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A NOVEL DECOUPLING NETWORK USING PARALLEL COUPLED LINES FOR INCREASING THE PORT ISOLATION OF TWO COUPLED ANTENNAS

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Abstract—A compact decoupling network for enhancing the ports isolation of two coupled antennas is proposed in this letter. Parallel coupled lines (PCLs) and transmission lines (TLs) with different electrical lengths are considered to control the magnitude and phase of this decoupling network, respectively. The coupling coefficient of the PCLs is adjusted with various line widths and coupled gaps so that the magnitude of this network will be equal to that of the coupled antennas. And the electrical length of the series TLs can be controlled to make the signals of coupled antennas and decoupling network out of phase. Thus, the mutual coupling between the coupled antennas can be canceled. A prototype is fabricated on a RO4003 print circuit board (PCB) for demonstration. The measured results agree quiet well with the simulation ones. High antenna isolation and good matching are simultaneously achieved at the center frequency, i.e., 925 MHz for global system mobile communications (GSM) which shows the compact decoupling network is suitable for reducing the isolation of size limited multi-antenna systems.

1. INTRODUCTION

Adaptive beamforming exploits the degrees of freedom available in multiple-antenna systems to adapt to the mobile communications environment and to improve the quality and availability of the transmission link. At the same time, traditional smart antenna systems

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are continuing in demand of array modules with lower costs in smaller and lighter formats. However, the major limitation for conventional arrays used in these systems of multi-antenna architecture is that the element spacing is usually around half a wavelength to avoid mutual coupling. If the spacing between radiators is reduced below half a wavelength, for applications in mobile terminals for instance, mutual coupling effects considerably decrease the antenna gain for certain "super directive" excitations [1]. Recently, many reports have been focused on diminishing the coupling of antennas. In [2–5], consideration and effect of mutual coupling between antennas array was discussed. In [6], the relation of the isolation and the arrangement of two nearby antennas with different operating bands in a cellular handset were studied. Antennas with reactive load [7] wavelength resonators such as electromagnetic band gap (EBG) structures [8, 9] and defected ground structures (DGS) [10, 11] and; lumped components [12]. Mushroom-like EBG structures are the ones that are usually inserted between patch antennas to prevent the propagation of surface waves for higher isolation and better radiation patters [13–15]. These EBG structures provide conspicuous decoupling effect, but suffer from complicated structures and large structure area. In [16], a broadband decoupling network for two tightly coupled antennas was proposed using inserting a second-order coupled resonator filter network between the coupled antennas. A similar approach of connecting circuits between elements has also been used to improve the impedance matching of a phased-array antenna over wide scan angles [17] since mutual coupling may vary the input impedance in different scanning angle. Investigation of reduction of mutual coupling between two planar monopoles using two $\lambda/4$ slots was presented in [18] while a novel design of decoupling network for a compact three-element array was proposed in [19].

In this paper, the authors propose a compact decoupling network for enhancing the ports isolation of two coupled antennas. Parallel coupled lines (PCLs) and transmission lines (TLs) with different electrical lengths are considered to control the magnitude and phase of this decoupling network, respectively. In Section 2, the theory of the proposed decoupling structure is presented. The required parameters of the network are derived based on the measured or simulated coupling coefficients of the closely coupled antennas. In Section 3, for predicting the radiation patterns of the coupled antennas, the equivalent circuit is constructed and analyzed. The S-parameters and phase of the network are designed to cancel the unwanted mutual coupling and; in Section 4, the measured results agree quiet well with the simulation ones. High antenna isolation and good matching are simultaneously achieved at the center frequency, i.e., 925 MHz for global system mobile communications (GSM) which shows the compact decoupling network is suitable for reducing the isolation of size limited multi-antenna systems. At last, a conclusion is given in Section 5.

