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WIDEBAND DIFFERENTIAL PHASE SHIFTER USING MICROSTRIP NONUNIFORM TRANSMISSION LINES

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Abstract—A new structure is proposed for wideband differential phase shifter. The proposed structure consists of a microstrip Nonuniform Transmission Line (NTL) and a microstrip Uniform Transmission Line (UTL). To optimally design the NTL, its strip width is expanded in a truncated Fourier series, firstly. Then, the optimum values of the coefficients of the series are obtained through an optimization approach to have low phase shift error and low reflection coefficient in desired frequency bandwidth. The usefulness of the proposed structure is studied using two examples.

1. INTRODUCTION

Differential Phase Shifters (DPSs) and Phase Shifters (PSs) have many applications in RF and microwave circuits such as phase discriminators, beam forming networks, frequency translators, power dividers and phase array antennas [1, 2]. The most conventional DPSs are Schiffman ones [3–6]. The Schiffman DPSs consist of a Uniform Transmission Line (UTL) and a single or multi-section coupled transmission line. The main disadvantages of Schiffman DPSs are two-dimensional spreading and having some discontinuities. Also, the most conventional PSs are loaded-line [7–9] or switched-line [9] ones. The loaded-line PSs consist of a UTL loaded by one of two stubs at two different points. The main disadvantage of the conventional PSs is their narrow band property. In this paper, we propose a new structure as a wideband DPS or PS. The proposed structure consists of a microstrip Nonuniform Transmission Line (NTL) and a microstrip UTL. The proposed structure has not any discontinuity, has nearly one-dimensional spreading and has the capability of wideband designing. To optimally design the NTL, its strip width is expanded in a truncated Fourier series, firstly. Then, the optimum values of the coefficients of the series are obtained through an optimization approach to have low phase shift error and low reflection coefficient in desired frequency bandwidth. The usefulness of the proposed structure is studied using two examples.

2. THE PHASE SHIFTER

In this section the new structure for DPSs or PSs is proposed. Figs. 1(a) and 1(b) depict top view of the strip of a microstrip DPS and PS (one bit of it), respectively. The proposed structures contain two transmission lines, one uniform (UTL) and one nonuniform (NTL). The length of the UTL and NTL are d_0 and d, respectively. The width of strips of the UTL and NTL are w_0 and $w(z)$, respectively, which correspond to the characteristic impedance of the Z_0 and $Z_c(z)$, respectively. The relative electric permittivity and the thickness of the substrate of both the UTL and NTL are ε_r and h, respectively. Two switches seen in Fig. 1(b) can be realized by PIN diodes. The phase difference between two matched ends of the UTL and NTL at frequency f are as follows, respectively

$$\varphi_0(f) = \text{Angle}\left(\exp\left(-j2\pi f\sqrt{\varepsilon_{re0}}d_0/c\right)\right) \tag{1}$$

$$\varphi(f) = \text{Angle}\left(S_{21}(f)\right) \tag{2}$$

where c is the velocity of the light and ε_{re0} is the effective relative electric permittivity of the UTL. We would like that the difference between these phase differences ($\Delta\varphi = \varphi - \varphi_0$), calling it the phase shift, be equal to the desired value $\Delta\varphi_d$ at all frequencies in the desired frequency bandwidth, i.e., from $f_{\min}$ to $f_{\max}$.

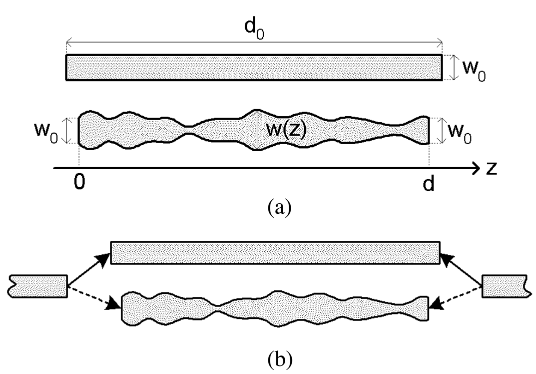

Figure 1. (a) Top view of the strip of a microstrip DPS (b) Top view of the strip of a microstrip PS (one bit).

