Progress In Electromagnetics Research Letters, Vol. 48, 45–49, 2014

Design of a Wideband Differential Phase Shifter with the Application of Genetic Algorithm

Jian-Xiao Wang*, Lin Yang, Yue Liu, Yi Wang, and Shu-Xi Gong

Abstract—In this paper, a wideband differential phase shifter has been analyzed and designed using Genetic Algorithm (GA). The differential phase shifter consists of two fixed main lines of length $\lambda/2$, and parallel open and short stubs of length $\lambda/8$, which are shunted at the edge points of the main lines, respectively. With the application of GA, an impedance match and minimum phase deviation for the desired phase shift over a wide frequency band are obtained. In order to verify the optimum results, simulation experiments are made and a 45° phase shifter is fabricated and measured. The phase shifter exhibits an impedance bandwidth ($|S_{11}| < -10\,\mathrm{dB}$) and a consistent 45° (±2°) phase difference bandwidth around 66%.

1. INTRODUCTION

Phase shifter is one of the most important components applied in microwave circuits, power dividers and feeding networks of antenna arrays. The performance of the phase shifter applied in the beam-shaped array antenna is one of the most important factors to limit the bandwidth of the beam-shaped patterns. Differential phase shifters are four-port circuits providing constant differential phase shift across their two output ports. A broadband differential phase shifter is presented in [1], in which multi-section coupled-lines are connected to a mirrored one to create a double-section to have a better coupling coefficient and frequency bandwidth. The amplitude and phase imbalance between the two paths are within 0.4 dB and 1 degree over the frequency band of 2 to 6 GHz. A 90° phase shifter using a T shaped open stub loaded transmission line is presented in [2]. Good performance is achieved with small insertion loss and phase deviation over a bandwidth of 82%. A broadband 90° differential phase shifter using a pair of multi-section radial transmission-line (TL) stubs is proposed in [3]. Global optimization is performed using the TL model followed by a local optimization based on a more accurate electromagnetic simulation. The measured operating bandwidth of the circuit is 101.5%. While ,the design methods of the phase shifters above are too complex and difficult to design. In this paper, a kind of differential phase shifter is analyzed and designed which is more suitable to use in the feeding network of beam-shaped array antenna.

The switched-network phase shifter in [4], which is suitable for phase shift of less than 90°, can offer a wideband and stable phase shift. The design details and exact performance of the 45° phase shifter are not given. This phase shifter is cited by [5] and exhibits an impedance bandwidth ($|S_{11}| < -10\,\mathrm{dB}$) around 48% and a constant 45° (±4°) phase difference over a frequency range of 24%. In this letter, Genetic Algorithm (GA) is applied to the optimization of the phase shifter proposed in [4] and a better performance of this type of phase shifter is obtained.

Genetic Algorithm (GA) is one of the most popular optimization algorithms, which is invented to mimic some of the processes observed in natural evolution. GA is the powerful stochastic algorithm based on the principles of natural selection and natural genetics. GA is widely used to the optimization

---

Received 15 May 2014, Accepted 29 July 2014, Scheduled 15 August 2014

* Corresponding author: Jian-Xiao Wang (wjx8902@126.com).

The authors are with the National Key Laboratory of Science and Technology on Antennas and Microwaves, Xidian University, Xi'an, Shaanxi 710071, China.

of the electromagnetic problems, such as designs of antenna arrays and microwave circuits [6]. The goal of the optimization is to find out the values of the Z_m and Z_s satisfying the requirements of the small phase deviation and the low VSWR for a given desired phase shift.

In this letter, a 45° phase shifter is fabricated and measured to verify the optimum results obtained with the application of the proposed method. The 45° phase shifter exhibits an impedance bandwidth ($|S_{11}| < -10\,\mathrm{dB}$) and a consistent 45° (±2°) phase difference bandwidth around 66%.

2. PHASE SHIFTER CONFIGURATION AND DESIGN

The structure of the phase shifter proposed in [4] is shown in Figure 1, which consists of two paths, Path 1 and Path 2. Path 1 is composed of a main transmission line of characteristic impedance Z_{m1} with an electrical length of 90° at the centre frequency and two parallel short-open stubs of characteristic impedance Z_{s1}, each with an electrical length of 45° at the centre frequency, which are open and shorted and are shunted at the edge points of the main line, respectively. The additional part in Path 2 compared from Path 1 is a main transmission line of characteristic impedance Z_0 with an electrical length of θ_0 to obtain the desired phase shift. Hence, Path 2 has a different phase property from Path 1, and the phase slope can be controlled by changing the values of Z_{mi} and Z_{si} according to the desired phase shift. The short-open stubs in Path 2 are applied to increase the phase slope appropriately. While, the short-open stubs in Path 1 are applied to make its phase slope close to that of Path 2 so as to obtain a stable phase shift over a wide frequency band. This type of phase shifter is designed to achieve stable phase shifts less than 90°.

