DESIGN OF MULTI-PORT NETWORK UTILIZING MICROSTRIP-SLOT TECHNIQUE FOR ULTRA WIDEBAND SYSTEM

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ABSTRACT

Nowadays, there is a lot of interest on the research and development related to ultrawideband system due to the increasing demands on the applications with low power, low cost and low interference. Thus, to cope with these demands, various researches are required for the development of front-end microwave components, which include six-port network as an alternative to a mixer-based design. The configuration of a six-port network is constructed by combining coupler and power divider. In the interest to have a simple design and convenient usage to form the six-port network with ultra wideband (UWB) operation, new power divider and coupler are designed by using microstrip-slot technique. All the proposed designs are simulated via the use of CST Microwave Studio 2010 and realized using Rogers TMM4 with a conductor coating of 35 µm, thickness of 0.508 mm and dielectric constant of 4.5. The developed prototypes of the proposed designs are verified by measurement using a vector network analyser (VNA). In this thesis, a design of two-section power divideris proposed with a great UWB performance of -3.8 dB ± 0.5 dB transmission coefficient and 0º ± 2º phase difference. This power divider has bandwidth improvement of 11.9% and size reduction of 23.33% compared to the conventional design. Meanwhile, for the coupler design, a UWB coupled-line coupler with zig-zag-shaped slot that has 3 dB ± 2 dB coupling coefficient and -90º ± 5º phase difference is proposed. The proposed coupler has 109.5% bandwidth improvement with the length reduction of 20% compared to the conventional coupler. The proposed UWB coupler is then implemented into a new proposed structure of UWB 90º power divider. Then, three configurations of six-port networks formed by UWB coupler, two-section power divider and 90º power divider are designed; which are named as Type I, Type II and Type III. From the observation, Type III demonstrates the best UWB performance with magnitude imbalance of ± 5 dB and phase imbalance of ± 10° that achieving the specified UWB design goal. Furthermore, Type III has the respective size reduction of 57.16% and 34.67% compared to Type I and II. In addition, by comparing to the previous works, the proposed design has broadest bandwidth of 100% and smallest size of 50.92 mm x 35 mm. Hence, the proposed six-port network has very well UWB performance with relatively compact size and simple design, which is easy to be fabricated.

ABSTRAK

Pada masa kini, terdapat banyak permintaan ke atas penyelidikan dan pembangunan yang berkaitan dengan sistem jalur lebar ultra (UWB) yang disebabkan oleh permintaan yang semakin meningkat terhadap aplikasi berkuasa rendah, kos yang rendah dan gangguan yang rendah. Oleh itu, untuk memenuhi permintaan ini, pelbagai penyelidikan diperlukan pada komponen gelombang mikro bahagian-depan, termasuk rangkaian enam-pangkalan sebagai alternative kepada reka bentuk berasaskan pencampur. Konfigurasi rangkaian enam-pangkalan dibina dengan menggabungkan pengganding dan pembahagi kuasa. Untuk memperolehi reka bentuk yang ringkas dan penggunaan yang mudah bagi membentuk rangkaian enam-pangkalan dengan operasi jalur lebar ultra (UWB), reka bentuk pembahagi kuasa dan pengganding yang baru telah direka dengan menggunakan teknik mikrojalur-alur. Kesemua reka bentuk yang dicadangkan disimulasi dengan menggunakan CST Microwave Studio 2010 dan dilaksanakan dengan menggunakan substratum Rogers TMM4 dengan 35 µm salutan konduktor, 0.508 mm tebal dan 4.5 pemalar dielektrik. Prototaip reka bentuk yang dicadangkan ditentusahkan dengan menggunakan Penganalisis Rangkaian Vektor (VNA). Di dalam tesis ini, reka bentuk pembahagi kuasa dua-bahagian yang dicadangkan mempunyai prestasi UWB terbaik dengan pekali penghantaran -3.8 dB ± 0.5 dB dan beza fasa 0º ± 2º. Pembahagi kuasa ini mempunyai 11.9% peningkatan jalur lebar dan 23.33% pengurangan saiz berbanding reka bentuk lazim. Manakala, bagi reka bentuk pengganding, pengganding UWB dengan menggunakan slot berbentuk zig-zag mempunyai -3 dB ± 2 dB pemalar gandingan dan -90º ± 5º beza fasa telah direka. Reka bentuk pengganding yang dicadangkan mempunyai 109.5% peningkatan jalur lebar dengan pengurangan panjang sebanyak 20% berbanding dengan reka bentuk lazim. Pengganding yang dicadangkan dilaksanakan ke dalam struktur baru pembahagi kuasa 90º UWB. Kemudian, tiga konfigurasi rangkaian enam-pangkalan direka daripada UWB pengganding, pembahagi kuasa dua-bahagian dan pembahagi kuasa 90º, dinamakan sebagai Jenis I, Jenis II dan Jenis III. Daripada pemerhatian, Jenis III menunjukkan prestasi UWB terbaik dengan ketidakseimbangan magnitud ± 5 dB dan ketidakseimbangan fasa ± 10^0 yang mencapai matlamat reka bentuk UWB yang ditentukan. Tambahan pula, Jenis III mempunyai 57.16% dan 34.67% pengurangan saiz berbanding Jenis I dan II. Di samping itu, dengan membandingkan reka bentuk yang sebelumnya, reka bentuk yang dicadangkan mempunyai lebar jalur yang paling luas sebanyak 100% dan saiz terkecil dengan 50.92 mm x 35 mm. Oleh itu, rangkaian enam-pangkalan yang dicadangkan mempunyai prestasi jalur lebar ultra yang sangat baik dengan saiz yang padat dan reka bentuk yang mudah untuk difabrikasi.