3. SYNTHESIS OF THE PHASE SHIFTER

In this section a general method is proposed to design optimally the proposed DPS or PS. Firstly, we consider the following truncated Fourier series expansion for the normalized width of strip of the NTL.

$$\ln(w(z)/h) = \sum_{n=0}^{N} C_n \cos(n\pi z/d) \tag{3}$$

Utilizing this truncated Fourier series expansion does not create any discontinuity in the resulted NTL. An optimum designed DPS or PS has to have constant phase shift in a defined frequency range. The optimum values of the coefficients C_n and the length d could be obtained through minimizing the following error function related to K frequencies between $f_{\min}$ and $f_{\max}$.

$$\text{Error} = \sqrt{\frac{1}{K}\sum_{k=1}^{K} \left|\text{unwrap}\left(\varphi(f_k)\right) - \text{unwrap}\left(\varphi_0(f_k)\right) - \Delta\varphi_d\right|^2} \tag{4}$$

where unwrap(p) is a function that unwraps phases p by changing absolute jumps greater than π to their 2π complement. Moreover, defined error function should be restricted by some constraints such as low input reflection, two end matching and easy fabrication, which could be written as follows

$$\max\left(|S_{11}(f)|\right) \leq \rho_{\max} \tag{5}$$

$$w(0)/h = w(d)/h = w_0/h \tag{6}$$

$$\max(w(z)/h) \leq (w/h)_{\max} \tag{7}$$

$$\min(w(z)/h) \geq (w/h)_{\min} \tag{8}$$

where $\rho_{\max}$ is the maximum allowable reflection coefficient and also $(w/h)_{\min}$ and $(w/h)_{\max}$ are the minimum and maximum values of $w(z)/h$, respectively. It seems that the best range of variation of the length of the NTL, d, in the optimization process may be $d_{\min} \leq d \leq d_{\max}$, where

$$d_{\min} = \begin{cases} d_0 - \dfrac{\Delta\varphi_d}{2\pi f_{\min}} & \Delta\varphi_d > 0 \\ d_0 - \dfrac{\Delta\varphi_d}{2\pi f_{\max}} & \Delta\varphi_d < 0 \end{cases} \tag{9}$$

$$d_{\max} = \begin{cases} d_0 - \dfrac{\Delta\varphi_d}{2\pi f_{\max}} & \Delta\varphi_d > 0 \\ d_0 - \dfrac{\Delta\varphi_d}{2\pi f_{\min}} & \Delta\varphi_d < 0 \end{cases} \tag{10}$$

To obtain the phase difference $\varphi(f)$, we have to analyze the NTL. There are some methods to analyze the NTLs such as finite difference [10], Taylor's series expansion [11], Fourier series expansion [12], the equivalent sources method [13] and the method of Moments [14]. Of course, the most straightforward method is subdividing NTLs into many uniform or linear electrically short sections [15, 16] with length Δz, which

$$\Delta z << \lambda_{\min} = \frac{c}{f_{\max}\sqrt{\varepsilon_r}} \tag{11}$$

Then the $ABCD$ matrix of the NTL will be as the multiplication of the $ABCD$ matrices of all short sections. The parameters A, B, C and D could be used to find the S parameters of the NTL as follows

$$S_{11} = \frac{AZ_0 + B - CZ_0^2 - DZ_0}{AZ_0 + B + CZ_0^2 + DZ_0} \tag{12}$$

$$S_{21} = \frac{2Z_0}{AZ_0 + B + CZ_0^2 + DZ_0} \tag{13}$$

It is worth to mention that it is possible to consider both transmission lines in Figs. 1(a) and 1(b) nonuniform, i.e., two NTLs instead of one UTL and one NTL, calling them Double DPS or PS. In these structures, one have to use two individual truncated Fourier series expansion (3) for each NTL.

4. EXAMPLES AND RESULTS

Consider a proposed microstrip phase shifter with $\varepsilon_r = 10$ with assumptions of $(w/h)_{\min} = 0.1$, $(w/h)_{\max} = 10$, $\rho_{\max} = -13\,\text{dB}$ and $w_0/h = 1$ ($Z_0 = 50\,\Omega$) and considering $d_0 = 1$, 2, 3 or 4 cm. We would like to design a difference phase shifter with $\Delta\varphi_d = +10°$ in a frequency range from 2.0 to 4.0 GHz (an octave bandwidth). Tables 1–2 show the optimum values of the parameters C_n and d and also Fig. 2 illustrates $w(z)$ of the NTL, considering $N = 10$. Also, Figs. 3–5 illustrate φ, φ_0, $\varphi - \varphi_0$ and $|\text{S}_{11}|$, respectively, versus frequency. It is seen that the absolute of the phase error is less than 0.3% for $d_0 = 4$ cm and also the absolute of the input reflection coefficient is less than -13 dB for all d_0s. One sees that as the length of the structure is chosen larger the phase error is decreased.

