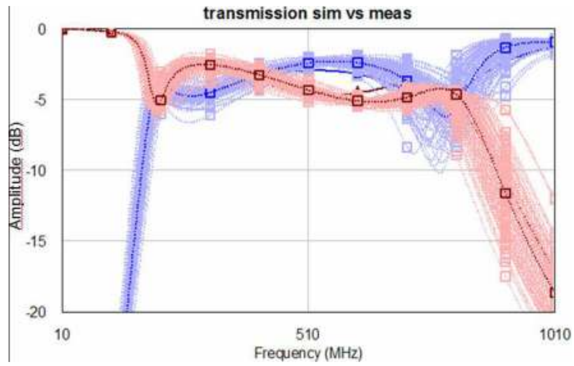

Fig. 16. Variation of the simulated amplitude response versus the inductance. The dark trace corresponds to the measurement.

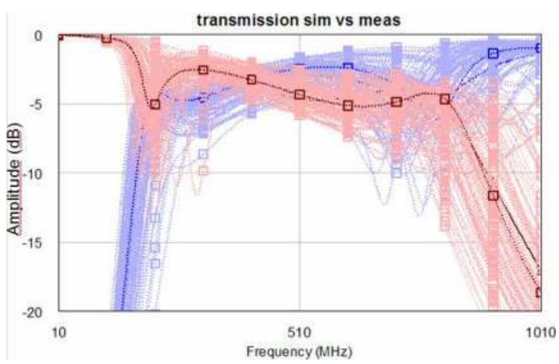

Fig. 17. Variation of the simulated amplitude response versus a jointly variation of the tolerance parameters. The dark trace corresponds to the measurement.

which are more sensitive and are somewhat out of this margin. It has also been seen that the least critical parameter is the permittivity since its variation affects the balun performance slightly. The most critical parameter is the inductor while the capacitor variation shows some intermediate performance between the one of the permittivity and the inductor parameters. As an example, Fig. 16 shows the amplitude balun performance versus the independently variation of the inductance.

From the second analysis stage it can be concluded that the balun performance suffers from larger variation than in the previous case since all the tolerance parameters are changing at the same time. As an example, Fig. 17 shows the amplitude balun performance versus the jointly variation of the capacitance, inductance and permittivity. Nonetheless, the balun still presents a good amplitude and phase balance performance through an approximate 4:1 bandwidth.

IV. Conclusion

A semi-lumped balun transformer for UHF and UWB dipoles has been presented in this paper. The proposed structure is based on two asymmetric 2nd order filters: one low pass filter and one high pass filter. The UWB performance has been achieved by shifting the HPF cutoff frequency toward lower frequencies and the LPF cutoff frequency toward higher ones. In addition, these filters also transform the variable antenna impedance into the desired source impedance by making use of a binomial transformer. Good agreement between simulations and measurements has been achieved. The prototype circuit shows good amplitude balance with a phase difference of 180° across a 4:1 bandwidth from 220–820 MHz. The losses are lower than 1 dB along the whole bandwidth.

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Design of Ultrawideband Mobile Phone Stubby Antenna (824 MHz-6 GHz)

Zhijun Zhang, Jean-Christophe Langer, Kevin Li, and Magdy F. Iskander

***Abstract*—An ultrawideband stubby antenna that covers all frequency bands between 824 MHz and 6 GHz, which include GSM 850 and 900, GPS, DVB-H US, DCS, PCS, UMTS, BT, WLAN 802.11b/g and WLAN 802.11a, with a VSWR better than 2.7:1 is described in this paper. The design procedure involves obtaining a wideband resonance from 1–6 GHz and using a matching network to compensate for the high capacitance of the antenna at the lower frequency band below 1 GHz. Parametric studies of this antenna are presented in this paper. The design was experimentally verified by constructing an ultrawideband antenna with a volume of $5 * 8 * 30\ \mathrm{mm}^3$. It is significant that the designed ultrawideband stubby antenna maintained a good impedance matching and radiation efficiency at all bands. An efficiency between $55 \sim 65\%$ is achieved in the lower band including $824 \sim 960\ \mathrm{MHz}$ band required for the GSM 850 and GSM 900 systems, and an efficiency value of $67 \sim 88\%$ is achieved at the rest of the bands starting with the GPS at 1575 MHz to 6 GHz.**

