Eigenmodal Feed Based Decoupling Network for Two Ports MIMO and Diversity

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***Abstract*—A decoupling network based on the excitation of the orthogonal patterns of the chassis wavemodes is presented. The coupling to the chassis wavemodes is mainly depends on the coupling element shape and position on the chassis. A two coupling element are optimized and placed on the short ends of 100mm×40mm chassis where the odd and even modes of the chassis major axis are strongly coupled. A modal feed network is presented to excite the odd and even chassis modes with their corresponding eigenvectors. The presented modal feed network provides an isolation of more than 20 dB between the two ports antenna system. External matching circuit is designed to match each of the chassis wavemodes impedance to the 50 ohm.**

Keywords—chassis wavemodes; coupling element; decoupling network; matching circuit; port isolation.

I. Introduction

In Multiple Input Multiple Output system (MIMO), the use of multiple antennas can result in an enhancement with respect to the capacity and data rate. Multiport antenna systems usually have the design goal of port isolation and pattern diversity. Applications, where the available space is limited like in current mobile handsets, result in a strong mutual coupling between antenna ports. The demand of antenna design for MIMO goes towards the coupling element-based antennas structure, where the chassis is the main radiator mainly at low frequencies. In coupling element-based antennas; the coupling element is a non-resonant antenna used to excite the chassis wavemodes through coupling to the electric field (capacitive coupling) or to the magnetic field (inductive coupling) [1]. In [2-4], the performance of coupling element-based antennas was analyzed by decomposing the structure into two resonant wavemodes; the antenna wavemode and the chassis wavemode. At frequency range around 1 GHz the chassis is the main radiator, while at 2 GHz frequency range; the contribution of the coupling element to the total radiation increases [4]. Above 3.1 GHz, the relative bandwidths obtained with an infinite ground plane and a 100mm×40mm chassis approach each other (the chassis dimensions electrically approach infinite ground plane) [5]. The impedance bandwidth is affected by the chassis length. In [2], the effect of the ground plane length on the impedance bandwidth (6 dB bandwidth) of a shorted patch antenna was studied at 900 MHz and 1800 MHz. The bandwidth of a coupling element-based antenna can be improved by enhancing the coupling to the dominant characteristic modes of the chassis [6]. For efficient coupling to the chassis modes, the location and shape of the coupling element have to be chosen suitably [5, 7]. For electric field coupling, the optimal location for a properly shaped coupling element on a rectangular chassis was found to be at the corner and short ends of the ground plane, where the electric field of the chassis resonant mode has its maximum. The theory of characteristic modes for conducting bodies was applied to investigate the optimal location of a coupling element on the chassis of a mobile phone [8, 9]. In this work two different models of two ports antenna systems are proposed for MIMO applications and diversity systems. The capacitive coupling elements dimensions and locations are optimized for strong coupling mainly to the odd (half-wavelength) and even (full-wavelength) modes of a 100mm×40mm chassis major axis. Modal feed network is designed to isolate the antenna ports. The concept of modal feed network is based on the decoupled the antenna ports by feeding the structure with the orthogonal eigenvectors of the array for the case of infinite ground [10] or by feeding the structure with the orthogonal eigenvectors of the chassis modes for the case of mobile terminals [11,12]. The isolated ports are matched to the 50 ohm using external matching circuit.

II. Theoritical Background

In coupling element based antenna, the chassis is considered as the main radiator which is excited via coupling element. In this work, a capacitive coupling element to couple to the electric field of the chassis modes is used. In [13], the characteristic mode theory was applied to analyze a wire grid model of a 100 mm x 40 mm conducting plate. The half- and full-wavelength resonant frequencies of the chassis major axis and the half-wavelength resonant frequency of the chassis minor axis were found as 1.26, 2.68, and 2.74 GHz and their respective radiation quality factors values are 2.3, 3.0, and 2.5. In order to selectively excite the chassis modes, suitable couplers arrangement on the chassis and their excitation phases should be optimized [14]. For our two port antenna system, two capacitive coupling elements (CCE) are placed at the middle point of the short chassis ends for selective excitation to the half-wavelength and full-wavelength chassis modes of the major axis Fig.1. In [11,12], for a selective excitation of the characteristic modes of the chassis near to their resonant frequencies, an arrangement of two and four capacitive coupling elements and a modal feed network has been proposed. A 180° hybrid based feed network was used to feed the structure by the eigenvectors of the selected chassis modes excitation. For the two port antenna system in Fig.1, the off-diagonal elements of the scattering matrix represent the mutual