Now, we would like to design a difference phase shifter with $\Delta\varphi_d = +50°$ in a frequency range from 2.0 to 4.0 GHz, considering $d_0 = 20$ cm. This phase shifter could be designed as a single ($M = 1$) section or cascading of multi (e.g., $M = 5$) sections with d_0=4 cm.

Table 1. Optimum values of the coefficients C_n for $\Delta\varphi_d = +10°$.

	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
d_0=1cm	-0.0199	0.0001	0.0042	-0.0000	0.0040	-0.0000	0.0039	-0.0000	0.0039	-0.0000	0.0039
d_0=2cm	-0.6674	-0.1724	0.0138	-0.3574	-0.3963	0.4257	0.3724	0.0650	0.2461	0.0391	0.4313
d_0=3cm	-0.7508	0.0237	0.3909	0.0273	0.2185	-0.0676	-0.6507	-0.0027	0.4735	0.0192	0.3185
d_0=4cm	-0.7888	-0.1232	0.6545	0.0607	-0.0125	-0.1203	-0.1774	-0.1850	0.3900	0.3678	-0.0659

Table 2. Optimum value of the length d for $\Delta\varphi_d = +10°$.

	$d_{\min}$	d	$d_{\max}$
$d_0 = 1\,\text{cm}$	8.3755	8.9659	9.1877
$d_0 = 2\,\text{cm}$	18.3755	18.3755	19.1877
$d_0 = 3\,\text{cm}$	28.3755	28.3755	29.1877
$d_0 = 4\,\text{cm}$	38.3755	38.9453	39.1877

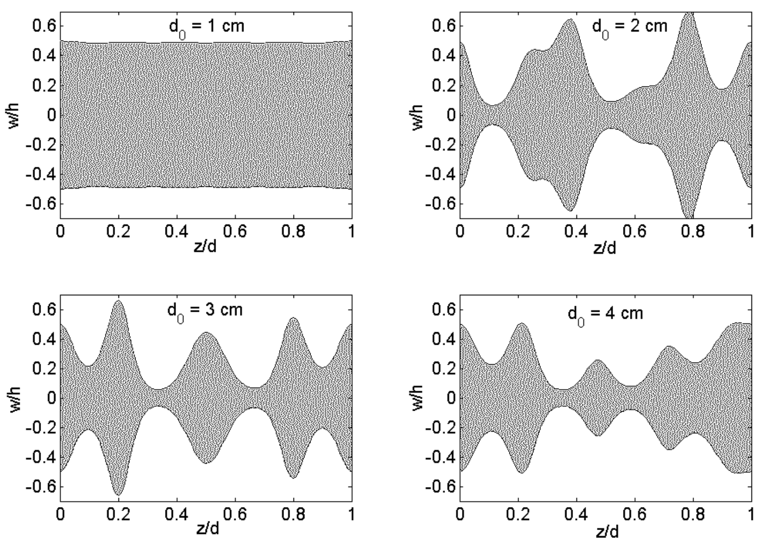

Figure 2. The top view of the resulted microstrip NTL for $\Delta\varphi_d = +10°$.

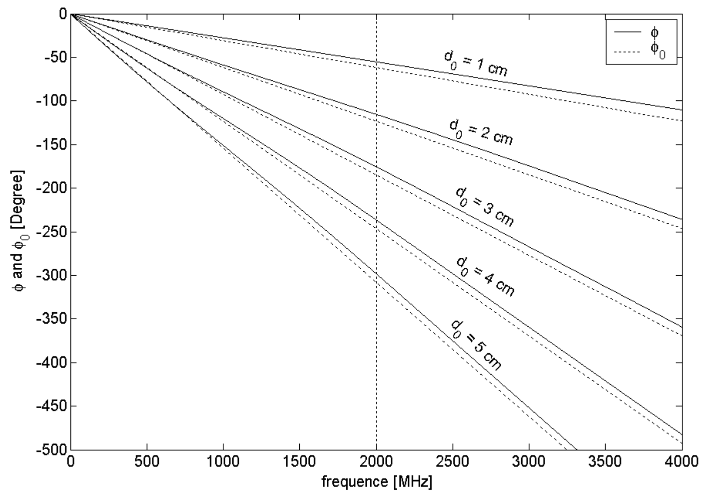

Figure 3. The phases φ and φ_0 versus frequency for $\Delta\varphi_d = +10°$.