***Index Terms*—Matching network, monopole antennas, multiband antennas, wideband antennas.**

I. Introduction

With the rapid growth of mobile communication industry, more and more functionalities are being integrated into a single mobile device. Meanwhile, the overall device size and also the available space inside a device for antennas are consistently shrinking. Five

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years ago, a cell phone needed only to cover four bands. In the near future, a state of art cell phone could have antennas that cover nine bands including Global System for Mobile (GSM) 850 (824–894 MHz), GSM 900 (880–960 MHz), Global Positioning System – GPS (1575 MHz), Digital Video Broadcasting-Handheld US (DVB-H US) (1670–1675 MHz), Digital Communication System (DCS) (1710–1880 MHz), Personal Communication System (PCS)(1850–1990) MHz, Universal Mobile Telecommunications System (UMTS) or 3G (1920–2175 MHz), Bluetooth or Wireless Local Area Network (WLAN) 802.11b/g (2400–2484 MHz) and WLAN 802.11a (5150–5875 MHz). More recently cell phone diversity antennas are emerging and this requires another set of antennas that cover up to seven bands: GSM850, GSM900, DCS, PCS, UMTS, WLAN 802.11g and 802.11a multiple-input multiple-output (MIMO) system.

Since the early 1990s, the cell phone industry started adopting multi-band cell phone antennas, such as multi-pitch helix antennas, mono-helix antennas, meander line antennas and multi-band planar inverted-F antennas (PIFA) [1]. Those kinds of antennas can be used to cover up to three or even four bands (GSM 850 and 900, DCS and PCS). With the help of a parasitic element [2], active switch and/or dual port antenna module, PIFA type antennas has been used to support up to six bands (GSM 850 and 900, GPS, DCS, PCS and UMTS). Guo *et al.* [3] have reported a double layer PIFA antenna with parasitic plate that can cover six bands (GSM 900, GPS, DCS, PCS, UMTS and 802.11b/g) with a volume of $36 * 17 * 8\ \mathrm{mm}^3$. Li *et al.* [4] reported a nine-band internal antenna, which was used to cover the same bands as the stubby antenna described in this paper, by using a large size radiating element. Li's antenna was installed perpendicular to the circuit board with an area of $50\ \mathrm{mm} * 50\ \mathrm{mm}$. Wong *et al.* [5] reported a cylindrical monopole antenna that covers from 1.8 GHz to 10.6 GHz with a volume of $20*10*10\ \mathrm{mm}^3$. Liu [6] reported a stamping antenna that covers from 1.713 to 12.68 GHz with a volume of $20 * 10 * 10\ \mathrm{mm}^3$. Liu's antenna can be easily fabricated by folding a single metal plate, with no additional welding process required. The antenna proposed in this paper uses a similar manufacture process.

To improve the antenna matching, matching networks have been widely used in cell phone antenna designs [8], [9] since 1990s. Tzortzakakis *et al.* [8] used a two-component high pass matching network to improve the lower band matching. Ollikainen *et al.* [9] used an open-ended quarter wavelength transmission line at lower frequency to form a secondary resonance thus improve the matching at the lower band. This paper used a four-component matching network to match both the lower and higher band simultaneously.

In this paper we present an ultrawideband stubby antenna that covers all current cell phone communication bands from 824 MHz to 6 GHz. This paper is based on [10]. The antenna has a volume of $5*8*30\ \mathrm{mm}^3$. The antenna is made of a folded V shape stamped sheet metal, which can be easily manufactured, and folded to form a three-dimensional shape. An efficiency value between $55 \sim 65\%$ is achieved at the lower band that includes the $824 \sim 960\ \mathrm{MHz}$ range, and an efficiency of $67 \sim 88\%$ is achieved at the upper desirable band from 1575 MHz to 6 GHz.

II. Design Approach and Simulation Results

It is well known that tapered structures can exhibit wide band properties. Bi-conical, disc-conical and bow-tie antennas [5], [7] can easily achieve ultrawideband coverage. For these kinds of antennas, however, the total length of antenna determines the lowest working frequency and the precision of the tapered feature near the feeding point determines the highest operating frequency.

