Progress In Electromagnetics Research Letters, Vol. 66, 9–14, 2017

Frequency-Tunable Phase Inverter Based on Slot-Line Resonator

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Abstract—This paper describes a frequency-tunable phase inverter based on a slot-line resonator for the first time. The control circuit is designed and located on the defected ground. None of dc block capacitors are needed in the microstrip line. A wide tuning frequency range is accomplished by the use of the slot-line resonator with two varactors and a single control voltage. A 180-degree phase inverter is achieved by means of reversing electric field with two metallic via holes connecting the microstrip and ground plane. The graphic method is used to estimate the operation frequency. For verification, a frequency-tunable phase inverter is fabricated and measured. The measured results show a wide tuning frequency range from 1.1 GHz to 1.75 GHz with better than 20-dB return loss. The measured results are in good agreement with the simulated ones.

1. INTRODUCTION

Reconfigurable microwave devices become more and more popular among today's telecommunication systems [1, 2]. A single reconfigurable device is capable of multiple operating conditions, reducing the size, weight, cost, and substantially improving the overall performances. These features are suitable for the need and complex environmental condition. The main principle of traditional frequency-tunable microwave structure is that the characteristic impedance of the transmission line is continuously changed by inserted varactorsfor example and can construct parallel varactors [3], series varactors [4], or a mixture of the parallel and series varactors [5] in the transmission lines.

Phase inverters (PI) are crucial components in many applications of microwave circuits such as rat-race hybrid [6], power splitting/combining network [7], filter [8] and directional coupler [9]. Some of the phase inverters are realized utilizing parallel-strip transmission line [8], coplanar waveguide [6] and coplanar strip [10]. Phase inverters are used to reduce size [6], enhance bandwidth [9] as well as isolate ports.

This paper proposes a novel frequency-tunable structure which is different from the traditional ones. This new structure is a microwave phase inverter based on a slot-line resonator. The frequency-tunable phase inverter's architecture is simple and compact. Most of prevenient reconfigurable microstrip devices' control circuits located in the side of transmission line. However, in this paper, the control circuit is designed located in the side of defected ground. For illustration, the measured and simulated performances of an experimental phase inverter designed to operate at frequency 1.1 GHz–1.75 GHz by changing the varactors' voltage are shown.

For further demonstration of the proposed phase inverter's function, the comparison between this novel phase inverter and phase inverters in other publications is listed in Table 1. It is shown that the frequency-tunable phase inverter is proposed for the first time.

Received 4 November 2016, Accepted 27 December 2016, Scheduled 1 February 2017

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Table 1. Comparisons with other works.

ITEM	Structure	Features	Circuit fabrication	Frequency-tunable
Reference line	180° translation line	Working in all frequency, large size	Single/ double sides	No
[6]	Coplanar Waveguide	Working in wide bandwidth, using bonding wires	Single side	No
[12]	Microstrip with defected ground structure (DGS)	Working in wide bandwidth, using metallic vias	Double sides	No
[8]	Parallel-strip	Working in all frequency, using metallic vias	Double sides	No
[10]	Coplanar Strip	Working in wide bandwidth, using bonding wires	Single side	No
This Work	Microstrip with slot-line	Working in narrow bandwidth, using metallic vias	Double sides	Yes

2. FREQUENCY-TUNABLE PHASE INVERTER DESIGN

The microstrip phase inverter using interdigital strip lines, metallic via holes and slot with short end in the ground was proposed [11]. For the first time, a microstrip phase inverter using interdigital strip lines and slot line resonator with tunable frequency is proposed in this paper. The operation frequency lies on the resonator frequency of the short end slot line in the ground. The configuration of the phase inverter is shown in Fig. 1. The left line with defected ground structure is the phase inverter, and the right line is the reference line used to compare phase difference with phase inverter. The 180-degree phase inverter is achieved by means of reversing electric field orientations with reference to the ground plane which is the same as [12, 13]. The difference and key of the phase inverter is the slot line resonator. The slot line on the ground is a symmetrical structure. As shown in Fig. 1, the two large slot annuluses with two varactors and two blocking capacitances act as the resonators with tunable frequency, which determine the frequency of the phase inverter. The inside and small slot annuluses with blocking inductor act as bias circuit for blocking AC.