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LIST OF ABBREVIATION

WiFi	-	Wireless Fidelity
DAS	-	Distributed antenna system
MIMO	-	Multiple input multiple output
FCC	-	Federal Communication Commission
UWB	-	Ultra wideband
Q	-	Quadrature coupler
D	-	Divider
CST	-	Computer Simulation Technology
VNA	-	Vector network analyzer
E	-	Electric
H	-	Magnetic
TGV	-	Through ground via
NTL	-	Non-uniform transmission line
MLS	-	Method of least squares
DGS	-	Defect ground-slotted
PMGA	-	Parallel micro-genetic algorithm
VBA	-	Visual Basic for Applications
CRLH	-	Composite right-/left-handed
BCC	-	Broadside-coupled capacitor
MSI	-	Meandering short-circuited stub inductor
IF	-	Intermediate frequency
QPSK	-	Quadrature phase shift keying
QAM	-	Quadrature amplitude modulation
DF	-	Direction finding
PCB	-	Printed circuit board
PTFE	-	Polytetrafluoroethylene

LIST OF SYMBOLS

Z_{ms}	-	Impedance of microstrip-slot
W_s	-	Slot of width
Z_m	-	Microstrip-impedance
W_m	-	Width of conductor
H	-	Thickness of substrate
E_r	-	Relative permittivity
ε_e	-	Effective dielectric constant
L_m	-	Length of microstrip line
k_0	-	Wave number in free space
θ	-	Electrical length in degree
f	-	Cut off frequency
c	-	Velocity of light in free-space
v_p	-	Phase velocity
β	-	Propogation constant
Z_s	-	Impedance of slot
λ_0	-	Free-space wavelength
A_i and B_i	-	Unknown complex constants
V_i	-	Output voltage
$J_o(.)$	-	Zeroth-order Bessel function
k_0, k_1, k_2, k_{es} and k_{em}	-	Propagation constants
ε_{rem}	-	Microstrip effective dielectric constant
ε_{res}	-	Slot effective dielectric constant

Z_{QT}	-	Impedance of quarter-wave transmission lines
C_g	-	Fringe capacitances
C_p	-	Parallel-plate capacitance
N	-	The number of section of the quarter-wave transformer
Z_L	-	Load impedance
C_n^N	-	Binomial coefficients
λ_{m-s}	-	Microstrip-slot wavelength
Z_{0e} and Z_{0o}	-	Even- and odd-mode characteristic impedance
C	-	Numerical value of coupling factor
S	-	Spacing
F	-	Slow wave factor
C_e	-	Even-mode capacitance
C_o	-	Odd-mode capacitance
v_p	-	Phase velocity of the propagation on the line
S_i	-	Emerging complex signal

