A Dual-Purpose Reconfigurable Negative Group Delay Circuit Based on Distributed Amplifiers

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Abstract—In this letter, a novel reconfigurable negative group delay distributed amplifier (NGD-DA) circuit is proposed. This NGD-DA offers a new method to realize negative group delay. By properly choosing the gain coefficient of each tap for the DA, we can synthesize the negative group delay at the reverse port of the DA in the frequency band of interest, while maintaining a flat gain at the forward port; this results in a dual-purpose DA. Moreover, the proposed NGD-DA is reconfigurable; the phase response at the reverse port can be simply controlled by adjusting the tap gain coefficients, and therefore the bandwidth as well as the amount of negative group delay can be manipulated. The proposed active NGD circuit is validated through theoretical explanation and experimental results.

Index Terms—Dispersion engineering, distributed amplifier (DA), dynamic power supply, negative group delay (NGD), superluminal group velocity, transversal filter.

I. INTRODUCTION

NEGATIVE group delay (NGD), although being counter-intuitive, has been proved its feasibility in electronic circuits using a simple bandpass amplifier at low frequency in [1]. In microwave regime, conventionally, bandstop structures are used to realize NGD circuitry; based on either series or shunt RLC resonators, many active and passive NGD circuitries have been proposed and demonstrated with or without tunability [2]–[5].

On the other hand, distributed transversal filters (DTF) are widely used in high speed signal processing such as equalization and pulse-shaping [6]. Recently, due to the emerging research on analog signal processing (ASP) [7], such topology has also been used in dispersive delay lines (DDL) to synthesize the desired group delay response [8]. In addition, DTFs are reconfigurable due to the capability of controlling the gain of each unit-cell [9]. Nevertheless, being essentially the same structure as distributed amplifiers (DA), DTFs usually utilize only one of the output ports (either forward or reverse port) to realize the desired response, whereas the other output port is often terminated [6].

Utilizing the reconfigurability of DTFs as well as making use of both the forward and reverse port of DAs, this work presents a new type of DA with a dual purpose. By properly choosing

the gain coefficients of the DA, it can produce NGD at the reverse port, and moreover, it preserves a flat gain response at its forward port as a conventional DA does. Furthermore, the proposed NGD-DA is reconfigurable. By adjusting the gain of each tap of the DA, we are able to manipulate the slope of the phase, and therefore the bandwidth as well as the amount of NGD can also be controlled.

As a result, the proposed design has several potential applications. Particularly, it is very promising to be used in the dynamic power supply or envelope tracking of power amplifiers (PA) [10], [11]. In a supply modulated PA, it is crucial that the dynamic power supply can accurately track the signal envelope in order to maximize the efficiency. The proposed NGD-DA can be used to compensate the time mismatch between the dynamic power supply and the signal envelope, and thus the system efficiency can be increased [12].

II. THEORETICAL ANALYSIS

To explain the idea of the proposed design, we first look at the general diagram of a distributed amplifier with N taps as shown in Fig. 1. The transfer functions of the forward and reverse port with respect to the input are [6]

$$H_{\text{FWD}}(\omega) = \frac{V_{\text{out\_FWD}}}{V_{\text{in}}}$$
$$= \sum_{k=1}^{N} G_k \exp\left(-j\omega\left(\sum_{i=1}^{k} \tau_{gi} + \sum_{m=k+1}^{N} \tau_{dm}\right)\right) \quad (1a)$$

$$H_{\text{REV}}(\omega) = \frac{V_{\text{out\_REV}}}{V_{\text{in}}}$$
$$= \sum_{k=1}^{N} G_k \exp\left(-j\omega\sum_{i=1}^{k}(\tau_{gi} + \tau_{di})\right) \quad (1b)$$

where G_k is the gain coefficient of the kth tap amplifier, τ_{gk} and τ_{dk} indicate the time delay of the kth section of the gate line and drain line, respectively. Furthermore, if we choose that $\tau_{gi} = \tau_{di} = \tau_0$, then the above equations will become

$$H_{\text{FWD}}(\omega) = \sum_{k=1}^{N} G_k \exp(-j\omega(N\tau_0)) \quad (2a)$$

$$H_{\text{REV}}(\omega) = \sum_{k=1}^{N} G_k \exp(-j\omega(2k\tau_0)). \quad (2b)$$

Now we try to synthesize the NGD by manipulating the reverse transfer function $H_{\text{REV}}(\omega)$ of the DA. First, consider a transfer function with a constant negative group delay

