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Design of Components for a Compact Ultra Wideband Microwave Imaging System

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***Abstract*- The paper describes the design of hybrid circuits and antennas for a compact ultra wideband (UWB) microwave imaging system aimed at operation from 3.1 to 10.6GHz. The design of these components is accomplished with the use of full-wave electromagnetic field analysis and design software. The components are developed and experimentally tested. They show good electrical performances over the specified band and thus they are ready to be incorporated in the proposed configurations of an UWB microwave imaging system.**

***Index Terms*- ultra wide-band antennas, couplers, power dividers, microwave imaging.**

I. INTRODUCTION

Since the Federal Communications Commission (FCC) in the USA released in February 2002 the unlicensed use of ultra-wideband (UWB) frequency spectrum from 3.1 to 10.6 GHz [1], there has been a remarkable research interest both in academia and industry in the development of ultra wideband technology [2].

Due to its inherent attributes, UWB is capable of bringing significant advances not only to wireless communications (delivery of high data rate transmission in the presence of existing communication systems) [2], [3] but also to other areas such as microwave imaging [4-7]. As UWB employs short duration pulses, it offers capability of detecting and locating small size irregularities within an imaged object, which cause a higher backscatter than the surrounding medium. As many applications require the imaging system to be portable and low cost, the challenge is to design low cost, low profile and compact UWB transmitter/receiver (transceiver) modules.

The present paper concentrates on the design of compact UWB couplers and dividers and low-profile small size antennas to form compact UWB transceivers for a microwave imaging system. The design of other components of this system such as signal generators and filters is not addressed here. With respect to these active and passive components, one can refer to [8] and [9], which provide valuable references on the two topics.

The paper is organized as follows. Section II presents the general configuration of a microwave imaging system including various configurations of transceivers. Section III presents the design of UWB couplers and dividers which are proposed to form devices for measuring UWB signals. Section IV describes low profile UWB antennas for the imaging system. Section V concludes the paper.

II. SYSTEM CONFIGURATION

Two general configurations of a microwave imaging system, which are considered here, are illustrated in Fig. 1.

The first configuration, shown in Fig. 1(a), is based on the principle of *monostatic radar* [10]. In this configuration, the same antenna is used for both transmitting and receiving of a microwave signal. As a result, the transceiver performs the function of reflectometer [6], [7].

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The configuration shown in Fig. 1(b) uses two antennas, which are displaced by some distance. In this case, the microwave imaging system is based on the principle of *bistatic radar* [10].

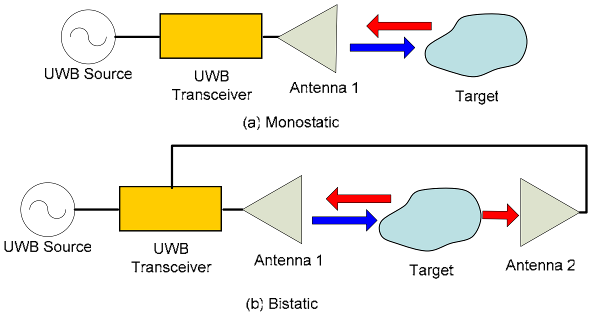

Fig.1. General configurations of a microwave imaging system of (a) *monostatic*, and (b) *bistatic* type radar.

An actual microwave imaging system may also include a mechanical scanning sub-system so that the transmitting/receiving antennas can be moved over a specific surface to obtain two or three dimensional representations of the imaged object [5], [7]. This function can alternatively be achieved by a properly configured transmitting/receiving antenna array, whose elements are suitably activated and deactivated.

As described in [5], [7], the task of measuring reflected or transmitted signals, as required by the microwave imaging system configurations of Fig. 1 (a) and (b), can be performed by a microwave Vector Network Analyser (VNA). This instrument is capable of measuring in the frequency domain a full set of S-parameters of a 2 port network. Because the microwave imaging system requires the information about reflected or scattered short duration pulses, an extra step is required to transform the measured signals from the frequency domain to the time/space domain.

