A Hybrid Nonlinear Delay Line-Based Broad-Band Phased Antenna Array System

R. P. Hsia, W.-M. Zhang, C. W. Domier, and N. C. Luhmann, Jr.

***Abstract*— Nonlinear delay line (NDL) technology has been utilized to implement a proof-of-principle, broadband, 8-channel, linear, hybrid NDL-based phased antenna array (PAA) system. The hybrid NDL's provide up to 267-ps analog, variable true time delay (TTD) with <5-dB measured insertion loss. A PAA system incorporating wide-band feed, transition, and antenna elements has been developed for broad-band (4–18 GHz), electronically controlled beam steering. The current system has demonstrated up to $\pm 18^\circ$ beam steering from 4 to 5 GHz, and $\pm 6^\circ$ at 6 GHz in good agreement with theoretical predictions; monolithic implementations have been designed to provide $\pm 19^\circ$ beam steering at frequencies up to 18 GHz and are currently being fabricated. This system provides a wide-band, low-cost, high-precision alternative to conventional PAA technologies.**

I. Introduction

The frequency bandwidth of a conventional phased antenna array (PAA) is ultimately limited by the array element (amplifiers, antennas, and transitions) bandwidth. However, a more severe limitation is often caused by the use of phase shifters to scan the beam [1]; true time-delay (TTD) technology potentially eliminates the bandwidth restriction. However, standard time-delay technology consists of switched transmission line sections wherein weight, loss, and cost increase rapidly with phase tuning resolution. A novel delay line concept was previously presented in a proof-of-principle demonstration, where an initial hybrid nonlinear delay line (NDL) was employed as a low-loss, electronically controlled, broad-band TTD line [2]. The varactor diode capacitance, and hence group velocity and time delay, is controlled by varying the dc bias on the line.

Herein, an 8-channel electronically controlled hybrid NDL-based PAA system is presented (see Fig. 1). The system consists of various wide-band components, including a microstrip Wilkinson power divider, a linear tapered slot antenna (LTSA) array, and broad-band transitions. Measurements show the hybrid NDL's employed in this implementation provide >100-ps time delay when biased between −3 and −15 V, with a maximum insertion loss of 6 dB at 4 GHz. Measurements on the power divider showed <3-dB loss from 4 to 20 GHz. The transition from coplanar waveguide (CPW) to slotline displayed <3-dB loss from 2 to 15 GHz, and the 1 × 8 LTSA array produced measured E-Plane, 3-dB beamwidths of ~30°, with a sidelobe level <−15 dB, from 6 to 18 GHz, in good agreement with theory. The combination of these wide-band elements provided significant flexibility for a broad-band system design. For the current system, hybrid NDL elements have been employed for use from 4 to 6 GHz; however, the same system components and implementation can be utilized at frequencies up to 18 GHz with lower loss monolithic NDL's to produce an extremely wide-band (4–18-GHz) PAA system.

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II. Basic Theory and System Design

A microstrip Wilkinson power divider was chosen as the system input feed to provide broad-band performance and matched, equal phase outputs. Simulation results using Libra showed <2-dB loss from 2 to 20 GHz, and >20-dB port to port isolation from 8 to 18 GHz.

The focus of this PAA system design was the NDL. In a periodic NDL, a relatively high impedance transmission line is loaded at regular spacing by a series of varactor diodes. By varying the applied dc bias, and thereby controlling the group velocity, the NDL generates TTD far below the Bragg cutoff frequency [2]. Hence, the delay time of each NDL section is a function of the dc bias, interconnection transmission line length, and varactor diode capacitance.

A CPW-based ten-section layout utilizing commercial beam-lead varactor diodes (MA/COM MA46580) was designed. The design employed a staggered diode configuration in order to reduce section capacitance while essentially maintaining overall line symmetry.

The antenna array design was based upon standard PAA theory [1]; the maximum beam steering angle $\theta_{\max}$ for a given antenna spacing d is frequency independent and is given by

$$\theta_{\max} = \sin^{-1}\left(\frac{c\tau}{d}\right) \tag{1}$$

where τ is a constant representing the amount of progressive TTD on each element. Taking into account the maximum time delay, number of array elements, desired antenna beam shapes, and array size, an interelement spacing of 0.5 in was chosen. With a maximum time delay of 100 ps, this translates to a predicted $\theta_{\max}$ of ±19° for eight elements. To achieve a more practical beam steering range of ±45°, 210 ps of TTD range is required with these same system criteria.