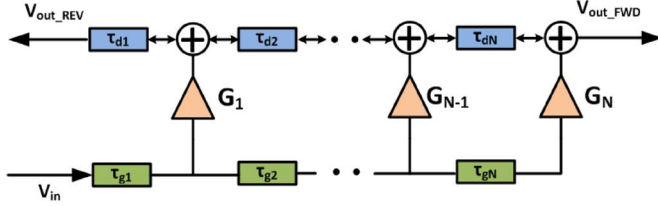$$T(\omega) = Be^{jb\omega} \quad (3a)$$

Fig. 1. Distributed Amplifier or distributed transversal filter topology.
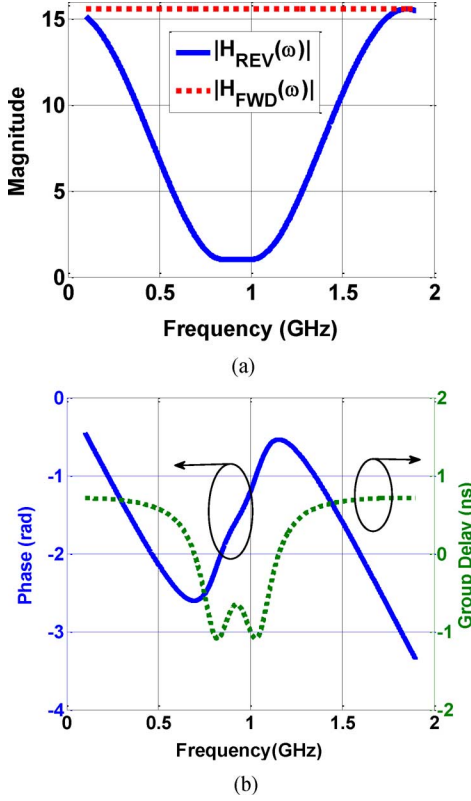

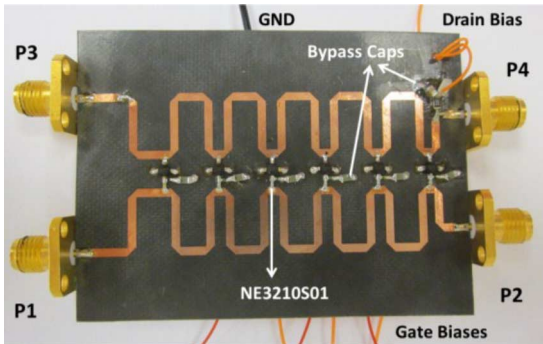Fig. 2. (a) Forward and reverse gains, and (b) the responses of reverse port.

Fig. 3. Prototype of the proposed NGD-DA.

where its group delay(GD) can be obtained as follows:

$$\text{GD} = \frac{-d\angle T(\omega)}{d\omega} = -b. \tag{3b}$$

Assuming b is a positive number, it is clear from (3) that the transfer function $T(\omega)$ has a magnitude of B and negative group delay of b. Now, let us find an optimal set of gain coefficients $\mathbb{G} = [G_1, G_2, \ldots, G_N]$ for a given N and b such that the group delay of $H_{\text{REV}}(\omega)$ is almost equal to $-b$ over a normalized fre-
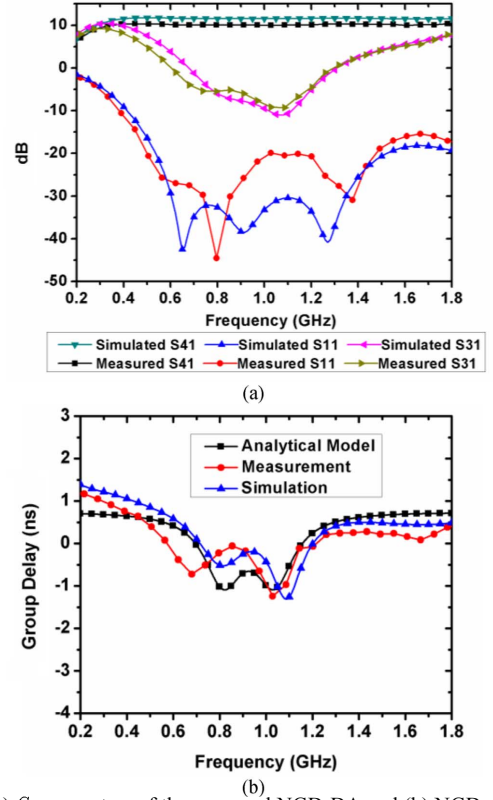

Fig. 4. (a) S-parameters of the proposed NGD-DA and (b) NGD with the bi-asing condition of $V_{g1} = -0.435$ V, $V_{g3} = -0.32$ V, $V_{g5} = -0.484$ V, $V_{g2} = V_{g4} = V_{g6} = -1$ V, and $V_d = 2.3$ V.