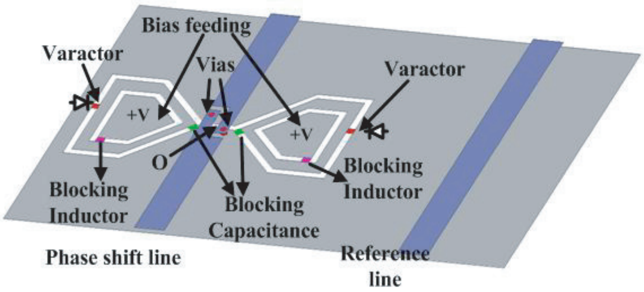


Figure 1. Configuration of the phase inverter with tunable frequency.

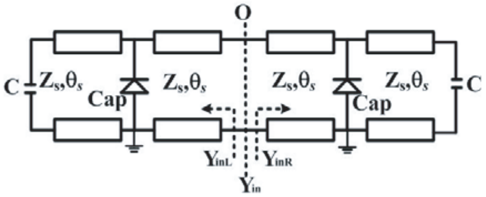


Figure 2. Equivalent circuit of the slot-line resonator with tunable frequency.

Figure 2 shows the corresponding equivalent circuit of the resonator formed by the end short slot line with varactors shunted at the middle of the one slot annuluses. Z_s is the characteristic impedance of the slot line, $\theta_s = \beta_s l_s = (\omega/v_p)l_s$ the electrical length, β_s is the phase constant of the slot-line, $\omega = 2\pi f$ the angular frequency, v_p the phase velocity, and l_s is a half of the physical length which is the length of slot-line at the side of the microstrip line. Cap corresponds to the junction capacitance value of the varactor which can be tuned by the reverse bias voltages. C corresponds to the dc block capacitances to obtain RF short.

When $1/\omega C \ll Z_s$, the input admittance Y_{in} can be expressed by the equivalent parallel resistances as:

$$Y_{in} = Y_{inR} + Y_{inL} \tag{1}$$

$$Y_{inR} = Y_{inL} = Y_s \frac{j(\omega \mathrm{Cap} + Y_s \tan\theta_s - Y_s \cot\theta_s)}{2Y_s - \omega \mathrm{Cap} \tan\theta_s} \tag{2}$$

where $Y_s = 1/Z_s$ is the characteristic admittance of the slot line. Y_{inR} is equivalent admittance on the right side of Y_{in}, and Y_{inL} is the equivalent admittance on the left side of Y_{in}. The condition for resonation can be expressed as:

$$\mathrm{Im}(Y_{in})\big|_{\omega=\omega_s} = 0 \tag{3}$$

where, ω_s is the resonant angular frequency. Combining Eqs. (2) and (3),

$$Y_s \tan^2\theta_s + \omega_s \mathrm{Cap} \tan\theta_s - Y_s = 0 \tag{4}$$

Solving Eq. (4), $\tan\theta_s$ can be expressed as follow:

$$\tan\theta_s = \frac{-\omega_s \mathrm{Cap} \pm \sqrt{\omega_s^2 \mathrm{Cap}^2 + 4Y_s^2}}{2Y_s} \tag{5}$$

$\tan\theta_s$ has two answers, only "+" in Eq. (5) is selected for the compact size of phase inverter. Then $\tan\theta_s$ can be expressed as follows:

$$\tan\theta_s = \frac{-\omega_s \mathrm{Cap} + \sqrt{\omega_s^2 \mathrm{Cap}^2 + 4Y_s^2}}{2Y_s} \tag{6}$$

Equation (6) can be solved by graphic method for a certain capacitance value of Cap, characteristic admittance value and electrical length of the slot-line.

SMV1232 (Alpha) is chosen as the varactor, and the capacitance of Cap changes from 0.86 pF, 1.05 pF, 1.51 pF to 2.67 pF (responding the control voltages change from 7 V, 5 V, 3 V to 1 V). The approximate characteristic impedance of the slot line is 85 Ω. Fig. 3 shows the resonant frequencies for different cases by the graphic method.