Linear tapered slot antennas (LTSA's) were chosen as the antenna elements due to their broad-band, high-gain performance [3], as well as for two-dimensional (2-D) stacking potential. Designs were simulated using a full-wave electromagnetic solver, Ansoft Eminence. The final design required a

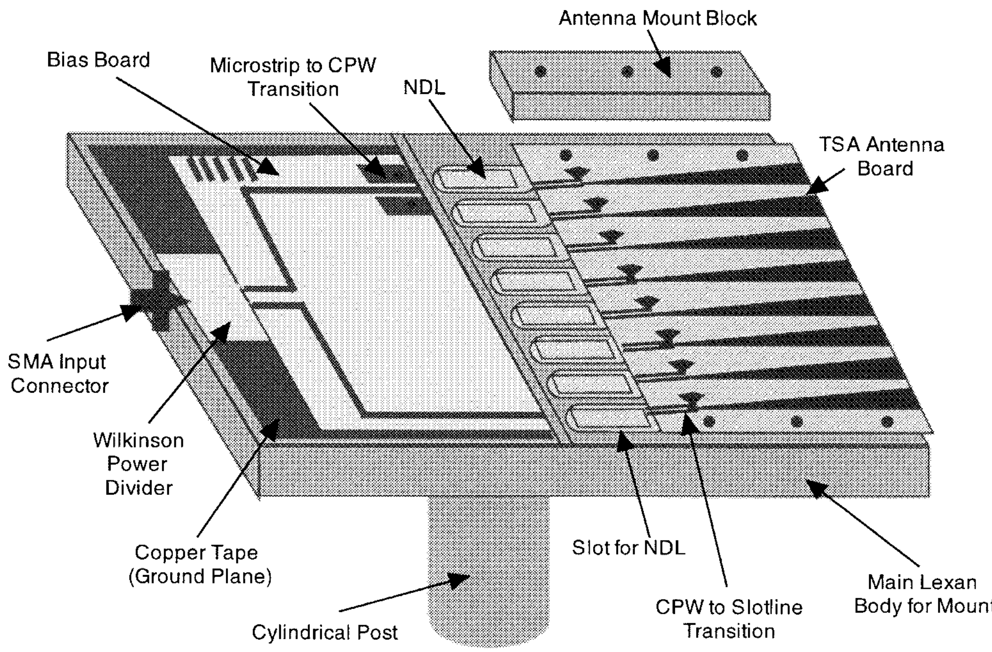

Fig. 1. Schematic of the 1 × 8 NDL-based PAA system.

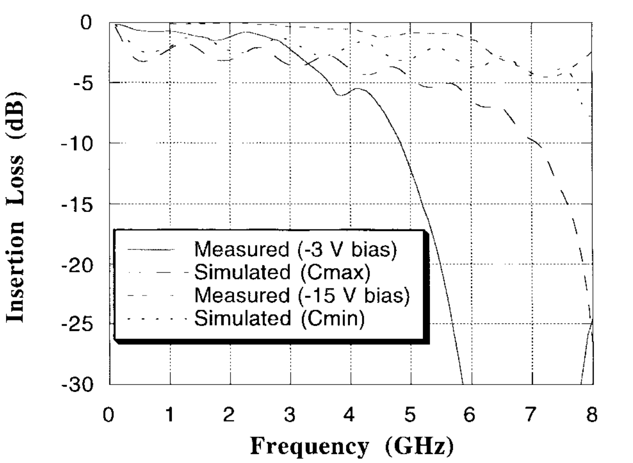

Fig. 2. Measured and simulated insertion loss for hybrid NDL using M/A COM varactor diodes.

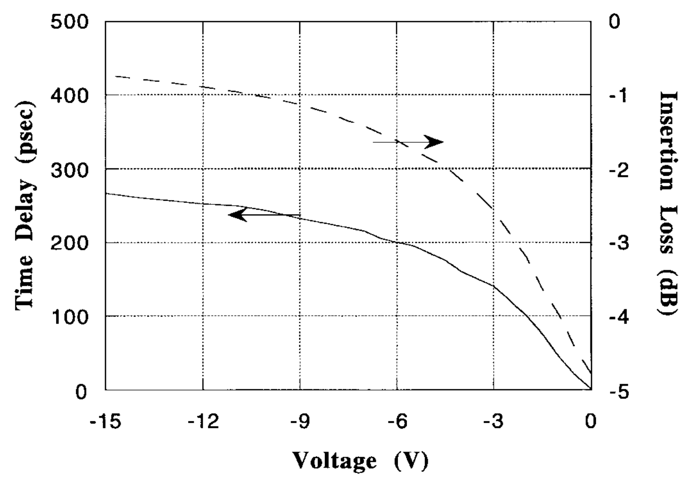

Fig. 3. Measured time delay and peak voltage insertion loss as a function of bias voltage for the M/A COM diode-based hybrid NDL.

shorter antenna length than standard LTSA designs in order to fit into the array design (2-in-long, 8° flare angle). Simulation results indicate a maximum antenna gain of ∼7 dB, with 3-dB beamwidths on the order of 40–45°.

The choice of the LTSA further required a broad-band transition from the NDL (CPW) to slotline. A uniplanar design employing a CPW short and slotline radial stub [4] was chosen for this system, both for its wide-band performance and ease of implementation. Designs were modeled using Eminence, and simulations showed <1.5-dB loss from 6 to 18 GHz.