This can be accomplished using an Inverse Fast Fourier Transform (IFFT), which is readily available in the VNA such as HP8510C [7]. The technique used in this case is named the step-frequency pulse synthesis (SFPS) technique. The advantage of SFSP technique over the direct pulse measurement technique [8] includes a higher attainable signal-to-noise ratio due to the use of narrowband electronics. Also this technique offers possibility of removing the sources of pulse distortion such as are introduced by antennas and transitions [11].

Because of its common availability in microwave laboratories, the conventional VNA, such as HP8510C, is useful in the phase of testing capabilities of a microwave imaging system. This approach has been demonstrated for microwave breast cancer detection systems in [4], [5], [7]. However, as the clinical prototype may require an electronically scanned array with antenna elements connected to a reflectometer or VNA, to achieve fast acquisition of a microwave image, the conventional VNA is too bulky and too expensive to be used to this purpose. As the result, designs of inexpensive and compact microwave reflectometers or VNAs are necessary.

An example of a low-cost compact reflectometer operating over a 2 to 12 GHz band for an UWB microwave breast cancer detection system has been reported in [6]. Here, we consider various configurations of microwave transceivers, which can offer similar capability.

Fig. 2 shows a few configurations of transceivers for use in an UWB microwave imaging system, which can be built using low-cost components. The configuration presented in Fig. 2(a) is obtained from reference [12]. The instrument is formed by a swept frequency source, two mixers, an in-phase power divider (D), a 90º hybrid Q (3dB coupler), two other couplers (not necessarily offering 3dB coupling), matched loads and an antenna. The part of the circuit enclosed by a broken line is named a *correlator*, which plays a similar role as a *complex ratio measuring unit* in the conventional VNA. It compares two complex signals to measure a complex reflection coefficient or transmission coefficient. Assuming that all of the components are ideal, this instrument is capable to provide in real-time the complex reflection coefficient [12].

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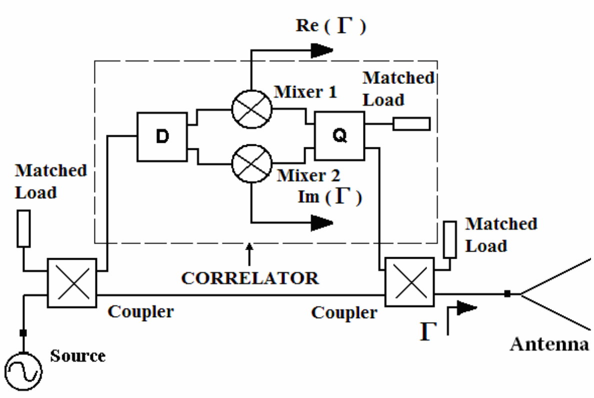
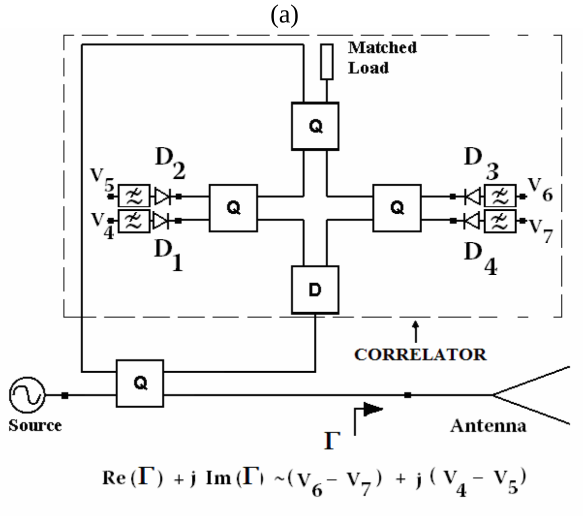


(a)



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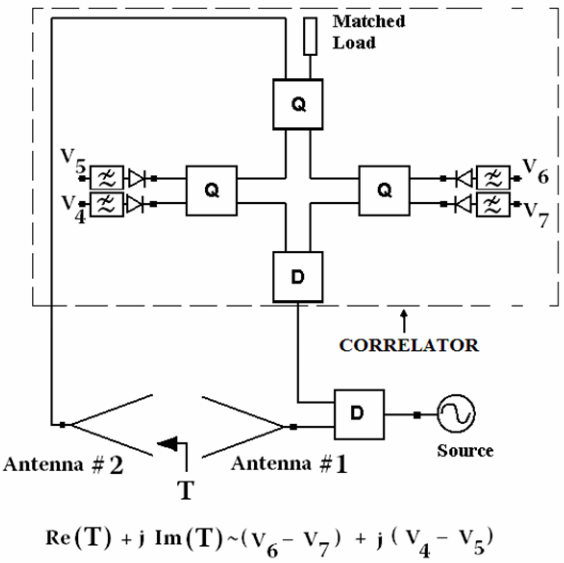

