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Tunable Band-Notched CPW-Fed UWB Monopole Antenna Using Capacitively Loaded Microstrip Resonator for Cognitive Radio Applications

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Abstract—In this paper, a new compact coplanar waveguide (CPW) ultrawideband (UWB) antenna with an electronically tunable notched band is proposed for an overlay onto cognitive radio (CR) systems. The proposed antenna utilized a rectangular microstrip resonator in the bottom layer to create a single notched band and to realize tunability and miniaturization using varactors. The center frequency of the notched band can be electronically tuned by changing the effective electrical length of the microstrip resonator, which is achieved by employing two varactor diodes at the resonator edges. Moreover, the simple biasing of the varactor diodes has a small effect on the antenna performance. Experimental results show that the proposed antenna can selectively have a band notch over a continuous operating band about 1.44 GHz from 4.77 to 6.21 GHz to prevent the interference to the primary users that are operating in this band such as the WLAN (5.15–5.35 GHz; 5.725–5.825 GHz) and the WiMAX (5.25–5.825 GHz). Good agreement is found between the simulated and the measured data.

1. INTRODUCTION

The scarcity of available spectrum for accommodating new services in combination with the under utilization of currently allocated spectrum has fueled research on alternative visions on communications over the last decade. It has been suggested that unlicensed (i.e., secondary) users could use portions of the spectrum that is licensed to primary users as long as the latter are not significantly affected. Cognitive radio (CR) was proposed and emerged to improve the management and utilization of the crowded RF spectrum. CR is a smart wireless communication system which has the ability to sense, adapt, and utilize tentatively inactive spectrum, which is referred to as a white space or a spectrum hole. There are three major CR network paradigms (that consider various degrees of interaction between primary and secondary users) have been identified: interweave, underlay and overlay [1]. In interweave systems, the secondary users detect the absence of primary user signals in space, time, or frequency and opportunistically communicate during these absences [2, 3]. In the underlay approach, secondary users should operate below the noise floor of primary users, and thus strict constraints are imposed on their transmission power (should be less than -42 dBm/MHz). One way to achieve this is to spread the transmitted signals of secondary users over an ultra-wide frequency band, leading to a short-range high data rate with extremely low transmission power. For underlay ultra-wideband (UWB) CR, the antenna should have an UWB operation without band notches. In the overlay UWB scenario, the antenna at the front-end of the CR device should be capable of operating over the whole UWB range, for sensing and locating the bands that are being active by primary users, but should also be able to produce band notches in its frequency response to prevent interference to these primary

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users [4]. In recent years, the UWB antennas with the rejection of one band [5, 6], multiband [7], and even reconfigurable bands have been presented and investigated [8–10]. Some common approaches include using PIN diodes [11]. However, additional electrical biasing lines may have an effect on the radiation performance of the antenna. In [12], a stepper motor was used for controlling different rejecting elements to obtain reconfigurable characteristics. Owing to the mechanical devices, the dimension and cost will be increased. Furthermore, adopting electrical, optical [13, 14], and mechanical methods as well as active elements by RF micro-electro-mechanical systems (MEMS). However, there are some related problems like the degradation of the switches on the antenna performance and the PIN diodes resistances, which require a large DC power. Electrical band-notched tunability using varactors has been widely implemented [4, 9, 15, 16] to obtain tunable notched bands such as in [4] where the varactor was attached to an open loop resonator at the bandstop filter part to achieve a continuous notched band of 0.57 GHz, while the antenna has a size of $180 \times 160\,\mathrm{mm}^2$. Similarly, in [9] a wide tunable range of 1.8 GHz band is achieved using the active semiconductor-based components whereas the UWB monopole antenna requires a ground plane area of $150 \times 150\,\mathrm{mm}^2$. Besides, the measured $|S_{11}|$ parameters are less than -5 dB at the desired notches. The sizes of the antennas in [15] and [16] are relatively small. However, the antenna in [15] has a narrow tuning notched band of 0.8 GHz and the reconfiguration of the antenna needs two biasing networks. While in [16] a varactor was integrated inside the slot at the radiator to provide a wide tuning range, but the slot in the radiator has a considerable effect on the radiation pattern. Thus, using these techniques CR systems should remove the interference between UWB and narrowband systems, e.g., wireless local area network (WLAN) operating at 2.4–2.483, 5.15–5.35 and 5.725–5.825 GHz, worldwide interoperability for microwave access (WiMAX) at 3.3–3.6 and 5.25-5.825 GHz, and international telecommunication union (ITU) service (8.025–8.4 GHz) to coexistent with these conventional wireless systems.