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CHAPTER 1

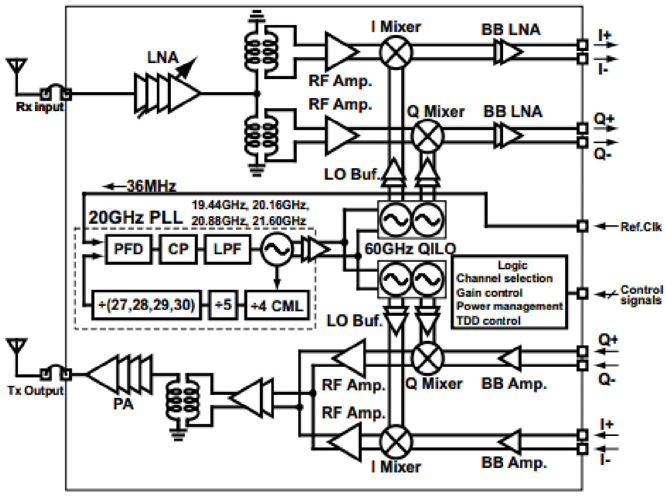
INTRODUCTION

1.1 Research Background

An unlicensed low power spectrum of ultra wideband (UWB) covering from 3.1 to 10.6 GHz has been specified by Federal Communication Commission (FCC) in 2002 [1] [2]. It has given an high impact to the communication sector due to its benefits and attractive features. FCC in [2] defines ultra wideband (UWB) as a fractional bandwidth that greater than 0.25 or occupies 1.5 GHz or more frequency spectrums. The minimum 1.5 GHz bandwidth is relevant only when the centre frequency is higher than 6 GHz. The Commission has authorized frequency band of 3.1 to 10.6 GHz for radar and wireless communication applications, which the major standards for wireless local area networks (LANs) are specified by IEEE 802.11 family standards and the smaller-scale standards based on ultra-wideband (UWB) communication. Since then, rapid development had been conducted parallel to the technology invented nowadays. Thus, due to that, low power, low cost, and low interference have been the requirements in UWB system. One of the interests is on six-port network.

A six-port network, or in more general case also known as, multi-port provides an alternative method to determine the complex voltage ratio of two signals [3] by performing mathematical transformations on power values measured at the output ports. This multi-port network is build from N-port networks, where the N should be greater than 5, equipped with scalar power detectors at its output ports. Where, the multi-port network is extensively implemented in many applications such as microwave parameter measurements [4], [5], [6], phase detectors in positioning systems [7], [8], [9], modulators and demodulators [10]-[11] in radar system [12]-[13] and wireless communications [14].

In order to support the requirement such in wireless communication system, various thorough research works are needed in component designs including alternative to mixer. Commonly, the design of mixer will involve active device, which needs a certain biasing voltage to be in an active state. In order to reduce the complexity of the design, the mixer-based approach can be replaced by using a six-port network in transceiver system particularly as modulator and demodulator as shown in Figure 1.1 [15]. A six-port, is formed by only using passive devices such as coupler, H-hybrid, and power divider [16]. By including these devices, it can reduce the complexity of the design and increase the performance of bandwidth.