For a discone antenna with a lowest working frequency of 800 MHz, the length and the diameter of the antenna are all about 160 mm. The size of this antenna is, therefore, too large to be integrated into modern mobile devices that operates in the GSM850 and GSM900 bands. One way to reduce the size of the antenna is to use a matching circuit to compensate for the high capacitance of the antenna at the lower frequency band. This technique enables obtaining a good impendence matching over extended frequency band. The antennae design described in this paper utilizes this approach.

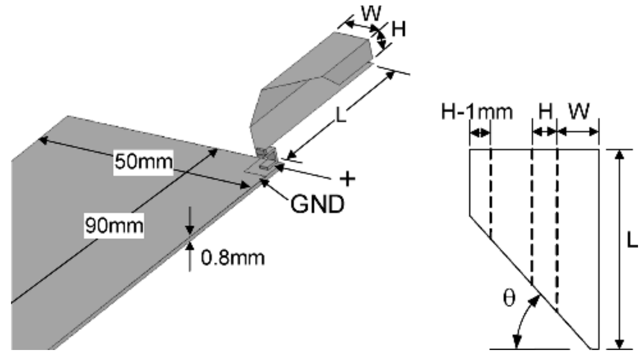

Fig. 1. Mechanical drawing of the proposed antenna.

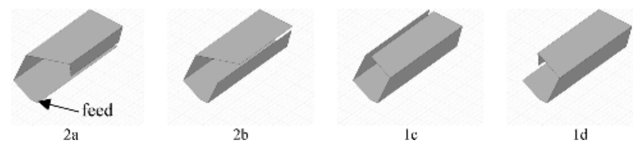

Fig. 2. Four antenna variants of proposed UWB stubby antenna.

Fig. 1 is the mechanical drawing of the antenna studied in this paper. The antenna consists of stamped sheet metal as shown on the right side of Fig. 1 and folded to a three-dimensional shape. The length of antenna is L, the width is W, the height is H and the taper angle is θ. The dimension of the FR4 printed circuit board (PCB) is $0.8\ \mathrm{mm}*50\ \mathrm{mm}*90\ \mathrm{mm}$. A C-clip is used to make contact between the antenna and feed point on the PCB. The C-clip is 3 mm high and has a $2\ \mathrm{mm} * 3\ \mathrm{mm}$ footprint.

When designing an antenna for a real phone project, the PCB size, C-clip height and antenna size are mostly determined by industry design engineers. In this paper, those parameters that are important to antenna performance were parametrically studied. Data presented in this paper can be used as a guideline to predict the antenna performance and also as a support claims when negotiating antenna dimensions and design alternatives with industry design engineers.

Although a matching network can be used to obtain good impedance matching, the antenna efficiency at the low band is still highly correlated to the antenna's VSWR or return loss when no matching network is used. An antenna can not achieve good performance if the original VSWR is too high. When designing the proposed antenna, the goal is to first optimize the antenna dimensions to obtain reasonably low VSWR response in the lower band and also acceptable VSWR values in the $1.5 \sim 3\ \mathrm{GHz}$ and $5 \sim 6\ \mathrm{GHz}$ bands without matching network. Matching networks are then used to improve and bring the VSWR values in the lower band in the acceptable range.

Fig. 2 shows four antenna variants of proposed UWB stubby antenna. The difference between four variants is in the location of the split line which is located in different corners of the antenna. Based on experimental observations, it is noted that when the dimensions W, H, L and the angle θ are the same, those four variants have similar VSWR response. The antenna in 2a was selected for further study in this paper because it is better from the mechanical durability point of view. The structure of antenna 2a is more flexible than other three, thus it has better drop test performance.

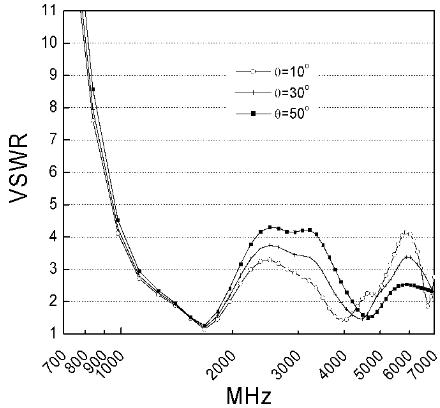

Fig. 3. Antenna VSWR versus different taper angle θ. $\mathrm{W} = 8$ mm, $\mathrm{H} = 5$ mm, $\mathrm{L} = 30$ mm, C-clip height $= 3$ mm.