In this work, a simple novel tunable band-notched CPW-fed UWB antenna is presented, fabricated, and discussed. The technique is based on using a rectangular microstrip resonator at the bottom layer to create a stop band unlike the conventional techniques. The proposed approach is based on electrically tuning the operating frequency of the incorporated band-stop filter by loading the resonator edges with two varactor diodes. Tunability is accomplished by altering the voltage across the varactor diodes. In Section 2, the theory and the structure of the proposed bandstop filter are discussed. Section 3 illustrates and presents the band-notched CPW-fed UWB antenna design parameters and the simulated results. Section 4 is devoted to the proposed tunable band-notched UWB antenna experimental results and discussions. A conclusion summarizes the results.

2. RECTANGULAR MICROSTRIP RESONATOR FILTER THEORY AND DESIGN

The proposed band-stop filter consists of a CPW feed and a microstrip resonator at the bottom layers as shown in Fig. 1(b), respectively. The rectangular microstrip resonator is a symmetrical type of distributed line resonators [17]. Because of the fringing effects, the microstrip resonator length (L_r) electrically looks greater than the physical dimension and extended by Δ on each side. The effective length of the microstrip resonator ($L_{r,\mathit{eff}}$) determines the fundamental resonant frequency and the harmonics. The microstrip resonator will resonate at its fundamental frequency f_o when excited from the center point and its length $L_r = \lambda_{go}$. The resonant frequency can be approximately estimated using

$$f_o = \frac{k\ c}{L_{r,\mathit{eff}}\sqrt{\varepsilon_{\mathit{eff}}}}, \quad L_{r,\mathit{eff}} = L_r + 2\Delta_r \tag{1}$$

where $k = 1, 2, 3, \ldots$, Δ_r denotes the extended incremental length, c is the velocity of the light in free space, and $\varepsilon_{\mathit{eff}}$ is the effective permittivity. To achieve tunability, the resonant frequency can be electrically tuned by loading the microstrip resonator with a low loss varactor at its two ends and adjusting the reverse voltage across the varactor diodes, this will be discussed in detail in the next section.

The bandstop filter structure is designed on an RO3003 substrate with a dielectric constant of 3, loss tangent of 0.0013, and a thickness of 0.762 mm. The CPW feeding in the top layer has a signal line width $W_1 = 3$ mm and a gap width $g = 0.2$ mm which ensure a $50\,\Omega$ characteristic impedance. The rectangular microstrip resonator is printed in the bottom layer as shown in Fig. 1(b). The length

