Experimental verification for time advancement of negative group delay in RF electronic circuits

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An experiment was performed on the signal cancellation loop that utilises a carrier wave (CW) and wideband code division multiple access (WCDMA) signals to show that negative group delays can be used to cancel out positive group delays. According to the closed loop measurements, a 30 dB signal cancellation for a CW signal and a WCDMA 4FA signal were obtained over a 30 MHz bandwidth at the WCDMA downlink band, with a fabricated two-stage planar negative group delay circuit.

Introduction: Since Garret and McCumber's prediction of the existence of faster than *c* group velocities [1], an experimental verification was performed by Chu and Wong [2]. Their experiment proved that picosecond laser pulses propagated superluminally through an absorbing medium in an anomalous dispersion region inside the optical absorption line. In another optical domain experiment by Wang *et al.*, the group velocity (and hence the group delay (GD)) was observed to be negative [3]. In the field of electronic circuit design, some passive lumped element networks, with specific conditions, were proved to have this negative group delay (NGD) property [4, 5].

One of the physical consequences of these NGDs is the observation that the peak of a smoothly varying pulse will be advanced in time as a result of the propagation. Such a seemingly non-causal phenomenon does not violate the principle of causality, because there is sufficient information in the early portion of any analytic voltage waveform to anticipate the entire waveform earlier in time [6]. Furthermore, it has been shown that causality is solely connected with the occurrence of discontinuities in a signal ('fronts' and 'backs'), and not with peaks in the voltage waveform [7]. Those works have only considered the pulse signal, whereas actual wireless communication systems utilise a specific bandwidth signal, e.g. a CDMA (hence arbitrary waveform in the time domain).

This Letter reports an experiment that has been performed on the signal cancellation loop that utilises a carrier wave (CW) and WCDMA signals to show the applicability of the NGDs to the time advancement of any arbitrary waveform.

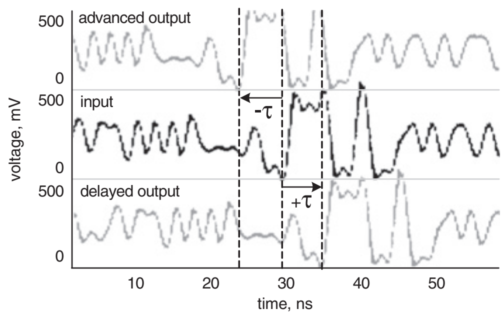

Fig. 1 *Simulation of time delayed and advanced output voltages for arbitrary waveform*

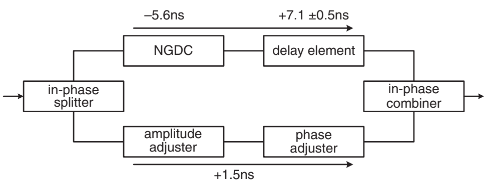

Fig. 2 *Schematic diagram of simple signal cancellation loop*

Time advance property of NGD circuit (NGDC): Fig. 1 illustrates the input (centre), the time delayed output (lower), and the time advanced output (upper) with a positive $(+\tau)$ and negative $(-\tau)$ GD, respectively. The time delayed output is obtained when the signal is applied to a normal electronic circuit, while the latter can be obtained when applied to the NGDC. When the input signal is applied to the cancellation loop of Fig. 2, the input signal will be cancelled at the output summing node if the amplitude, the out-of-phase, and the GD balance conditions are matched simultaneously. Conversely, if the cancelled signal is sufficiently small at the output node, we may conclude that time advancement occurred and that it is useful for an arbitrary waveform.

Planar NGDC design: The magnitude and phase of the reflection coefficient for the reflective parallel (RP) network (Γ_{RP}) can be determined using the input impedance of the RP network. Thus, the GD and the reflection loss can be expressed as (1) and (2) by assuming a resonance condition at the desired operating frequency. The GD is a function of capacitance (C_{RP}) and resistance (R_{RP}) [8]:

$$GD_{RP}|_{\omega=\omega_0} = -\left.\frac{d\phi_{in,RP}}{d\omega}\right|_{\omega=\omega_0} = \frac{4R_{RP}^2 Y_0 C_{RP}}{(R_{RP}Y_0)^2 - 1} \quad (1)$$

$$\Gamma_{RP}|_{\omega=\omega_0} = \frac{1 - R_{RP}Y_0}{1 + R_{RP}Y_0} \quad (2)$$

The magnitude of the NGD is proportional to R_{RP} and C_{RP}, provided that R_{RP} is smaller than 50 Ω. In the case of $R_{RP} > 50$ Ω, the NGD cannot be achieved, abruptly providing the positive GD. From (2), a greater NGD induces greater signal attenuation, delivering a trade-off to the designer, as the reflection coefficient is equal to the insertion loss for the reflective circuit.

To overcome the limited feasibility of the designed component values, a transmission line resonator concept using a specific length of open or short terminated transmission line is adopted to replace the LC circuit [8].

