A Novel Tunable Transmission Line and Its Application to a Phase Shifter

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***Abstract*—This letter describes the design of a novel transmission line, where characteristic impedance can be adjusted electronically, and its application to a phase shifter. A tunable transmission line enables microwave circuit designers to have flexibility and better return loss which can enhance its tuning range. A UHF band distributed analog phase shifter, as well as a tunable transmission line, is presented. The characteristic impedance of a fabricated novel transmission line varies from 10 to 69.5 Ω, which demonstrates its tunability, and the fabricated UHF phase shifter using this novel line shows the possibility of better reflection coefficient and wider tuning range over the conventional capacitively-loaded distributed phase shifter.**

***Index Terms*—Phase shifters, transmission lines, tunable circuits and devices.**

I. Introduction

TRANSMISSION lines are an essential component in microwave circuits as distributed elements based on transmission lines become important in the way that frequency goes higher. While the demands for wireless communications increase and they become complex, radio frequency (RF) front-ends need multiband or wideband circuits to satisfy several standards of wireless systems, hence, it makes a tunable circuit essential. An adaptive controlled system which can enhance the performances of a wireless system also requires the tunable devices and circuits. In this letter, a new type of tunable transmission line is introduced in order to satisfy those demands.

The most frequently used method to adjust the characteristic impedance of a transmission line is a capacitively-loaded line [1], [2]. Phase shifters and tunable filters are good applications using this concept [3], [4]. Comparing the conventional methods, we have added a metal layer between signal line and ground as the third metal which is connected by a switch with the ground layer as shown in Fig. 1(a). Assume that the dielectric constants of ε_1 and ε_2 have the same value and the equivalent capacitance per unit length between the signal line and the inserted metal, C1, is significantly larger than C2 which originates from the inserted metal and ground. When the switch is on, the equivalent circuit can be expressed as shown in Fig. 1(b), and the line can have a low value of Z_C. On the other hand, the equivalent circuit can be expressed as shown in Fig. 1(c) when the switch is off, and the line can have a high value of Z_C. As shown in Fig. 1(d), we substitute a varactor for the switch, by which the circuit has continuous values of Z_C with the bias voltages. Its higher limit of Z_C is determined by the structure in Fig. 1(c) and the lower one depends on the structure in Fig. 1(b).

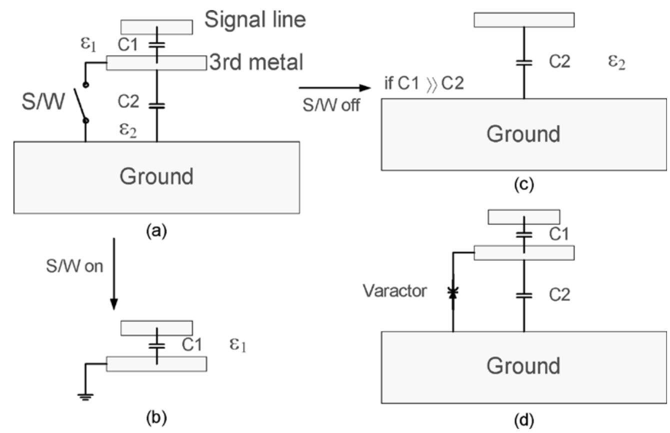

Fig. 1. Schematic diagram of (a) a novel transmission line with variable characteristic impedances, and its equivalent circuits when a switch is (b) on and (c) off. The modified diagram of (a) for continuous varying Z_C which adopts a (d) varactor diode.

II. Tunable Transmission Line

Based on the concept of a new tunable transmission line, we have designed a variable Z_C transmission line using commercial varactors diodes at UHF band. In general, the input impedance of a transmission line with a load, Z_L, is expressed in (1), where β is the propagation constant and l is the length of the line. If the line has a quarter wavelength, the input impedance and characteristic impedance have a relationship of (2) and we can estimate Z_C using the Smith chart

$$Z_{\text{in}} = Z_C \left[\frac{Z_L + jZ_C \tan\beta l}{Z_C + jZ_L \tan\beta l}\right] \tag{1}$$

$$Z_C = \sqrt{Z_{\text{in}} Z_L}. \tag{2}$$

For the practical implementation with a conventional substrate and hybrid elements, we modify the vertical structure of a variable Z_C transmission line in Fig. 1(d) into a uniplanar structure using coplanar waveguide (CPW)-like transmission line. Fig. 2 shows the block diagram of the designed tunable Z_C transmission line. In order to achieve a tight coupling between signal line and the inserted third metal layer, lumped capacitors, C_S and C_{SE}, are added, which enlarge the tuning range. For the supply of dc bias to varactors and the suppression of parasitic

