Balanced Distributed-Element Phase Shifter

Hongjoon Kim, Sung-Jin Ho, Chih-Chuan Yen, Kae-Oh Sun, and D. W. van der Weide

***Abstract*—We present a balanced distributed-element phase shifter based on a nonlinear transmission line (NLTL) structure. Results show the second harmonic is more than 13 dB lower at 0-V bias than a conventional single-ended NLTL phase shifter. We fabricated both balanced and conventional NLTL phase shifters with the same coplanar waveguide (CPW) design and diodes, and observed that phase shifting and insertion loss for both structures were quite similar, yet harmonic distortion was greatly improved in the balanced structure.**

***Index Terms*—Balanced structure, harmonics, nonlinear transmission line (NLTL), phase shifter, varactor.**

I. INTRODUCTION

THERE are many applications for the nonlinear transmission line (NLTL) structure, such as shock wave generator [1], sampling circuit driver, harmonic generator [2], and variable delay line [3]–[6]. Using the NLTL structure as a phase shifting circuit is attractive because of its compatibility with the NLTL pulse generator fabrication processes. This holds out the possibility of fully-integrated coherent measurement systems [6].

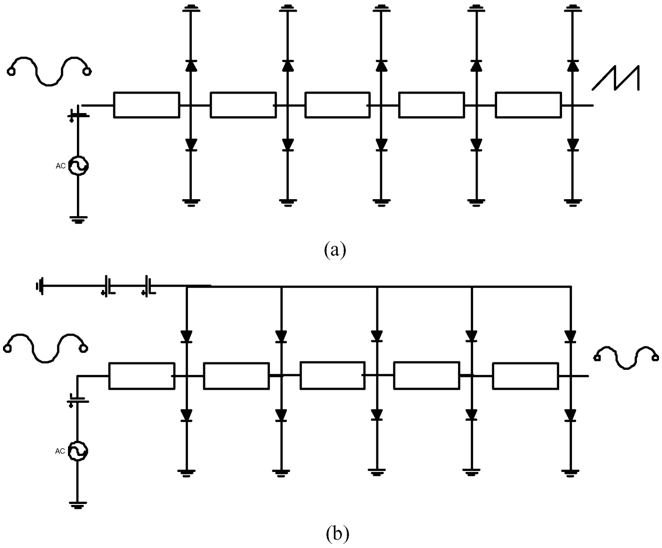
In an NLTL structure, varactor diodes are usually distributed on a coplanar waveguide (CPW). The nonlinearity arises from the voltage-variable diode capacitance. With dc bias on the line, we can control the time delay of the structure, which is the basic NLTL phase shifter principle. A balanced structure is a very effective way to reduce nonlinearity. We only change diode polarity and add one more bias line, whose voltage is double that of the conventional single bias line.

II. BASIC THEORIES FOR BALANCED STRUCTURE

Because much of this work is based on NLTLs, and there are numerous papers on NLTL and NLTL-based phase shifters [1]–[6], we only briefly review the background required to explain the balanced structure.

In a basic NLTL, diodes are periodically placed with spacing d. Because it is a low-pass filter structure, it has a periodic cut-off frequency (Bragg frequency). Using a lumped element model, we can approximate the value by

$$f_{\text{Bragg}} = \frac{1}{\pi \cdot \sqrt{L_l[C_l + C_d(V)]}} \tag{1}$$



(a)

(b)

Fig. 1. Comparison of NLTL based phase shifter structure. (a) Conventional structure. (b) Balanced structure. Diode polarity in upper side is changed and voltage doubled bias line is added.

where L_l and C_l are line section inductance and capacitance respectively and $C_d(V)$ is voltage variable diode capacitance. When the signal propagates on this NLTL, the phase velocity of a wave on the NLTL is a function of voltage and is given by

$$\mu_p = \frac{d}{\sqrt{L_l[C_l + C_d(V)]}}. \tag{2}$$

The diode capacitance value decreases as we increase reverse bias. Thus, at the peak of the sinusoid where diode capacitance is large, the signal propagates slower, while at the trough where diode capacitance is small, it propagates faster, generating a shock wave and harmonics when the drive signal is sufficiently large [1]. In a single-ended NLTL phase shifter, the diode cathodes are grounded [see Fig. 1(a)]. In a balanced structure, one side of the line has diodes reoriented, with an additional voltage doubled bias line [see Fig. 1(b)].