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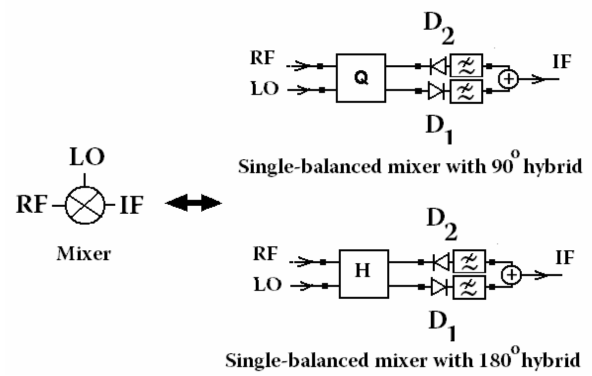

(d)

Fig. 2. Configurations of transceivers for use in an UWB microwave imaging system: (a) reflectometer with mixers, (b) reflectometer with square-law diode detectors, (c) for measuring a transmission coefficient between two antennas. (d) Configurations of a single-balanced mixer employing either 90º (Q) or 180º (H) hybrids.

A similar capability is offered by the device shown in Fig. 2(b). This is under the condition that the diode detectors shown in Fig. 2(b) operate in a *square-law region* [12-14]. The configuration drawn in Fig. 2(b) is capable to provide information about real and imaginary components of the complex reflection coefficient from the measured voltages (V_4, V_5, V_6 and V_7) at the outputs of the square-law detectors. This is accomplished by performing the subtraction operation using analogue or digital means.

One can deduce that the operation of the instruments of Fig. 2(a) and (b) are similar in principle when a single-balanced mixer uses a 90º hybrid (Q), as shown in Fig. 1(d).

Fig. 2(c) presents an analogous (to that of Fig. 2(b)) instrument but which is measures the transmission coefficient between two antennas. One can see that the configuration of Fig. 2(c) uses the same correlator, as shown in Fig. 2(b). The differences between the two circuits concern the parts outside the correlator, as they are configured to measure either the reflection or transmission coefficient. Fig. 2(d) indicates the possibility of employing a single-balanced mixer with a 180º hybrid (H) to design a reflectometer

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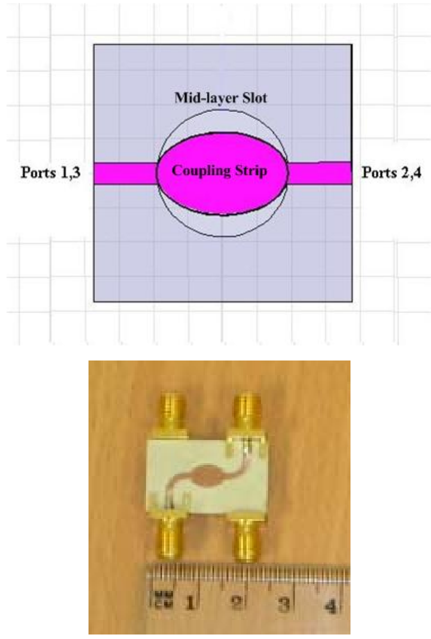
of Fig. 2(a). A similar replacement of the Q hybrids (terminated in the diodes) by H hybrids can be done with respect to circuits shown in Fig. 2(b) and Fig. 2(c).

The above explanations of operation indicate that the devices illustrated in Fig. 2(a), (b) and (c), are capable to measure a complex reflection or transmission coefficient, similarly as the conventional VNA. Their advantage over its conventional counterpart is that they can be developed at a very low cost because they do not require sophisticated and expensive electronics. For the devices shown in Fig. 2(a), (b), (c), signal processing can be accomplished by a Personal Computer (PC) equipped with Analogue-to-Digital converters (ADC) connected to the outputs of the correlator circuit. If one aims at precise measurements, configurations of Fig. 2(b) and (c) are advantageous over the one shown in Fig. 2(a) because voltages at the outputs of the diodes are available separately. As the result, these configurations leave the possibility of precise calibration, as explained by the six-port theories in [12-14]. The same PC can be used to control a swept frequency generator or trigger and record short duration pulses, and process the recorded data to construct microwave images of an object under investigation.