quency band $\Omega = [\omega_{n1}, \omega_{n2}]$. The problem becomes an optimization problem and can be expressed as

$$\text{minimize max} \left\{ \left| \sum_{k=1}^{N} G_k \times \exp(-j\omega(2k\tau_0)) - e^{jb\omega} \right| \right\} \tag{4}$$

for $\omega \in \Omega$ and $B = 1$. One can use convex optimization techniques to solve for the coefficient set $\mathbb{G} = [G_1, G_2, \ldots, G_N]$ in (4). In addition, if we force all the elements in G to be non-negative when solving the above optimization problem, the forward gain descried in (2a) will be positively added up as well. Now, given the DA has six taps or $N = 6$, an optimal set obtained from (4) would be

$$\mathbb{G} = [5.5, 0, 7.29, 0, 2.79, 0]. \tag{5}$$

This is the optimal set that we will use for the following analysis of our proposed design.

Fig. 2(a) plots the magnitude of the forward and reverse transfer functions descired in (2) with the time delay $\tau_0 = 0.135$ ns, using the optimal gain coefficient set of (5). An NGD of 0.866 ± 0.216 ns can be observed from 0.762 GHz to 1.089 GHz as shown in Fig. 2(b). In addition, in NGD region, the phase at the reverse port increases with respect to the frequency, while the magnitude reaches its minimum at unity as designed in (4). On the other hand, the forward port has a flat gain response whose magnitude is simply the summation of $\mathbb{G}$.

III. VERIFICATIONS

To realize the desired transfer functions described previously, we fabricated the entire circuit on a PCB using Rogers RO5880
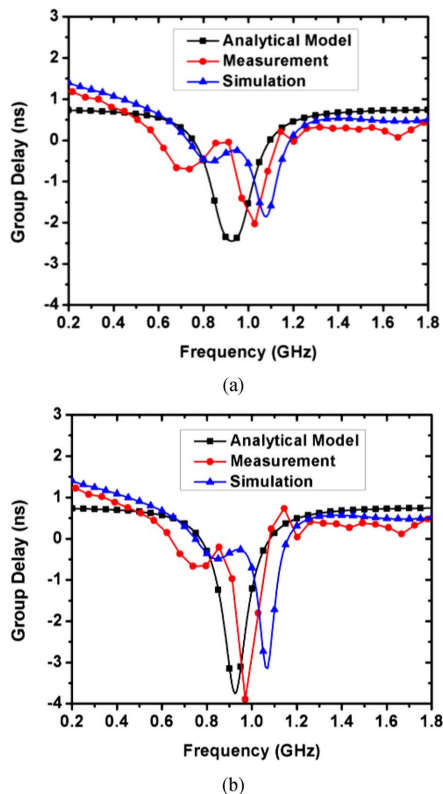
(a)

(b)

Fig. 5. Group delay of the proposed NGD-DA at (a) $V_{g1} = -0.465$ V and (b) $V_{g1} = -0.495$ V.

with a dielectric constant of 2.2 and thickness of 20 mils as shown in Fig. 3. The DA contains six taps, in which we use NEC's Hetero Junction FET, NE3210S01, for the active devices. The gain control of each tap can be done by adjusting the transconductance of the transistors. In order to do so, the gate biases have been designed so that each transistor can be gate-biased individually.

The transistors of the DA need to be biased according to the ratio that is obtained from (5). It is noted that when the gain coefficient is zero, it indicates the transistor is turned off. Furthermore, the drain bias is chosen high to lower the sensitivity of the transconductance. As a result, the gate biases are $V_{g1} = -0.435$ V, $V_{g3} = -0.32$ V, $V_{g5} = -0.484$ V, $V_{g2} = V_{g4} = V_{g6} = -1$ V, and the drain bias is $V_d = 2.3$ V. The simulated and measured S-parameters at this biased condition are plotted in Fig. 4(a), indicating a good agreement. The measured reverse gain (S_{31}) reaches a minimum of around -10 dB at 1.05 GHz and is greater than -10 dB elsewhere in the NGD region, which is around 0.6 GHz–1.1 GHz as shown in Fig. 4(b). On the other hand, the measured forward gain (S_{41}) has a flat response of around 10 dB throughout the NGD region. The measured S_{11} is below -20 dB in the NGD region, showing a good input matching of the DA.

