

Internal Unilaterization Technique for CMOS mm-Wave Amplifiers

Babak Heydari, Ehsan Adabi, Mounir Bohsali, Bagher Afshar, Amin Arbabian and Ali M. Niknejad
Berkeley Wireless Research Center, UC Berkeley EECS Department, Berkeley, CA 94720 USA

Abstract—An internal unilaterization technique for cascode devices is analyzed and demonstrated in 90nm CMOS technology. The substrate network of the device has been incorporated in a circuit technique together with an LC tank on the top gate of the cascode structure. The structure is accurately modeled and conditions for unilaterization of the cascode are derived in terms of the LC tank parameters. An increase in the maximum stable gain from 7.5dB to 20dB has been verified in the measurements using this technique.

Index Terms—unilaterization, CMOS amplifiers, cascode amplifiers, mm-wave

I. INTRODUCTION

The last few years have witnessed an increasing interest in millimeter-wave communication systems. Applications such as digital video, personal area networks and Gb/s home networking, automotive radar and other high data rate areas are the driving forces to focus attentions toward high bandwidth communication systems. These market trends coincided with a universal regulatory facilitation, freeing a large bandwidth around 60 GHz in America and Japan and specifying the 77 GHz band for automotive radar applications. CMOS for all its clear advantages including low cost and potential for integration with other parts of the system is thus a natural candidate to be explored.

Present day CMOS devices however suffer from a rather low gain at millimeter wave frequencies. The maximum available and stable gain of CMOS devices drop continuously due to a simultaneous decrease in the forward gain and increase in the reverse gain of the device as the frequency increases. Unilaterization is a common technique used to cancel out the effect of the reverse feedback and as a result increases the available gain of the device. Techniques for unilaterization based on the isolation of the input and output or using different methods of feedback have been proposed for different amplifier architectures. Analysis and designs of these techniques are mainly based on using external components and considering the familiar hybrid- π model of the device. As the frequency goes up into millimeter-wave regime, the device substrate effects including body capacitors and substrate resistive network become important and should be considered in analysis. This paper will show that the substrate network could also be used deliberately to realize unilaterization in the mm-wave band, often beyond the “kink” frequency where the

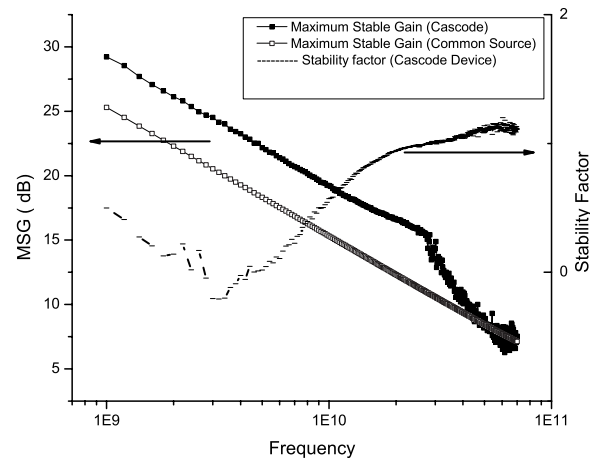


Fig. 1. Comparison of maximum stable gain (MSG) between a common source and cascode structure using similar current.

cascode gain is dropping. The unilaterization technique based on the substrate network of CMOS devices has been theorized and realized for a sample cascode structure and verified experimentally.

II. TWO PORT UNILATERIZATION

Unilaterization is a two port technique that nullifies the reverse transfer parameter S_{12} of a general two port network. The technique is applied to extend the bandwidth of amplifiers and increase the gain and stability of a circuit at a specific frequency of interest. The gain of a two port network could be increased to the limit of its maximum unilateral gain or Mason’s gain [1][2]. For a single transistor in a common source configuration, the effect of the gate to the drain capacitor, C_{gd} , is the main mechanism responsible for increasing the reverse transconductance. Feedback via C_{gd} is usually reduced using a cascode configuration, which is arguably the most widely used topology for RF low-noise amplifiers [3]-[4].

