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Active Microwave Circuit With Negative Group Delay
Blaise Ravelo, André Pérennec, Marc Le Roy, and Yann G. Boucher

Abstract—In this letter, we report on the design, simulation and implementation of an active negative group delay circuit that operates at 1 GHz with a group delay and a gain, respectively, around −2 ns and 2 dB. Analytical formulas are proposed to demonstrate that the adopted topology is able to simultaneously achieve negative group delay (NGD) and gain while fulfilling active device constraints. The theoretical and simulated results are both validated by frequency measurements of a two-stage active microwave circuit.

Index Terms—Active devices, negative group delay (NGD).

I. INTRODUCTION

F or numerous applications, particularly in modern high-speed telecommunications, flat group delay or linear phase is necessary to avoid distortion in the baseband signals. In the microwave domain, group delay equalizers are used to compensate for group delay variations mostly introduced by filters [1] or amplifiers [2]. Time delay variations are also known to cause instabilities in feedback circuits in oscillator applications [3].

To reduce such perturbations, Lucyszyn et al. [3], [4] have put forward an original negative group delay synthesizer. This narrow band Microwave Integrated Circuit synthesizer, built with varactors, field effect transistors (FET) and lumped components, operates in reflection and needs a coupler to pass into transmission. High negative group delay (NGD) values are obtained at 1 GHz but also with high losses. Since this first proposal in microwave domain, several topologies exhibiting negative group delay have been proposed and we can merge these devices in two categories according to their operating frequencies.

The first one, essentially devoted to the microwave frequency, is represented by its low frequency model, i.e., the transconductor phase versus an instabilities in feedback circuits in oscillator applications [3].

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The group delay of the series RLC network in shunt, on its own, can be expressed versus its quality factor, \( Q \)

\[
\tau_{RLC}(\omega_0) = \frac{-2QZ_0}{\omega_0(2R + Z_0)}.
\]

For the active cell (Fig. 1), this expression is modified as

\[
\tau_{cell}(\omega_0) = \frac{-2QZ_0}{\omega_0(R + R_0Z_0/R_{ds} + Z_0)}.
\]

From (1) and (5), it becomes evident that increasing \( L \) improves \( Q \) and thus the NGD value while narrowing the resonance band and reducing the NGD bandwidth. Moreover, in (5), if \( R_{ds} \) is higher than \( Z_0 \), the negative group delay value can be slightly improved in the active topology. These equations force us to give priority to an FET with high \( g_m \) and \( R_{ds} \) values and in that case a compromise between low \( R \) and high \( L \) values may be found to achieve gain and an NGD value. These explanations may be partially summed up by the following ratio:

\[
\left| \frac{S_{21}(\omega_0)}{\tau_{cell}(\omega_0)} \right| = \frac{g_mR^2}{L}.
\]

From (3), output matching may also be obtained for a high \( R_{ds} \) value and a not too small \( R \) value (toward \( Z_0 \)). Input matching can simply be done with a shunt resistor \( R_m \) (Fig. 2) at the FET input. Then, the input return loss is simply expressed as

\[
S_{11}(\omega_1) = \frac{R_m - Z_0}{R_m + Z_0}.
\]

And at the resonance, the transmission parameter is modified as follows:

\[
S_{21}(\omega_1) = -\frac{2R_mR_1Z_0Z_mR_{ds}}{(R_m + Z_0)(Z_0R_{ds} + Z_1R_1 + R_1R_{ds})}.
\]

### III. Circuit Implementation and Experimental Results

To validate the concept of active device with NGD, we built a circuit operating at centimetric wavelengths to avoid too many high frequency parasitic effects and to stay in the validity domain of the FET model. A two stage device ensures that all our objectives could be reached with a significant margin, i.e., at least a group delay below -2 ns, gain around 2 or 3 dB and input/output matching below -10 dB. Then, from these values and by inverting (1), (3), (7), and (8), the component values can be calculated for the specified FET. If both stages resonate at the same frequency, the total insertion losses and group delay are expressed as

\[
S_{21T} = \frac{S_{211}S_{212}}{1 - S_{211}S_{112}} = \frac{2g_m^2R_1^2R_{ds}R_1R_2Z_0R_m}{(R_1 + R_{ds})(Z_0 + R_m)(R_2Z_0 + Z_3R_{ds} + R_{ds}R_2)}
\]

\[
\tau_T = \tau_1 + \tau_2 = \frac{2LR_{ds}^2}{(R_1 + R_{ds})(R_1R_{ds} + R_1Z_0 + R_{ds}Z_3)}
\]

where the index 1, 2 and \( T \) correspond, respectively, to the first and second stages and to the overall circuit. Finally, the electromagnetic simulation (ADS Momentum software) shows responses really close to the results obtained from our analytical low frequency model except for a slight shift in the resonance frequency. First, we biased the circuit \((V_{GS1} \text{ and } V_{DS1})\) in Figs. 2 and 3 in a traditional way for both the gates and the drains. Fig. 4 compares the EM simulation results to measurements for the scattering parameters and the group delay. These results were obtained with no adjustment. One should note the good agreement between simulations and measurements, especially for the gain and the group delay values that reach respectively 1.68 dB and -2.3 ns with matching better than 10 dB. The slight
Fig. 4. (a), (b) Measured and simulated $S$-parameters and (c) group delay.

A shift in the frequency measurements is fully explained by the $L$ and $C$ component tolerances (see Fig. 4).

We obtain a better agreement compared with the passive circuits operating at a similar frequency band [5], a higher NGD value is reached with fewer cells and the NGD bandwidth is slightly improved while meeting all the active design requirements. We further biased the transistors between $L_1$ and $C_1$ and between $L_2$ and $C_2$ through the high value inductors ($V_{GS2}$ and $V_{DS2}$ in Figs. 2 and 3). Under this configuration, the results of the second set of measurements were exactly the same as the first ones. So, the $RLC$ networks ensure two functions and the whole circuit could be simplified.

IV. CONCLUSION

An active circuit showing NGD and gain simultaneously is, for the first time, designed and implemented at microwave frequencies. Measurements are really close to those expected from our analytical equations and, at 1 GHz, a 2 dB gain is associated with a $\pm 2$ ns group delay. This topology may also be transposed to higher frequency bands with a more complete FET modeling and by passing $RLC$ lumped components into distributed planar technology. Tunable capacitances and inductances could be used separately or together to control either the frequency or the level of the NGD. Moreover, stages with different resonant frequencies would produce broadband NGD suitable for ultra wideband (UWB) applications and for baseband numerical signals in inter- or intra-chip interconnects.

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