978-1-4799-3662-5/14/$31.00

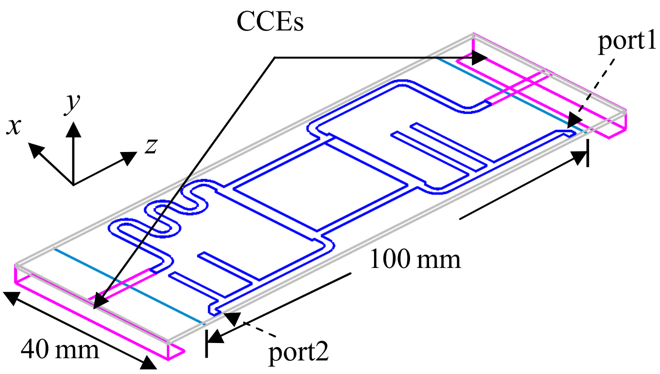


Fig. 1. Geometry of a two port center feed antenna structure.

coupling between ports. The S-parameters of combined feed network and two ports antenna system are given by

$$\begin{aligned} S^c &= U^t S U \\ &= \mathrm{diag}[\lambda_h, \lambda_f] \end{aligned} \quad (1)$$

where S is the symmetric scattering matrix for the two ports antenna system, and the unitary matrix U is the orthonormal eigenvectors of S

$$U = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \quad (2)$$

The two-column vectors of U represent the excitation vectors for the half- and full-wavelength characteristic current modes of the chassis with related excitation eigenvalues denoted by λ_h, λ_f respectively($\lambda_h = S_{11} - S_{12}, \lambda_f = S_{11} + S_{12}$). Exciting with the eigenmodes of the chassis, due to their orthogonal nature this results in an isolated ports ($S^c_{ij} = 0, \text{for } i \neq j$) but mismatched ($S^c_{ii} \neq 0$). External matching network is required to match each port to the 50 ohm individually. The modal feed network that is required to generate the orthogonal eigenmodes of the chassis should have the scattering matrix S^m described in a block matrix notation by

$$S^m = \begin{bmatrix} 0 & U^t \\ U & 0 \end{bmatrix} \quad (3)$$

where U is defined in (2). Substituting (2) in (3) gives

$$S^m = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{bmatrix} \quad (4)$$

The modal feed network required for the two port antenna system in Fig.1 may simply be modeled as a 180° hybrid. The CCEs are off-ground elements with a ground clearance of 10 mm; the off-ground antenna element provides better matching to 50 ohm at the design frequency (1800 MHz for our design) than the on-ground element [15, 16]. The dimensions of the whole structure are $120 \times 40 \times 5\,\mathrm{mm}^3$. The CCE is bent from the top for better coupling to the chassis modes. The 180° hybrid of the modal feed network is replaced by a branch line coupler with extra phase shift of 90 degree between its output ports to excite in phase corresponding to the even chassis mode and 180° out of phase corresponding to the odd chassis mode eigenvectors. The S-parameters of the two port antenna with and without the modal feed network are presented in Fig.2. Good port isolation of more than 20dB between antenna ports at 1.8 GHz is obtained. The modal feed network presented here supports pattern diversity between the chassis modes radiation patterns. Same concept could be applied for pattern diversity between array eigenmodes radiation patterns of infinite ground [10].

III. Different Two Ports Antenna Configurations

The modal feed network in section II provides decoupled antenna ports by feeding the structure with the first two orthogonal eigenvectors of the chassis. External matching network then is required to match the two ports to the 50 ohm. Matching over a wider frequency band is proportional to the number of lumped elements in the matching circuit; if an L-section matching circuit is chosen, then multiple L-sections are required for sufficient frequency band. In Fig.3, the potential bandwidth for a single CCE placed at the middle of the short end of a 100mm×40mm chassis is plotted as a function of the number of lumped elements in the external matching circuit at 0.9 GHz and 2.2 GHz. In [12], the authors aim to solve for wider impedance bandwidth by modifying the ground plane. Slots with optimized widths and lengths were created in the ground for better frequency band. Modification in the ground plane will modify the modes current distributions of the chassis which in turns modify the corresponding radiation patterns of the chassis modes. In this work, a comparison between two different configurations of two ports antenna with respect to the ports isolation and radiation patterns is presented. In A the case of slotted ground plane with a single stub as an external matching circuit is considered, while in B slots in the ground plane are replaced by more complicated external matching circuit realized in microstrip lines as a double stub.