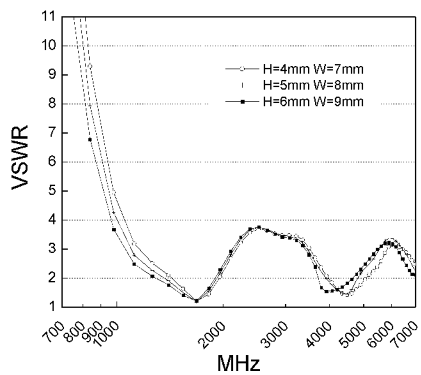

Fig. 4. VSWR versus antenna width and height $\mathrm{L} = 30$ mm, C-clip height $= 3$ mm, $\theta = 30°$.

It is important to mention at this point that from Figs. 3–5, all data presented are simulation data which does not include the use of a matching network. As stated earlier, the goal is to optimize the antenna dimensions to obtain acceptable lower band response and balanced VSWR values in the upper band between $1.5 \sim 3$ GHz and $5 \sim 6$ GHz without a matching network. After obtaining an optimized antenna design based on these simulations, a matching network will be designed and used to obtain good impedance matching across all bands. The simulation tool used in all the reported simulations is HFSS® by AnSoft, and the design procedure included changing the antenna dimensions W, H, L, and the taper angle θ. To better distinguish the VSWR difference of various designs at the lower band, a logarithmic scale was used on the frequency axis (X axis) in all VSWR versus frequency plots in this paper.

Fig. 3 shows the simulation results illustrating the impact of the taper angle θ on the antenna's VSWR. All three antennas have the same dimensions of $\mathrm{W} = 8$ mm, $\mathrm{H} = 5$ mm, $\mathrm{L} = 30$ mm with a C-clip height $= 3$ mm, except for the antenna taper angle, which is varied between 10° and 50°. From these results it may be seen that the taper angle has little impact on the lower band, but it does change the response in the higher band. Fig. 3 also shows that the taper angle can be used to balance the VSWR values between $2.5 \sim 3$ GHz and $5 \sim 6$ GHz bands. When increasing the antenna taper angle from 10° to 50°, the VSWR from $5 \sim 6$ GHz is improved from 4.1:1 to 2.5:1, but the VSWR from $2.5 \sim 3$ GHz is degraded from 3.2:1 to 4.2:1. Taper angle of 30° has a balanced VSWR of 3.5:1 in both band, thus is used as the optimal angle to carry out the rest of the optimization simulations.

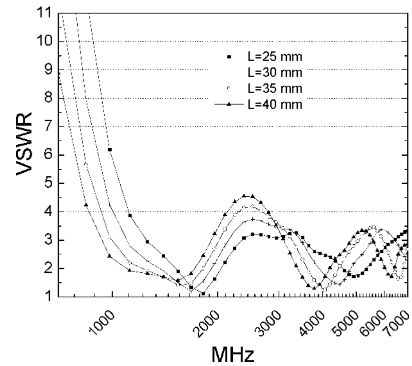

Fig. 5. VSWR versus antenna length $\mathrm{W} = 8$ mm, $\mathrm{H} = 5$ mm, C-clip height $= 3$ mm, $\theta = 30°$.

Fig. 4 shows the simulation results of three antennas with different width and height. The three antennas have different width and height, which are $4\ \mathrm{mm} * 7\ \mathrm{mm}$, $5\ \mathrm{mm} * 8\ \mathrm{mm}$ and $6\ \mathrm{mm} * 9\ \mathrm{mm}$ respectively. All three antennas have the same length $\mathrm{L} = 30$ mm, C-clip height $= 3$ mm, and $\theta = 30°$. When the height and width of the antenna increases, the higher band performance does not significantly change while the lower band performance of antenna improves. At 824 MHz, the VSWR of antennas with dimension of $4\ \mathrm{mm} * 7\ \mathrm{mm}$, $5\ \mathrm{mm} * 8\ \mathrm{mm}$ and $6\ \mathrm{mm} * 9\ \mathrm{mm}$ are 10.3, 8.7 and 7.4 to 1, respectively. Based on these results, an antenna with dimensions of $5 * 8\ \mathrm{mm}^2$ is selected as a good compromise.