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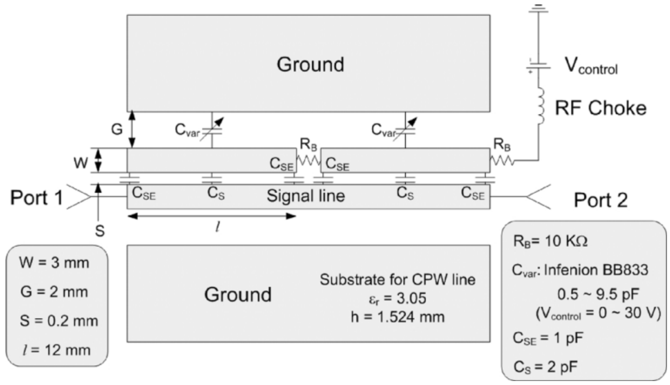

Fig. 2. Schematic diagram of a tunable transmission line on the modified CPW structure.

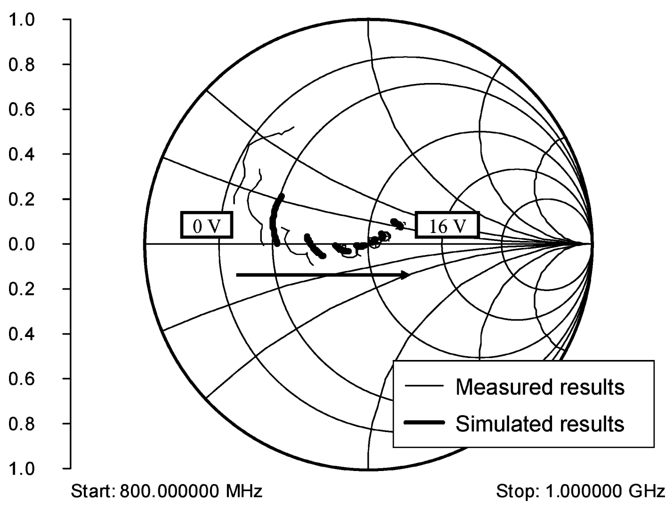

Fig. 3. Simulated and measured results with the varying bias voltages of 0 to 16 V of the tunable transmission line (for 0, 2, 4, 6, 8, 10, and 16 V).

antiresonance which comes from the length of the inserted third metal, we cut the RF path and insert a chip resistor, R_S, with a high value. We used a dielectric substrate with a relative dielectric constant, ε_R, of 3.05 and the height of 1.524 mm in order to implement a CPW line with high Z_C. For the varactor to have capacitances of 0.5 to 9.5 pF, with respect to the bias voltage of 0 to 30 V, Infenion BB833 is indicated as $C_{\rm var}$ in Fig. 2. The fabricated tunable transmission line has an overall dimension of 2.9×1.0 cm^2. We have performed circuit modeled simulation using Agilent ADS. The simulated result in Fig. 3 shows that Z_C can be electronically varied from 19 to 65 Ω at the center frequency of 900 MHz, when the bias supply varies from 0 to 16 V. The impedance has a parasitic reactance element due to the lumped elements, such as varactors and chip capacitors, while the control voltage varies. It comes from the difference of propagation constants for the different bias conditions. However, its level is quite low within a specific frequency band. Scattering parameter measurements were performed using Agilent 8753D network analyzer over the frequency range from 0.8 to 1 GHz. Fig. 3 also gives the measured responses of the characteristic impedance of the transmission line in which the tuning range was found to be 10 to 69.5 Ω. Compared with the simulated result, it agrees well with the simulated one except for the minor discrepancy due to the parasitics of varactors.

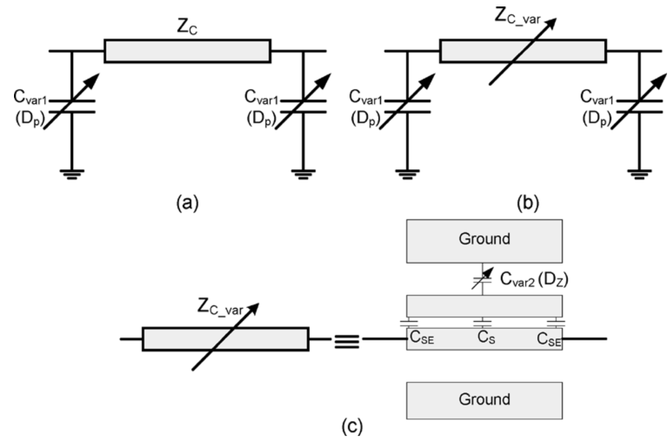

Fig. 4. Schematic diagram of a phase shifter using novel tunable transmission line: (a) a unit cell of the conventional distributed phase shifter, (b) a unit cell of a proposed phase shifter, and (c) a detailed block diagram for the realization of a tunable transmission line.