Experimental verification: For experimental verification, a goal was set to design a two-stage reflective planar NGDC with a total GD of −6 ns, an insertion loss of 0 dB, and a bandwidth of 30 MHz centred on the WCDMA downlink band (2.125–2.155 GHz). The proposed circuit consists of a 90° hybrid and two planar NGDC units (units 1 and 2) the centre frequencies of which were 2.125 and 2.155 GHz, respectively, as shown in Fig. 3. By connecting those two units in a cascade, a flat GD and transmission response could be obtained for the operating bandwidth. The overall insertion loss could be compensated for by general purpose small signal amplifiers, the gain of which was notated as *G* in Fig. 3. A compensation capacitor (C_{COMP}) was connected in parallel to the R_{RP} to compensate for the minute parasitic inductance of chip resistors so that R_{RP} did not have any reactive impedance.

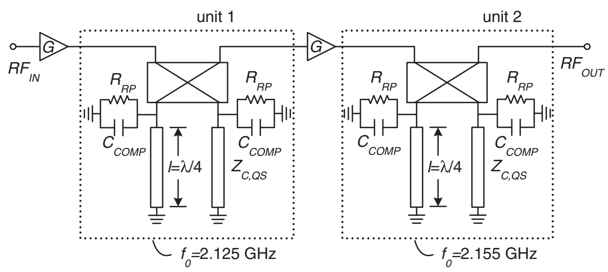

Fig. 3 *Circuit diagram of reflection-type planar NGDC*

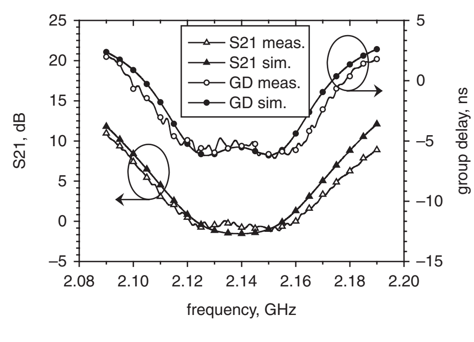

Fig. 4 *Simulated and measured amplitude and group delay response*

Fig. 4 shows the simulation and measurement results of the fabricated two-stage planar NGDC. Measured results agree well with simulation results, achieving a GD of −5.6 ns, and an insertion loss of 0.2 dB.

The GD and the insertion loss were -5.65 ± 0.25 ns and 0.21 ± 0.06 dB at the operating frequency, respectively. A small amount of the GD and the magnitude error is due to the connecting elements and the gain of the small signal amplifiers.

By providing the amplitude, the out-of-phase and the GD matching conditions between the two paths, a loop suppression of about 30 dB was achieved with the CW signal, as shown in Fig. 5. This result can be interpreted into the out-of-phase mismatch of $\pm 1.8°$, the amplitude mismatch of ± 0.28 dB, and the GD mismatch of ± 0.16 ns, when all the other conditions are assumed to be perfectly matched. In the case when the WCDMA 4FA signal was applied, around 30 dB suppression was obtained, as shown in Fig. 6. This implies that the proposed NGDC can successfully compensate for the positive GD of a normal electronic circuit using the time-varying envelope modulation signal. The bandwidth of 20 dB suppression reaches up to 45 MHz. Some degradation was observed near the band edge. It can be optimised by increasing or reducing the frequency offset of the two centre frequencies of the two NGDC units.

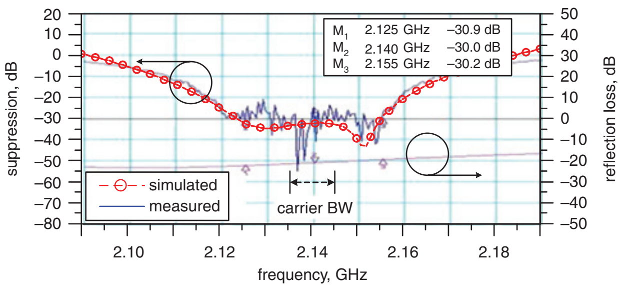

Fig. 5 *Simulated and measured closed loop cancellation results with CW signal*

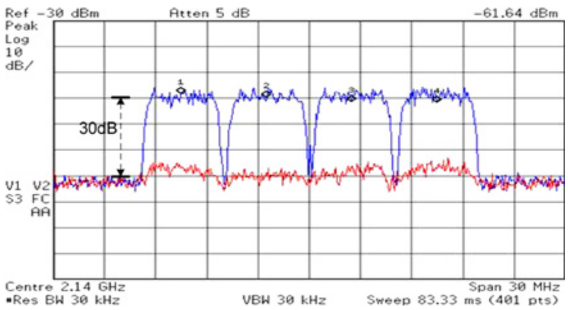

Fig. 6 *Measured output spectrum by open loop (unsuppressed) and closed loop (suppressed) with WCDMA 4 FA signal*

Conclusion: An experiment has been performed on a signal cancellation loop that utilises CW and WCDMA signals to show that the NGD can be used to cancel out a positive GD. According to the assumption and the closed loop measurement results, it can be concluded that the time advancement property can be also applied to the system using a signal with an arbitrary waveform.

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One or more of the Figures in this Letter are available in colour online.

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