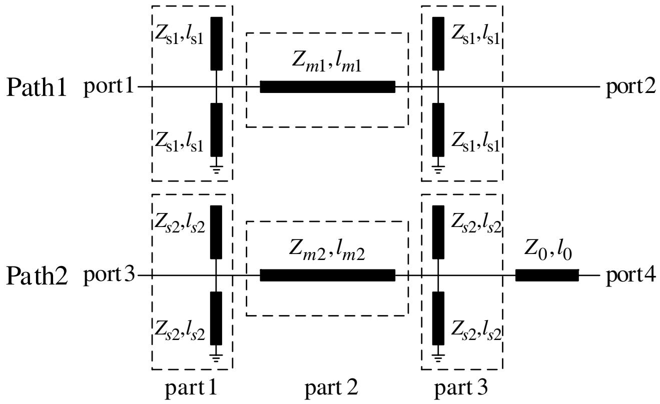


Figure 1. Structure of the wideband phase shifter proposed in [4].

Since Path 1 and Path 2 are independent from each other, Path 1 and Path 2 can be considered as two independent two-port networks. As the $ABCD$ matrix has the advantage of cascade connection and the transformation from $ABCD$ matrix to scattering matrix has been known, this phase shifter is analyzed with the application of $ABCD$ matrix and scattering matrix. The $ABCD$ matrix of Path i can be calculated with A_{1i}, A_{2i}, A_{3i}, where A_{1i}, A_{2i} and A_{3i} are the $ABCD$ matrixes of part 1, part 2 and part 3 of Path i, respectively, for $i = 1$ or 2.

$$A_i = A_{1i}A_{2i}A_{3i} = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \tag{1}$$

$$A_{1i} = A_{3i} = \begin{bmatrix} 1 & 0 \\ j\frac{1}{Z_{si}}(\tan\theta_{si} - \cot\theta_{si}) & 1 \end{bmatrix} \quad A_{2i} = \begin{bmatrix} \cos\theta_{mi} & jZ_{mi}\cos\theta_{mi} \\ j\frac{1}{Z_{mi}}\cos\theta_{mi} & \cos\theta_{mi} \end{bmatrix} \tag{2}$$

$\theta_{mi} = \pi * \bar{f}$, $\theta_{si} = (\pi/4) * \bar{f}$ and $\theta_0 = \Delta\varphi * \bar{f}$ are electrical lengths of l_{mi}, l_{si} and l_0, respectively. $\Delta\varphi$ is the desired phase difference between two paths at the center frequency, and $\bar{f}$ is the normalized frequency.

Considering the transformation from $ABCD$ matrix to scattering matrix, the scattering parameters of Path 1 and Path 2 can be expressed with the calculated $ABCD$ matrix.

$$\Delta\varphi(\bar{f}) = angle(S_{12}) - angle(S_{34}) \tag{3}$$

$$angle(S_{12}) = angle\left(\frac{2(A_1D_1 - B_1C_1)}{A_1 + B_1 + C_1 + D_1}\right) \quad angle(S_{34}) = angle\left(\frac{2(A_2D_2 - B_2C_2)}{A_2 + B_2 + C_2 + D_2}\right) - \theta_0 \quad (4)$$

$$S_{11} = \frac{Z_0(A_1 - C_1Z_0 - D_1) + B_1}{Z_0(A_1 + C_1Z_0 + D_1) + B_1} \quad S_{33} = \frac{Z_0(A_2 - C_2Z_0 - D_2) + B_2}{Z_0(A_2 + C_2Z_0 + D_2) + B_2} \quad (5)$$

As a phase shifter, the stable phase shift and low input VSWR are required. For the design goal of 2° maximum phase deviation and VSWR $\leq 1.15:1$, the objective functions of GA can be defined as below.

$$\left|\Delta\varphi(\bar{f}) - \Delta\varphi\right| \leq 2^\circ \quad (6)$$

$$\mathrm{VSWR}_1 = \frac{1 + |S_{11}|}{1 - |S_{11}|} \leq 1.15 \quad \mathrm{VSWR}_3 = \frac{1 + |S_{33}|}{1 - |S_{33}|} \leq 1.15 \quad (7)$$