In the conventional NLTL structure, both diodes tend to slow the phase velocity at the peak and accelerate it at the trough of the sinusoid. In a balanced structure, one of the diodes tend to slow the phase velocity while the other diode accelerates it, yet the overall line capacitance changes in the same way for both structures. Thus, harmonic distortion is much lower in the balanced structure. This improved performance in harmonic distortion has several advantages. When it is used in a phased antenna array (PAA) system [4], [5], one can use much larger power with much lower harmonic distortion. When it is used as frequency translator [6], the single-sideband modulated signal exhibits less distortion.

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The authors are with the Department of Electrical and Computer Engineering, University of Wisconsin, Madison, WI 53706 USA (e-mail: hongjoon@cae.wisc.edu).

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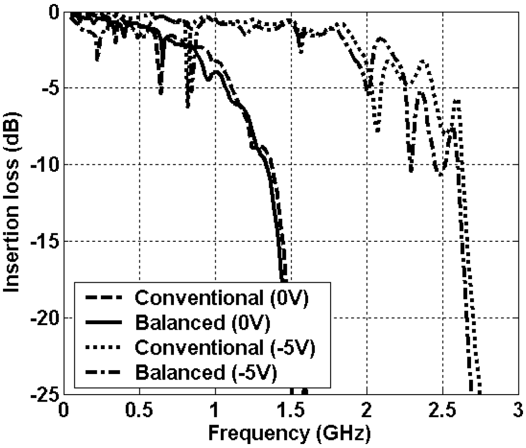


Fig. 2. Insertion loss as a function of frequency at 0 V and −5 V dc bias for both structures.

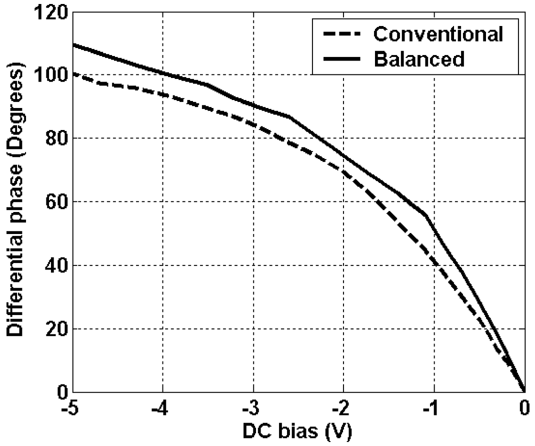


Fig. 3. Phase variation as a function of bias voltage for both structures at 500 MHz. Little difference is observed between the two structures.

III. Circuit Design and Fabrication

We fabricated phase shifter on Rogers RT/Druid 3010 (ε_r =10.2) by attaching Alpha Industries hyper-abrupt junction GaAs flip-chip varactor diodes (GMV-9821 ($Cj0 = 1.07$ pF, $\mathrm{Cmax}/\mathrm{Cmin} \approx 3.6$ for 0–5 V reverse bias)) using conductive silver epoxy. The NLTL was designed to have $Z_0(\mathrm{V}) = 50\ \Omega$ at 0-V bias in order to optimize the total insertion loss of the transmission line. We used ten sections and 20 diodes for both structures.

