Investigation of Pulse Dispersion in a Carrier-Based UWB System with LO Leakage Cancellation

Cemin Zhang,[1] Adel Elsherbini,[2] Aly E. Fathy,[1] Mohamed Mahfouz[1]

[1] Department of Electrical Engineering and Computer Science, University of Tennessee Knoxville, Knoxville, TN 37996
[2] Electrical Engineering and Computer Science Department, University of Michigan at Ann Arbor, Ann Arbor, MI 48109

Received 2 February 2009; accepted 22 April 2009

ABSTRACT: Local oscillator (LO) leakage in a carrier-based ultrawideband (UWB) system is a major design concern. In many cases, mixer LO-RF isolation is not sufficient and the LO leakage is well above the useful UWB signal. However, this leakage can be substantially reduced by using a notch filter located before the UWB transmitting antenna as long as it will not lead to unacceptable signal distortion. Therefore, various filter parameters, such as the filter order and 3 dB rejection bandwidth, have been studied to see their effects on providing sufficient band rejection level to reduce the unwanted LO leakage while minimizing the transmitted pulse dispersion. Time domain simulations and measurements have been utilized to evaluate the pulse dispersion using both the relative signal's first pulse amplitude and the pulse time delay spread. Int J RF and Microwave CAE 19: 669–675, 2009.

Keywords: LO leakage; notch filter; UWB system; pulse dispersion

I. INTRODUCTION

Carrier-based ultrawideband (UWB) impulse radar systems have been widely used in many areas such as UWB localization and communication systems [1, 2]. However, the carrier leakage, which is due to the limited LO-RF mixer isolation, will cause many problems such as: a) signal to noise ratio reduction and data loss [3]; b) signal demodulation degradation which would cause DC offset at the receiver side [4]; c) unacceptable interference with other existing services [5]; d) possible FCC transmitted signal limit violation.

To address these problems, the most straightforward way is to increase the LO-RF isolation of the up-converter at the transmitter side. However, currently available commercial mixers have been reported to provide a maximum LO-RF isolation of around 45 dB with an LO driving power of 13 dBm [6]. Thus, the LO leakage at the RF port is around −32 dBm before amplification, which is significantly higher than the useful UWB signal spectrum that is below −41.3 dBm according to the FCC regulation. Another technique is to divert a part of the LO signal, upon using a phase-shifter, and then add it back to the RF-output of the mixer to cancel the LO signal [7]. However, such a technique implies very complex mixer design. Recently, many researchers have investigated the use of a band-notched UWB monopole antenna to avoid the interference with the existing WLAN system. Various kinds of slots have been integrated as part of the monopole patch to create the notch filter effect [8, 9]. Similar ideas could be applied here to reject the carrier leakage of the impulse UWB system. However, the use of a slot filter can cause deterioration of the antenna perform-

Correspondence to: C. Zhang; e-mail: czhang5@utk.edu
DOI 10.1002/mmce.20390
Published online 16 July 2009 in Wiley InterScience (www.interscience.wiley.com).

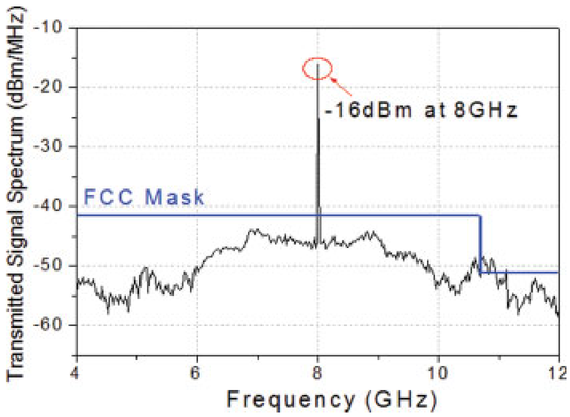


Figure 1. Power spectral density of modulated pulse signal showing the LO leakage far exceeds the useful UWB signal spectrum. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

ance with respect to its gain and efficiency [10]. Even though the slot-notched monopoles only provide limited rejection level of less than 15 dB, a multiorder band-stop filter [11] could be utilized to provide an adequate rejection level to eliminate the carrier leakage. Nevertheless, the relations between the UWB signal dispersion and the filter parameters need to be studied to optimize the band-stop filter design and minimize subsequent signal distortion. Time domain UWB signal performance analysis such as the first pulse amplitude (FPA) and time delay spread (TDS) will be carried out as they are essential parameters in developing UWB positioning and communication systems.

