which may result from manufacturing tolerances in the other components in the system. A significant number of VGAs function on the principle of using a fixed gain amplifier followed by a variable attenuator to control the gain. That approach causes the VGA to have a high noise figure (NF) even in the high gain states, which makes them unattractive for use in receiver frontends. In this Letter, we demonstrate a new wideband VGA that addresses the NF problem over a wide gain range.

Conventional wideband amplifiers such as the common-gate (CG) amplifier or the common-source (CS) shunt-feedback amplifier often have difficulties in achieving a low NF (∼3 dB) while maintaining a good impedance match, or suffer from limited gain and stability. Distributed and travelling wave amplifiers [1, 2] can provide a low NF, good impedance match, and flat gain over a wide range of frequencies, but typically consume a large chip area and power.

More recently, inductive degeneration and multi-section inductor-capacitor (LC) networks have been reported [3] for wideband impedance matching and low NF. However, the use of several inductors on-chip consumes a large area and increases cost. Noise cancelling [4, 5] on the other hand is an effective approach for achieving a low NF and an impedance match simultaneously without the need for large inductors or feedback. Nevertheless, limited gain control has been reported if at all, and common variable gain techniques such as current steering, variable feedback and variable bias often suffer from deteriorated NF and input matching.

In this Letter, a 1–5 GHz noise-cancelling, gm-boosted amplifier is presented using 0.18 µm CMOS, with variable gain control introduced in its signal combination and noise cancellation circuit. Such an approach can provide a low NF (<4.8 dB) over an 11 dB gain range, and with a very good input match (<−13 dB). The VGA is suitable for low-cost, low-power wireless communications, including 3–5 GHz (low-band) ultra-wideband (UWB) digital radios, and 20–60 GHz millimetre-wave radios operating with an intermediate frequency (IF) in the 1–5 GHz range.

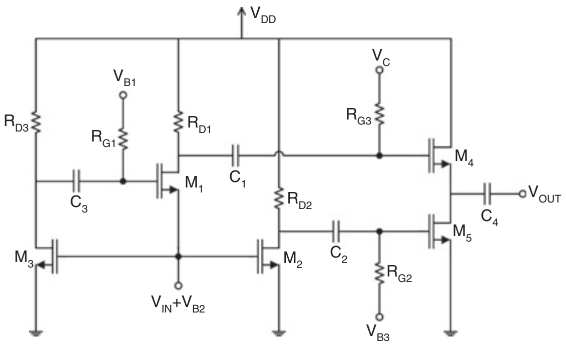

Fig. 1 *Circuit schematic of VGA (biasing not shown)*

Circuit architecture and design: A circuit schematic of the proposed VGA is shown in Fig. 1. It consists of a common-gate amplifier (M_1) that provides a wideband input impedance match without using bulky inductor-capacitor (LC) networks. An inverting common-source amplifier M_3 is introduced between the gate and source of M_1 to boost its effective transconductance G_m from g_{m1} to $(1-A)g_{m1} \simeq (1+g_{m3}R_{D3})g_{m1}$. This improves the input match, reduces NF and increases the gain [6]. The often severe trade-off between the impedance match and NF is now relaxed.

To reduce further the NF over a wide bandwidth, the output noise of the matching device (M_1) is cancelled using another common-source amplifier M_2 and a common-drain, common-source combiner M_4-M_5 as shown in Fig. 1. The noise current of M_1 (I_{dn}) flows out of the drain but into the source creating two correlated noise voltages with opposite polarities, $V_D \simeq -R_{D1}I_{dn}/(1+G_mR_S)$ and $V_S \simeq R_SI_{dn}/(1+G_mR_S)$, respectively, where R_S is the signal source impedance (50 Ω). However, the signal voltages at these nodes are in phase. Thus with the inverting amplifier M_2 and the difference combiner M_4-M_5, the noise contribution of M_1 is cancelled while the signal is added. Cancellation can be achieved if, to the first order, $g_{m5}g_{m2}R_SR_{D2} \simeq g_{m4}R_{D1}$. Furthermore, the width and transconductance of the common-source device M_2 are made sufficiently large for relatively small noise contribution.