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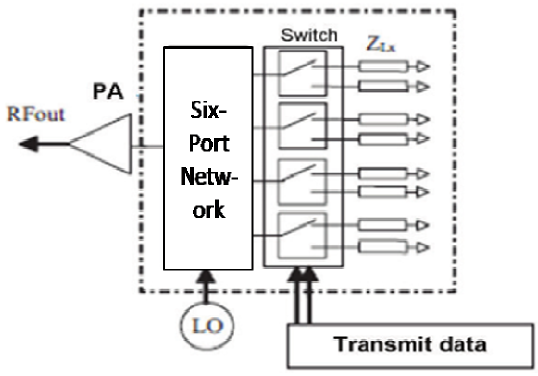

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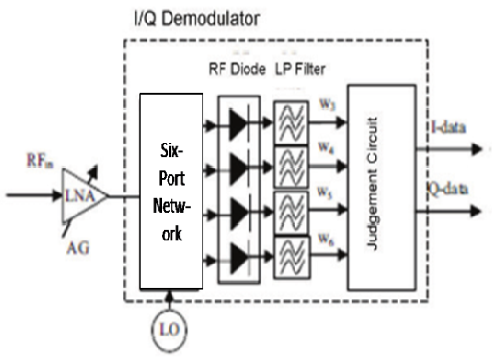

(c)

Figure 1.1 Block diagram of (a) conventional transceiver with mixer-based approach, and (b) transmitter and (c) receiver of six-port transceiver [15]

Thus, in this thesis, a new design of six-port network by using a single substrate with slots formed in the ground plane, that offers an ultra wideband performance, compact size and better fabrication tolerance is presented. The ultra-wideband operation of 3.1 to 10.6 GHz is chosen as the designated frequency band due to its unlicensed usage [17]. This led to the increment of spectral efficiency and more wireless applications can be introduced and enhanced. Besides, UWB can provide high data rate over a very short range and also UWB system consumes low power transmission and robustness against multipath fading and noise. By using operating frequency of 3.1 to 10.6 GHz (UWB), the proposed six-port can overcome the bandwidth limitation reported in Section 2.6.2 of Chapter 2. Design and the analysis on S-parameter performance of proposed six-port network, which formed by 3-dB coupler and power divider is implemented in CST Microwave Studio.

1.2 Problem Statement

Particularly, in transceiver communication system, to be in active state, the design of mixer involves a certain biasing voltage. Consequently, this requirement leads to a more complex design. Thus, to solve the problem, the mixer-based approach can be replaced by using a six-port network. Six-port network is a passive linear circuit, which can be constructed by the combination of the coupler, power divider and/or H-hybrid. These components must be designed to operate in the UWB frequency range to permit construction of the UWB six-port network. In the interest to have ultra wideband component, there are important issues need to be concerned.

In the previous research, the designs of UWB quadrature coupler (Q) and divider (D) hybrids are accomplished by implementing a few of planar technologies such as multilayer microstrip-slot [18], [19], [20], [21], [22], [23] ground-slot technique [24], [25], [26] combination of step-impedance and parallel coupled-line approach [27], and floating potential method [28]. However, the configuration in [18], [19], [20], [21], [22], [23] which required two substrates, might difficult to be handled during fabrication process due to a very fine fabrication tolerance imposed by the air gap between each layer. The existence of the air gap degrades the actual measured performance and become incomparable to the simulated results. Even though, the best isolation performance is obtained by the design in [26], Bialkowski and Wang argued that this configuration requires a lot of care in aligning its two substrates [24]. This statement also supported by Zheng in [29]. Where, the author stated, the multilayer technology is difficult to be fabricated and the ineluctable gap between different layers may cause much more insertion loss, which is definitely undesirable in component designs.

In last few years, there are efforts to design such ultra wideband device using only one substrate [24], [25], [26], [27], [28]. This will eliminate some of multilayer design technique limitations such as air gap and misalignment. Unfortunately, designing a device across ultra wideband frequency range using only one substrate is not an easy task. Many researchers faced difficulty in dealing with a very small design size such as too thin width of transmission line [26] and extremely narrow spacing between coupled-lines [27]. The design of H-hybrid presented by Aikawa and Ogawa in [26] has very thin size of coupled slot-lines and must be fabricated carefully to avoid an undesired result. While, the visible discrepancy shown by power divider design in [27] is mainly due to the zero fabrication tolerance in etching the tight coupled-line with small spacing of 0.06 mm. The design presented in [26] and [27] are difficult to be fabricated in common fabrication laboratory due to the width and gap are tremendously thin. Thus, generally each dimension size of the fabricated designs must be accurate to ensure that the device can be operated across the desired operating frequency of 3.1 to 10.6 GHz. Meanwhile, in [25], the microstrip-slot technique is used to design power divider component. From the result between simulation and measurement, the proposed divider operated at UWB frequency range. However, the isolation between output ports is no better than 10 dB, which commonly required in the divider design [25]. Then, for the coupler design, in [30], the rectangular slot underneath coupled lines is proposed. The proposed design has increased the spacing between coupled lines to 0.12 mm. However, the design of [30] has some limitation of the leaked field, which may affecting the performance of device and at once cause unwanted interference with the other devices in the integrated system. Also, in [28], the 3 dB coupler using floating-potential method is proposed. Even though the performance is good across UWB frequency range, but the width of spacing must be exactly 0.13 mm to avoid the degradation of performance, when the spacing is increased or decreased more than 0.02 mm.