In the following sections, an overview of our UWB local positioning system and the transmitting carrier leakage are discussed, followed by a system simulation that is used to quantify the relation between the notch filter parameters and the dispersion of the UWB signals (such as FPA and TDS). Section III covers the implementation and performance of typical band-notched filters. Then, in Section IV, both the spectrum and the time domain measurements are investigated to validate our simulated results. Finally, a brief conclusion is given in Section V.

II. MOTIVATION AND SYSTEM MODELING USING ADS

In our experimental localization system set-up [2], a 300-ps Gaussian pulse modulates a carrier signal centered at a fixed frequency, i.e., 8 GHz, which is transmitted through an omni-directional UWB antenna. Directional Vivaldi receiving antennas are located at distinct positions to receive the modulated pulse signal. However, the up-converter at the transmitter side requires high LO driving power, and the up-converter cannot provide enough LO-RF isolation, which leads to an undesirable carrier leakage at 8 GHz that is well above the UWB signal spectrum, as shown in Figure 1. Such leakage needs to be filtered using a notch filter.

To analyze the effect of using the notch filter on the transmitted signal (shown in Fig. 1), an Agilent-ADS2006A CAD model has been developed as shown in Figure 2. The transmitter and receiver were directly connected through a simplified channel model, i.e., the antenna effects were not included in

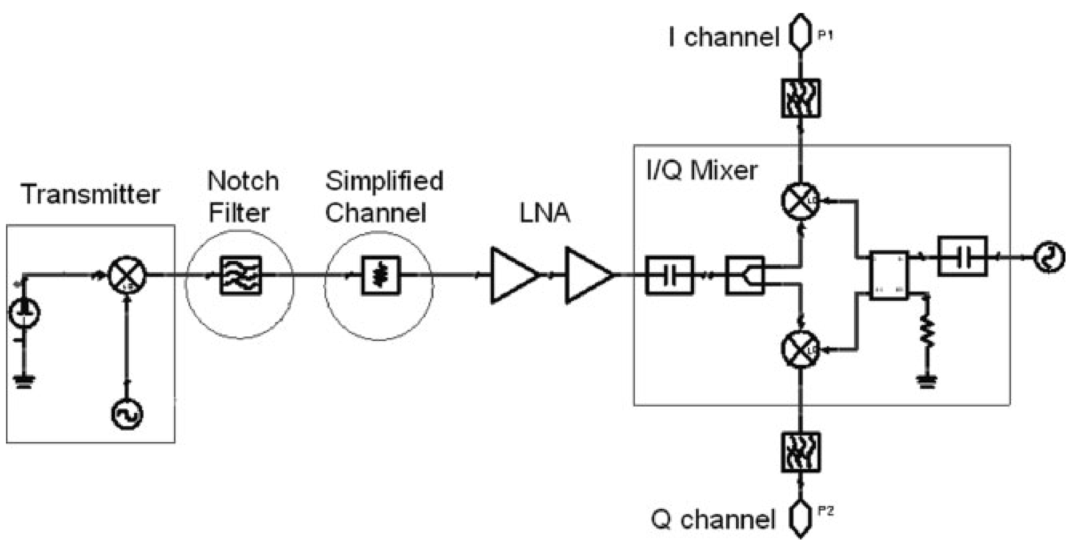


Figure 2. ADS model of the simplified localization system where the signal dispersion due to antennas has not been considered.

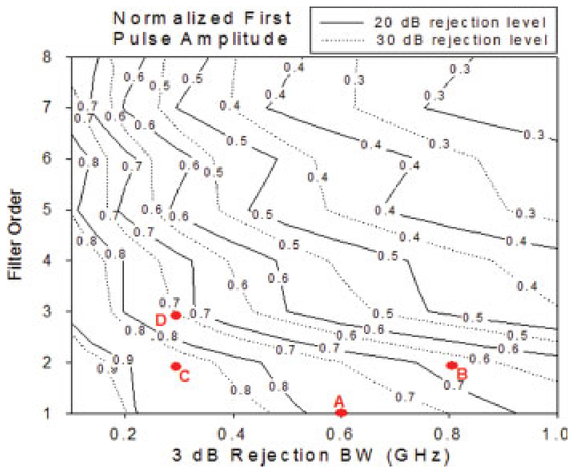


Figure 3. The first pulse amplitude vs. the filter bandwidth and order: increasing the filter order for a given rejection bandwidth would lead to less first pulse amplitude and using wider rejection bandwidth for the same filter order would also lead to amplitude reduction. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