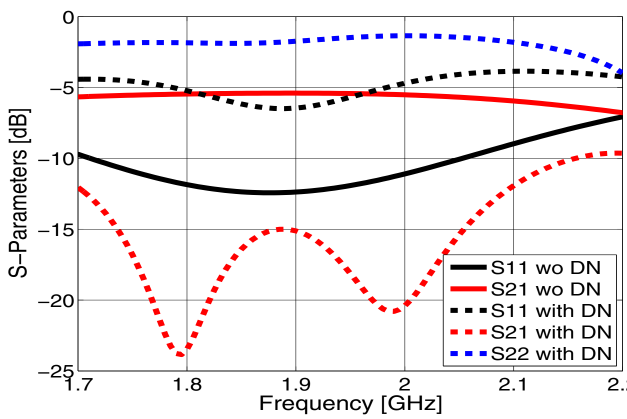


Fig. 2. S-parameters of the two ports antenna system in Fig.1 with and without a modal feed network.

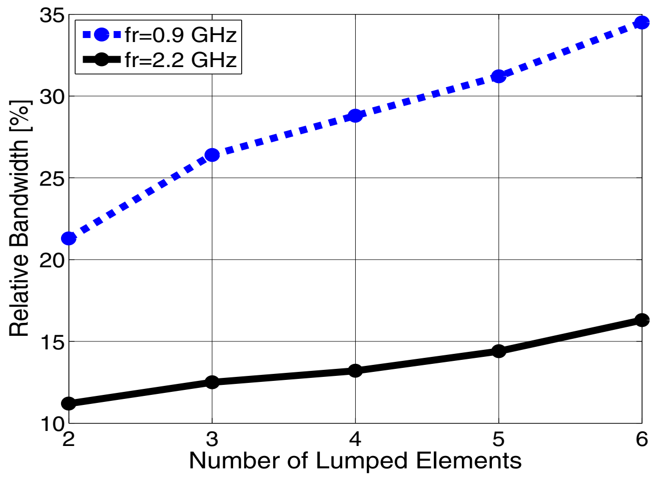


Fig. 3. Relative bandwidth vs number of lumped elements in the external matching circuit.

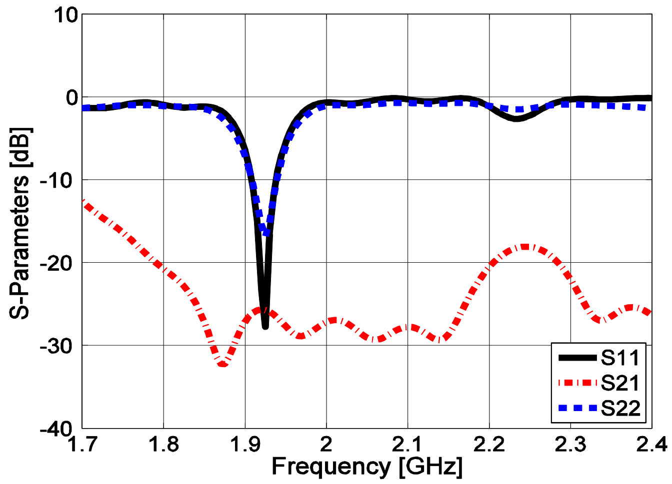


Fig. 4. S-parameters of the two ports antenna system with a slotted ground plane and a single stub as an external matching circuit.

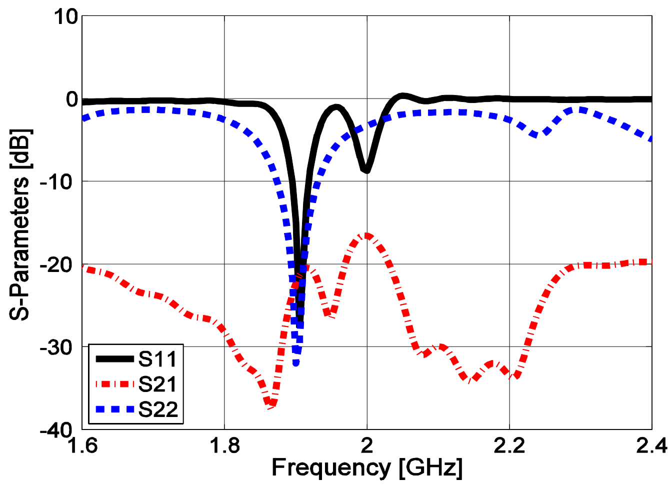


Fig. 5. S-parameters of the two ports antenna system with a double stub matching circuit configuration.