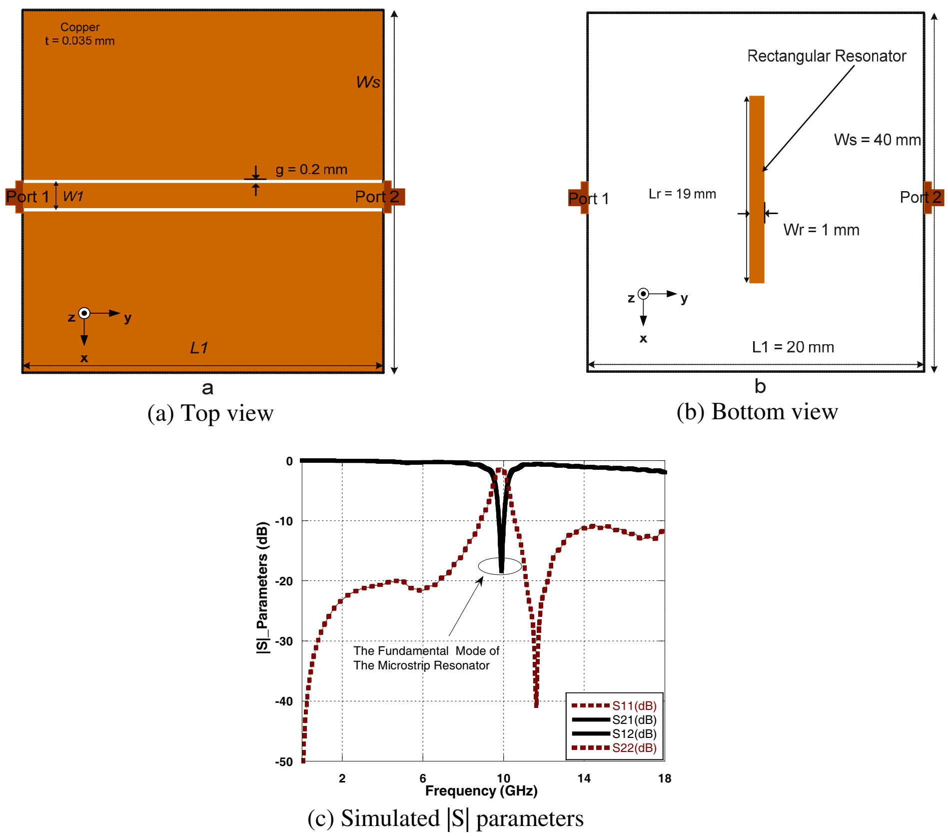


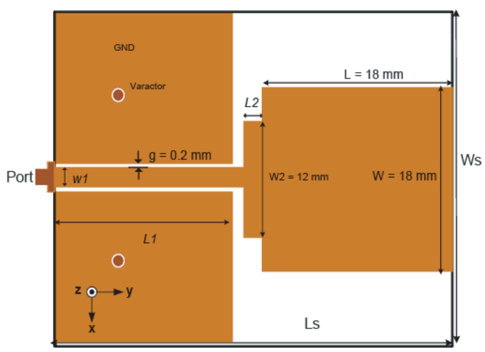
Figure 1. Schematic of the proposed CPW-fed microstrip resonator band-stop filter and $|S|$ parameters results.

and width of the resonator are $L_r = 19\,\text{mm}$, and $W_r = 1\,\text{mm}$, respectively. The filter has dimensions of length $L_1 = 20$ mm and width $W_s = 40\,\text{mm}$. Fig. 1(c) shows the simulated $|S|$-parameters of the filter (without varactors) with a time domain solver using a 3D full-wave analysis software package Computer Simulation Technology (CST) [18]. The results show that the microstrip resonator bandstop filter operates at the fundamental resonant frequency of 9.95 GHz with a percentage error of 0.5% compared to the theoretically calculated frequency of 10 GHz using Equation (1). This relatively high resonant frequency can be miniaturized to the UWB range by capacitively loading the resonator using two varactor diodes as it will be discussed in the next section.

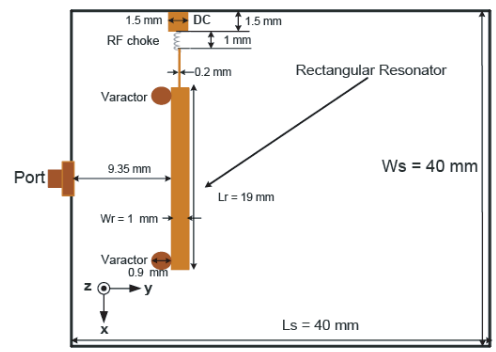
3. PROPOSED TUNABLE NOTCHED-BAND CPW-FED UWB ANTENNA

The proposed antenna is depicted in Fig. 2. A microstrip resonator band-stop filter is included in the CPW feed [19]. Most of the recently published approaches include utilizing resonators at the top layer [4] or etching different slots on the ground plane or inside the patch [16]. Compared to these techniques, using microstrip resonator at the bottom layer has some advantages, such as very steady radiation pattern, high band rejection, and simplicity to control the center frequency of the notch. The patch dimensions are $W = L = 18\,\text{mm}$, $L_2 = 2\,\text{mm}$, and $W_2 = 12\,\text{mm}$. The design of the bandstop filter has been previously discussed in Section 2. The bandstop filter modifies its operating frequency by changing the length of the rectangular microstrip resonator. This can be done by incorporating two varactors to the edges of the resonator to control the resonant frequency of the band-stop filter with the same resonator physical length. In the simulation part, we realized and implemented the two varactor diodes by their equivalent circuit model as shown in Fig. 2(e) with a junction capacitance $C_j = C$, a series inductance $L_s = 0.7\,\text{nH}$, a series resistance $R_s = 0.6\,\Omega$, and a parallel capacitance $C_p = 0.05\,\text{pF}$ of the varactor. The varactor involved in this design is SMV 1405 from Skyworks Solutions Inc. with the tunable capacitance from 0.63 to 2.67 pF corresponding to the reverse-bias voltage from 30 to 0 V [20]. The DC biasing of the two varactors is achieved by connecting the microstrip resonator to an RF choke coil through a thin bias line then to a Vcc pad to provide the required DC voltage as shown in Fig. 2(b). The antenna has dimensions of length $L_s = 40$ mm and width $W_s = 40$ mm. Fig. 2(c) and Fig. 2(d) show the simulated $|S|$-parameters and the peak realized gains of the proposed band-notched antenna. Moreover, the antenna without varactors is also simulated and fabricated as a reference. The results show that the proposed reconfigurable band-notched antenna is tunable in a continuous wide frequency of 1.3 from 4.6 to 5.9 GHz by changing the varactor diode junction capacitances from 0.63 to 2.67 pF accordingly. Added to this a good miniaturization is achieved by using the varactor diodes.