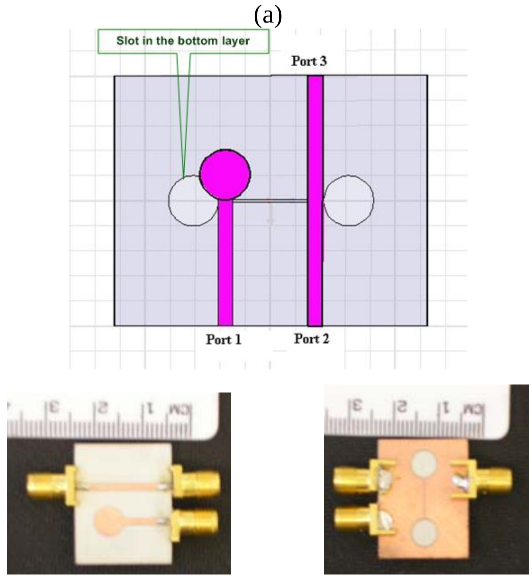
The next sections describe the design of compact UWB couplers, dividers and antennas to build the instruments of Fig. 2(a-c). The preliminary dimensions of these components are obtained using simple design formulas. These structures are then optimized using commercially available full electromagnetic wave analysis and design tool, such as Ansoft High Frequency Structure Simulator or equivalent. In the next step, these components are manufactured and experimentally tested.

III. DESIGN OF UWB COUPLERS AND DIVIDERS

In the undertaken work, the focus is on planar UWB couplers with coupling in the range of 3 to 10dB and on in-phase and out-of-phase dividers, all featuring a compact size. Obtaining an UWB performance of these devices in planar microstrip technologies is very challenging [15]. The layouts and photographs of the investigated couplers and dividers are shown in Fig. 3.



(a)



Top layer view Bottom layer view

(b)

Fig.3. Configurations and photographs of the investigated 3dB coupler (a) and out-of-phase power divider (b)

The chosen configurations of couplers and dividers use multi-layer microstrips accompanied by slots. The use of both strips and slots, which are complementary in terms of supporting either electric or magnetic surface currents, seems to be the key factor to achieving an ultra wideband performance of these small size devices.

The UWB coupler shown in Fig. 3(a) consists of three conductor layers interleaved by two dielectric layers. The top conductor layer includes an elliptically shaped microstrip, which is connected to two microstrip transmission lines forming ports 1 and 2. The bottom conductor layer is similar to the top layer but the ports here are port 3 and 4. The two layers are coupled via slot, which is made in the conductor ground plane supporting the top and bottom dielectric layers.

An analysis of this slot-coupled microstrip coupler can be performed using an even-odd mode approach, which is applicable to symmetric four-ports [15], [16]. In an initial step, the microstrips and slots can be assumed of rectangular shape. In this case, a quasi-static analysis for even and odd-mode excitations similar to the one described in [16] can be applied. From this analysis, initial dimensions of the strips and slot can be worked out, given the value of coupling and the associated even and odd mode characteristic impedances. The results of this analysis are the width and lengths of microstrips in the upper and bottom layer, and the width of the slot. The slot length is equal to the length of coupled microstrip lines.

In the next step, the shape of the strips and the slot are adjusted for the best performance in terms of coupling flatness, and high return and isolation losses. This step is performed using a full-wave electromagnetic analysis software package, such as Ansoft HFSS. Only a few manual iterations are required to obtain the final design that features UWB performance. Through these simulations one can find that an elliptical shape of the microstrips and the slot results in an UWB performance of the coupler. In the manufacturing process of this device, the curved microstrip lines are purposely added, as shown in photograph of Fig.3, to incorporate SMA connectors.