Meanwhile, in six-port network design, there are several techniques have been proposed in order to produce a six-port network that can operate in ultra wideband operating frequency range. Such as in [31], the multilayer techniques is proposed. The excellent performance has been achieved across UWB frequency band. However, due to the use of two substrates in the multilayer structure, it is facing the challenges of misalignment and air gap problem. Then, in [32], Palencia et. al used a combination technique of planar and coaxial technology. The proposed design has achieved good performance, which operates in the frequency band of 0.7 to 6 GHz. However, the appearance is bulky, as it uses a power divider and couplers connected with the coaxial cables. Then, in [33]-[34], several six-port network designs employing single layer technique has been designed, where the good result has been obtained across wider frequency range. However, the UWB coverage is still not achievable.

Therefore, by considering these problems in designing UWB components, new coupler and power divider with the consideration of simple design shape and method will be proposed with the goal to have simple design and convenient usage to form a multi-port network.

1.3 Objective of the Research

The works undertaken in this thesis are aiming on the following objectives:

1) To design new UWB coupler and power divider that will be used to form a six-port network.
2) To apply the designed coupler and power divider in constructing the six-port network.
3) To investigate the performance of six-port network across UWB frequency band of 3.1 to 10.6 GHz.

By achieving the stated objectives, the new designed six-port network with very well UWB performance can be used in many applications. One of the applications is to replace mixer-based approach in the communication transceiver design to act as modulator and demodulator. Thus, this will subsequently reduce the design complexity and increase the bandwidth performance. Therefore, communication transceiver with capability of wideband operating frequency, low power consumption, lower manufacturing cost and low interference can be accomplished.

1.4 Scope of the Research

This research focuses on the design of a UWB six-port network that can be operated within the UWB frequency range from 3.1 GHz to 10.6 GHz. A UWB six-port network, is comprised of UWB power divider and UWB coupler. In order to develop a UWB six-port network, the scope of this research is divided into five parts. Firstly, the characterization and formulation of a microstrip-slot impedance are studied. The study are performed in order to derive new equations of microstrip-slot impedance, Z_{ms}. Then, the various structures of couplers and power dividers are designed, simulated, optimized, fabricated, and measured. The novel components of UWB power divider and UWB coupler will be selected to form a UWB six-port network. The simulation and optimization process of individual components and the six-port network is performed using Computer Simulation Technology (CST). Next, the analytical study of coupler and power divider will be performed to observe the behaviour of UWB performance, which also has been carried out using Computer Simulation Technology (CST).

Planar dielectric materials, also known as substrates play an important role in designing microwave circuits and sub-system. As it is crucial to select the best substrate, this proposed study will also look into the investigation of substrates. Followed by that, fabrication of the designed power divider and coupler will be carried out by implementing the most suitable substrate.

The performance of the fabricated components are then verified and experimentally tested by using a vector network analyzer (VNA). The last stage is to use the designed power divider and coupler to form the six-port network. The performance of six-port network will be investigated across UWB frequency band. All simulated and measured results, including transmission coefficients, reflection coefficients and phase differences between the output ports of all designed components, are analyzed and carefully discussed.