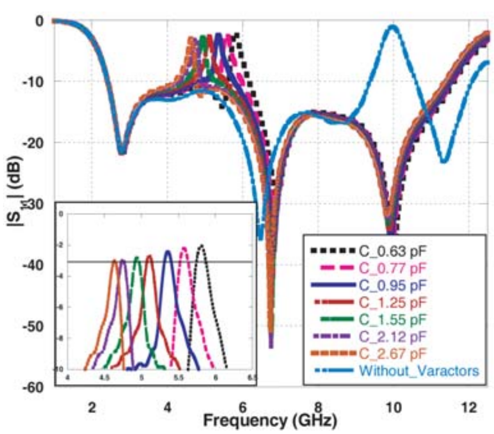
Figure 3 contains the normalized realized gain radiation pattern results at $C = 2.67$ pF of the proposed band-notched UWB antenna at selected frequencies (3.5, 5.5, 8, and 10.5 GHz) over the operating band. It is clear that the antenna has a very stable radiation patterns in the E (yz-plane) and H (xz-plane) planes over the whole operating frequency range and confirms the desired beams of omnidirectional patterns of a monopole antenna.



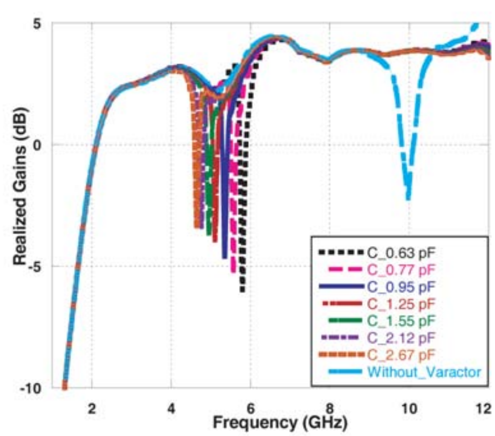
(a) Top view



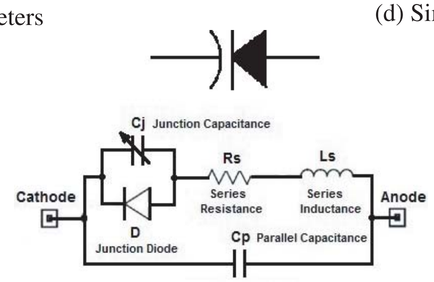
(b) Bottom view



(c) Simulated $|S_{11}|$ parameters

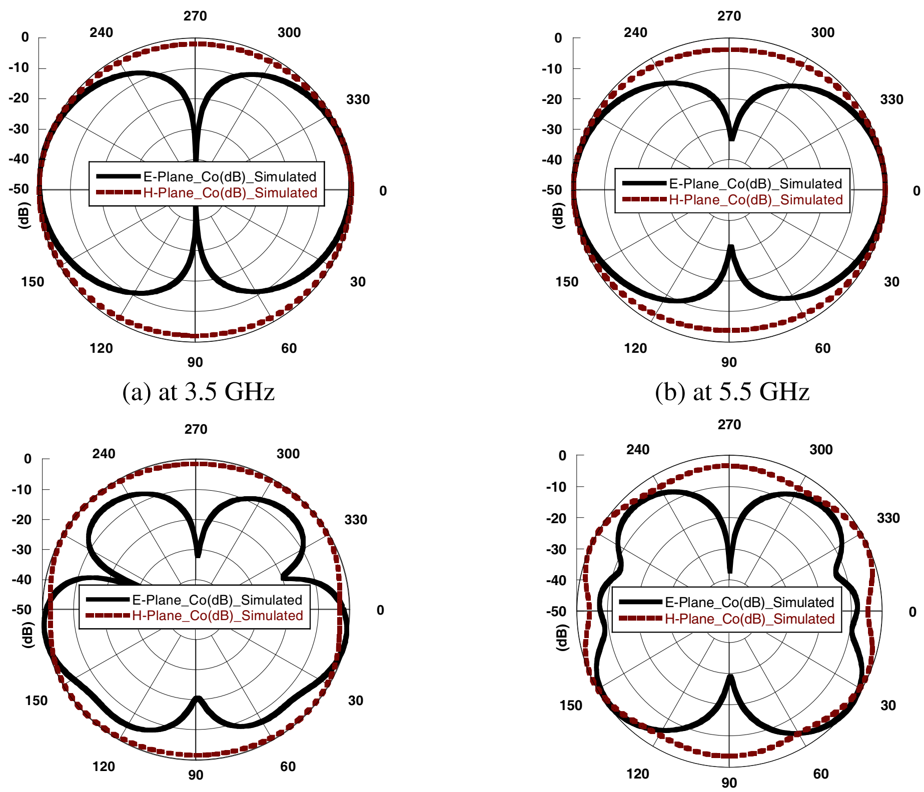


(d) Simulated peak realized gains



(e) Equivalent circuit model of the SMV 1405 varactor diode

Figure 2. Schematic of the proposed CPW-fed UWB antenna, $|S_{11}|$ parameters, and peak realized gains.



(a) at 3.5 GHz (b) at 5.5 GHz

(c) at 8 GHz (d) at 10.5 GHz

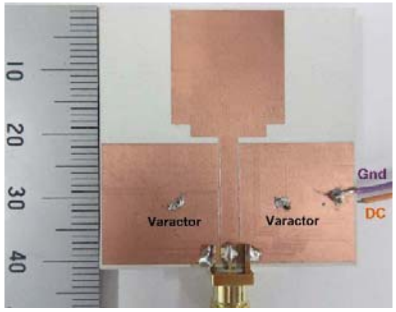
Figure 3. The proposed antenna normalized radiation pattern results at $C = 2.67$ pF.

4. EXPERIMENTAL RESULTS AND DISCUSSION

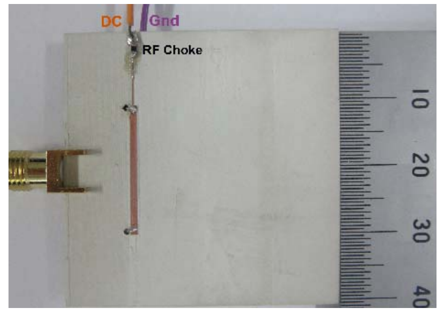
The proposed tunable band-notched antenna has been fabricated and measured to validate experimentally the approach of achieving frequency band notch reconfiguration operation. The photographs of the top and bottom views of the fabricated antenna are shown in Fig. 4. By supplying different voltage levels to the two varactors, the total length of the microstrip resonator changes accordingly, and hence the bandstop filter tunes its operating