A. Two Ports Antenna with Slotted Ground Plane

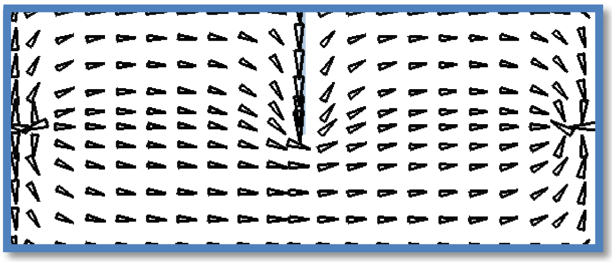
In this two ports antenna configuration; four slots with 1 mm width are made in the ground plane; two slots of 0.05 λ length are created at the middle of the chassis long edges, while two slots of 0.21λ length are created at the middle of the chassis short edges. The CCEs are off-ground elements with a ground clearance of 13.5 mm. The dimensions of the whole structure are $127\times40\times6\,mm^3$. A single stub matching circuit is designed to match the ports to the 50 ohm impedance. The single stub position and length for each port, the ground clearance of the CCEs, the CCEs height, and the slots length are all optimized for good matching and port isolation at 1.91 GHz. Matched and isolated ports of more than 20 dB at 1.91 GHz is obtained Fig.4.

B. Two Ports Antenna with Double Stub Matching Circuit

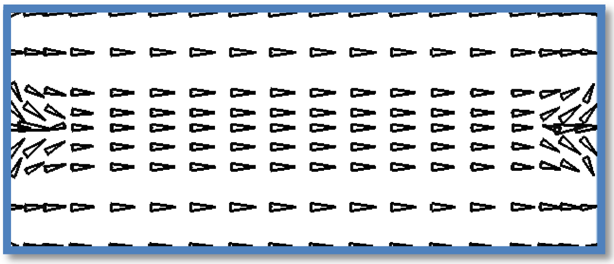
In this two ports antenna configuration the four slots in the ground plane in A are replaced by a double stub external matching circuit to match the antenna ports to the 50 ohm. The CCEs are off-ground elements with a ground clearance of 10 mm. The dimensions of the whole structure are 120×40×4 mm^3. The double stub position and length for each port, the ground clearance of the CCEs, and the CCEs height are all optimized for good matching and port isolation at 1.90 GHz. Matched and isolated ports of more than 20 dB at 1.90 GHz is obtained Fig.5.

In configuration A, creating slots in the ground plane easily match to the 50 ohm impedance through modifying the current distributions of the chassis modes. Slots lengths, widths, and positions are optimized so that the odd and even modes resonances are matched. For comparison, the current distribution of the odd chassis mode with and without a slot at the middle point of the chassis long edge is shown in Fig.6. Creating a slot changes the current path for the odd mode; the mode resonance is a function of the slot length. For the even chassis mode, its resonance is not a function of the slot length at the middle of the chassis long edge. While the odd and even modes resonances are a function of the slot length at the middle of the chassis short edge. In B, the slots are replaced by a multiple resonances external matching circuit. The radiation patterns of the odd and even chassis modes for the two ports antenna with and without a slotted ground plane are presented in Fig. 7 and 8 respectively. With respect to the elevation pattern, the creation of slots in the ground plane does not any more keep the symmetry for the odd and even chassis modes, while for azimuth pattern, the odd mode pattern becomes more directive. For the two configurations, the correlation coefficient gives a good indication to describe the diversity performance of the two ports antenna for MIMO. The correlation coefficient can be calculated from the three dimensional complex far field radiation patterns or from the scattering parameters if an isotropic environment is assumed. In [17], the envelope correlation coefficient is derived and computed from the scattering parameters of the system as

$$\rho_e = \frac{\left|S_{11}^{*}S_{12} + S_{21}^{*}S_{22}\right|^2}{\left(1-\left|S_{11}\right|^2-\left|S_{21}\right|^2\right)\left(1-\left|S_{22}\right|^2-\left|S_{12}\right|^2\right)} \qquad (5)$$



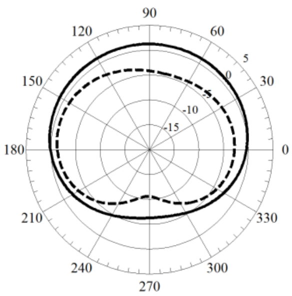
(a)



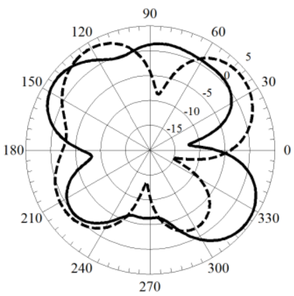
(b)

Fig. 6. Current distribution of the odd chassis mode (a) with and (b) without a slot at the middle point of the chassis lone edge.