III. Experimental Realization

All design layouts were drawn in Autocad. The microstrip based power divider was fabricated by ATF Products. Measured results showed <3-dB loss from 4 to 20 GHz. A separate printed circuit board (PCB) was used to transition the microstrip to CPW, using low-inductance via holes on both sides of the microstrip center conductor. Experiments showed this design was effective to ∼15 GHz.

The NDL circuit and various antenna layouts were fabricated on a 10-mil-thick ($\varepsilon_r = 10.5$) substrate by Cirtech, Inc. Varactor diodes were mounted on the boards using silver epoxy; predicted and measured insertion loss for representative lines at two bias voltages, using an HP 8510 Network Analyzer, are shown in Fig. 2. The −6-dB cutoff point occurred at ∼4 GHz at −3 V, significantly worse than the simulation results. Discrepancies are attributed to losses and imperfections in the fabricated CPW lines, but more importantly, to parasitics from the silver epoxy mounting. The delay lines were also tested with a Tektronix 11 810 digital sampling oscilloscope, using a ∼60-ps rise time 100-mV peak voltage input signal. The measured TTD variation, and peak voltage insertion loss as a function of bias voltage are shown in Fig. 3, indicating a maximum time-delay variation of 267 ps and a maximum loss

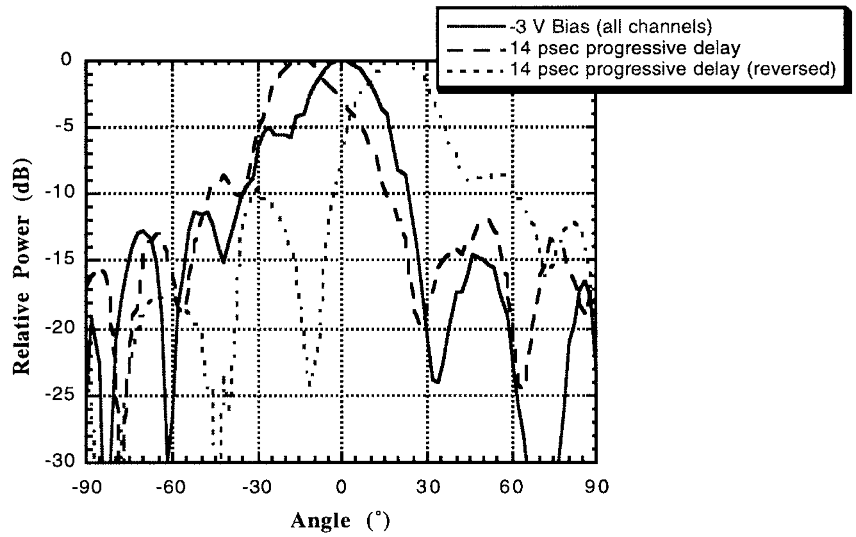

Fig. 4. Measured beam steering results using the hybrid NDL-based PAA system at 5 GHz.

of ~5 dB. For a required variation of ~100 ps, this NDL can thus be operated with a minimum bias voltage of −4 V.

Antenna pattern measurements were performed using the UCD Anechoic Chamber; measured and simulated results for a single LTSA element, as well as an 8-element array, indicated good agreement with theoretical predictions.

All components were integrated onto a custom Lexan mount, using gold wire bond interconnects with external components, such as bias cables and connectors, soldered onto the system. The size of the total array implementation was approximately 8 in × 5 in. Each channel was individually biased using a Joeger DAC-16 D/A converter, allowing electronic control of each NDL's time delay. A computer control program was utilized to allow input of a desired bias voltage for each channel, and subsequently activating a standard antenna pattern sweep. Bias configurations were chosen using the test results in Fig. 3 as calibration values. Fig. 4 shows representative measured beam steering results at 5 GHz. An initial measurement was made with all channels at a fixed bias (−3 V), producing the centered antenna pattern. A bias arrangement corresponding to ~14-ps progressive time delay was then applied, showing approximately 18° of maximum beam steering (the bias pattern was then reversed to move the beam in the opposite direction). From (1), the predicted maximum beam steering is ±19°, indicating very good agreement. Measurements at 6 GHz provided ±6° beam steering (±8° predicted).

IV. Discussion

The performance of the current system is ultimately limited by the use of hybrid NDL technology. The parasitic capacitances and physical size of the beam-lead diodes limit the maximum frequency to which this technology can be applied. To increase the Bragg cutoff frequencies, monolithic fabrication is essential [2]. Incorporating advanced monolithic diode technology with lower junction capacitance (femtofarad range) and larger capacitance ratios (6–10) allows the design of much shorter (lower loss) lines, or alternatively, similar length lines with much larger delay range. For instance, to achieve ±45° steering capability, a monolithic design with $C_{\max}/C_{\min}$ ratio of 8 and $C_{\max}$~80 fF could require only 100 sections (<3-dB predicted insertion loss at 18 GHz).

Nevertheless, the hybrid NDL-based system shows the validity of the approach and demonstrates the potential of the individual system components, as well as their successful integration. Depending upon the application, the current system can readily be modified to increase the maximum beam steering angle or the frequency bandwidth.

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