Distributed Amplifiers with Non-Uniform Filtering Structures

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Abstract—This paper presents a new design concept to better control both passband and stop-band characteristics of distributed amplifiers (DAs) by using non-uniform filtering structures instead of conventional constant-k sections. Two circuit prototypes with Butterworth and Chebyshev filtering were designed using network synthesis method, and implemented in a $0.18\mu\text{m}$ digital CMOS technology. The Butterworth prototype achieved 11.7dB gain, 9GHz bandwidth, and -5dB/GHz roll-off. The Chebyshev one achieved 10dB gain, 8.5GHz bandwidth and -8dB/GHz roll-off.

Index Terms—CMOS, distributed amplifiers, filtering functions, wideband

I. INTRODUCTION

Rapid progress in wideband communications, such as ultra wideband (UWB) and fiber-optic systems, are driving demands for front-end amplifiers with multi-gigahertz bandwidth. Distributed amplifiers (DAs) have always been one of the top choices for wideband amplification [1]–[3]. Recently, advances in silicon technologies make it possible to build fully-integrated CMOS DAs with multi-GHz bandwidth [4]–[8], which are very attractive because of silicon's low cost and integration capability with baseband circuits.

Not surprisingly, most of these research efforts focus on achieving large bandwidth, which means that the design usually addresses only the passband characteristics of DA's frequency response. On the other hand, wideband systems increasingly require good out-of-band spectrum control to reject interference and reduce noise. For example, in impulse radio UWB systems, there are very stringent requirements on the signal spectrum due to concerns of interference with existing wireless services [9]. Therefore, tighter control over the overall DA frequency response is needed, and good stop-band characteristic is highly desirable. This is particularly important for CMOS DAs since they tend to have a slow slope in the stop-band due to the lossy on-chip transmission lines.

This paper will demonstrate a new design concept for DAs: by synthesizing the (artificial) transmission lines as non-uniform filters with specific frequency response, the DA's spectrum can be controlled not only within the pass-band, but also in the stop-band.

II. NON-UNIFORM FILTERING

Conventional DAs usually use constant-k sections as the basic iterative structures in the gate and drain lines, and hence the latter become uniform (artificial) transmission lines (Fig. 1). M-derived sections are usually used at terminations to improve matching. Although widely adopted, constant-k

Fig. 1. A conventional constant-k DA (bias not shown).

Fig. 2. Model of a generic DA with non-uniform filtering structures, showing the i -th tap. For simplicity, gate and drain lines are assumed to be identical.

sections are only one of the possible filtering structures in distributed amplifiers. The necessary condition for distributed amplification is that the signals traveling in the forward direction add in-phase, and those traveling in the reverse direction are absorbed by terminations. Therefore, non-uniform filtering structures may also be used for transmission lines in the DA design.

Can the phase synchronization be maintained if we use a non-uniform filtering structure in a distributed amplifier? To answer this question, we analyze a DA with *lossless* non-uniform filtering structures, and ideal transistors (unilateral and no parasitic resistance), as shown in Fig. 2. We are concerned only about the signal flowing through the i -th tap, and hence only its gate-line voltage and transconductance is shown. The other parts of gate and drains lines are separated into the left block L_i and right block R_i . We define the impedance looking into the two directions as Z_{Li} and Z_{Ri} . The voltage transfer from gate line to drain line at this tap is

$$\frac{v_{di}}{v_{gi}} = \frac{g_{mi}}{Y_{Li} + Y_{Ri}} \quad (1)$$

where $Y_{Li} = 1/Z_{Li}$, $Y_{Ri} = 1/Z_{Ri}$, and g_{mi} is the transistor transconductance. Signals on gate line and drain line are in

(a)

(b)

Fig. 3. Comparison of DAs with different filtering functions (simulated): (a) magnitude response (b) phase response.

synchronization if the right-hand side of Eqn. (1) is a real number, i.e.,

$$\text{Im}\{Y_{Li}\} + \text{Im}\{Y_{Ri}\} = 0 \quad (2)$$

It can be shown [10] that for a lossless passive network split into two parts like in Fig. 2,

$$\left| \frac{Z_{Li}^* - Z_{Ri}}{Z_{Li} + Z_{Ri}} \right| = |\Gamma_1| = |\Gamma_2| \quad (3)$$

When $\Gamma_1 = \Gamma_2 = 0$, $Z_{Li}^* = Z_{Ri}$ or $Y_{Li}^* = Y_{Ri}$. Therefore, the synchronization requirement is satisfied within the passband, given that both transmission lines are matched at terminations ($\Gamma_1 = \Gamma_2 = 0$). Note that the phase synchronization condition (Eq. (2)) implies maximum power transfer in the pass-band, but is generally not satisfied in the stop-band, which usually helps the stop-band performance.

In the prototypes we report below, the filtering structures of the gate-line and drain-line are constructed as Butterworth and Chebyshev functions since both are common low-pass filters used in microwave applications. It is expected that given the same bandwidth, the Butterworth one is quite close to the conventional constant-k case, with flat response within the

(a) Butterworth

(b) Chebyshev

Fig. 4. Normalized design parameters for both filtering structures implemented as LC artificial transmission lines.