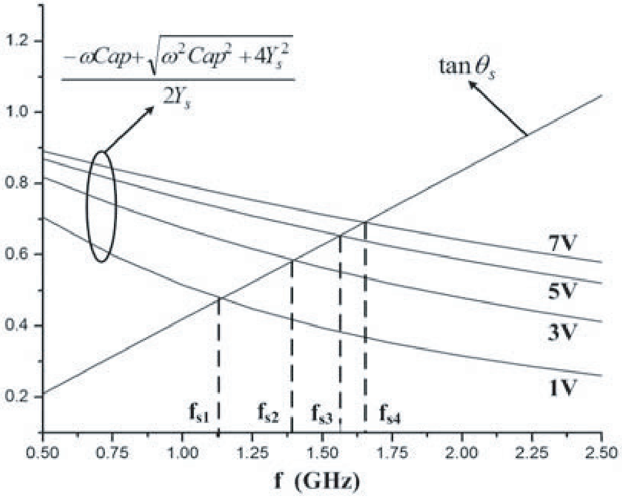


Figure 3. Resonant frequencies of the slot-line resonator.

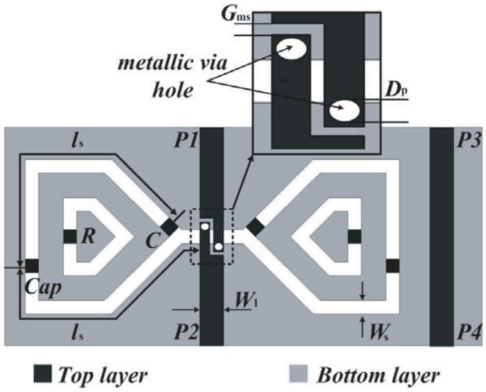
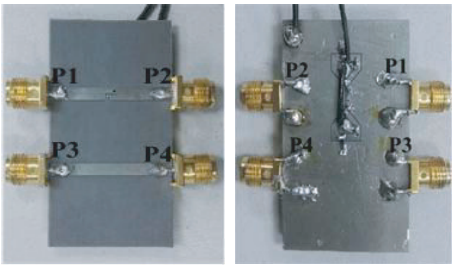
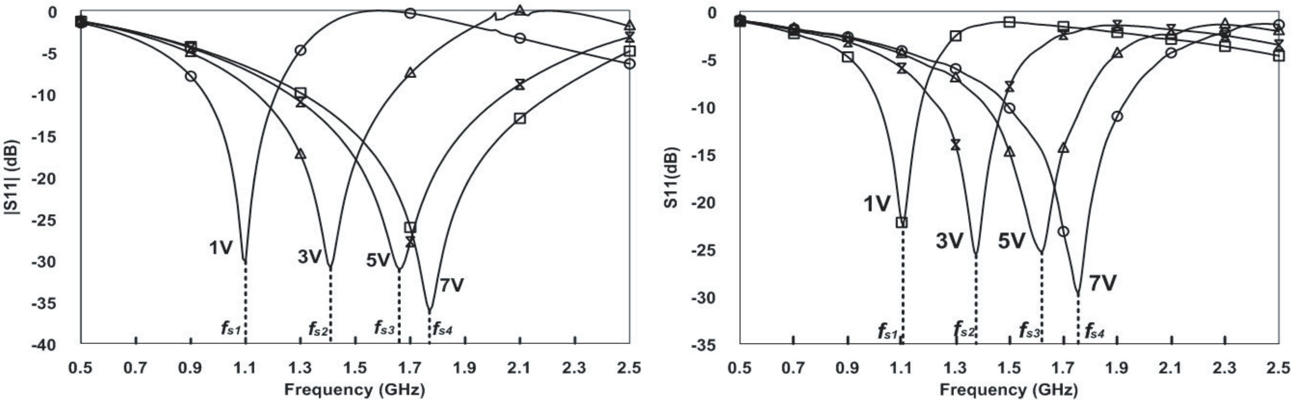


Figure 4. The dimensions of the phase inverter.



(a) (b)

Figure 5. Photograph of the fabricated phase inverter. (a) Top side. (b) Bottom side.



(a) (b)

Figure 6. S_{11} of the phase inverter (a) Simulated results. (b) Measured results.