2. DECOUPLING THEORY

The configuration of a decoupling network using PCL and TLs between two closely coupled antennas is illustrated in Fig. 1. Assuming perfectly matched ports, the power fed to port 1 can be dispensed through three ways. The first way is going through antenna and then radiates into free space, i.e., patch 1. The second way is flowing out to another antenna through the mutual coupling between two antennas, i.e., patch 2. And the third way is also flowing out to another antenna from the PCL, i.e., patch 3. With properly chose characteristics of the PCL and TLs, the undesired mutual coupling due to patch 2 can be mitigated by the power transformed from patch 3.

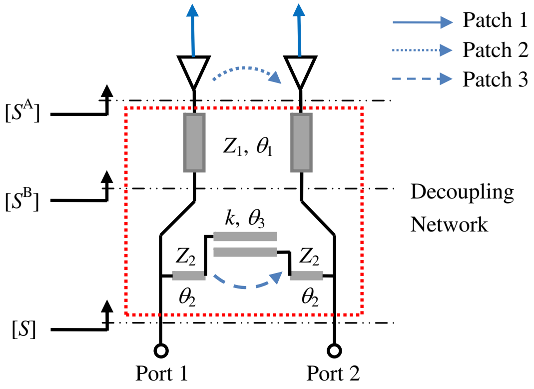


Figure 1. The functional blocks of the proposed decoupling network using PCL and TLs.

In this work, a dual antennas system with good input impedance matching but poor isolation is first assumed as shown in Fig. 1. For simplicity, the antennas are symmetrical to each other and the input impedances are matching well. Then, a four ports decoupling network is proposed, with two output ports connected to the antennas with loaded TLs for matching and two ports connected with port 1 and port 2 with shunt PCL for reducing the mutual coupling. The scattering matrix of the coupled antennas can be denoted as

$$\left[S^A\right] = \begin{bmatrix} 0 & \alpha e^{j\phi} \\ \alpha e^{j\phi} & 0 \end{bmatrix} \tag{1}$$

where α and ϕ are the magnitude and phase of the coupling coefficient between coupled antennas. After adding a TL to each antenna, the insertion loss remains infinite while the coupling coefficient experiences an extra phase delay of $2\theta_1$. Thus, the scattering matrix can be replaced as

$$\left[S^B\right] = \begin{bmatrix} 0 & \alpha e^{-j(2\theta_1-\phi)} \\ \alpha e^{-j(2\theta_1-\phi)} & 0 \end{bmatrix} \tag{2}$$

Once this scattering matrix is known, the corresponding admittance matrix $[Y^B]$ can be easily derived [20]. And then, the admittance matrix $[Y]$ of the input port 1 is equal to

$$[Y] = \left[Y^B\right] + \left[Y^{\mathrm{PCL}}\right] \tag{3}$$

where Y^{PCL} is the admittance matrix of the two ports network composed of parallel coupled lines and transmission lines (patch 3). The components of the scattering matrix $[S]$ are related to these components through the following formulas [21]:

$$S_{21} = \frac{-2Y_{21}Y_0}{Y_0^2 + 2Y_{11}Y_0 + Y_{11}^2 - Y_{21}^2} \tag{4a}$$

$$S_{11} = \frac{Y_0^2 - Y_{11}^2 + Y_{21}^2}{Y_0^2 + 2Y_{11}Y_0 + Y_{11}^2 - Y_{21}^2} \tag{4b}$$

where Y_0 represents the characteristic admittance of the input ports. Since our purpose is to eliminate the coupling of the two ports, the coupling coefficient S_{21} should be zero. Thus, the required S-parameters of the PCL can be obtained and the electrical length θ_2 and θ_3 can be adjusted to control the phase while the coupled coefficient k of the PCL can be employed to control the magnitude, respectively.

3. DESIGN AND DISCUSSION

A practical example is presented as shown in Fig. 2 to demonstrate the advantages of the proposed decoupling network.