The next component to develop low-cost equipment for measuring the reflection or transmission coefficient is a power divider. With respect to the devices, shown in Fig. 2(a-c), both in- and out-of-phase dividers can be explored. For the in-phase division, an UWB performance can be achieved using a multi-stage Wilkinson power divider. However, such a design is not necessarily of compact size, as each of the stages has to be quarter-wavelength. Here, the design of an out-of-phase power divider is presented that offers compact size and UWB operation.

Fig. 3(b) reveals the layout and photograph of the investigated planar out-of phase (180º) equal-power divider. The three ports of the divider are at the top layer of the PCB while the ground plane is at the bottom layer of the circuit. There is a slot in shape of a narrow rectangle ended with two circles in the middle of the ground plane. This slot is responsible for coupling the wave from the input port to the two output ports. This form of coupling from a slotline to a microstrip is responsible for creating a series connection between input port (port 1) and two microstrip output ports (port 2 and 3) resulting in a 180º signal division. As the 180º phase shift is due to the inherent property of the series (slot to microstrip) connection, the remaining challenge is to obtain a good return loss of the input port. As observed in Fig. 3(b), the transition discontinuities from the slotline to the microstrip are compensated with the use of circularly shaped slot and microstrip stubs. By using the chosen configuration, as shown in Fig. 3(b), only a few manual iterations performed with a full-wave electromagnetic analysis software package, such as Ansoft HFSS, are required to obtain the final dimensions of this hybrid circuit.

IV. DESIGN OF UWB ANTENNA

The investigations are focused on two types of UWB antennas, whose configurations are shown in Fig. 4.

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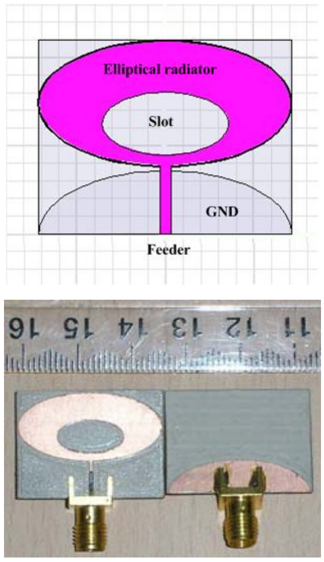
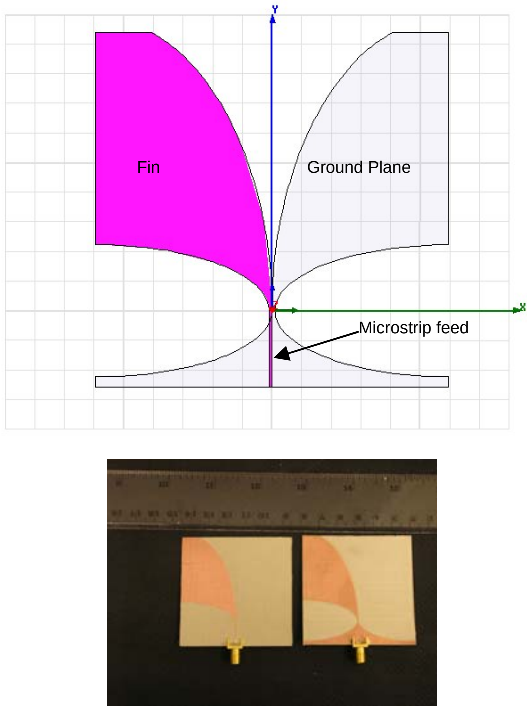


(a)



(b)

Fig. 4. Configurations and photographs of the investigated UWB antennas, (a) omnidirectional and (b) directional.

The first type is an omni directional planar monopole antenna. In terms of operation, this antenna is similar to those described in [17], [18]. It features a fully planar format and offers an UWB performance. The second type antenna is a Vivaldi (tapered slot) antenna. Its operation has been described in [19]. Here, the aim is to obtain it in the compact form, the issue not investigated in [19].

Both antenna designs aim at 10dB return loss, suitable radiation pattern and distortionless signal transmission over the UW frequency band defined here as 3.1-10.6GHz. Similarly as for the couplers and dividers, a full-wave electromagnetic analysis software package is used to accomplish these antennas design. Following the initial guidelines described in [17-19], only a few manual iterations involving the use of this software are required to obtain satisfactory performance of the two types of UWB antennas.