frequency. The varactors used in this work are the SMV 1405 [20] with dimensions of $1.3 \times 0.9 \times 0.7\,\mathrm{mm}^3$ and are installed in the holes between the top and the bottom metal layers. The DC biasing of the varactor is achieved by connecting the varactor cathode to an RF choke coil through a thin bias-line as shown in Fig. 4(b). This bias-line has a length of 8 mm and a width of 0.2 mm, which corresponds to a high-impedance line to reduce losses and spurious radiation, and is connected to a $1.5 \times 1.5\,\mathrm{mm}^2$ pad. The pad is used to solder the DC supply line to adjust the reverse voltage across the surface mounted varactor diodes. The varactor anodes are connected to the antenna ground plane. A 47 nH RF choke (Murata LQM18N) is incorporated to prevent any RF leakage to the DC supply. The $|S_{11}|$ parameter measurements are performed using Anritsu 37269D vector network analyzer.

The fabricated antenna provides a measured band-notched tuning range of around 1.44 GHz from 4.77 to 6.21 GHz for a reverse bias voltage range of 0–30 volts with varactor capacitance range of 2.67–0.63 pF respectively as shown in Fig. 4(c). In addition, a good miniaturization is achieved by capacitively loading the microstrip resonator using two varactor diodes from 10 GHz to around 5 GHz. Slight and acceptable shifts in central frequencies between the simulated and the measured data are found. The differences could be accounted for the actual varactor capacitive range compared to the datasheet, varactor component modeling, soldering, feed network, wires and fabrication errors.