Fig. 5 shows the simulation results of four antennas with different antenna length. The antenna length varies from 25 mm to 40 mm. All four antennas have the same dimensions of $\mathrm{H} = 5$ mm, $\mathrm{W} = 8$ mm, C-clip height $= 3$ mm and $\theta = 30°$. As the antenna length increases, the VSWR of the antenna at the lower band improves significantly. At 824 MHz, the VSWR values of antennas of lengths 25 mm, 30 mm, 35 mm, and 40 mm are 12.9, 8.7, 6.2, and 4.6 to 1, respectively. It is observed that the higher band VSWR does significantly degrade with the change in length, while the lower band's performance improves, as expected, with the length increase. As a compromise between industry design and antenna performance, a length of $\mathrm{L} = 30$ mm is selected for the proposed design. It needs to be mentioned, when the L changes, the optimized θ might are different from 30°. The 30° is used here just to show the general trends.

III. Experimental Measurements and Results

A prototype antenna with following dimensions, $\mathrm{H} = 5$ mm, $\mathrm{W} = 8$ mm, $\mathrm{L} = 30$ mm, C-clip height $= 3$ mm and $\theta = 30°$, was manufactured and tested. Generally speaking, the larger an antenna is the better the performance is at the lower frequencies. The lower band efficiency of an antenna is expected to improve with the increase in the antenna size.

Fig. 6 shows the measured S11 data of the prototype antenna before applying the matching network. The dashed line circle inside Fig. 6 is the 3:1 VSWR circle. There are two markers that indicate the start frequency, 824 MHz, and the stop frequency, 6 GHz, of the desired operating band of the prototype antenna.

To match the lower band of a wide band antenna or a multiband antenna, only two types of components can be used, which are shunt inductor and series capacitor. Because the shunt inductor and series capacitor has more impact on the lower band than on the higher band. The order of those two components is decided by the impedance moving path on the Smith Chart. As shown in Fig. 6, the matching networking

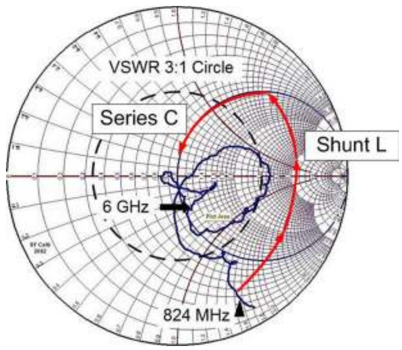

Fig. 6. Measured $S11$ data of prototype antenna before applying matching network.

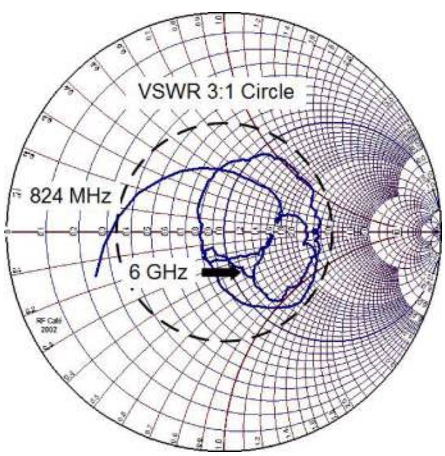

Fig. 7. $S11$ data when only a 9.5 nH shunt inductor and a 2.2 pF series capacitor are used.

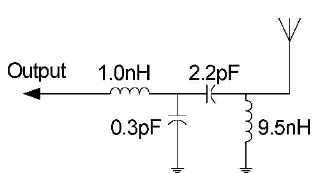

Fig. 8. Matching network to achieve a VSWR better than 2.7:1 across entire band.

used for the proposed antenna has to have a shunt inductor first and then a series capacitor if looking from the antenna side. Fig. 7 shows the $S11$ data when only a 9.5 nH shunt inductor and a 2.2 pF series capacitor are used. It is clear after using the two matching components, the return loss of the lower band has met the requirement. It also can be seen that the impedance of the higher band is on the bottom-right side of the perfect matching point, thus two extra matching components are used to improve the high band performance. Based on the similar consideration mentioned above, for the higher band, only shunt capacitor and series inductor can be used. If looking from the antenna side, the higher band matching networking includes first a 0.3 pF shunt capacitor and then a 1.0 nH series inductor.