The next step concerns their manufacturing and experimental testing. The antennas are assessed in terms of return loss (with respect to a 50ohm coaxial measurement system) and radiation patterns, which are obtained in an anechoic chamber at chosen frequencies within the 3.1-10.6GHz band. The last measurement concerns the quality of transmission of pulses. It is accomplished using two identical antennas suitably separated. First, the transmission coefficient between the two antennas in the frequency domain over the 3.1-10.6GHz band is measured and then the acquired data undergoes an IFFT to obtain the antennas response in the time domain.

V. RESULTS

The 3, 6 and 10dB couplers were developed in 0.508mm Rogers RO4003C substrate. The total dimensions of these couplers including curved microstrip ports are 15mm*25mm. The out-of-phase divider which was also manufactured in 0.508mm Rogers RO4003C substrate is only 20mm*25mm. The elliptically shaped planar monopole was developed in 0.64mm Rogers RT6010LM substrate and features small dimensions being 20mm*26mm. The Vivaldi antenna which was manufactured in 0.64mm Rogers RT6010LM substrate is 50mm by 50mm.

Table 1 shows the measured performances of the developed 3, 6 and 10dB couplers. The presented results indicate an excellent performance of these hybrids despite their very small size. The size is about one quarter guided wavelength in microstrip at the frequency of 6.5GHz.

Table 1: Performance of the developed directional couplers in the 3.1-10.6GHz band

Coupler Type	Coupling (dB)	Isolation (dB)	Return Loss (dB)
3dB Coupler	3 ±0.8dB	>26dB	>25dB
6dB Coupler	6 ±1.4dB	>27dB	>23dB
10dB Coupler	10±1.5dB	>24dB	>21dB

Table 2 presents the measured results for the developed 3dB out-of-phase power divider.

Table 2: Performance of the developed power divider in the 3.1-10.6GHz band

S21(dB)	S31(dB)	S11(dB)	Phase difference stability (degree)
3 ± 0.7	3 ± 0.7	>12	180°± 0.25°

The power is equally divided between the two output ports with a return loss in the input port better than 10dB across the whole band. This is accompanied by a very stable phase performance with the phase difference between the two output ports of 180º.

Table 3 reveals the results for the developed planar monopole antennas.

Table 3 Performance of the developed UWB antennas.

Antenna Type	BW(GHz)	RL (dB)	Gain (dB)	Distortion in impulse response (with respect to peak value) %
Omni-Directional	3-15	>15	2.8	<15%
Directional	2.75-11	>13	7	<8%

For the omnidirectional type, the bandwidth is extremely large and the average gain is around 2.8dB although the antenna is compact in size. The measured results for the directional UWB planar antenna of antipodal Vivaldi type show a relatively high peak gain (of 7dB). The 10dB return loss covers the whole UWB. The next experimental test concerns an impulse response that is accomplished between two identical antennas. In the case of planar monopole, one antenna has a fixed position and orientation while the second antenna is rotated. For the case of Vivaldi, the two antennas are aligned for best transmission.

Using the time domain capability of HP8510C VNA, the received pulse is compared with the transmitted pulse. The received pulse distortion can be assessed with respect to the level and duration of ringing. In Table 3 only the level of ringing in terms of percentage with respect to the peak of the received pulse is indicated. It can be observed that the UWB planar monopoles show a slightly larger level of distortion than the Vivaldi antenna.

VI. CONCLUSION

This paper has reported on the design of planar components for a compact UWB microwave imaging system. The considered components include UWB couplers, dividers and antennas. These components have been studied in terms of their electrical performances, which include such factors as return loss, coupling, isolation, radiation patterns, and quality of pulse transmission. All of the presented components have shown excellent UWB performances despite being of a very small size. Both the simulation and measurement results indicate that they are ready for inclusion in low- cost compact UWB reflectometers and VNAs, as proposed here. Using the simulated or measured results for the constituting components, the operation of the proposed instruments can be emulated in the frequency and time domains prior to their actual development.

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REFERENCES

[1] New public safety applications and broadband internet access among uses envisioned by FCC authorization of ultra-wideband technology-FCC news release (February 14, 2002) (http://ftp.fcc. Gov /Bureaus/ Engineering_Technology/

[2] G. R. Aiello and G. D. Rogerson, "Ultra-wideband wireless systems," *IEEE Microw. Mag.*, vol. 4, no. 2, pp. 36–47, Jun. 2003.

