Numerical study and experimental validation of a four-way feeding network with 45 deg broadband phase shifts for antenna array applications

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A four-way network with 45 deg output phase shifts for feeding antenna array is studied in this work. To widen the phase imbalance, quarter wavelength short stubs with suitable characteristic impedances are introduced and numerically analyzed. Meanwhile, the wideband magnitude imbalance is also discussed by extending the inter-stage transmission line with proper electric length. The study is further confirmed by developing a prototype feeding network centered at 3 GHz. Results from the fabricated prototype network exhibit wideband good performance, both from numerical evaluations and experimental demonstrations.

Key words: broadband, 45 deg phase shift, magnitude imbalance, phase imbalance, feeding network.

1 Introduction

The feeding network is a fundamental part of an antenna/array. Basically, it is developed from microwave power division network that is based on three- or four-port networks with, maybe, proper phase shifts among outputs [1]. Generally, the four-port network can be in-phase, out-of-phase or orthogonal between the two outputs while the third output is isolated, while for the three-port case, it is easy to provide in-phase or, in some situations, out-of-phase between the outputs.

To now, studies on the power division networks, especially for the three-port ones, are extensive. These studies are primarily focused on size reduction [2–4], dual- or multi-band incorporating with multi-function like filtering [5–9], *etc.* To feed an antenna array, dedicated RF power applied to each antenna element is necessary in practice, thus making the unequal power division to be of important. It is found the microwave printed circuit board (PCB) based planar division networks generally facilitate small division ratios, in most cases, up to 1:2 [4, 7]. To achieve large division ratios, composite transmission lines such as left/right-handed lines or defected ground structures are employed [10–12]. In general, these techniques are complex building process. The large division ratio can also be realized by transmission line loadings [13, 14], and new topologies are reported to achieve this purpose at the expense of occupied circuit areas [15, 16].

On the other hand, it is known that for the phase-controlled array antenna, the phase relation would be more important than the magnitude distribution for its feeding network. A literature review found there are relatively few researches dedicated to discussing the phase

shifted multi-port networks. In [17], Darwish, *et al* reported an $i\pi$ network that characterizes the output phase difference related to the number of outputs with $180/N$ degree. Thus for a four-way divider, $N = 4$, and 45° phase shift can be observed between adjacent outputs, but for six ways, N should be 6 and therefore, the outputs could share 30° phase shifts. For practical antenna/array feeding, designated phase shifts are required in many cases. To achieve arbitrary phase shifts, branch-line coupler based four-port network is investigated [18]. But the design methodology and theory is not applicable to the case for the three terminals.

In this work, a coupled line based three-port division network is investigated, where two-stage tree-type division achieves one-to-four ways with 45° phase shift in sequence. In this study, we primarily discuss on the inter-stage transmission line and the designated inter-stage 90° phase shift for bandwidth enhancement. The study is based on numerical analysis by parameter sweeping. All studies are finally examined from simulations and experiments by developing a prototype demonstrator with broadband magnitude and 45° phase shift responses. The presented design method and model can be applied to developing antenna feeding network in which the radiation elements are required to be phase shifted excitations.

2 Architecture of the division network

Figure 1 illustrates the architecture of the studied network, where port 1 serves as the input while ports 2 to 5 are outputs that are 45° phase lag in sequence. A pair of coupled line is employed to implement the power division [19]. The outputs of the first stage present 90°

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Fig. 1. Studied four-way feeding network: (a) – architecture, (b) – fabricated prototype

Fig. 2. Magnitude and phase imbalances for the inter-stage line $L_1 = \lambda_g/64$ with $Z = Z_0$ and $0.6Z_0$: (a) – magnitude imbalance, (b) – phase difference

Fig. 3. Magnitude and phase imbalances for the inter-stage line $L_1 = \lambda_g/4$ with $Z = Z_0$ and $0.6Z_0$: (a) – magnitude imbalance, (b) – phase difference

phase difference and then, they are applied to the second stage, where the final outputs further present desired 45° phase difference. Notice that here all outputs are equal magnitude.

The phase difference is realized by differentiating the transmission line sections, thus the length between L_1 and L_2 should be differentiated as a quarter wavelength,

while the one between L_3 and L_4 should be half of a quarter wavelength. Further, to implement consistent phase responses within an enhanced frequency band, phase compensation stub is loaded to the reference output port of each power division unit [20]. Each loaded stub is quarter-wavelength short circuited with characteristic impedance Z for Stub 1 and Z_0 for Stub 2 and Stub 3, where Z is a

Fig. 4. Magnitude and phase imbalances for the inter-stage line $L_1 = 3\lambda_g/8$ with $Z = Z_0$ and $0.6Z_0$: (a) – magnitude imbalance, (b) – phase difference

Fig. 5. Magnitude and phase imbalances for the inter-stage line $L_1 = \lambda_g/2$ with $Z = Z_0$ and $0.6Z_0$: (a) – magnitude imbalance, (b) – phase difference

variable for further parameter study and Z_0 is the system reference impedance. The coupled line section is discussed from the coupled line theory, while the rest transmission lines are all referred to the system impedance of Z_0 , that is $50\ \Omega$ in general.

