Novel Low-Loss Delay Line for Broadband Phased Antenna Array Applications

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***Abstract*—The microwave propagation velocity along a nonlinear transmission line is a function of dc bias, hence, a nonlinear transmission line (NLTL) can be utilized as a broadband delay line. A hybrid NLTL has been fabricated in a proof-of-principle experimental concept test where a 1.1-ns true time delay with <4-dB insertion loss has been measured in good agreement with theory. A 2 × 2 NLTL-based antenna array has been utilized to demonstrate beam steering at 5 GHz. Using parameters appropriate to varactors tested by our group at 60 GHz, a monolithic NLTL is predicted to exhibit <3.4-dB insertion loss and 200 ps delay at 20 GHz.**

I. Introduction

A PHASED antenna array consists of multiple stationary antenna elements that are fed coherently and employ variable phase or time-delay control at each element to scan a beam to a given angle in space. The frequency bandwidth of the array is often limited by the use of phase shifters to scan the beam instead of time-delay devices. The use of true time delays instead of phase shifts would eliminate the bandwidth restriction. Standard time-delay technology, however, consists of switched sections of transmission lines. The weight, loss, and cost of this digital-type delay line increases rapidly with the resolution of the phase tuning and becomes impractical if fine tuning of the phase is required. Therefore, to build a broadband phased antenna array, a low-loss and broadband delay line is essential.

A delay line concept is presented in this letter, where a nonlinear transmission line (NLTL) has been employed as a low loss, broadband true time delay line. Bias-dependent phase delay on a Schottky contact microstrip line has been studied before; however, the distributed transmission line is very lossy [1]. An NLTL consists of a coplanar transmission line loaded with varactor diodes. The diode capacitance is a function of bias voltage; hence, the group velocity of the NLTL is a function of the dc bias. Previously, NLTL's have been generally employed as short pulse and harmonic generators by utilizing their large signal characteristics [2]–[4]. In this work, however, the small signal characteristics of the NLTL have been utilized.

In this letter, the basic theory of the nonlinear delay line (NDL) is presented. A proof-of-principle experiment has been conducted where a delay line has been fabricated to provide 1.1-ns true delay for 0.5–2.0 GHz with less than 4 dB maximum insertion loss in good agreement with theory. Broadband beam steering has been demonstrated with the delay line and a 2 × 2 slot bow-tie antenna array.

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II. Basic Theory

In a periodic NLTL, a relatively high impedance transmission line is loaded at regular spacing by a series of varactor diodes serving as voltage-dependent shunt capacitors. By utilizing a first-order approximation, the high impedance interconnecting transmission lines can be approximated by L-C sections.

The group velocity of this LC network is given as

$$\nu_g = \frac{l}{\sqrt{L(C_{\text{line}} + C_{\text{diode}}(V)}} \tag{1}$$

and the ladder-network cut-off frequency f_{Bragg} is given as

$$f_{\text{Bragg}} = \frac{1}{\pi\sqrt{L(C_{\text{line}} + C_{\text{diode}}(V))}}. \tag{2}$$

In the above, L is the series inductance, C_{line} is the shunt line capacitance, and $C_{\text{diode}}(V)$ is the shunt diode capacitance, respectively.

For frequencies significantly lower than the Bragg cutoff, the group velocity of the NLTL is essentially frequency independent. Hence, the delay time resulting from each section of the NLTL is a function of dc bias voltage, interconnection transmission line length, and varactor diode capacitance, as given by

$$\Delta t(V) = \sqrt{L_{\text{line}}(C_{\text{line}} + C_{\text{diode}}(V))} - \sqrt{L_{\text{line}}(C_{\text{line}} + C_{\text{min}})}. \tag{3}$$

The maximum time delay of the entire transmission line is then given as

$$\Delta T = \sum\left(\sqrt{L_{\text{line}}(C_{\text{line}} + C_{\text{max}})} - \sqrt{L_{\text{line}}(C_{\text{line}} + C_{\text{min}})}\right) \tag{4}$$

where C_{max} and C_{min} are the maximum and minimum capacitance values, respectively, of the varactor diodes. Since the varactor diodes are reverse biased, at low frequencies, the NLTL circuit has very low insertion loss (<3 dB) over a very broadband region.