[3] Z. Irahhauten, H. Nikookar, and G. J. M. Janssen, "An overview of ultra wide band indoor channel measurements and modeling," *IEEE Microw. Wireless Compon. Lett.*, vol. 14, no. 8, pp. 386–388, Aug. 2004.

[4] E.C. Fear, S.C. Hagness, P.M. Meaney, M. Okoniewski and M.A. Stuchly, "Enhancing breast tumor detection with near-field imaging," *IEEE Microwave Magazine*, March 2002, pp. 48-56.

[5] X. Li, E.J. Bond, B.D. van Veen, and S. Hagness, "An overview of ultra-wideband microwave imaging via space-time beamforming for early-stage breast-cancer detection", IEEE Antennas and Propagation Magazine, vol. 47, No.1, February 2005.

[6] M. K. Choi et al., "Compact mixer-based 1–12 GHz reflectometer", IEEE Microw. Wireless Compon. Lett.,, vol. 15, No.11, pp. 781-783, Nov. 2005.

[7] M.E. Bialkowski, W.C. Khor and S. Crozier, "A planar microwave imaging system with step-frequency synthesized pulse using different calibration methods," Microwave and Optical Techn. Letters, Vol. 48, No 3, pp. 511-516, 2006.

[8] J-C. Liu, S-T Lu, C-W Wu, C-Y Liu, and M-H Chiang, "Modified Pulse Shaper Design with picosecond duration and wideband response for UWB applications," Microwave and Optical Techn. Letters, Vol. 48, No 4, pp 744-749, 2006.

[9] J. Gao, L. Zhu, W. Menzel, and F. Bögelsack, "Short-circuited CPW multiple-mode resonator for ultra-wideband (UWB) bandpass filter", IEEE Microw. Wireless Compon. Lett., vol. 16, no. 3, pp. 104–1-6, March 2006.

[10] D. Pozar, *Microwave Engineering*, ch.12, John Wiley & Sons Inc., 3rd edition, 2005.

[11] W.H. Weedon, W.C. Chew and P.E. Mayes, "A step-frequency radar imaging system for microwave nondestructive evaluation", Progress in Electromagnetics Research, PIERS 28, 121-146, 2000.

[12] P.I. Somlo and J.D. Hunter, *Microwave Impedance Measurement*, ch. 5 and 6, IEE Electrical Measurement Series 2, Peter Peregrinus, 1985.

[13] C. A. Hoer, "Using six-port and eight-port junctions to measure active and passive circuit parameters," NES Tech. Note 673, 23 pp. Sept. 1975.

[14] M.E. Bialkowski and A.P. Dimitrios, "A step-frequency six-port network analyser with a real-time display", AEU Intl. J. of Electronics and Comm. vol. 47, No. 3, pp. 193-197, 1993.

[15] R. Mongia, I. Bahl and P. Bhartia, *RF and Microwave Coupled-Line Circuits*, Artech House, 1999

[16] M-F. Wong, V.F. Hanna, O. Picon and H. Baudrand, "Analysis and design of slot-coupled directional couplers between double-sided substrate microstrip lines," IEEE Trans. Microwave Theory Techn., vol. 29, No. 12, pp. 2123-2129, Dec. 1991.

[17] J. Liang, C.C. Chiau, X. Chen, C.G. Parini, "Printed circular disc monopole antenna for ultra-wideband applications", *Electronics Letters*, vol. 40, no. 20, Sept., 2004.

[18] S.Padhi, S. Zagriatski, S. Crozier, and M.E. Bialkowski, "Investigations into printed monopole antennas for ultra-wideband (UWB) applications", Proc. 2005 IEEE AP-S USNC/URSI Symposium, vol. 2A, pp. 651-654, 3-8 July 2005, Washington, D.C., USA.

[19] J.D.S. Langley, P.S. Hall and P. Newham, "Balanced antipodal Vivaldi antenna for wide bandwidth phased arrays", IEE Proc. Microwaves, Antennas and Propagation 143 (1996), 97-102.