The gain of the amplifier is varied by controlling the combiner's bias current and transconductance using the gate control voltage V_C of the common-drain device M_4. The higher the value of V_C, the higher the bias current and the signal gain. The range of V_C is from 0.49 V ($\simeq V_T$) to 1.85 V ($\simeq V_{DD}$). As the g_m-boosted common-gate stage (M_1, M_3) is largely unaffected by changing V_C or the combiner bias current, the input match can remain relatively stable as the gain is varied. Furthermore, if the transconductance of M_4 and M_5 (g_{m4} and g_{m5}) vary in a similar fashion with V_C, the degree of noise cancellation and the NF can remain largely unchanged.

Experimental results: The VGA was fabricated in a standard (six-metal, single-poly) 0.18 µm CMOS process. It occupies a die area of about 515 × 525 µm^2 including bonding pads and on-chip decoupling capacitors, while the core VGA circuit area is only 250 × 270 µm^2. The integrated circuit (IC) consumes less than 10 mW of power from a 1.8 V supply at minimum gain and less than 19 mW at maximum gain.

A direct on-wafer measurement of the IC was carried out using coplanar RF probes. Fig. 2 shows the forward transmission $|S_{21}|$ coefficient of the amplifier for different control voltages (0.49–1.85 V). The gain ranges from 11 to −5 dB at the centre frequency of 2.4 GHz, with less than 3 dB deviation over the 1 to 5 GHz bandwidth. Fig. 2 also shows the measured input reflection coefficient $|S_{11}|$ of the VGA, indicating an input return loss of more than 14.5 dB at 2.4 GHz or more than 13 dB over the full 1–5 GHz bandwidth for all gain levels.

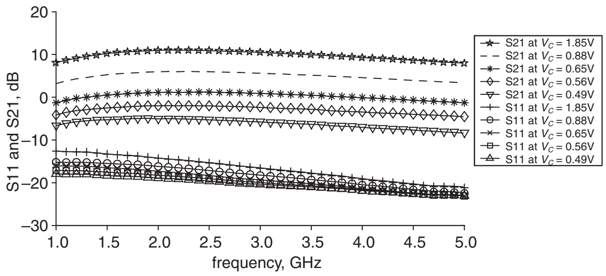

Fig. 2 *Measured input reflection $|S_{11}|$ and forward transmission $|S_{21}|$ coefficients for different control voltages*

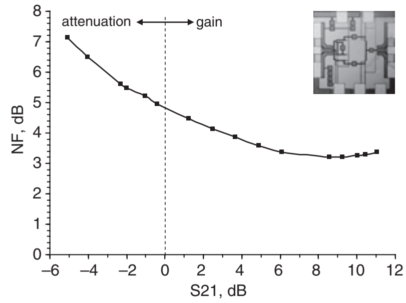

Fig. 3 *NF against gain performance at 2.4GHz*

The NF against gain performance of the VGA at 2.4 GHz is plotted in Fig. 3. It shows less than 4.8 dB NF from 0 to 11 dB gain and less than 4 dB NF for 3 to 11 dB gain. It also depicts a low NF of about 3.2 dB for the high gain range from 5.5 to 11 dB. The amplifier's input-referred two-tone third-order intercept point (IIP3) was measured at 2.4 GHz and is higher than 0 and −4.5 dBm at minimum and maximum gain, respectively. Fig. 4 is a plot of the NF over the 1–5 GHz bandwidth for different gain settings (i.e. $|S_{21}|$ at 2.4 GHz), indicating an average NF from about 3.6 to 7.7 dB with better than ±0.85 dB flatness.

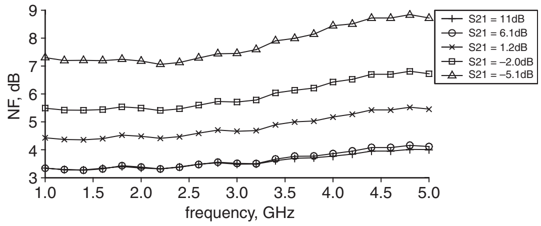

Fig. 4 *Measured NF for different gain settings ($|S_{21}|$ at 2.4 GHz)*

Table 1 summarises the proposed VGA's performance compared with other gigahertz-range VGAs that have been reported recently [1, 2, 6, 7]. It achieves a lower NF of 3.2 dB (minimum) and has comparative or better input match and IIP3. The VGA's chip area is also significantly smaller than most, and the design in [7] is developed in a more expensive technology (90nm CMOS) with a smaller feature size. Note that in [1, 2, 6] the NF is reported only at maximum gain, while in [7] the NF deteriorates further to 30 dB.