The cascode structure is not unilateral however in the millimeter frequency range. The assumption is invalidated mainly due to the path from the output to the input shaped by a series of capacitors, gate to drain capacitors of both transistors and the gate to source capacitor of the cascode device. As a result the gain benefit that normally associated

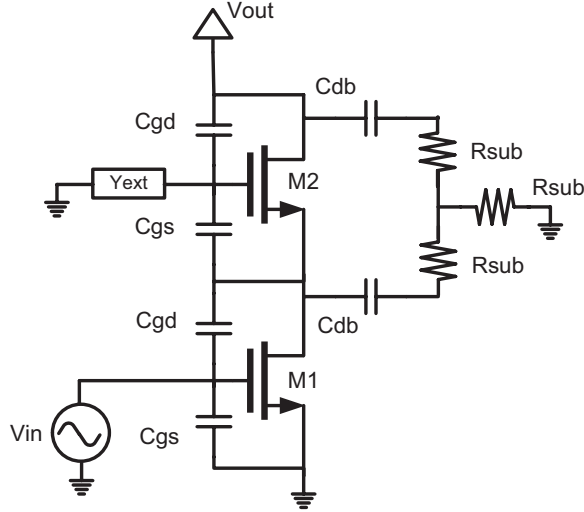


Fig. 2. Circuit model used in analysis of reverse transconductance of cascode structure.

with cascode structures is not necessarily available at mm-wave frequencies. Fig. 1 compares the measured maximum available gain (*MSG*) between a normal common source device and a cascode device. As evident in the figure, the maximum available gain of the cascode device is considerably higher at high frequencies, but gets close to the value for the common source device at mm-wave frequencies. At 60 GHz for example, both devices show similar *MSG* of around 7.5 dB.

The key observation is that there is another path from the input to the output through the substrate. This path works against the first effect by decreasing the reverse transconductance of the device. In fact the loop is a positive feedback loop with a less than unity gain. The net effects of these two mechanisms shape the actual feedback of the cascode structure. As will be shown in the next section, the value of the reverse gain is also a function of the impedance on the gate of the cascode transistor and as a result could be manipulated and set to a desired value by properly assigning the network and corresponding values on the second gate.

III. CONDITIONS FOR UNILATERIZATION

Fig. 2 shows a structure that has been used for analysis. To simplify the problem, values of corresponding capacitances in both transistors have been set to be equal, i.e. $C_{gs1} = C_{gs2}$, $C_{gd1} = C_{gd2}$, $C_{db1} = C_{db2}$ and three resistors of the substrate resistance are also assumed to be the same. Y_{ext} represents a conductance whose real and imaginary parts will be determined according to the unilaterization condition and will be set externally as a part of the device design.

Solving the network, it can be shown that the external network, Y_{ext} , to satisfy the magnitude of Y_{12} equal to

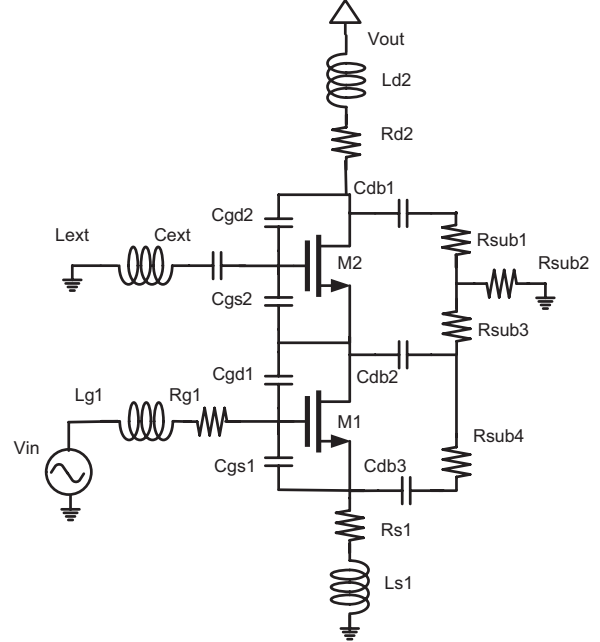


Fig. 4. Small-signal model of a cascode structure.