A more general expression of the dispersion relation for this system is given as

$$\cos\beta 1 - \cos k1 + \frac{\omega C Z_o}{2}\sin\ k1 = 0 \tag{5}$$

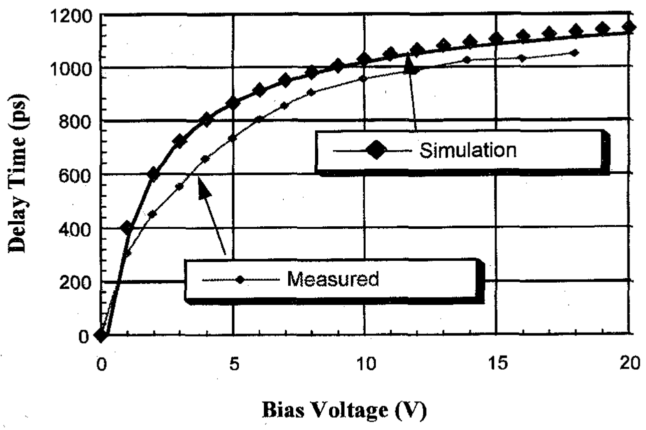

Fig. 1. Measured and simulated delay time as a function of bias voltage.

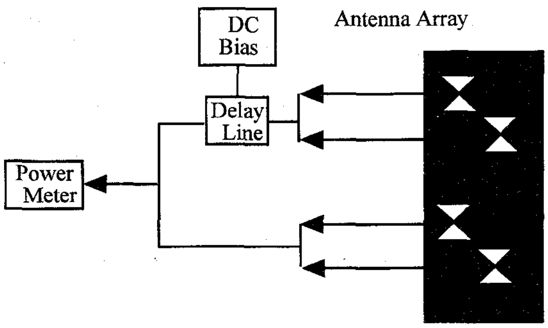

Fig. 2. Sketch of the antenna configuration.

where Z_0 and k are the impedance and wavevector of the interconnection transmission line, respectively, and β is the NLTL small signal wave vector. The phase velocity is given as

$$\nu_p = \frac{\omega}{\beta} = \frac{l\omega}{\arccos\left(\cos\frac{\omega l}{\nu} - \frac{\omega C Z_o}{2}\sin\frac{\omega l}{\nu}\right)} \tag{6}$$

while the group velocity is

$$\nu_g = \frac{\partial\omega}{\partial\beta} = \frac{l\sin(\beta l)}{\left(\frac{l}{\nu} + \frac{C Z_o}{2}\right)\sin\frac{\omega l}{\nu} + \frac{\omega C Z_o l}{2\nu}\cos\frac{\omega l}{\nu}}. \tag{7}$$

From the above, it is readily seen that for frequencies well below the Bragg cut-off, the calculated group velocity and phase velocity are essentially equal and frequency independent of an NLTL. For example, we have examined an NLTL designed to have a cut-off frequency of 100 GHz, interconnection line impedance of 90 Ω, and NLTL impedance of 50 Ω. For this transmission line, the group velocity varies by less than 1% over the frequency range from dc to 20 GHz.

Planar GaAs diodes with over 1 THz cut-off frequencies have been reported [5], [6], i.e., the NLTL can be built with >300 GHz Bragg cut-off. Simulations indicate that the NLTL can be utilized as a broadband delay line from 1–60 GHz, which is limited by the NLTL dispersion. For narrow frequency band applications, however, the NLTL can be utilized up to 200 GHz.

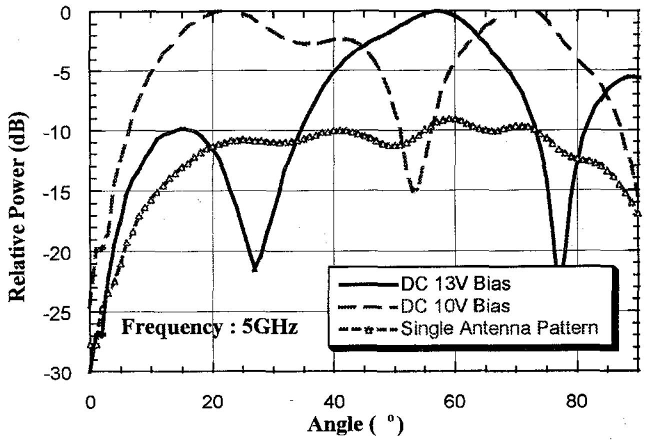

Fig. 3. Antenna pattern of the 2 × 2 antenna array at 5 GHz.