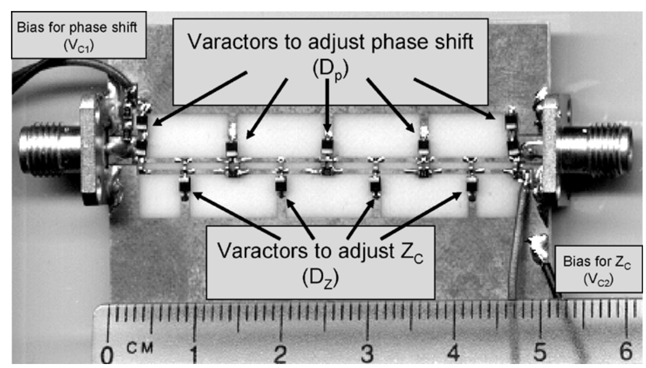

Fig. 5. Photograph of the fabricated UHF phase shifter.

III. Design of a Phase Shifter

A conventional distributed phase shifter has a unit cell as in Fig. 4(a). Overall input impedance should be designed to vary around 50 Ω and its delay will be changed, while variable capacitance devices, such as varactor diodes ($D_{\rm p}$), have different values of capacitance ($C_{\rm var1}$). In this case, the return loss can be degraded due to varying $C_{\rm var1}$ while a transmission line, which is inductive, has a fixed value of Z_C. It usually limits the tuning range of phase shifters. If we are able to implement a device in Fig. 4(b), wider tuning range of phase shifters can be achievable. As presented in the previous section, a novel tunable transmission line has the property to adjust Z_C independent of $C_{\rm var1}$ which is the dominant element to decide the phase shift value. Fig. 4(d) illustrates how a tunable Z_C transmission line can be implemented with conventional devices such as CPW lines and lumped elements. In contrast to a tunable Z_C line in the previous section, its simulated result shows that Z_C can be electronically varied from 55 to 100 Ω at the center frequency of 800 MHz, which has higher value of Z_C for impedance of a phase shifter.

The fabricated UHF phase shifter is photographed in Fig. 5. It has an overall dimension of 4.9×2.0 cm^2. We have performed circuit modeled simulation using Agilent ADS. It consists of four blocks of tunable Z_C line and five tuning varactor diodes, $D_{\rm p}$, which are adjusted by dc bias, $\mathrm{V_{C1}}$. Varactor diode, D_Z, with adjustable capacitance, $C_{\rm var2}$, is controlled by $\mathrm{V_{C2}}$ so as

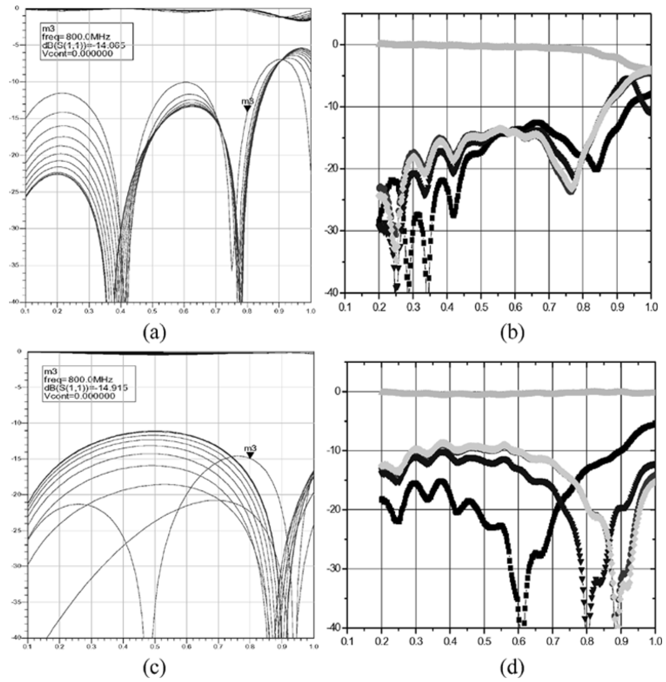

Fig. 6. Return losses and insertion losses of the phase shifter with different V_{C2} supplies (0 to 20 V): (a) simulated result when maximum phase delay occurs ($V_{C1} = 6.5$ V), (b) measured result for the condition of (a), (c) simulated result when minimum phase delay occurs ($V_{C1} = 20$ V), and (d) measured result for the condition of (c).

to have better return losses with monotonically increasing phase difference.