Fig. 8 shows the final matching network implemented to achieve a VSWR better than 2.7:1 across the entire band. All four elements are 0402 ($1\ \mathrm{mm} * 0.5\ \mathrm{mm}$) surface mount chip components.

Fig. 9 shows the measured $S11$ data of the prototype antenna with the matching network. In Fig. 9, there is some measurement phase error (negative reactance slope) approaching 6 GHz. The reason is when the

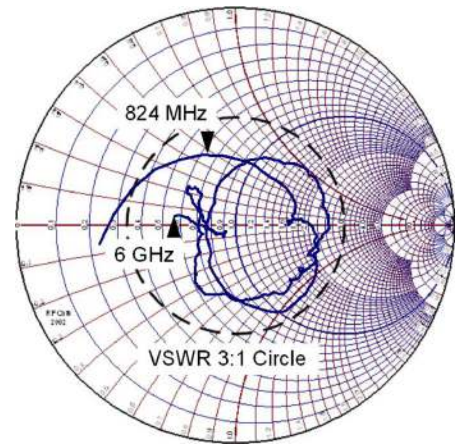

Fig. 9. Measured $S11$ data of prototype antenna with matching network.

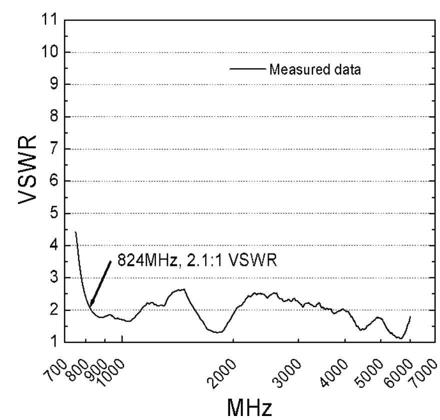

Fig. 10. Measured VSWR data of the prototype antenna with matching network.

network analyzer was calibrated, it was calibrated to the SMA connector of the fixture pigtail instead of the matching circuit on the board. The standard port extension function of the network analyzer was used to simply shift the phase reference point to the matching circuit. That causes the larger phase error in the higher frequency band. To be more accurate, some means of calibration needs to be done instead using port extension method. The port extension method is widely used in the cell phone industry which can give quite accurate return loss measurement but not phase measurement.

Fig. 10 shows the measured VSWR data. The measured VSWR is below 2.7:1 across the entire band. At the GSM 850 and 900 ($824 \sim 960\ \mathrm{MHz}$) band, the VSWR is below 2.1:1. At the $1575 \sim 1675\ \mathrm{MHz}$ (GPS and DVB) band, the VSWR is below 2.0:1. At the $1710 \sim 1990\ \mathrm{MHz}$ (DCS and PCS) band, the VSWR is below 1.8:1. At the $1920 \sim 2175\ \mathrm{MHz}$ (UMTS) band, the VSWR is below 1.8:1. At the $2400 \sim 2484\ \mathrm{MHz}$ (802.11b/g) band, the VSWR is below 2.5:1. At the $5150 \sim 5875\ \mathrm{MHz}$ (802.11a) band, the VSWR is below 1.8:1.

Fig. 11 shows the measured efficiency data. A Satimo Stargate-64 3D near field chamber was used to measure the efficiency and patterns of the prototype antenna. The efficiency is defined as the ration of radiated power versus total available power from power source. Thus the efficiency value includes all impacts from mismatch loss, dielectric loss, conductor loss and matching component loss.

From the results shown in Figs. 10 and 11, it may be noted that at the $824 \sim 960\ \mathrm{MHz}$ band the efficiency is less than 65% when the VSWR

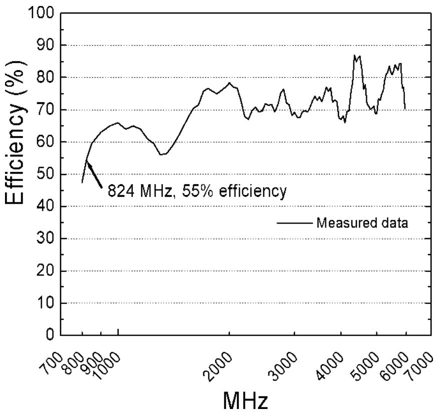

Fig. 11. Measured efficiency data of the prototype antenna with matching network.