1.5 Contributions of the Research

In this thesis, there are five major contributions are presented. The first contribution is the characterization and formulation of a microstrip-slot impedance, which not yet done by other researchers and reported in other works. The equations are derived by using completing square curve fitting method, in which, the relation between characteristic impedance of microstrip-slot (Z_{ms}) with the slot of width (W_s) and microstrip-impedance (Z_m) is studied based on the substrates with different thickness of 0.508 mm, 0.762 mm and 1.542 mm and relative permittivity between 2 to 5.

The second contribution is a compact design of two-section power divider, which operates over ultra wideband frequency range of 3.1 - 10.6 GHz. The microstrip-slot technique is applied to reduce the size of circuit and achieve wide bandwidth coverage. Where, the rectangular slots are implemented at the ground plane, which positioned symmetrically underneath second and third arms of each microstrip quarter-wave transformer to reduce its length up to 33.34%. This attribute leads to a compact and reduced-size power divider by 23.33% with the dimension of 20 mm x 23 mm and ease of fabrication. The bandwidth performance is improved up to 11.94% compared to the conventional divider.

The third contribution is a new design and analysis of compact ultra wideband (UWB) 3 dB coupled-line coupler. The design of proposed coupled-line structure with zig-zag-shaped slot at the ground plane has shown a greater efficiency for allowing operation at a wider bandwidth, producing a compact size component and minimizing the need of narrow spacing between the coupled lines, which lead to easier fabrication process. In addition, the proposed structure of 3 dB coupled-line coupler is analyzed in order to achieve a strong coupling factor. From the analysis, by adjusting the dimension of the proposed 3-dB coupled-line coupler, the coupling strength can be varied in order to satisfy the strong coupling of 3 dB.

The fourth contribution is a new 90º power divider design that requires an appropriate phase difference of -90º with equal power division, which has being implemented from the proposed ultra wideband 3 dB coupler. The 90º phase difference between the output ports is maintained, which contributed by the quarter wavelength of coupled-line and slotted line underneath.

Then, for the last contribution is concerning the design of new UWB six-port network. The designed six-port is formed by the designed individual components which are proposed divider and coupler. The performance of the proposed six-port is observed and analysed.

1.6 Thesis Outline

This section discusses the thesis outline, where the outline is divided into seven chapters. For Chapter 1, the overview of the whole project is discussed, which includes the research background, problem statement, objectives of the research, scope of the research, contributions of the research, and lastly, thesis outline.

Meanwhile in Chapter 2, it is focusing on the literature reviews, where the basic concept of microstrip line, slotline, power divider, H-hybrid, coupler, and six-port network are discussed. Furthermore, the previous related works are reviewed, which mainly focus on the design techniques and characteristics in designing power divider, H-hybrid, coupler, and six-port network.

In Chapter 3, the methodology of this research is discussed. The research work flows of the whole research are presented, which includes design specifications, flow charts and substrate used.

Next, in Chapter 4, the characterization and formulation of a microstrip-slot impedance is presented. The equations are derived by using completing square curve fitting method, based on the relation between characteristic impedance of microstrip-slot (Z_{ms}) with the slot of width (W_s) and microstrip-impedance (Z_m) with different thickness of substrates and relative permittivity. These proposed equations are used in the design of power divider. Next, in this chapter, four designs of power dividers are presented. A simple analysis on suitable length of two-section quarter-wave transformer that formed by microstrip-slot lines is conducted and elaborated in detail.

In Chapter 5, there are several designs of quadrature couplers are proposed. All the performance of the designed quadrature coupler is observed across the designated frequency range. In the quadrature coupler design, several analyses are performed, which are the effect of the techniques, the coupling and the even- and odd-mode characteristic impedance. The analysis and performance of the designed quadrature couplers are described and discussed thoroughly in this chapter.

Furthermore in Chapter 6, three types of six-port networks are designed and presented. The results of the whole six-ports are elaborated and analysed. The comparison of the designs and the performances is further conversed in this chapter.

Lastly, in Chapter 7, the conclusion is drawn. The findings from the research, contributions and recommendations for future works are proposed and described. Moreover, the list of references and appendices are provided at the end of this thesis.

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