our model to focus on signal dispersion due to the notch filter. In our analysis, the peak amplitude of the first pulse was calculated as a function of the filter order and its associated 3-dB rejection bandwidth. As noted from Figure 3, in an ideal case, the higher amplitude is obtained when using a relatively narrow rejection band as most of the useful energy remains intact. In practice, however, there are a number of limitations that prevent the utilization of extremely narrow band notch filters such as: the limited realizable Q factor in a small volume, the fabrication tolerance, and the local oscillator's aging and temperature stability drifting effects. Meanwhile, the FPA decreases as the filter order increases, so it is required to minimize the utilized filter order. For example, for a 500 MHz filter rejection bandwidth shown in Figure 3, the relative FPA decreases from 0.8 to 0.6 as the filter order increases from 1 to 4. However, notch filters with single filter order generally cannot provide adequate rejection level to eliminate the carrier leakage.

Another important consideration for the notch filter utilization in the carrier-based UWB systems is the TDS. In this context, we will adapt a TDS definition as the time after which the pulse does not exceed −20 dBc of its first peak amplitude. As can be seen from Figure 4, in general, increasing the filter order leads to an increase in the pulse TDS. Since a notch filter with a higher filter order features sharper notch band edges, the steeper transition in the frequency domain would result in a stronger and longer ringing effect in the time domain, giving rise to a longer pulse TDS. Hence, increasing the order to achieve a higher rejection level could lead to a higher dispersion, especially when the rejection bandwidth is relatively large according to Figure 4. In summary, it is required to utilize a narrow band rejection filter with the possibly lowest filter order for an adequate rejection level, i.e., about 30 dB for our carrier-based UWB system.

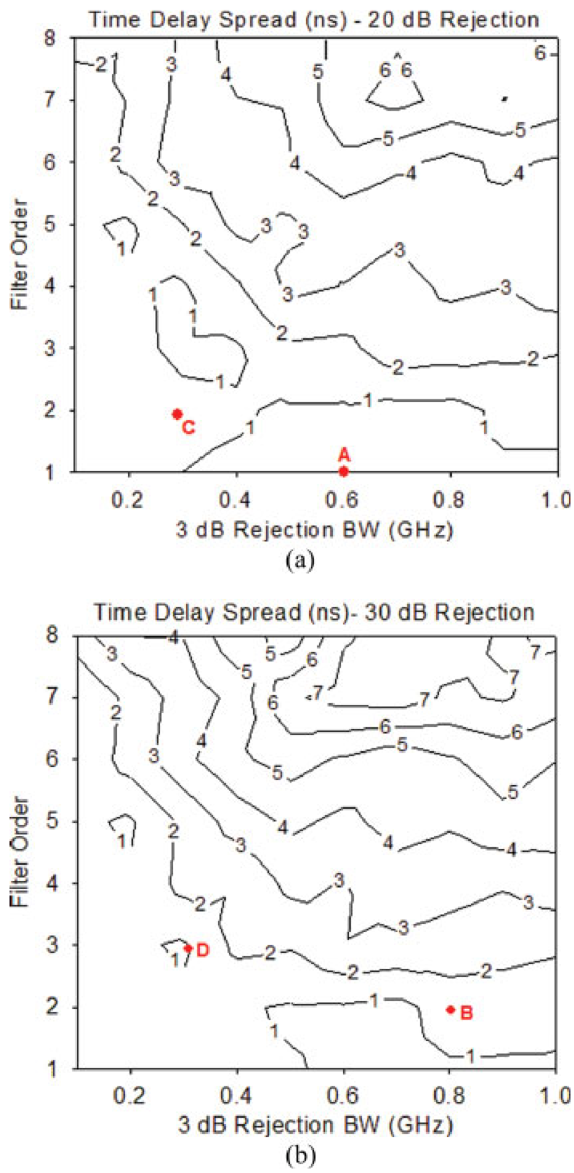
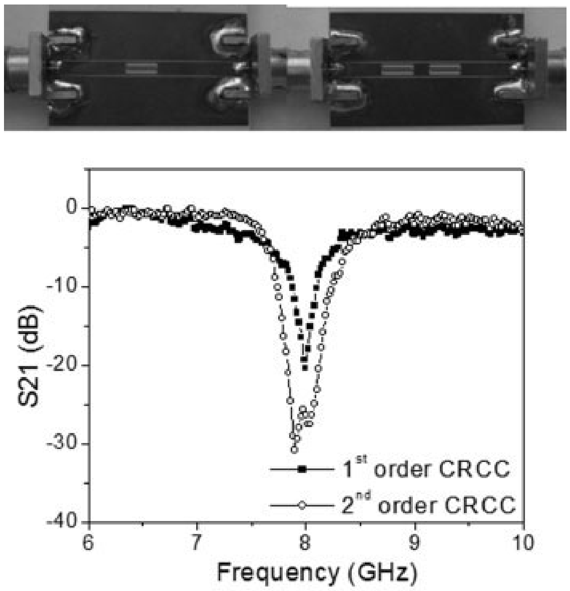
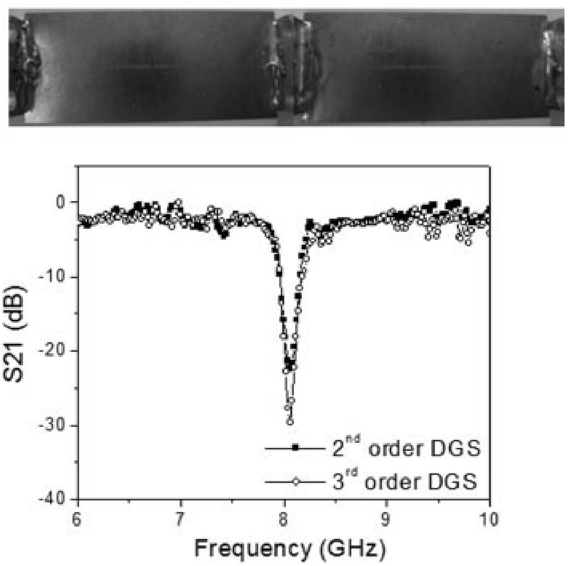