The envelope correlation coefficient calculated from (5) for the two port antenna with a slotted ground is $1.067e^{-4}$, while for the two ports antenna with a double stub matching circuit, the calculated envelope correlation coefficient is $9.157e^{-7}$. Scattering parameters used in (5) are obtained from EM simulation. In real environment, the correlation coefficient will be higher. Anyway it gives a good indication for the diversity performance of the system.

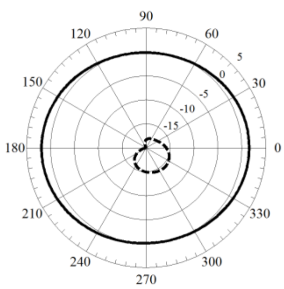


(a)

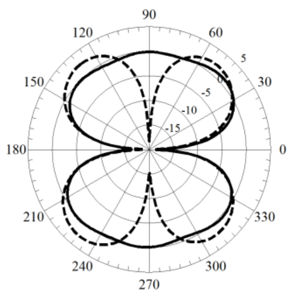


(b)

Fig. 7. Radiation patterns of the odd (solid) and even (dash) chassis modes for the two ports antenna with a slotted ground configuration. (a) H-plane, and (b) E-plane. All pattern cuts are with respect to the axis given in Fig.1.



(a)



(b)

Fig. 8. Radiation patterns of the odd (solid) and even (dash) chassis modes for the two ports antenna with a double stub matching circuit configuration. (a) H-plane, and (b) E-plane.

In both configurations, a narrow frequency band is obtained due to the low input resistance of the coupling element. Microstrip line realization of the matching circuits also yields in a narrow frequency band. Bandwidth enhancement could be obtained by optimizing the CCE dimensions in comparable to the chassis dimensions for the purpose of high input resistance of the CCE. On the other hand multi stages matching circuit of high-Q reactive elements instead of distributed elements can compensate for a narrow frequency band.

IV. EXPEREMENTAL RESULTS

The two configurations in A and B are fabricated on RO4003 substrate of thickness 0.813mm, dielectric constant $\varepsilon_r = 3.38$, and loss tangent 0.0027. The CCE are made from copper plate of thickness 100 μm. The decoupled ports for the two ports antenna configuration in A are matched to the 50 ohm with a single stub, while in B a double stub matching circuit is used. The fabricated whole structure for both configurations A and B with a decoupling and matching circuits are shown in Fig.9 and 10 respectively. Measured scattering parameters for the two ports antenna system with and without a slotted ground plane are shown in Fig.11 and 12 respectively. An isolation of around 20dB is obtained for the two ports antenna system without a slotted ground plane.

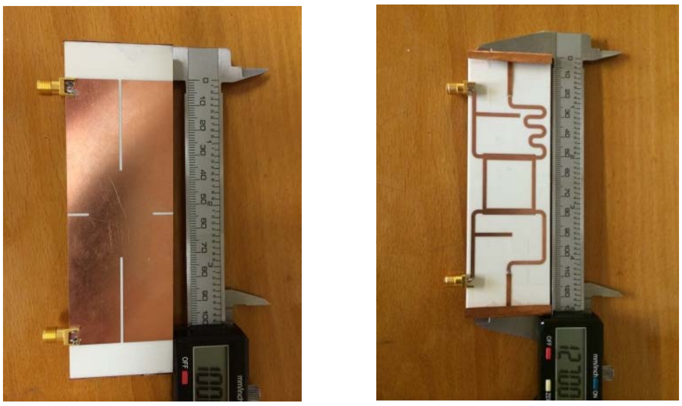


Fig. 9. Top and bottom side view for the two ports antenna configuration in A with a slotted ground and a single stub matching circuit.