Fig. 4(b) plots the group delay under the same bias condition as mentioned above. The results are compared among the analytical model depicted in (2b), the simulation carried out by Advanced Design System (ADS), and the experimental measurement. These results show a very good agreement except a slight frequency shift. A broad band NGD from 0.6 to 1.1 GHz can be observed in the measurement. The frequency shift may be due to handmade fabrication errors.

The proposed NGD-DA is then tested with different bias conditions. By setting the gate bias of the first tap to $V_{g1} = -0.465$ V, we can observe a NGD of 2 ns at around 1 GHz in the measurement as shown in Fig. 5(a). As shown in Fig. 5(b), when we further set $V_{g1} = -0.495$ V, we will obtain a NGD of around 4ns at 1 GHz. This results in a good reconfiguribility of the proposed NGD-DA. The coefficients sets that we use for the analytical models are [4.84, 0, 7.29, 0, 2.79, 0] and [4.73, 0, 7.29, 0, 2.79, 0] for $V_{g1} = -0.465$ V and $V_{g1} = -0.495$ V, respectively. The simulation and measurement agree well, whereas the discrepancy between them and the analytical model may be due to the tiny leakage current from the off transistors as well as the extra paracitics in the fabricated circuit. In addition, it is worth mentioning that in the case that $V_{g1} = -0.495$ V, the measured forward gain still maintains a flat gain of 9.44 dB, which is still reasonably high.

IV. CONCLUSION

In this work, we proposed an active NGD circuit based on DA topology. The proposed NGD-DA has dual purposes: while creating the NGD in the reverse port, it can still maintain a flat high gain response in the forward port. In addition, it is also demonstrated the proposed NGD-DA is reconfigurable by adjusting the gate bias. The proposed design is promising to be used in dynamic power supply or envelope tracking in PAs to eliminate the time mismatch between the RF signal path and the envelope path.

REFERENCES

[1] M. W. Mitchell and R. Y. Chiao, "Negative group delay and 'fronts' in a causal system: An experiment with very low frequency bandpass amplifiers," *Phys. Lett. A*, vol. 230, pp. 133–138, Jun. 1997.

[2] B. Ravelo, A. Perennec, and M. Le Roy, "Synthesis of broadband negative group delay active circuits," in *IEEE Int. Microw. Symp. Dig.*, Jun. 2007, pp. 2177–2180.

[3] H. Noto, K. Yamauchi, M. Nakayama, and Y. Isota, "Negative group delay circuit for feed-forward amplifier," in *IEEE Int. Microw. Symp. Dig.*, Jun. 2007, pp. 1103–1106.

[4] H. Choi, Y. Jeong, J. Lim, S. Y. Eom, and Y. B. Jung, "A novel design for a dual-band negative group delay circuit," *IEEE Microw. Wireless Compon. Lett.*, vol. 21, no. 1, pp. 19–21, Jan. 2011.

[5] S. Lucyszyn, I. D. Robertson, and A. H. Aghvami, "Negative group delay synthesiser," *Electron. Lett.*, vol. 29, no. 9, pp. 798–800, Apr. 29, 1993.

[6] A. Borjak, P. P. Monteiro, J. J. O'Reilly, and I. Darwazeh, "High speed generalized distributed-amplifier-based transversal-filter topology for optical communication systems," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 8, pp. 1453–1457, Aug. 1997.

[7] C. Caloz, S. Gupta, B. Nikfal, and Q. Zhang, "Analog signal processing (ASP) for high-speed microwave and millimeter-wave systems," in *Proc. Asia-Pacific Microw. Conf.*, Dec. 2012, pp. 691–692.

[8] B. Xiang, A. Kopa, Z. Fu, and A. Apsel, "Theoretical analysis and practical considerations for the integrated time-stretching system using dispersive delay line (DDL)," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 11, pp. 3449–3457, Nov. 2012.

[9] Y. Zhu, J. D. Zuegel, J. R. Marciante, and H. Wu, "A reconfigurable, multi-Gigahertz pulse shaping circuit based on distributed transversal filters," in *Proc. IEEE ISCAS*, May 2006, pp. 4232–4235.

[10] B. Kim, J. Moon, and I. Kim, "Efficiently amplified," *IEEE Microw. Mag.*, vol. 11, no. 5, pp. 87–100, Aug. 2010.

[11] E. McCune, "Envelope Tracking or polar—Which is it?," *IEEE Microw. Mag.*, vol. 13, no. 4, pp. 34–56, Jun. 2012.

[12] F. Wang, A. Yang, D. Kimball, L. Larson, and P. Asbeck, "Design of wide bandwidth envelope tracking power amplifers for OFDM applications," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 4, pp. 1244–1255, Apr. 2005.