Fig. 5. Circuit schematic of the prototype DAs.

pass-band, while the Chebyshev one shows faster roll-off in the stop-band, but its phase response is less linear (Fig. 3).

III. CIRCUIT DESIGN

We chose three-stage designs for the prototype DAs, which are typical for CMOS DAs. So the order of corresponding filters is determined to be seven. Network synthesis method [10] is used to generate the initial design. The normalized design parameters of LC ladder structure, beginning with a series element, for low-pass Butterworth and Chebyshev filtering, are shown in Fig.4 [10]. The real inductance and capacitance values can be scaled from the normalized filter parameters:

$$L_k = \frac{Z_0 g_k}{\omega_c} \quad (4)$$

$$C_k = \frac{g_k}{Z_0 \omega_c} \quad (5)$$

where L_k , C_k are the physical inductance and capacitance values in the ladder structure, Z_0 is the characteristic impedance, ω_c is the cut-off frequency, and g_k is the normalized design parameter in Fig. 4.

The schematic of prototype DAs is shown in Fig.5. The cut-off frequency $f_c = \frac{\omega_c}{2\pi}$ of both gate and drain lines is specified to be 10 GHz. The characteristic impedance (Z_0) of both gate

(a) Butterworth

(b) Chebyshev

Fig. 6. Chip micrograph of the prototype DAs.

and drain lines is $50\ \Omega$. In this schematic, inductors $L'_k = L_k$, while on the gate line the input capacitance of each gain cell is designed to be C_k . On the drain line, extra shunt capacitors C'_k are added with output capacitance of each stage to form C_k . The inductance and capacitance values for Butterworth and Chebyshev filtering are listed in the inset table of Fig. 5,

Cascode configuration is chosen for the gain cell because of its large output impedance and wideband frequency response. A cascode current mirror provides dc bias. L_b and the C_b represent the bias tees and dc blocks in the test set-up. Off-chip wideband $50\ \Omega$ terminations are used in the measurement.

The inductors are initially designed using Asitac to optimize for Q. Then the area of inductors is minimized to reduce the parasitic capacitance, which is important to maintain the constant inductance value within the pass-band. Then the complete gate and drain lines are simulated in Sonnet to generate wideband s-parameters for circuit simulation.

IV. MEASUREMENT RESULTS

The prototype DAs were fabricated using National Semiconductor's $0.18\ \mu\text{m}$ digital CMOS technology with bulk silicon substrate. Spiral inductors are constructed using the $2\ \mu\text{m}$ thick bump metal layer. The design rule on this metal layer results in low self-resonance frequency for the spiral inductors, and hence limited the achievable bandwidth of the prototype DAs. The chip photos are shown in Fig. 6. The chip size is $1.6\ \text{mm} \times 0.9\ \text{mm}$ for the Butterworth one, and $1.8\ \text{mm} \times 1.1\ \text{mm}$ for the Chebyshev one. The power supply is 1.5 V for both DAs. The power consumption is 51 mW and 54 mW for the Butterworth and Chebyshev DAs, respectively.

The frequency responses of both DA chips were measured

(a)

(b)

(c)

(d)

Fig. 7. Measured performance of the prototype Butterworth DA: (a) power gain; (b) phase response; (c) input return loss; (d) output return loss.

via on-wafer probing. Due to the inaccuracy of on-chip capacitors and the modeling of inductor loss, there is a sloping response below 2 GHz. The gain of the Butterworth DA is $11.7\ \text{dB} \pm 0.6\ \text{dB}$ from 2.5 GHz to 9 GHz, as shown in Fig. 7. The input return loss is better than $-17\ \text{dB}$ within 8.5 GHz, and the output return loss is better than $-14\ \text{dB}$ within 9.3 GHz. The small signal gain of the Chebyshev DA is $10\ \text{dB} \pm 1.0\ \text{dB}$ from 2.5 GHz to 8.5 GHz, as shown in Fig. 8. The input return loss is better than $-11\ \text{dB}$ within 9.6 GHz, and the output return loss is better than $-10\ \text{dB}$ within 8.6 GHz. The transition rate to the stop-band is $-5\ \text{dB}/\text{GHz}$

(a)

(b)

(c)

(d)

Fig. 8. Measured performance of the prototype Chebyshev DA: (a) power gain; (b) phase response; (c) input return loss; (d) output return loss.

for the Butterworth DA and -8 dB/GHz for the Chebyshev DA. It can be seen that both prototypes match the simulation very well.

The nonlinearity performance of the DAs is also characterized (Fig. 9). The input IP3 of the Butterworth DA is better than 4.5 dBm from 2 GHz to 7 GHz. The Chebyshev one is better than 5 dBm from 1 GHz to 8 GHz.

V. CONCLUSION

We demonstrated that non-uniform filtering structures can be used in DAs for better control of the frequency response

Fig. 9. Input IP3 of the prototype DAs.

in both pass-band and stop-band. Prototype DAs with Butterworth and Chebyshev filtering designed and implemented using a $0.18\mu\text{m}$ digital CMOS technology. Measurement results verified the new design concept.

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