Besides, in order to make sure the impedances of Z_{mi} and Z_{si} are practicable, the values of Z_{mi} and Z_{si} cannot be too large or too small. For a microwave substrate with thickness of 1 mm and relative dielectric constant of 2.55, the characteristic impedances ranging from 40 Ω to 150 Ω with the width ranging from 4.0 mm to 0.23 mm are practicable. Hence, the values of Z_{mi} and Z_{si} are subject to certain limit.

$$40 \leq Z_{mi} \leq 150 \quad 40 \leq Z_{si} \leq 150 \quad (8)$$

Genetic Algorithm is a stochastic global searching algorithm used to solve complicated problems by simulating the evolutionary course of natural selection and natural inheritance of biology circles. In Genetic Algorithm, code space is used to replace problem space, fitness function is regarded as evaluating criterion, code population is regarded as evolution base, selection and genetic mechanism is actualized by genetic operation on individual bit chain of population. A repeated course is formed in this way. The individual of population evolves ceaselessly by recombining some important genes of code bit chain stochastically, and approaches to the optimal gradually till reaching the goal of solving the problem ultimately [7]. Since Genetic Algorithm is a well-known optimum method, there is no need to illustrate its details in this paper. With the Equations (6), (7) as the objective functions and the Equation (8) as the limit to Z_{mi} and Z_{si}, the standard GA function within Matlab is called to optimize the phase shifter.

Here, the optimized values of Z_{mi} and Z_{si} for certain phase difference $\Delta\varphi$ is shown in Figure 2. The simulated responses of the phase shifters for different desired phase differences is shown in Figure 3 corresponding to the parameters in Figure 2. It is necessary to point out that the responses in Figure 3 are calculated using the Equations (3) and (7).

In order to verify the design method, a 45° phase shifter of this kind is designed and measured in the next section.

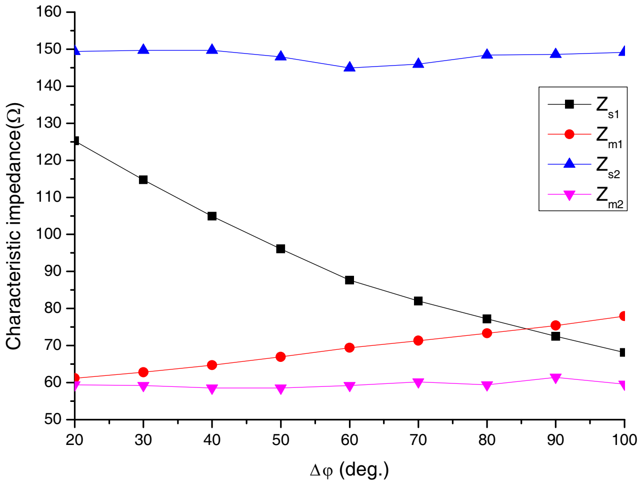
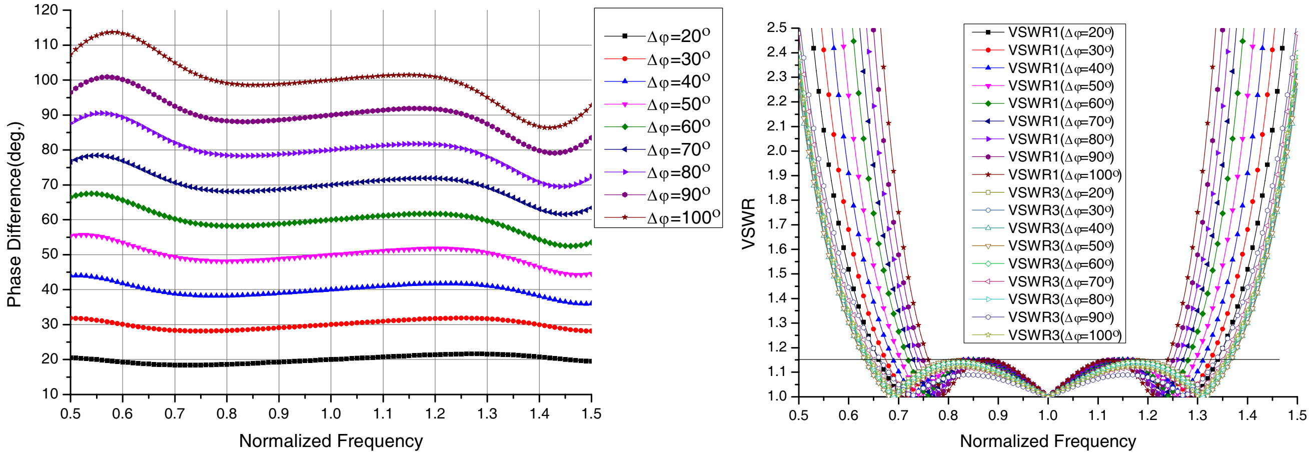


Figure 2. Z_{mi} and Z_{si} impedance relation versus phase shift (design graph).