Fig. 6(a) and (b) are its simulated and measured results when the maximum phase delay occurs ($V_{C1} = 6.5$ V). Since the capacitance of the varactor (Infenion BB833) for 0 V of the bias voltage, is 9.5 pF and it is too high to apply for UHF phase shifter, so we restrict V_{C1} from 6.5 to 20 V by which the Bragg frequency grows up [5]. Each graph contains several lines which indicate the frequency responses while V_{C2} varies from 0 to 20 V. Both results show that the return loss can be enhanced while the phase shift is almost constant with varying V_{C2}. Fig. 6(c) and (d) are the results when the minimum phase delay occurs ($V_{C1} = 20$ V). Also, the return loss can be better whilst the phase shift keeps steady except for very low value of V_{C2}.

Its differential phase shift is calculated and demonstrated in Fig. 7 which shows the differential phase shift as a function of frequency for several bias values for the condition that the return losses are less than -12 dB up to 850 MHz. It can be seen from this graph that, at 850 MHz, the differential phase shift is continuously variable from 0° to 90° by adjusting the bias. When V_{C2} is fixed, tuning range with the same return loss property shrinks to 85°. The measured results in Figs. 6 and 7 have minor discrepancy with the simulated ones. The parasitic of varactor diode mainly caused it. If we utilize a tuning device with less parasitic such as MEM's varactors and BST varactors, the performances can be enhanced. Also, cascading this block can make the tuning range wider.

From the measured data the figure of merit (FOM) (i.e., °/dB) for the phase shifter can be extracted. Some typical data are given as follows. For a fixed V_{C2} of 20 V, when V_{C1} varies the figures of merit are 86°/dB, 104°/dB and 114°/dB for $V_{C1} =$ 6.5, 8, and 10 V, respectively. As can be seen, the FOM increases against V_{C1}. This is because the capacitance of the varactors used is actually decreased when the bias voltage V_{C1} increases, resulting in a higher quality factor at a larger V_{C1}. Using high Q varactors can improve the FOM. Also, a higher FOM can be obtained if referring to another V_{C2}.

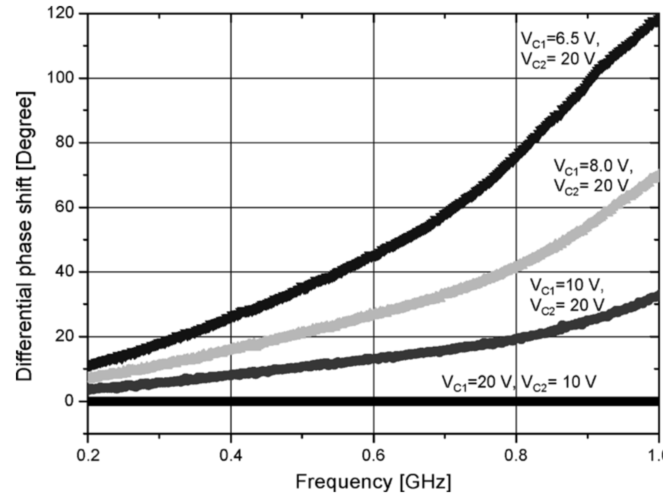

Fig. 7. Differential phase shift versus frequency for selected values of varactors bias. The phase shift is with respect to the transmitted phase at $V_{C1} = 20$ V and $V_{C2} = 10$-V bias.

IV. Conclusion

This letter has proposed a new type of tunable Z_C transmission line and its application to a phase shifter to have better return loss which makes the tuning range wider. It is promising for high performance transceiver and reconfigurable antenna systems. The measurements of the experimental demonstrator show that the proposed tunable Z_C transmission line has a broad tuning range. This phase shifter, as well as a tunable transmission line, can be easily constructed by applying conventional MMIC techniques. It is especially promising for the RF MEMS applications when switches are used for the digitally controlled tunable transmission line and phase shifter.

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