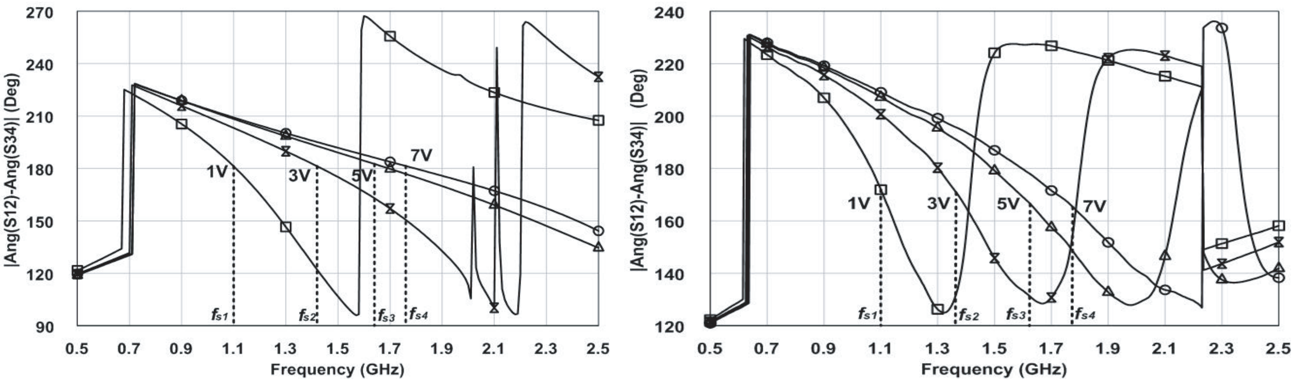
3. EXPERIMENTAL RESULTS

The dimensions of the phase inverter are shown in Fig. 4. The width of the microstrip lines is chosen as $W_1 = 2.46\,\text{mm}$, corresponding to microstrip line's characteristic impedance of $Z_1 = 50\,\Omega$. The slot-line in the ground is bended for structuring bias circuit and compactness. The width of the slot-line is chosen as $W_s = 0.2\,\text{mm}$, corresponding to slot-line's characteristic impedance of $Z_s = 85\,\Omega$. The gap between interdigital microstrip lines is chosen as $G_{ms} = 0.2\,\text{mm}$, slot length chosen as $l_s = 16.55\,\text{mm}$, and diameter of the metallic vias chosen as $D_p = 0.3\,\text{mm}$. The value of the blocking capacitors is 220 pF, and value of the resistances is 1.5 kΩ. The resistors are chosen to replace the blocking inductors.

Figure 5 shows pictures of the fabricated phase inverter. The fabricated board has an area of $30 \times 45\,\text{mm}^2$. A substrate with dielectric constant 2.2, loss tangent $\delta = 0.0029$ and thickness $h = 0.8\,\text{mm}$ is chosen. The phase inverter was simulated using the Ansoft HFSS13.0. The measurements were made by an AV3672 vector network analyser.

The simulated and measured performances are shown in Fig. 6 and Fig. 7. From the measured $|S_{11}|$ of the phase inverter in Fig. 6(b), the operation frequency can be tuned from 1.1 GHz, 1.37 GHz, 1.63 GHz to 1.75 GHz with better than 20 dB return loss corresponding to the control voltages 1 V, 3 V, 5 V to 7 V, respectively. It is shown that the resonant frequencies estimated by graphic method match well with the simulated and the measured results.

In Fig. 7(b), the measured phase differences have a phase deviation less than 15 deg at every operation frequency. The large phase deviation is due to the signal delays caused by via holes and can



(a) (b)

Figure 7. Phase difference of the phase inverter. (a) Simulated results. (b) Measured results.

be compensated by using longer reference line. In Fig. 7(a), owing to using the deembed settings of the port to reduce the via holes influence, the simulated phase inverter has a phase deviation less than 3 deg at every operation frequency.

4. CONCLUSION

A frequency-tunable phase inverter with a novel simple control circuit and a slot-line resonator is proposed. The resonant frequencies are estimated by the graphic method. The proposed frequency tunable phase inverter has the potential in construction of frequency tunable, such as filters, power dividers, directional coupler, rat-race hybrid and antenna. Good matching between the simulated and measured results is obtained. The results show that the proposed phase inverter's operation frequency can be tuned continuously from 1.1 GHz to 1.75 GHz. Ordinary microwave integrated circuit (MIC) fabrication process can be used in the simple and compact structure.

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