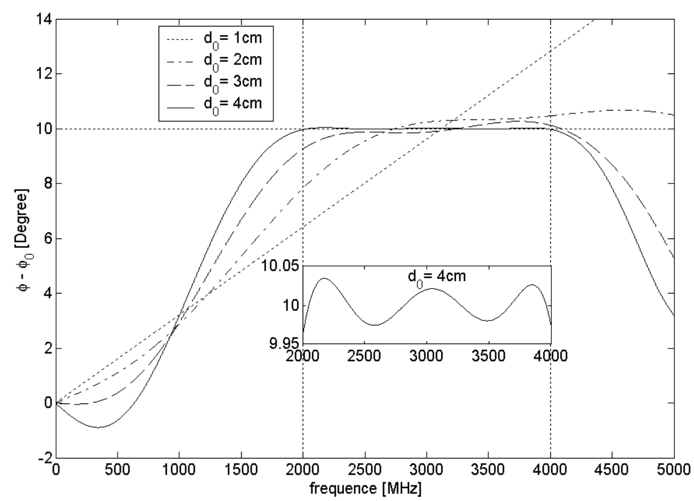

Figure 4. The phase shift $\varphi - \varphi_0$ versus frequency for $\Delta\varphi_d = +10°$.

Tables 3–4 show the optimum values of the parameters C_n and d and also Fig. 6 illustrates $w(z)$ of the NTL, considering N=10. Also, Figs. 7–8 illustrate $\varphi-\varphi_0$ and $|S_{11}|$, respectively, versus frequency. It is seen that the absolute of the phase error is less than 4% for both cases of $M = 1$ and 5 and also the absolute of the input reflection coefficient

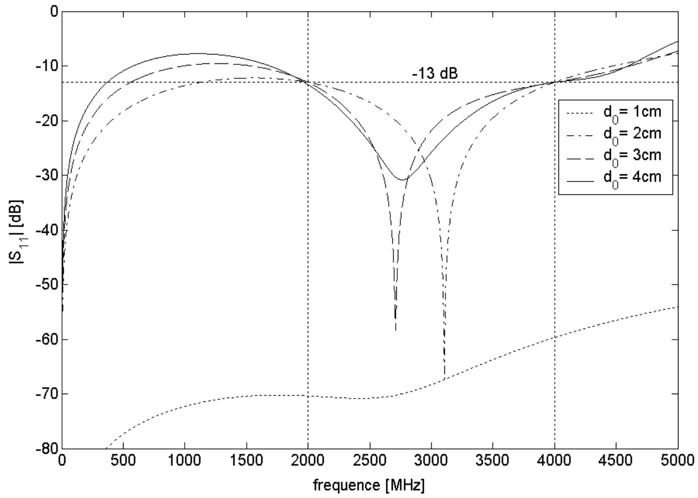

Figure 5. The absolute of S_{11} versus frequency for $\Delta\varphi_d = +10°$.

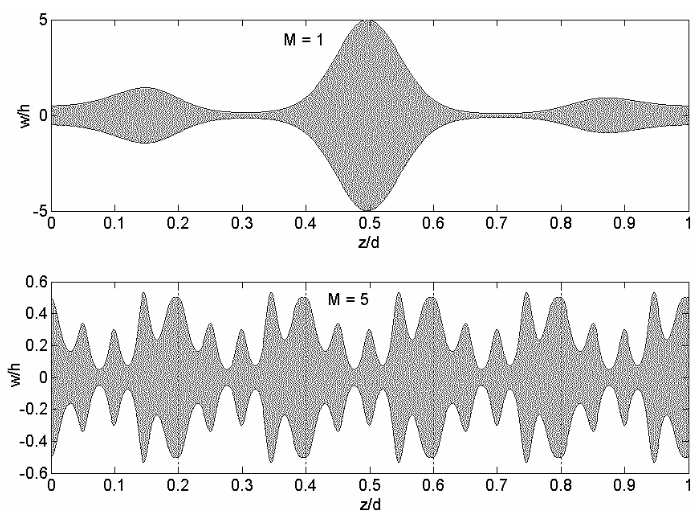

Figure 6. The top view of the resulted microstrip NTL for $\Delta\varphi_d = +50°$.

is less than -13 dB for both cases. However, the maximum of resulted $w(z)/h$ of the case $M = 1$ is much greater that that of the case $M = 5$. In the other hand, the amount of variations of the resulted $w(z)/h$ of the case $M = 5$ is much more that that of the case $M = 1$.

