An Electronic UWB Continuously Tunable Time-Delay System With Nanosecond Delays

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***Abstract*—We propose and demonstrate an electronic system achieving continuously tunable time-delays with nanosecond-scale delay excursions for ultra-wideband signals. Our demonstration system yields an adjustable delay of up to 1.6 ns for input signals spanning 3 to 7 GHz. The key component is a dispersive length of microstrip line created by etching a chirped electromagnetic bandgap structure in the conducting strip.**

***Index Terms*—Bandgap devices, microstrip circuits, tunable delay lines, ultra-wideband (UWB) systems.**

I. Introduction

AMID the growing popularity of ultra-wideband (UWB) systems for short-to-mid-range wireless communication systems and radars, there is an increased need to establish a signal processing toolbox for bandwidths of several GHz. In particular, tunable UWB delay systems have generated interest owing to their role in the beam-steering of phased-array antennas (PAA) [1], synchronizing UWB receivers [2], and potentially in pulse-position modulation encoding [3].

Several approaches have recently been reported for implementing UWB true-time delay (TTD), including microwave photonics [4], [5], periodic varactor-loaded lines [6], and CMOS design [2]. Although the reported photonics-assisted techniques yielded large (nanosecond) delay excursions, they require potentially tough-to-integrate optical hardware [4], [5]. In contrast, broadband electronic techniques generally offer delays in the range of tens-to-hundreds of picoseconds (sufficient for beam-steering in PAA applications) and are more compact in design [2], [6]. Nevertheless, synchronous UWB systems remain in need of continuously tunable delay ranges reaching the nanosecond scale [2] in systems that are easy to integrate with existing microwave technologies.

In this work, we demonstrate a system consisting of two lengths of microstrip line, an adjustable local oscillator, and commercial mixers and directional couplers to yield continuously tunable UWB delays on the order of nanoseconds. Using a total meandered length of 36 cm of microstrip line, our demonstration system achieves 1.6 ns of continuously adjustable delay for signals of 4 GHz bandwidth.

Manuscript received July 26, 2007; revised November 16, 2007. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC).

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Digital Object Identifier 10.1109/LMWC.2007.915039

II. Design of a Tunable UWB Delay Line

The key component of the proposed system is the chirped electromagnetic bandgap (CEBG) transmission line, an UWB structure featuring strong reflection-mode dispersion [7]. These structures are long, but simple to fabricate in planar microwave technologies Here, we employ microstrip CEBGs featuring linear frequency-chirped periodic modulations of the strip-width along their length, as in [7]. At each point down the line, a different frequency is reflected according to the local period. A microstrip of length "L" on a substrate of effective permittivity "$\varepsilon_{\mathrm{eff}}$" can be designed for a group delay slope "σ" (s/Hz) and bandwidth "$\Delta\omega$" according to

$$\sigma = \frac{2L\sqrt{\varepsilon_{\mathrm{eff}}}}{\Delta\omega \cdot c} \tag{1}$$

where c is the speed of light in a vacuum. The interested reader is referred to [7] for further information on CEBGs.

The demonstration system is presented in Fig. 1 and is patterned after a familiar tunable delay configuration for sub-GHz frequency regimes using chirped surface-acoustic-wave (SAW) structures [8]. In the first step, an UWB input signal of bandwidth $\Delta\omega_{\mathrm{RF}} = \omega_2 - \omega_1$ is difference-frequency mixed with an ultra-broadband voltage-controlled oscillator (VCO), the acting local oscillator (LO), at frequency $\omega_{\mathrm{LO}} \pm \Delta\omega_{\mathrm{LO}}/2$. The output intermediate frequency (IF), is passed to the first dispersive transmission line (CEBG1) and a broadband directional coupler is employed to circulate the signal. In the CEBG, the signal experiences reflection after traveling a distance down the line determined by the IF, which is controlled by adjusting the VCO. The round-trip time (and hence delay) of the signal in the CEBG line is therefore determined by the VCO and the chirp (group delay slope "σ") of the line, according to

$$\Delta t = \left| \sigma \cdot \frac{\Delta\omega_{\mathrm{LO}}}{2\pi} \right|. \tag{2}$$

As a consequence of the signal being broadband, it is also dispersed while traveling down the CEBG line in addition to being delayed. To recover the original signal, it is down-converted to its original frequency band (by mixing again with the LO and filtering for the difference frequency). This mixing step causes an inversion in the chirp of the signal (i.e., a down-chirped signal becomes up-chirped). The result must be compressed with a second, shorter dispersive line (CEBG2) having the same group

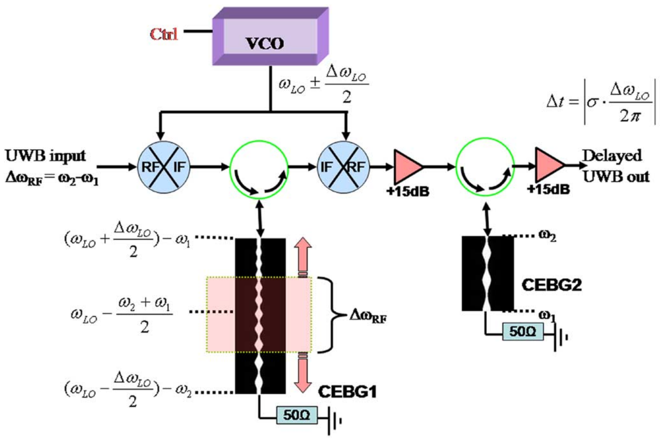

Fig. 1. Schematic of the tunable UWB delay system. The shaded region indicates the bandwidth of the signal as it is reflected from the CEBG—its location along the line "CEBG1" can be adjusted by tuning the VCO.