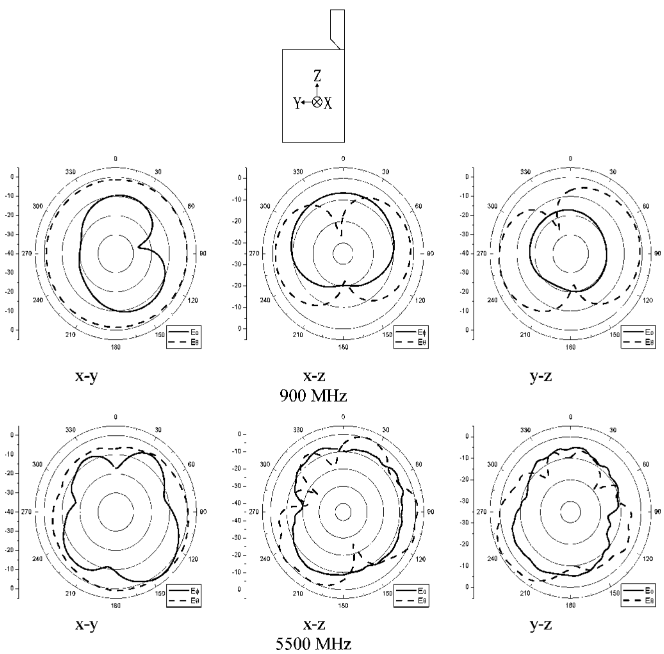

Fig. 12. Measured antenna patterns.

values are better than 2.1:1. The lowest efficiency is actually 55% at 824 MHz and this is where the VSWR value is the highest without the matching network. If better than 55% efficiency is required, the highest VSWR without matching network at the band edge of 824 MHz will have to be improved in the original design say by increasing the antenna height, width and/or length as demonstrated in Figs. 4 and 5.

At the higher band, the overall efficiency is better than that at the lower band because the antenna VSWR at the higher band is quite low even without a matching network. From 1575 MHz to 6 GHz, an efficiency of $67 \sim 88\%$ was achieved. At the $1575 \sim 1675$ MHz (GPS and DVB-H US) band, the efficiency is $67 \sim 72\%$, while at the $1710 \sim 1990$ MHz (DCS and PCS) band, the $1920 \sim 2175$ MHz (UMTS) band, the $2400 \sim 2484$ MHz (802.11b/g) band, the $5150 \sim 5875$ MHz (802.11a) band, the efficiencies are $75 \sim 79\%$, $70 \sim 78\%$, $69 \sim 72\%$, and $70 \sim 83\%$, respectively.

Fig. 12 shows the measured radiation patterns at 900 and 5500 MHz. At 900 MHz, the antenna is similar to a dipole, which has a dominant polarized pattern E_θ. At higher frequency, because the current can be excited at both vertical and horizontal edges of PCB, the patterns are less polarized.

IV. Conclusion

An ultrawideband stubby antenna that covers all frequencies between 824 MHz to 6 GHz with a VSWR better than 2.7:1 is described in this paper. The design procedure is based on optimizing the antenna dimensions to achieve acceptable VSWR and high efficiency values in the higher frequency band and then improving the performance at the lower band using a matching network. HFSS is used in the simulations and a prototype was built and tested to verify the concept. The measured data show that an efficiency of $55 \sim 65\%$ is achieved in the lower $824 \sim 960$ MHz band that includes the GSM 850 and 900, wireless systems and a $67 \sim 88\%$ efficiency is achieved in the 1575 MHz to 6 GHz band that includes GPS (1575 MHz), DVB-H US (1670–1675 MHz), DCS (1710–1880 MHz), PCS (1850–1990) MHz, UMTS or 3G (1920–2175 MHz), Bluetooth 802.11b/g (2400–2484 MHz) and WLAN 802.11a (5150–5875 MHz) systems.

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