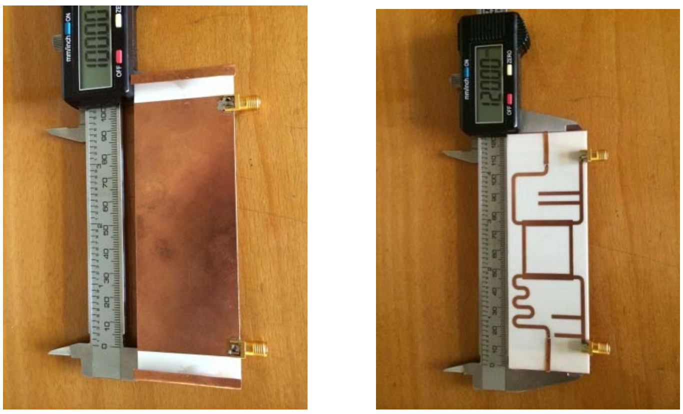


Fig. 10. Top and bottom side view for the two ports antenna configuration in B with a double stub matching circuit.

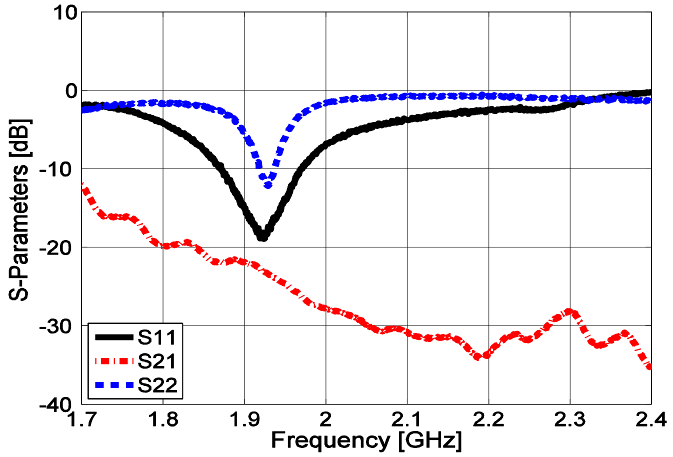


Fig. 11. Measured S-parameters for the two ports antenna configuration in A with a slotted ground plane.

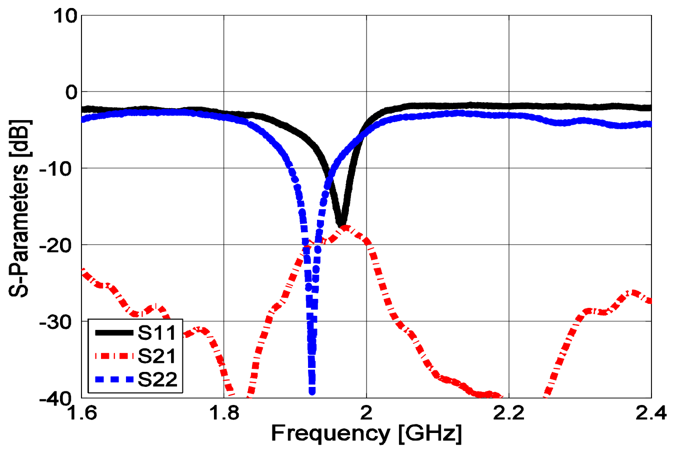


Fig. 12. Measured S-parameters for the two ports antenna configuration in B without a slotted ground plane.

An isolation of around 20dB is obtained for the two ports antenna without a slotted ground plane. The measured S_{22} and S_{21} are in a good agreement with the simulated ones. The resonant frequency for S_{11} is a little bit shifted from 1.90 GHz due to load the chassis ends ,where the odd chassis mode is strongly coupled, with a coaxial cables for feeding the structure. For the slotted ground configuration, an isolation of more than 20 dB is obtained over a wide frequency range. The shift in the resonant frequency for S_{11} is compensated by modifying the external matching circuit for port 1 to be a double stub matching circuit instead of a single stub. With a double stub matching circuit for port 1 in addition to slots in the ground plane, a wider bandwidth is obtained compared to the two ports antenna in configuration B with respect to S_{11} .

CONCLUSION

In this paper, a modal feed based decoupling network for two ports antenna for MIMO and diversity systems is presented. The modal feed network provides an isolation of more than 20 dB around 1.9 GHz between the two ports antenna system. External matching circuit is designed to match each of the chassis modes to the 50 ohm. Two different configurations with and without a slotted ground plane are fabricated and compared. The scattering parameters and the radiation patterns for both are presented and discussed. Slots in the ground plane can easily match the chassis modes to the 50 ohm by changing the current distribution of the modes, which in turns modify the patterns of the chassis modes. In both configurations, an isolation of 20 dB is obtained at the design frequency.

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