Figure 4. Time delay spread vs. the filter bandwidth and order: for a given bandwidth the time delay spread increases upon increasing the filter order, especially for relatively large rejection bandwidth. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]



(a)



(b)

Figure 5. Measured transfer characteristics of (a) 1st and 2nd order CRCC band-stop filters, and (b) 2nd and 3rd order DGS band-stop filters.

III. IMPLEMENTATION OF BAND NOTCHED FILTERS

To experimentally validate the above analysis, various conventional band-stop filters with different rejection bandwidths and filter orders were fabricated. The compact planar structure was chosen for those filters due to the limited size constraints for the transmitting tag in our UWB system. One way of realizing these band-stop filters is to integrate a compact coplanar waveguide (CPW) resonant cell (CRCC) to the CPW feed line [12]. As can be seen from Figure 5a, the fabricated 1st and 2nd order CRCC filters feature 600 MHz and 800 MHz rejection bandwidths, respec-

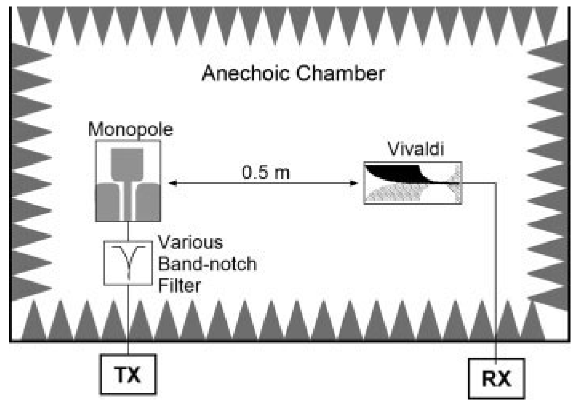
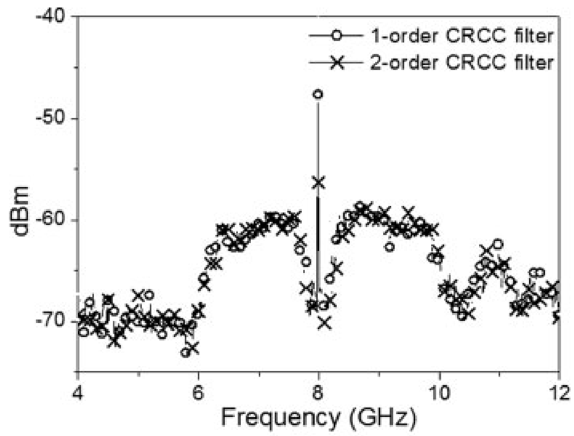
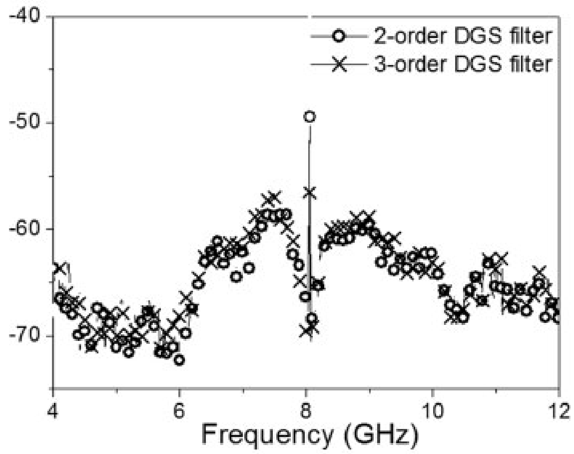


Figure 6. Experiment setup in an anechoic chamber.