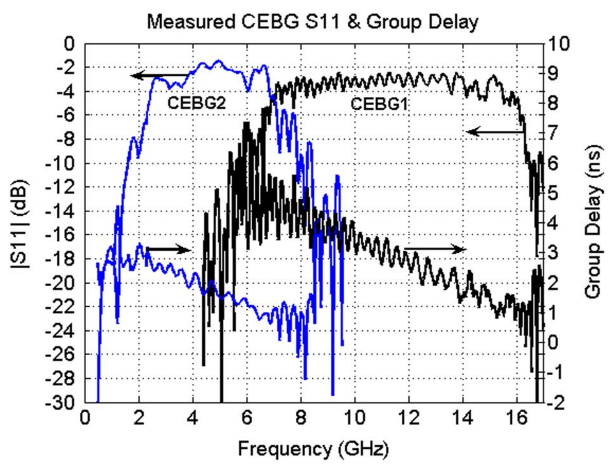

Fig. 2. Measured S11 (magnitude, group delay) from both CEBGs, which share the same group-delay slope but different frequency bands.

delay slope as the first but occupying only the band of the original UWB input signal.

III. Simulation and Experiment

Two CEBG structures were fabricated on an alumina substrate (1.27 mm thick, $\varepsilon_r = 9.5, \tan\delta = 0.0007$) diced to 10 cm by 5 cm. They were designed to have a group delay slope of -0.4 ns/GHz and were meandered to fit on the etched area. The CEBG1 structure was 21.6 cm in length and spanned 8 to 16 GHz (see Fig. 2), while the "baseband" CEBG2 line was 14.8 cm and spanned 3 to 7 GHz. Measured S_{11} magnitude and group delay responses are presented in Fig. 2 using a 20 GHz Agilent VNA (8703 B). Some group delay ripple is evident (a characteristic of chirped bandgap structures [7]), but introduces only mild distortion owing to the broadband nature of the input signals. Each CEBG microstrip was baseplate-mounted, connectorized to SMA and paired with an appropriate broadband commercial 6 dB directional coupler.

A first test signal (Fig. 3) was generated using a 500 mV, 3 Gbps train of pulses run through a commercial broadband mixer (LO= 5 GHz) to simulate an UWB waveform with frequency content concentrated between 3 and 7 GHz. This signal was then up-converted using commercial passive

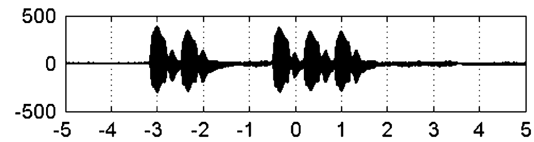

Fig. 3. Input signal #1: a 3 Gbps pulse train of 13 b ("1010000010101"), centered on a 5 GHz carrier. Spectral content is concentrated between 3–7 GHz.

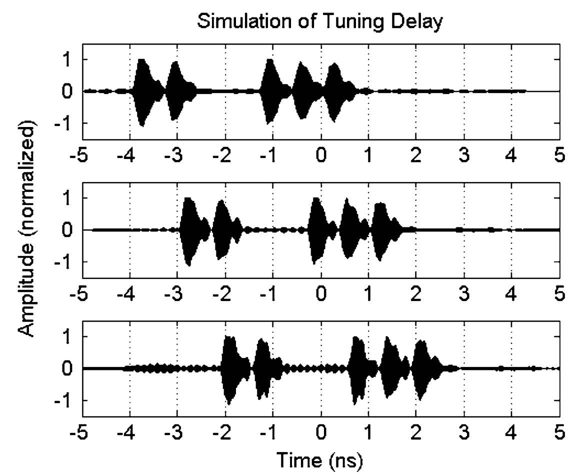

Fig. 4. Simulation of delay using the input of Fig. 3 and assuming ideal CEBGs and lossless mixing and filtering. Three LO frequencies are used: 18.3 GHz (top), 15.9 GHz (center), 13.8 GHz (bottom).