3 Parameter study of the network

To characterize the expected wideband responses, parameter sweeping study is carried out; here specific focuses lie in the lengths L_1 and L_2 of transmission-line sections and the characteristic impedance Z of the Stub 1. The center operation frequency in this study is 3 GHz. We use microstrip transmission-line model to perform parameter study, and the Agilent ADS2007 software is utilized to numerically analyze the frequency response of such a network.

As shown in Fig. 1(a), the length L_1 can be ideally zero but for practical layout and junction considerations, a small value of $L_1 = \lambda_g/64$ is first studied, where λ_g is the guided wavelength at the center frequency. On the other hand, two cases are considered for the characteristic impedance Z of the Stub 1; that are $Z = Z_0$ and $Z = 0.6Z_0$. The latter choice is based on the fact that for a $50\ \Omega$ system, this corresponds to a transmission line of $30\ \Omega$ and for many cases, such a characteristic impedance

may be, determined by a specified microwave substrate, the minimum realizable impedance in practice.

Here, we mainly examine the frequency response based on the magnitude and phase imbalances. Figure 2 describes the above mentioned case, *ie* $L_1 = \lambda_g/64$, $Z = Z_0$ and $Z = 0.6Z_0$, respectively. Thus $L_2 = 17\lambda_g/64$, namely a constant length extension of a quarter wavelength to present 90° phase difference. From Fig. 2(a), it is seen that with reducing the characteristic impedance Z of the Stub 1, the magnitude fluctuation would be increased, while Fig. 2(b) shows this reduction can decrease the phase imbalance. This means to improve the phase imbalance, low impedance Z is preferable. Figure 3 illustrates the case for length L_1 is increased to a quarter wavelength while under the same conditions for $Z = Z_0$ and $Z = 0.6Z_0$. From these results, here one can see increasing L_1 can reduce the magnitude imbalance as shown in Fig. 3(a), thus broadening the operation bandwidth. Meanwhile, reducing L_1 also flats the phase responses as recorded in Fig. 3(b), where a smaller impedance Z again yields a flatter phase fluctuation.

Further, extensions the length L_1 to $3\lambda_g/8$ and $\lambda_g/2$ are respectively investigated as depicted in Figs. 4 and 5, where one can see the lower margin under the same magnitude imbalance would be shifted to higher frequencies for $L_1 = 3\lambda_g/8$ as compared to Figs. 4(a) and 5(a). How-

Fig. 6. Performance from simulations: (a) – return losses, (b) – insertion losses and magnitude imbalance, (c) – phase response and phase difference, (d) – port isolations

ever, the phase response could exhibit smaller fluctuation within a wider bandwidth, as compared to Figs. 4(b) and 5(b). This parameter sweeping study indicates the reference length L_1 of the inter-stage transmission line should be optimally and eclectically chosen, while the line impedance of the short-circuited Stub 1 should be low. It is mentioned that in this process, owing to only parameters L_1 , L_2 and Z being swept while the rest parameters being constant, the curves corresponding to $|S_{31}| - |S_{21}|$ and $\text{Ang}(S_{31}) - \text{Ang}(S_{21})$ in Figs. 2 to 5 are overlapped and always consistent. Based on the above study, L_1 and Z are set to $\lambda_g/2$ (thus $L_2 = 3\lambda_g/4$) and $0.6Z_0$ in the following design. Notice that this although yields an increased layout area, we are primarily based on the achieved electric performance, focusing on the comprehensive magnitude and phase imbalances.

4 Developing a 45° phase shifted four-way power division network with enhanced bandwidth

The microwave substrate utilized in this work has a relative permittivity of $\epsilon_r = 2.65$ with a thickness of $h = 1$ mm and a loss tangent of $\tan \delta = 0.005$ at 10 GHz. It is a double-sided copper plated PCB with a copper thickness of 0.018 mm for each side.

The design starts from a single stage coupled line division network with in-phase outputs. It has been shown that the use of coupled line to develop this kind of net-

work could facilitate the design flexibility in practice [19]. Consequently, we initially set each line of the pair of coupled line has a characteristic impedance of $2^{1/2}Z_0$, corresponding to the conventional case. With optimal electromagnetic analyses, its dimension is found to be the line width of 1.45 mm with the coupling gap of 0.55 mm.