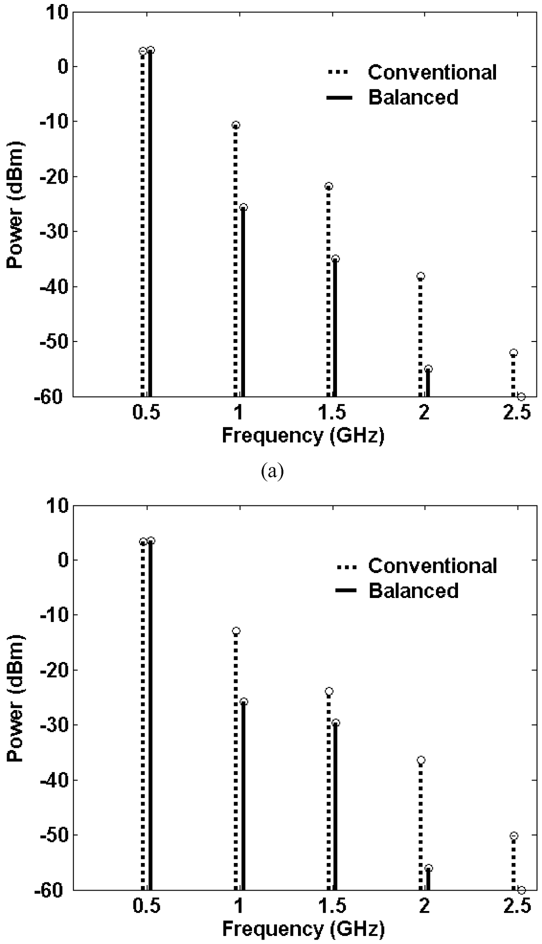
IV. Test and Results

We measured S-parameters with an Agilent E8364A network analyzer. According to (1), the Bragg frequency is approximately 1.6 GHz at 0-V bias which agrees well with the measured result for both structures (see Fig. 2). Because the two structures have the same dimensions and number of diodes, they behave almost identically. To see how the balanced structure reduces harmonics, let the operating frequency be much lower than the Bragg frequency. In this experiment, we used 500 MHz, where both have very similar phase variation with voltage (see Fig. 3).

To compare harmonics, we used an Agilent E4448 spectrum analyzer. Since the balanced structure requires an additional voltage-doubled bias line [see Fig. 1(b)], all discussion of the balanced NLTL will assume that a doubled voltage was applied to the additional bias line. For example, if we state that the experiments were conducted with a −1-V dc bias, the reader should assume that a −1-V and an additional −2-V dc bias was applied to the balanced structure.

With a +4-dBm input at 500 MHz, we measured harmonics at 0 V and −1 V. Fig. 4(a) and (b) show harmonic components of both structures when the dc bias is 0 V and −1 V. Harmonics below −60 dBm were below the noise floor. All of the harmonics of the balanced structure are at least 13 dB lower than the conventional structure at 0 V. At −1 V, we also can see that harmonics are lower in the balanced structure. As we increase dc bias, the capacitance variation is reduced, so the harmonic difference between two structures was diminishes.

These benefits are much more pronounced if we increase input power (Fig. 5). Also, for the structures reported here, phase variation is around 100° at 500 MHz, so if we add more sections to increase phase variation, harmonic generation will increase, as well. For these cases, the balanced structure is a better solution to minimize nonlinearities.



(a)

(b)

Fig. 4. Comparison of harmonics for both structures. Input power is +4 dBm (500 MHz). (a) DC bias 0 V for both structures. All harmonics are −13-dB lower in the balanced structure. (b) DC bias is −1 V. Differences are smaller than 0 V case.

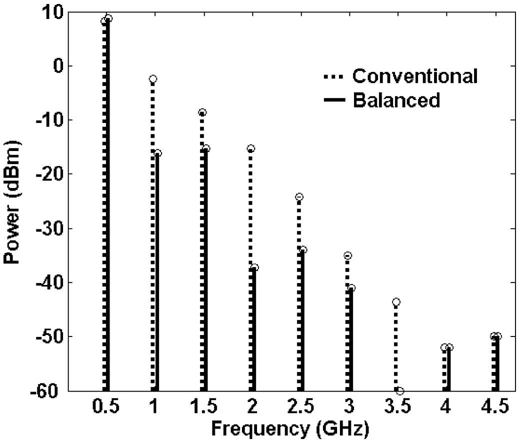


Fig. 5. Output spectrum when higher power (+10 dBm at 500 MHz) is applied at −1-V bias.

V. CONCLUSION

We have introduced and demonstrated a distributed-element phase shifter based on a balanced NLTL structure. It minimizes nonlinearities inherent in the NLTL structure without additional devices or more complex control. Although the circuit was implemented in a hybrid, the differences will be clearer in an integrated circuit that minimizes parasitics.

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