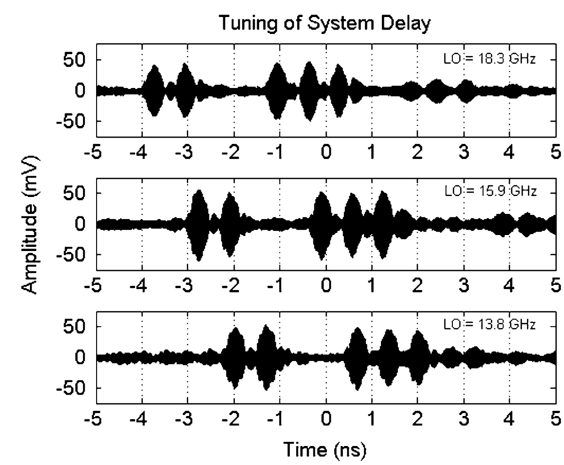

Fig. 5. Experimentally measured output for the same three LO frequencies shown in Fig. 4. Some slight distortion of the input envelope has occurred due to the rippled responses of the CEBGs and mixer noise contributions.

triple-balanced mixers. We used as our LO a simple sinusoidal signal generator, tuned by hand between 13.8 and 18.3 GHz ($\Delta\omega_{\mathrm{LO}} = 2\pi \cdot 4.5$ Grad/s) in the place of a broadband VCO, which was not available. The signal was reflected by the first CEBG, down-converted in another mixer, and amplified using a pair of commercial 15 GHz, +15 dB amplifier to compensate for losses incurred in mixing and the directional coupling. The signal was then passed to the final CEBG and amplified once more before detection with a high-frequency sampling oscilloscope.

Simulation results from MatLAB, presented in Fig. 4, were obtained by assuming lossless, ideal CEBGs with linear group-delay slopes and flat amplitude-responses. Results are shown for three values of LO (18.3, 15.9, and 13.8 GHz) which include the delay extremes. Oscilloscope measurements of the output signal are presented in Fig. 5 for comparison with the same three LO

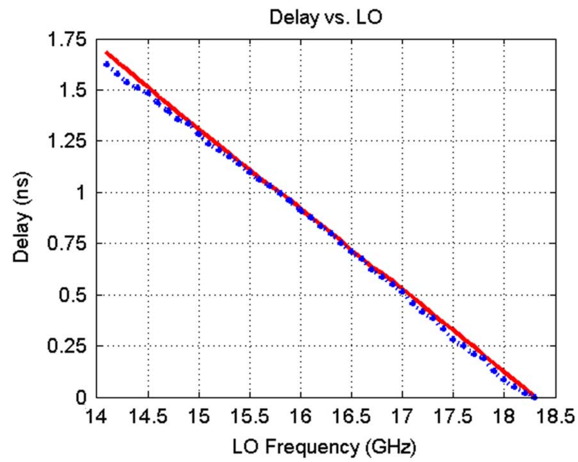

Fig. 6. Simulated (solid) & measured (dash) delay, based on location of first signal peak, as the LO frequency is tuned. The measured result is very nearly linear with an average slope of -0.393 ns/GHz, close to the -0.4 ns/GHz target.

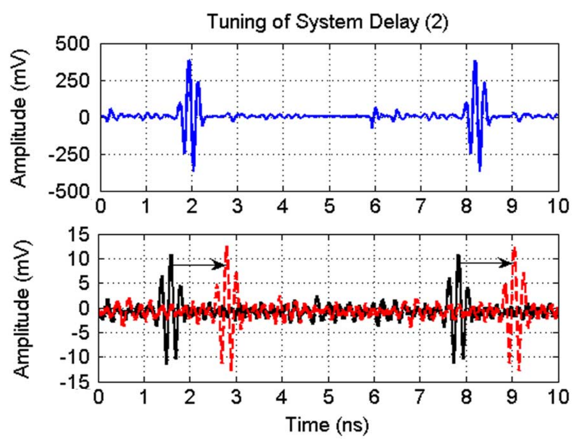

Fig. 7. (Top) Test UWB signals generated using shaped impulses. (Bottom) Measured time-delayed responses for LO = 17.5 GHz (solid) and 14.3 GHz (dash).

values. A graph of simulated and measured delay, based on the location of the first signal peak, is presented in Fig. 6, showing very good agreement and a full-scale delay excursion of 1.6 ns (a measured group delay slope of -0.393 ns/GHz).

A second UWB test signal consisted of a train of shaped-impulses with content in the 3–7 GHz range, which more readily permits direct observation of the signal phase content. This signal was generated by passing a 70-ps impulse (generated by a Picosecond Pulse Labs 3600D) through a specially synthesized EBG microstrip designed using a synthesis algorithm for creating customized UWB pulse shapes [11]. The original signal and time-delayed outputs are presented in Fig. 7 for two LO frequency points (17.5 GHz and 14.3 GHz). Outputs in this case have been subjected to 10-point averaging in the digital oscilloscope for clarity and to distinguish from some mixer noise-leakage in down-conversion (no image-suppression filtering was used).

IV. Discussion

This demonstration illustrates the principles of operation of the system, but is by no means optimized. Recent demonstrations of small UWB 3-dB directional couplers [9], superimposed EBG structures [10], and the possibility of stripline-based CEBGs with higher $\varepsilon_{\mathrm{eff}}$, all present options for minimizing both size and losses incurred by using a pair of CEBGs. Active broadband mixers could be employed instead of discrete amplifiers to retain signal levels. The authors suspect that the principal challenge associated with the deployment of this system would be the design of a suitably broadband VCO with sufficient power to drive a pair of mixers, since the bandwidth of such a VCO is a determining factor of system delay based on (2).

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