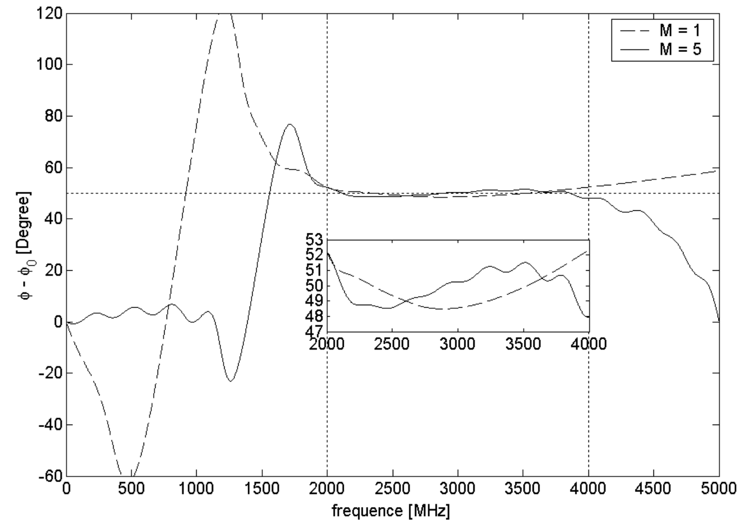

Figure 7. The phase shift $\varphi - \varphi_0$ versus frequency for $\Delta\varphi_d = +50°$.

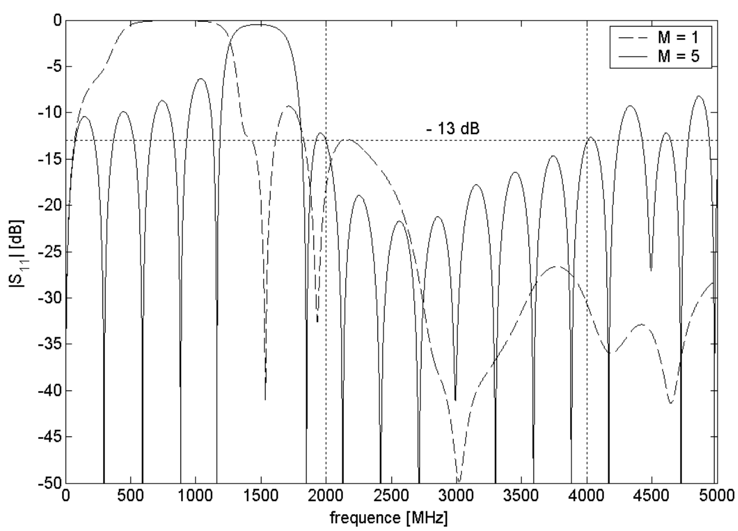

Figure 8. The absolute of S_{11} versus frequency for $\Delta\varphi_d = +50°$.

Table 3. Optimum values of the coefficients C_n for $\Delta\varphi_d = +50°$.

	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
$M = 1$	0.2249	0.2220	-0.2328	-0.1200	1.0049	-0.1174	-1.0023	-0.0173	-0.0795	0.0326	0.0849
$M = 5$	-0.8139	-0.2443	0.5684	0.1403	-0.0204	-0.0152	-0.0345	-0.0394	0.5788	0.1587	-0.2784

Table 4. Optimum value of the length d for $\Delta\varphi_d = +50°$.

	$d_{\min}$	d	$d_{\max}$
$M = 1$	191.8773	192.5084	195.9386
$M = 5$	191.8773	194.2772	195.9386

5. CONCLUSION

A new structure was proposed for wideband differential phase shifter. The proposed structure consists of a microstrip Nonuniform Transmission Line (NTL) and a microstrip Uniform Transmission Line (UTL). To optimally design the NTL, its strip width is expanded in a truncated Fourier series, firstly. Then, the optimum values of the coefficients of the series are obtained through an optimization approach to have low phase shift error and low reflection coefficient in desired frequency bandwidth. The usefulness of the proposed structure was verified using two examples. It was observed that the optimally designed structures might yield a good performance if their length is chosen large sufficiently. Also, multi-section type of the proposed structure will have low deeply and fast changed strip with respect to single section type of it.

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