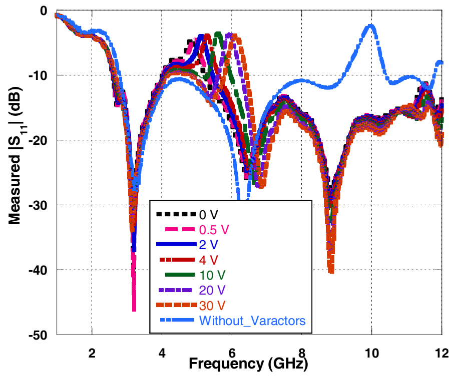
Figure 5 contains a comparison between the simulated and measured normalized radiation pattern results at $C = 0.63$ pF and 30 volts of the proposed band-notched UWB antenna at selected frequencies



(a) Top view

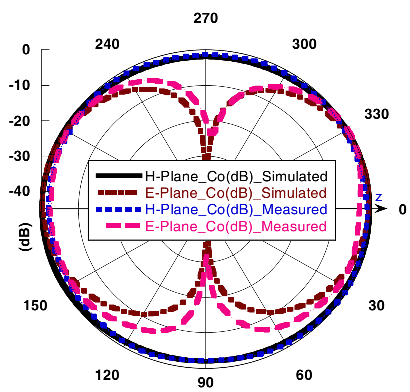


(b) Bottom view

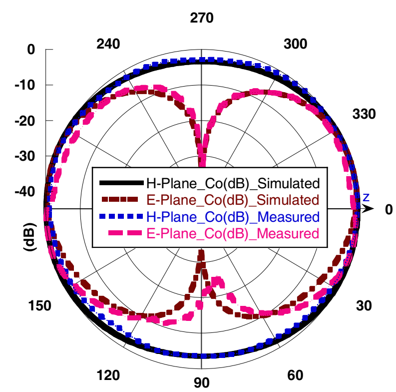


(c) Measured $|S_{11}|$ parameters

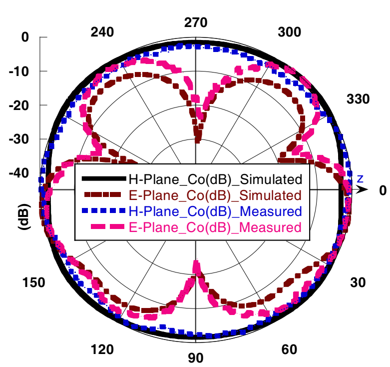
Figure 4. Photograph of the proposed fabricated CPW-fed UWB antenna and $|S_{11}|$ parameters.



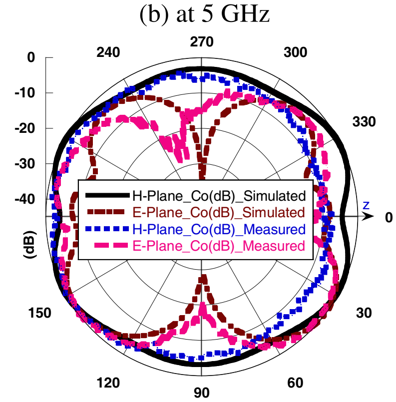
(a) at 3.5 GHz



(b) at 5 GHz



(c) at 8 GHz

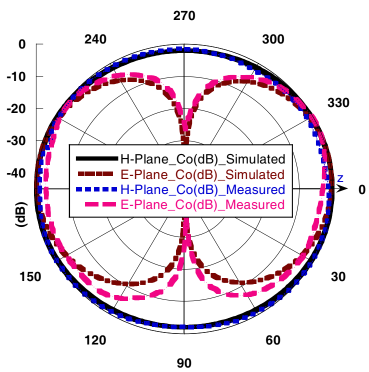


(d) at 10.5 GHz

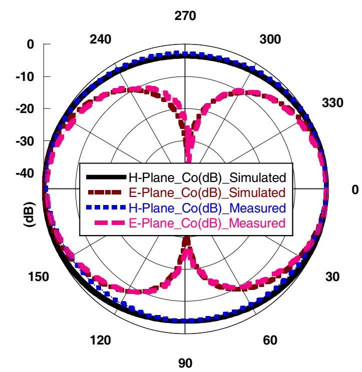
Figure 5. The proposed antenna measured normalized radiation pattern results at $C = 0.63\,\text{pF}$ and 30 Volts.