Correspondingly, this could make the pair of coupled line having the even- and odd-mode characteristic impedances of $Z_{0e} = 86.48 \Omega$ and $Z_{0o} = 55.13 \Omega$, yielding the characteristic impedance $Z_0 = \frac{1}{2}(Z_{0e} + Z_{0o})$ for each line being 70.8Ω that is very close to $2^{1/2}Z_0$. Further, by extending the two outputs with different line length and introducing the quarter-wavelength short circuited Stub 2 shown in Fig. 1, 45° phase shift is achieved between the two outputs, where $L_3 = 12.82$ mm, $L_4 = 21.52$ mm. Stub 2 (the same for Stub 3) is placed at 5.78 mm away from the output node of the coupled line and has a line width of 2.7 mm with its length of 16.96 mm. The short circuit is realized by a metal interconnection hole to the ground with a radius of 0.6 mm. One can see the length difference between L_3 and L_4 is 8.7 mm, corresponding to $\lambda_g/8$, thus presenting 45° phase difference between ports 2 and 3 or ports 4 and 5.

With two stages in cascaded, a four-way division network with 45° phase shift is designed, where the inter-stage has the line length as studied in section 3, that is $L_1 = 34.96$ mm and $L_2 = 52.44$ mm, corresponding to $L_1 = \lambda_g/2$ and the difference between L_1 and L_2 being $\lambda_g/4$. Meanwhile, Stub 1 is placed at 17.48 mm away

Fig. 7. Performance from simulations: (a) – return losses, (b) – insertion losses and magnitude imbalance, (c) – phase response and phase difference, (d) – port isolations

from the output node of the coupled line and has a line width of 5.5 mm (corresponding to $0.6Z_0$) with its length of 16.42 mm.

Figure 6 shows the achieved performance from electromagnetic simulations, where the simulator is the use of Ansoft Ensemble 8. The return losses are plotted in Fig. 6(a), where it is seen within a wideband from less than 2.5 GHz to over 4 GHz, they are better than 10 dB for all ports. Fig. 6(b) records the insertion losses and magnitude imbalances at all outputs; referred to a magnitude imbalance of 0.5 dB could yield a frequency range from 2.45 GHz to 3.8 GHz. The phase responses and phase difference are given in Fig. 6(c); one can see flat phase responses are observed, again, from 2.45 GHz to 3.8 GHz under a fluctuation of $\pm 5^\circ$. Eventually, the isolation performance among all outputs is described in Fig. 6(d); it is found from 2.3 GHz to 3.8 GHz, the isolations are all better than 15 dB. These results indicate the developed division network works well within a wide frequency band.

5 Experimental validation of a fabricated prototype network

The above developed network is further fabricated for experimental examination its electric performance. Shown in Fig. 1(b) is the photograph of the fabricated prototype demonstrator. The measurements are carried

out by using Agilent N9918A vector network analyzer with full two-port calibrations. Fig. 7 presents the performance from measurements, where referred to Fig. 6, Fig. 7(a) shows the return losses for all ports, while the insertion losses and magnitude imbalance are displayed in Fig. 7(b). Figures 7(c) and (d) respectively illustrate the phase responses along with the phase imbalance as well as the port isolations.

From measurements, it is found the return losses are better than 10 dB in the band of from 2 GHz to 4 GHz as recorded in Fig. 7(a). The insertion losses are generally 6.4 dB with ideal values of 6 dB for one-to-four ways. It is observed that from 2.55 GHz to 4.15 GHz, the magnitude imbalance is within 0.5 dB. Also, Fig. 7(b) indicates the center operation frequency from measurements is slightly shifted to the higher frequency; this could be attributed to fabrication uncertainty. The measured phase difference shown in Fig. 7(c) reveals that within a wide frequency band, the phase response is flat, where referred to a fluctuation of $\pm 5^\circ$, it is found the band covers from 2.08 GHz to 4.02 GHz. Hence one can find the common frequency band is ranged from 2.55 GHz to 4.02 GHz under the given magnitude and phase imbalances of 0.5 dB and $\pm 5^\circ$, respectively. Finally, the port isolation, as illustrated in Fig. 7(d), shows better than 15 dB within the band of interest.

The measurements show good agreement with the simulations, as compared with Fig. 6. These results again in-

dicating the developed demonstrator behaves good performance, and the presented design methodology is effective.

6 Conclusions

A wideband four-way power division network is studied in this contribution, where special focus lies in the inter-stage transmission line for 90° phase difference and its phase compensation technique. Studies show a lower line impedance of the phase compensation stub and a proper line length at the reference output could yield a wider operation bandwidth. In this study, a line impedance of $0.6 Z_0$ for the compensation stub and a line length of $\lambda_g/2$ for the inter-stage transmission line are found to achieve optimally comprehensive performance. Experiments for the fabricated prototype demonstrator validate the study well. It is believed the developed network can be served as the feeding network of related antenna array for wideband operations.

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