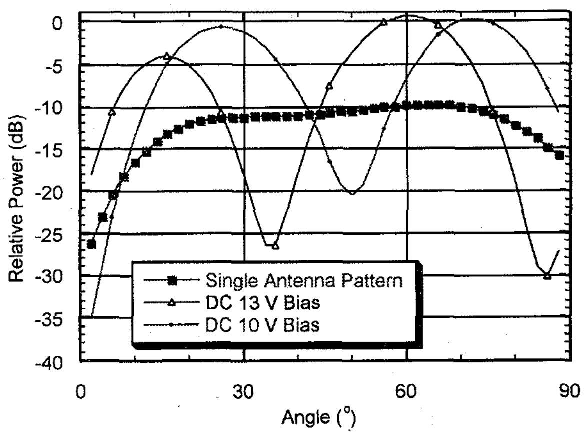

Fig. 4. Simulated antenna pattern of antenna array.

III. Experimental Approach

A hybrid nonlinear transmission line has been fabricated to demonstrate broadband true time delay by utilizing commercial varactor diodes (MA/COM MA46580 Beam Lead GaAs Tuning Diode). The NLTL consists of a printed circuit board (PCB) loaded with varactor diodes as the nonlinear elements and coplanar waveguide (CPW) has been utilized for the interconnection transmission lines.

The PCB is fabricated on RT Duroid 6010 with a dielectric constant of 10.5. The NLTL large signal impedance is chosen as 50 Ω, and 50-Ω CPW lines have been employed to connect the NLTL and SMA connectors. The impedance of the interconnection line is 85 Ω. The NLTL consists of 50 sections with section lengths of 98 mil, center conductor line width of 16 mil, and gap spacing of 35 mil. The beam lead varactor diodes were mounted on the PC board with silver epoxy.

The hybrid NLTL has been tested with a Tektronix 11 810 digital sampling oscilloscope equipped with a 50-GHz sampling head. Short input pulses with ~300-ps rise time and 100-mV peak voltage have been utilized as the test signals. The true delay time dependence on bias voltage is shown in Fig. 1. Simulated and measured results agree within 10%, where the discrepancy is believed to be due to the parasitics associated with the diode and coplanar transmission line interconnection.

S-parameter measurements with an HP 8510 network analyzer show that this hybrid NLTL has <3.4 dB insertion loss over the frequency range of $0.5 \sim 2.0$ GHz, in relatively good agreement with the predicted value of 2.6 dB using the measured diode parameters.

A 2×2 antenna array has been utilized to demonstrate beam steering with the hybrid NLTL. The antenna configuration is shown in Fig. 2, where the array consists of slot bow-tie antennas for use as the broadband receiver elements. Beam steering has been demonstrated at 2, 3, 5, and 6 GHz. The antenna patterns at 5 GHz are shown in Fig. 3. The phased antenna array significantly reduces the beam width and improves the received power level.

With this 2×2 antenna array configuration, as shown in the plot, the antenna array has been shown to yield ~10 dB improvement in peak power level as compared with a single slot bow-tie antenna, where theoretical calculations predicted a 10.5-dB peak power increase. A simulated antenna pattern is shown in Fig. 4.

IV. Discussion

The performance of the current NLTL is limited by the capacitance value and the physical size of the beam lead diodes. To increase the Bragg cut-off frequency, diodes with smaller capacitance values (i.e., smaller areas) and shorter transmission line lengths are required. Therefore, for higher-frequency applications, monolithic fabrication is essential. Monolithic NLTL's have been fabricated for short pulse and harmonic generation. Multibarrier devices (SQBV and SSQBV) have been utilized to increase the power handling of the NLTL significantly. This technology can be easily adapted for delay-line applications [7].

Monolithic microfabrication not only reduces the cost of the NLTL, but also reduces the parasitics associated with commercial diode packages. The most important improvement is flexibility in designing the diode area and layout. The limitation on the device size drops from ~10 mil down to ~3 μm (for readily available ultraviolet photolithography technology), which indicates an improvement of the Bragg cut-off frequency from 6 to 400 GHz. Extensive design and simulation work has been conducted. For a 200-ps true time-delay line, simulations predict <1.5-dB insertion loss at 10 GHz and ~3.4-dB insertion loss at 20 GHz. In this simulation, a varactor diode model with ~1.3-THz device cut-off frequency has been employed, which is based on the actual parameters of the diodes fabricated in our previous 60-GHz quasioptical grid array work [8].

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