(3.5, 5, 8, 10.5 GHz) over the operating wideband. It is obvious that the radiation patterns in the E (yz-plane) and H (xz-plane) planes are stable over the whole operating frequency range and confirm the desired beams of an omni-directional patterns of a monopole antenna.

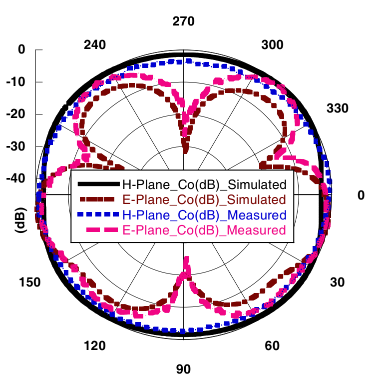
For more investigations of the antenna performances, the measured and simulated normalized radiation pattern results of the proposed antenna at $C = 2.67$ pF and zero volt are plotted and compared in Fig. 6. These results show that the radiation patterns in the E (yz-plane) and H (xz-plane) planes are steady over the whole operating band with a good agreement. Furthermore, using microstrip resonator at the bottom layer has no significant effect on the radiation pattern characteristics of the antenna.



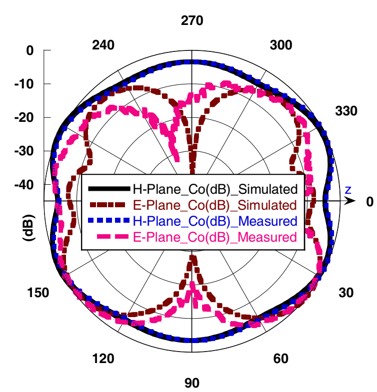
(a) at 3.5 GHz



(b) at 5.5 GHz



(c) at 8 GHz



(d) at 10.5 GHz

Figure 6. The proposed antenna measured normalized radiation pattern results at $C = 2.67$ pF and 0 Volt.

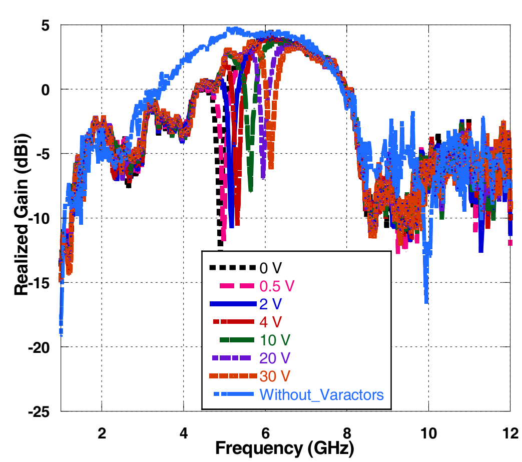


Figure 7. Realized gains of the proposed band-notched antenna with and without varactors.

The measured antenna realized gains (at front side) at selected voltages are depicted as a function of frequency in Fig. 7 and compared to the realized gain of the reference antenna. The measured realized gains of the proposed band-notched antenna show that there are some losses at lower frequencies. The losses could be attributed to the soldering, feed network, wires and imperfections of the components (SMV 1405 and RF choke).

5. CONCLUSIONS

In this paper, a design of a novel compact frequency tunable band-notched antenna for overlay CR applications has been presented, fabricated, and measured for the validation purposes. In this simple design, a wide continuous tunable notched band about 1.44 GHz is successfully achieved by integrating a band-stop filter using rectangular microstrip resonator into the feed line of a planar UWB antenna. The tunability technique has been accomplished by loading the resonator with two varactor diodes. A wide tunable band from 4.77 to 6.21 GHz has been experimentally obtained by varying the reverse voltage across the varactor diodes to filter the WLAN (5.15–5.35 GHz; 5.725–5.825 GHz) and the WiMAX (5.25–5.825 GHz), which lie in these bands. Furthermore, the radiation patterns are very stable over the operating frequency range. With this feature, the proposed band-notched antenna is convenient for the spectrum overlay CR front end system.