(a) Responses of phase difference

(b) Responses of VSWR

Figure 3. Simulated responses for different desired phase shifts.

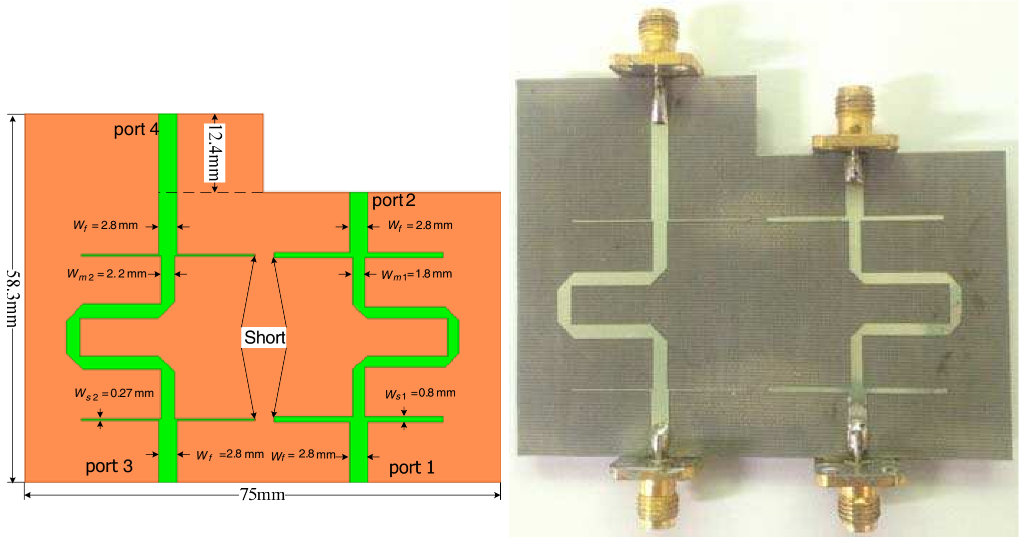


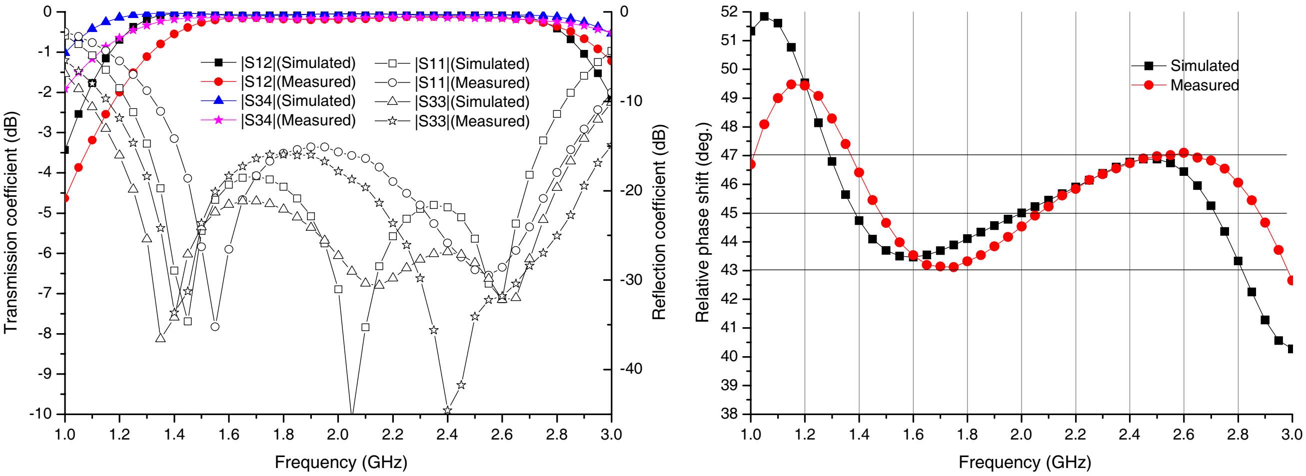
Figure 4. Structure and photograph of the 45° differential phase shifter.