zero, is given by the following equations shown in Fig. 3. For practical component values of cascode structures, to make the device unilateral at mm-wave ranges, the external network could be realized with a series LC tank. Since a capacitor is usually placed at the top gate to provide a low impedance DC bias, a series short transmission line lead could satisfy the condition using proper sizing for both components. It is important to bear in mind that capacitors, especially finger “MOM” capacitors, already include some series inherent inductance which should be modeled and utilized in the device design.

IV. ACTIVE CIRCUIT MODELING

To accurately design the external network and later use the device in circuit applications, the device needs to be modeled carefully. This is especially crucial since available foundry models are not generally valid and accurate in mm-wave frequency ranges. Fig. 4 shows a small-signal circuit that is used to model the device. It’s a combination of the conventional hybrid- π model for transistors, external parasitic capacitances, resistances and inductances plus a substrate network with a shared node at the resistive node.

The modeling procedure starts with properly de-embedding pad structures and external leads from the measured device using standard open/short techniques. Initial values of small-signal elements are then approximated using a combination of the foundry model and calculations based on hot/cold low frequency measured data. The equivalent circuit with its initial values are then fed to a global optimizer such as Agilent ICCAP together with the de-embedded measured data.

$$\Re(Y_{ext}) = \frac{\omega^2 C_{gd} (G_{sub}^2 ((3C_{gs} + C_{db})g_{m2} + -3C_{gs}G_{sub}) + C_{db}C_{gs}\omega^2 (2C_{db}g_{m2} + C_{gs}G_{sub} - 2C_{db}g_{m2}))}{(G_{sub}^2 + \omega^2 C_{db}^2) (G_{sub}^2 + \omega^2 C_{gs}^2)}$$

$$\Im(Y_{ext}) = \omega \left(3C_{gd} - C_{gs} + \frac{C_{gd}G_{sub} (C_{db}g_{m2} - C_{gs}G_{sub})}{(C_{db}^3\omega^2 + C_{db}G_{sub}^2 - C_{gd}G_{sub}^2 - C_{db}^2C_{gd}\omega^2)} - \frac{G_{sub}C_{gd} (2C_{db} - 3C_{gd}) (G_{sub} - g_{m2})}{(C_{db} - C_{gd})(G_{sub}^2 + C_{gd}^2\omega^2)} \right)$$

Fig. 3. Equations for the real and imaginary component of Y_{ext} in order to unilaterize the cascode.