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REFERENCES

1. Al-Husseini, M., A. Ramadan, A. El-Hajj, K. Y. Kabalan, Y. Tawk, and C. G. Christodoulou, "Design based on complementary split-ring resonators of an antenna with controllable band notches for UWB cognitive radio applications," *IEEE International Symposium on Antennas and Propagation (APSURSI)*, 1120–1122, July 2011.
2. Tawk, Y., J. Costantine, and C. G. Christodoulou, "Cognitive radio and antenna functionalities: A tutorial [Wireless Corner]," *IEEE Antennas and Propagation Magazine*, Vol. 56, No. 1, 231–243, 2014.
3. Tawk, Y., M. Bkassiny, G. El-Howayek, S. K. Jayaweera, K. Avery, and C. G. Christodoulou, "Reconfigurable front-end antennas for cognitive radio applications," *IET Microwave Antennas Propagation*, Vol. 8, No. 5, 985–992, 2011.
4. Trad, I. B., J. M. Floch, H. Rmili, L. Laadhar, and M. Drissi, "Planar elliptic broadband antenna with wide range reconfigurable narrow notched bands for multi-standard wireless communication devices," *Progress In Electromagnetics Research*, Vol. 145, 69–80, 2014.
5. Abbas, S. M., Y. Ranga, A. K. Verma, and K. P. Esselle, "A simple ultra wideband printed monopole antenna with high band rejection and wide radiation patterns," *IEEE Transactions on Antennas and Propagation*, Vol. 62, No. 9, 4816–4820, Sept. 2014.
6. Satyanarayana, B. and S. Mulgi, "Design of planar band-notched monopole antenna for 2.4 GHz WLAN and UWB applications," *Microwave and Optical Technology Letters*, Vol. 5, No. 1, 249–2501, 201.
7. Wu, Z.-H., F. Wei, X.-W. Shi, and W.-T. Li, "A compact quad band-notched UWB monopole antenna loaded one lateral L-shaped slot," *Progress In Electromagnetics Research*, Vol. 139, 303–315, 2013.
8. Cai, Y., H. Yang, and L.-Y. Cai, "Wideband monopole antenna with three band-notched characteristics," *IEEE Antennas and Wireless Propagation Letters*, Vol. 13, 607–610, 2014.

9. Loizeau, S. and A. Sibille, "Reconfigurable ultra-wide band monopole antenna with a continuously tunable band notch," *IET Microwave Antennas Propagation*, Vol. 8, No. 5, 346–350, 2014.
10. Li, C. M. and L. H. Ye, "Improved dual band-notched UWB slot antenna with controllable notched band-widths," *Progress In Electromagnetics Research*, Vol. 115, 477–493, 2011.
11. Ojaroudi, N., N. Ghadimi, Y. Ojaroudi, and S. Ojaroudi, "A novel design of microstrip antenna with reconfigurable band rejection for cognitive radio applications," *Microwave and Optical Technology Letters*, Vol. 56, No. 12, 2998–3003, 2014.
12. Lotfi, P., M. Azarmanesh, and S. Soltani, "Rotatable dual band-notched UWB/triple-band WLAN reconfigurable antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 12, 104–107, 2013.
13. Zhao, D., L. Lan, Y. Han, F. Liang, Q. Zhang, and B. Wang, "Optically controlled reconfigurable band-notched UWB antenna for cognitive radio applications," *IEEE Photonics Technology Letters*, Vol. 26, No. 21, 2173–2176, 2014.
14. Zheng, S. H., X. Y. Liu, and M. M. Tentzeris, "Optically controlled reconfigurable band-notched UWB antenna for cognitive radio systems," *Electronics Letters*, Vol. 50, No. 21, 1502–1504, October 2014.
15. Li, T., H. Zhai, L. Li, C. Liang, and Y. Han, "Compact UWB antenna with tunable band-notched characteristic based on microstrip open-loop resonator," *IEEE Antennas and Wireless Propagation Letters*, Vol. 11, 1584–1587, 2012.
16. Aghdam, S. A., "A novel UWB monopole antenna with tunable notched behavior using varactor diode," *IEEE Antennas and Wireless Propagation Letters*, Vol. 13, 1243–1246, 2014.
17. Hong, J.-S. and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications Theory Analysis and Design*, 1st Edition, Wiley & Sons, New York, 2001.
18. CST Microwave Studio, ver. 2015, Computer Simulation Technology AG, Japan, AET, 2015
19. Sam, W. Y. and Z. Zakaria, "A review on reconfigurable integrated filter and antenna," *Progress In Electromagnetics Research B*, Vol. 63, 263–273, 2015.
20. 'DataSheetSMV1405', http://www.skyworksinc.com/Product/552/SMV1405_Series.