In this network, port 1 and port 2 are used as the input ports while port 3 and port 4 connect with two coupled antennas. As above analysis, the magnitude and phase of this network can be determined by the scattering matrix $[S^A]$ of the closely coupled antennas.

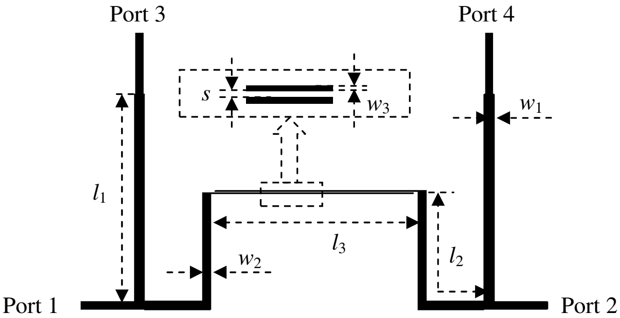


Figure 2. Layout of the proposed decoupling network.

3.1. Magnitude Control

Figure 3 plots a basic circuit of parallel coupled lines, where Z_{oe} and Z_{oo} are the even-mode and odd-mode impedance, and θ_3 denotes the electrical length. For $\theta_3 = \pi/2$, we obtain

$$\begin{cases} \dfrac{Z_{oe}}{Z_0} = 1 + \left(\dfrac{Z_0}{k}\right) + \left(\dfrac{Z_0}{k}\right)^2 \\ \dfrac{Z_{oo}}{Z_0} = 1 - \left(\dfrac{Z_0}{k}\right) + \left(\dfrac{Z_0}{k}\right)^2 \end{cases} \tag{5}$$

where Z_0 is the characteristic impedance and k the coupling coefficient of the coupled lines. Then, the insertion loss of the PCLs can be controlled by the coupling coefficient k, as shown in Fig. 4. When the coupling coefficient k of the PCL increases from 0.1 to 0.5, the insertion loss will be also increase from −10 dB to almost 0 dB. Then, the magnitude of this network will be controlled by the strip width and gap width of the PCL. Shown in Table 1 is the relationship between the physical parameters and coupling coefficient of the PCL. The network is fabricated on a substrate with dielectric constant of 3.38, loss tangent of 0.0027, and thickness of 0.8 mm.

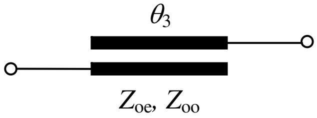


Figure 3. Equivalent circuit of parallel coupled lines.

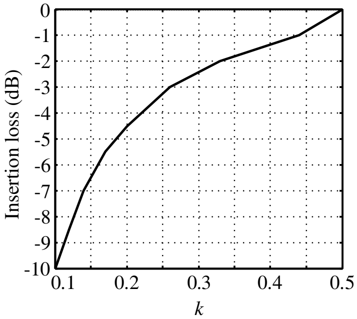


Figure 4. Insertion loss of the PCL versus different coupling coefficient k.

Table 1. Relationship between the physical parameters and coupling coefficient.

w_3 (mm)	0.2	0.3	0.2	0.3
s (mm)	0.1	0.2	0.3	0.4
Z_{oe} (Ω)	195	160	176	149
Z_{oo} (Ω)	62	68	86	82
k	0.52	0.40	0.34	0.28

3.2. Phase Control

In this work, both magnitude and phase of the decoupling network are important factors for us to improve the isolation of the closely coupled antennas, as shown in Eq. (1)–Eq. (4). The equivalent circuit of the coupled line is plotted in Fig. 5.

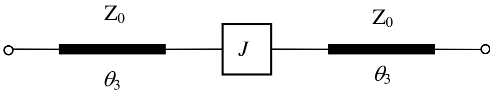
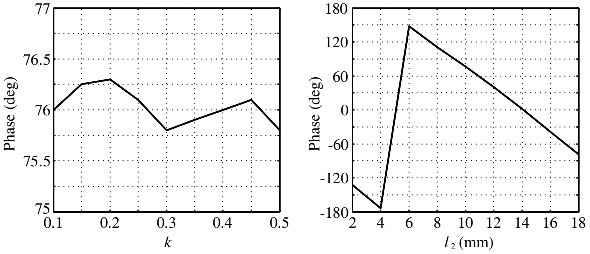


Figure 5. Equivalent circuit of the PCLs.