Table 1: Summary of VGA performance in comparison with other works

	Area (mm^2)	DC power (mW)	Max. $|S_{21}|$ (dB)	Min. NF (dB)	$|S_{11}|$ (dB)	IIP3 (dBm)	Bandwidth (GHz)	Gain range (dB)
[1]	1.43	6.4	12	6	>7	−10	1.6–12.1	−18 to 12
[2]	1.16	9	8.6	4.2	16	1.8	0.03–7	−10 to 8
[6]	0.17	9.3	13	4.1	17	−13	1.0–8.5	8 to 13
[7]	0.01	2.5	50 (A_V)	17	N/A	−13 (P_{1dB})	0.01–2.2	−10 to 50
This	0.067	10–19	11	3.2	>13	0	1.0–5.0	−5 to 11

Conclusion: A 1–5 GHz general purpose VGA has been developed in 0.18 μm CMOS with a NF as low as 3.2 dB for the gain range of 5.5 to 11 dB. The NF remains below 4.8 dB over the gain range from 0 to 11 dB. A good input match below −13 dB is also achieved over the entire gain control range of −5 to 11 dB. The measured IIP3 at 2.4 GHz is better than 0 and −4.5 dBm at minimum and maximum gain, respectively. The IC occupies an area of only 0.067 mm^2 and consumes less than 19 mW from 1.8 V.

13 November 2010
doi: 10.1049/el.2010.3226

A.M. El-Gabaly and C.E. Saavedra (*Department of Electrical and Computer Engineering, Queen's University, Kingston, Ontario, Canada K7L 3N6*)

E-mail: ahmed.elgabaly@queensu.ca

References

1 Shin, S.-C., Lin, C.-S., Tsai, M.-D., Lin, K.-Y., and Wang, H.: 'A low-voltage and variable-gain distributed amplifier for 3.1–10.6 GHz UWB systems', *IEEE Microw. Wirel. Componen. Lett.*, 2006, **16**, (4), pp. 179–181

2 Zhang, F., and Kinget, P.: 'Low power programmable-gain CMOS distributed LNA for ultra-wideband applications'. IEEE Symp. on VLSI Circuits, Kyoto, Japan, June 2005, pp. 78–81

3 Bevilacqua, A., and Niknejad, A.M.: 'An ultra-wideband CMOS LNA for 3.1 to 10.6 GHz wireless receivers'. IEEE Int. Solid-State Circuits Conf., San Francisco, CA, USA, February 2004, pp. 382–533

4 Bruccoleri, F., Klumperink, E.A.M., and Nauta, B.: 'Noise cancelling in wideband CMOS LNAs'. IEEE Int. Solid-State Circuits Conf., San Francisco, CA, USA, 2002, pp. 406–407

5 Chen, W.-H., Liu, G., Zdravko, B., and Niknejad, A.M.: 'A highly linear broadband CMOS LNA employing noise and distortion cancellation', *IEEE J. Solid-State Circuits*, 2008, **43**, (5), pp. 1164–1176

6 Tsang, T.K.K., Lin, K.-Y., and El-Gamal, M.N.: 'Design techniques of CMOS ultra-wide-band amplifiers for multistandard communications', *IEEE Trans. Circuits Syst. II, Express Briefs*, 2008, **55**, (3), pp. 214–218

7 Wang, Y., Afshar, B., Cheng, T.-Y., Gaudet, V., and Niknejad, A.M.: 'A 2.5 mW inductorless wideband VGA with dual feedback DC-offset correction in 90 nm CMOS technology'. IEEE Radio Frequency Integrated Circuits Symp., Atlanta, GA, USA, June 2008, pp. 91–94