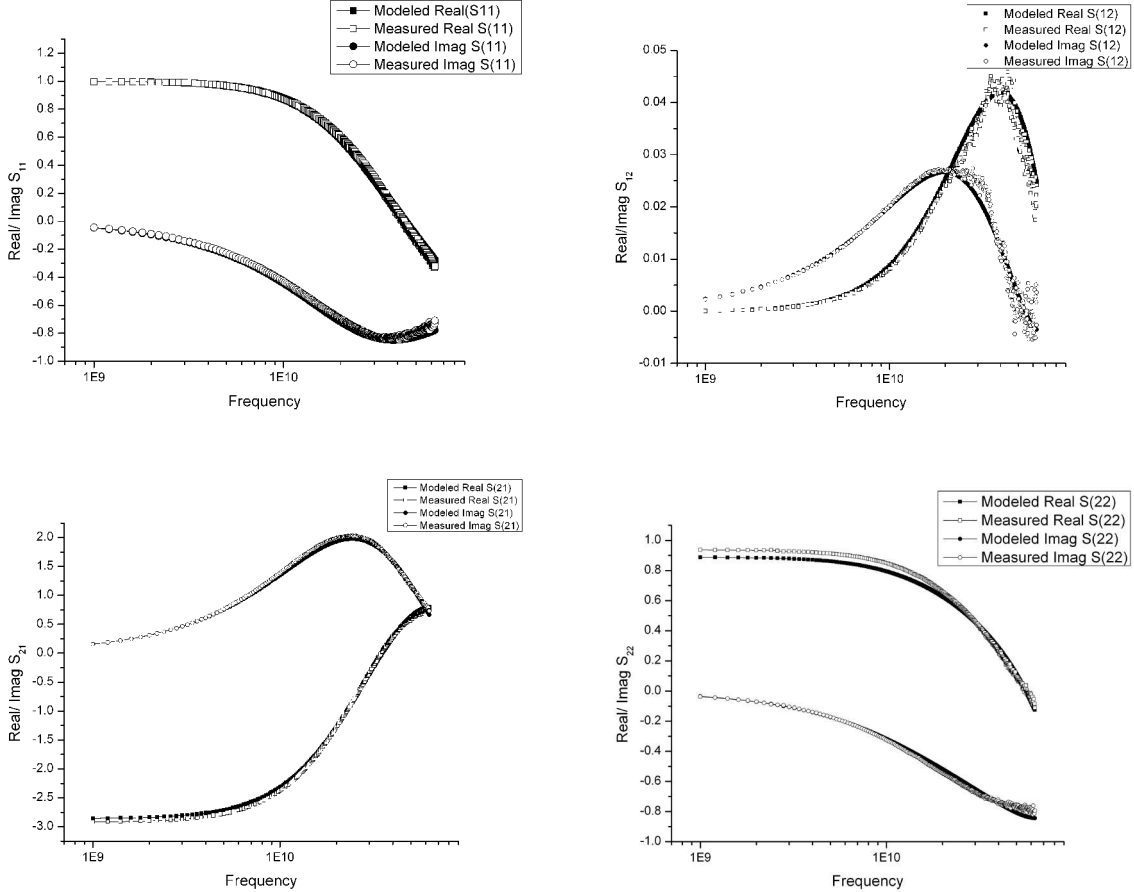


Fig. 5. Comparison of measured and modeled device S -parameters up to 65 GHz.

To test the accuracy of the model, a sample $40\mu\text{m}/90\text{nm}$ is measured and modeled using the proposed method. The close match between measured and modeled S -parameters up to 65 GHz as shown in Fig. 5 confirms the validity of the model and the modeling procedure.

V. EXPERIMENTAL RESULTS

The unilaterization procedure was implemented on a sample $80\mu\text{m}/90\text{nm}$ cascode device using an integrated 2 pF external capacitor in series with a total of 50 pH of external inductance. The 2 pF finger ‘‘MOM’’ capacitor was modeled and its internal inductance was used in the modeling process.

Fig. 6 shows the measured and modeled S_{12} of the device as well as the maximum available gain up to 65 GHz. The fall-off of the magnitude of the reverse reflection parameter, S_{12} after 20 GHz corresponds to the increase in the maximum available gain in the same frequency range. Both these effects are well in agreement with the modeling results. The peak gain at 50 GHz is close to 20 dB which is drastically larger than the 8 dB gain for the case of normal cascode, as shown previously in Fig. 1.