When the electrical length of the PCL is set as $\pi/2$ at the center frequency, the phase is also fixed and it will keep unchanged with different k, as show in Fig. 6(a). So, another two transmission lines are loaded in this decoupling network to control the phase, as shown in Fig. 6(b).



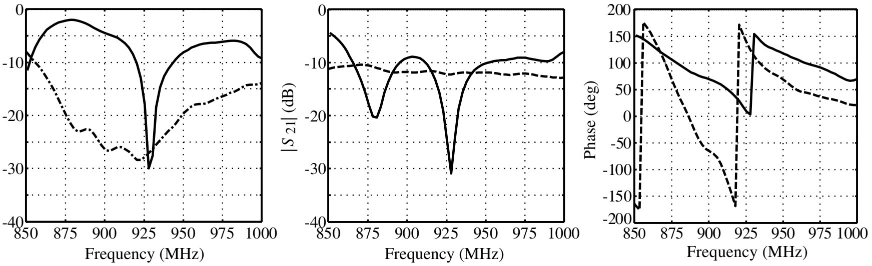
(a) (b)

Figure 6. Change of phase versus (a) coupling coefficient of the PCL and (b) length of the TL.

As analyzed in this section, both the magnitude and phase of the decoupling network can be controlled by the PCL and TL respectively to make formula (4a) equal to zero. By this way, the insolation of the closely coupled antennas will be improved.

4. RESULTS

A practical model is fabricated with $l_1 = 48.7\,\mathrm{mm}$, $l_2 = 39.1\,\mathrm{mm}$, $l_3 = 48.8\,\mathrm{mm}$, $w_1 = 2.4\,\mathrm{mm}$, $w_2 = 2.0\,\mathrm{mm}$, $w_3 = 0.4\,\mathrm{mm}$, and $s = 0.3\,\mathrm{mm}$. In this example, a pair of printed antennas both operated at 925 MHz are placed closely to each other. A compact decoupling network is then designed and inserted between the two antennas for decoupling and matching. The measured results of the coupled antennas with and without proposed decoupling network are shown in Fig. 7. The mutual coupling of two closely coupled antennas is about $-12\,\mathrm{dB}$ at the center frequency with no decoupling network loaded.



(a) (b) (c)

Figure 7. Measured (a) $|S_{11}|$, (b) $|S_{21}|$ and (c) phase of two closely coupled antennas with (—) and without (- - -) the decoupling network.

And after the proposed circuit inserted, the insertion loss is improved to be more than −30 dB while the return loss is kept about unchanged which shows the compact decoupling network is suitable for reducing the isolation of size limited multi-antenna systems. In Fig. 7(c), the phase of the closely coupled antennas is plotted. Obviously, the phase is about 0 deg at the resonant frequency (925 MHz) when the proposed decoupling network is loaded. A photograph of the antennas used in this work is proposed in Fig. 8(a) while the decoupling network loaded between two coupled antennas is shown in Fig. 8(b).

(a) (b)

Figure 8. Photographs of (a) antennas used in this work and (b) the proposed decoupling network.

5. CONCLUSION

In this work, a decoupling network using parallel coupled lines and transmission lines for improving the isolation of two closely spaced antennas of the same frequency is proposed. The decoupling network is simple and compact, which contains a pair of coupled lines and two transmission lines for impedance matching. The insertion losses between the coupled antennas were greatly improved from 12 dB to more than 30 dB at the center frequency while the input return losses remained better than 25 dB. Its experiment characteristics are in good agreement with theoretical analysis validating a simple approach of decoupling network design.

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