3. SIMULATION AND EXPERIMENTS

In order to verify the design method, a 45° differential phase shifter operating at the central frequency of 2.0 GHz is designed, fabricated and measured. With the design method proposed in this paper, design parameters of 45° differential phase shifter are obtained as below, $Z_{s1} = 99.2$, $Z_{m1} = 66.1$, $Z_{s2} = 146.8$, $Z_{m2} = 59.8$. It is designed on the microwave substrate with thickness of 1 mm and relative dielectric constant of 2.55, and the simulation is based on the full-wave software HFSS. Figure 4 shows the modal structure and the photograph of the phase shifter. The overall size of the phase shifter is $75\,\text{mm} \times 58.3\,\text{mm}$.

The differential phase shifter is measured using R&S ZVB20 network analyzer. The phase delays of path 1 and path 2 are measured respectively, and the differential phase shift is the phase delay difference between two paths. Figure 5 shows the simulated and measured *s*-parameters and phase difference between two paths.

The measured results agree well with the simulated ones. It is observed from Figure 5(a) that the phase shifter exhibits an impedance bandwidth ($|S_{11}| \leq -10\,\text{dB}$, $|S_{33}| \leq -10\,\text{dB}$) and a low insertion loss bandwidth (insertion loss is less than 0.5 dB) around 66%, from 1.4 GHz to 2.8 GHz. Referring to



(a) s-parameters (b) phase shift between two paths

Figure 5. Simulated and measured performances of the 45° differential phase shifter.

Figure 5(b), it is seen that the phase shifter achieves a consistent 45° (±2°) output ports phase difference over a frequency range of 1.4 ∼ 2.95 GHz (71%). Hence, the phase shifter exhibits an impedance bandwidth ($|S_{11}| \leq -10\,\text{dB}$, $|S_{33}| \leq -10\,\text{dB}$) and a stable phase difference bandwidth ($45° \pm 2°$) around 66%, from 1.4 GHz to 2.8 GHz. The designed phase shifter in this paper obtain a better performance than that of the modal used in reference [5].

4. CONCLUSION

In this letter, a general method to design a conventional wideband differential phase shifter for phase difference less than 90° is presented. The phase shifter is analyzed with the application of *ABCD* matrix and optimized employing GA. With the proposed method, a 45° phase shifter is designed and fabricated. The 45° phase shifter exhibits an effective bandwidth of 66% from 1.4 GHz to 2.8 GHz for $|S_{11}| \leq -10\,\text{dB}$, $|S_{33}| \leq -10\,\text{dB}$ and a stable phase difference ($45° \pm 2°$). The measured results verify that the method proposed in this letter is effective. This type of phase shifter is a good candidate as part of the feeding networks for wideband beam-shaped antenna arrays.

REFERENCES

1. Mohammadpour-Aghdam, K., N. Komjani, G. Vandenbosch, and W. De Raedt, "A broadband modified differential phase shifter for microwave applications," *Proceedings of the 39th European Microwave Conference*, 69–72, Rome, Italy, Sep. 2009.
2. Zheng, S. Y., W. S. Chan, and K. F. Man, "Broadband phase shifter using loaded transmission line," *IEEE Microwave and Wireless Components Letters*, Vol. 20, No. 9, 498–500, Sep. 2010.
3. Yeung, S. H., Q. Xue, and K. F. Man, "Broadband 90 differential phase shifter constructed using a pair of multisection radial line stubs," *IEEE Trans. on Microwave Theory and Techniques*, Vol. 60, No. 9, 2760–2767, Sep. 2012.
4. Eom, S.-Y. and H.-K. Park, "New switched-network phase shifter with broadband characteristics," *Microwave and Optical Technology Letters*, Vol. 38, No. 4, 255–257, Aug. 2003.
5. Liu, C.-R., S.-Q. Xiao, Y.-X. Guo, Y.-Y. Bai, and B.-Z. Wang, "Broadband circularly polarized beam-steering antenna array," *IEEE Trans. on Antennas and Propagat.*, Vol. 61, No. 3, 1475–1479, Mar. 2013.
6. Yang, Y. and X.-J. Yu, "Cooperative coevolutionary genetic algorithm for digital IIR filter design," *IEEE Trans. on Industrial Electronics*, Vol. 54, No. 3, 1311–1318, Jun. 2007.
7. Yan, T.-S., Y.-Q. Tao, and D.-W. Cui, "Research on handwritten numeral recognition method based on improved genetic algorithm and neural network," *Proceedings of the 2007 International Conference on Wavelet Analysis and Pattern Recognition*, 1271–1276, Beijing, China, Nov. 2007.