The noise performance of the device was simulated using Pospieszalski noise model with the aid of the proposed small-signal circuit [5]. The equivalent noise parameter γ was set to 1.3 as suggested by [6]. The effect of unilater-

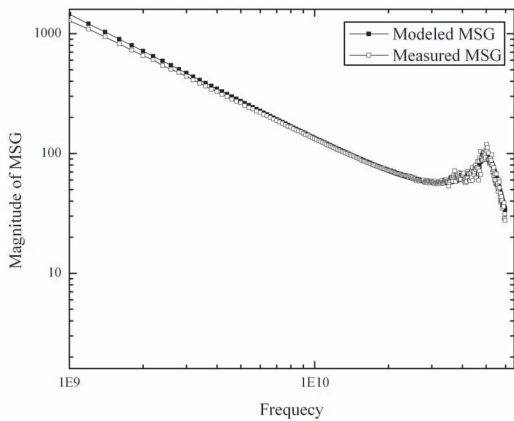
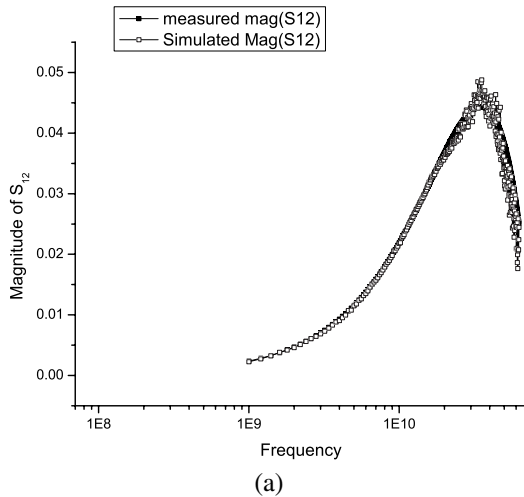


Fig. 6. (a) Measured device S_{12} and (b) device maximum stable gain up to 65 GHz.

ization technique was investigated on the minimum noise figure and equivalent noise resistance (R_n) by changing the series inductance at the second gate LC tank. The effect is minor as shown in Fig. 7. While NF_{min} decreases slightly when the device goes into unilateral region, R_n increases and no clear overall benefit or disadvantage is associated with technique in terms of noise performance. However, the technique enables the designer to trade-off gain for noise optimization which results in an overall more power efficient amplifier.

VI. CONCLUSION

An internal unilateralization technique for cascode devices using substrate network and top gate of the device was analyzed and implemented. This technique could be applied to mm-wave circuits especially amplifiers to increase the gain of each stage and reduce the power consumption of the circuit. Increasing gain at a specific frequency could also give way to trade off some gain to obtain better

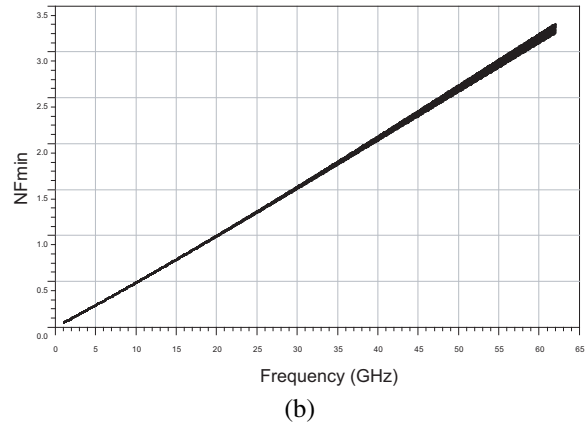
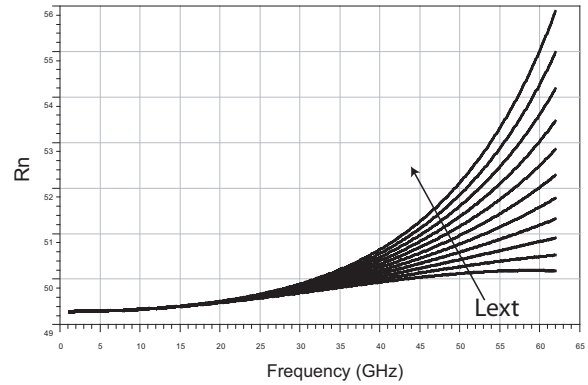


Fig. 7. (a) Simulated device noise resistance parameter R_n and minimum achievable noise figure NF_{min} .

performance in terms of linearity or noise depending on the specific application of the circuit.

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