(a)



(b)

Figure 7. Received signal power spectral densities without demodulation.

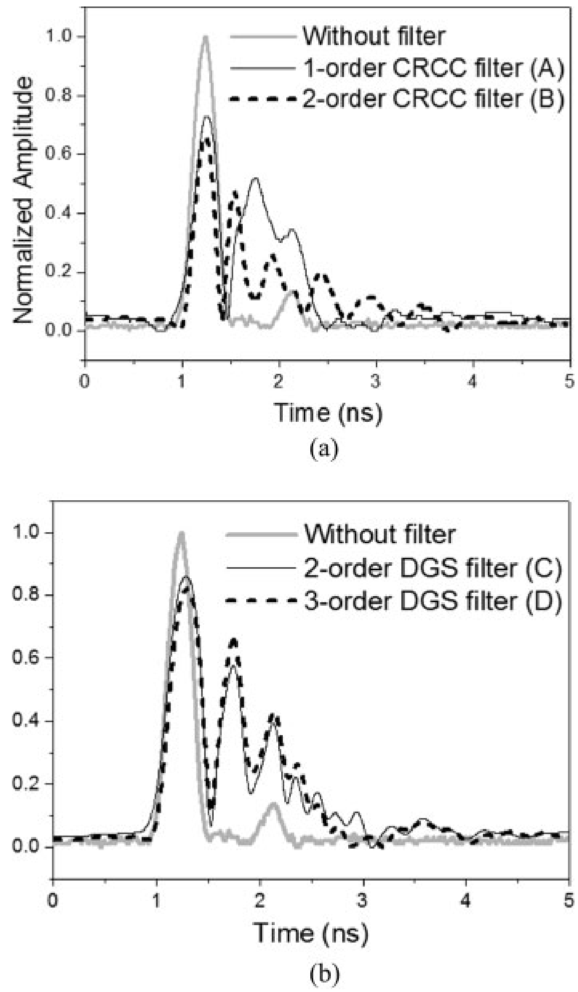


Figure 8. Measured time domain responses for (a) CRCC notched filters and (b) DGS notched filters.

tively. The 2nd order CRCC filter provides a rejection level close to 30 dB, which is adequate for eliminating the LO leakage indicated in Figure 1. To achieve a narrower rejection bandwidth and improve the Q factor, a U-slot shaped defected ground structure (DGS) under the microstrip line was adapted [11]. Figure 5b shows the measured transfer characteristics of the 2nd and 3rd order DGS band-stop filters. The rejection bandwidth of ~300 MHz at 8 GHz corresponds to a high Q factor of 27. In this case, the 3rd order DGS filter provides a sufficient LO rejection. In summary, to achieve high rejection levels for a given topology, it is necessary to increase the filter order. However, it could lead to unacceptable pulse dispersion with respect to the FPA and TDS as previously mentioned. Time domain measurements will be given in the next section to investigate those effects.

IV. EXPERIMENTAL VALIDATION

As seen in Fig. 6, the same experimental setup (as shown in Fig. 2) has been utilized in an anechoic chamber to measure the frequency and time domain response of the various fabricated band-stop filters. To minimize the received UWB signal distortion due to antennas and clearly see the filter effects, low dispersion UWB monopole and Vivaldi antennas with a wide operating bandwidth from 5 to over 12 GHz were utilized. The UWB monopole transmitting antenna was placed in front of the UWB Vivaldi receiving antenna at a fixed distance of 0.5 m.

The spectrums of the received signals without demodulation are shown in Figure 7. As can be seen, the 2nd order CRCC and 3rd order DGS notched filter provide sufficient rejections to eliminate the LO leakage as expected.

In the time domain measurements, we studied the impact of various band-stop filters on the FPA and the TDS. As shown in Figure 8, the measured pulse amplitudes are normalized with respect to the received signal without band-stop filter. As predicted, the 2nd order CRCC filter has the lowest pulse amplitude compared to the DGS designs because of its relatively wider rejection bandwidth. The performance of the 1st and 2nd order CRCC filters, as well as the 2nd and 3rd DGS filters are denoted by symbols A, B, C, D (in Figs. 3 and 4) respectively and has been summarized in Table I. The simulated results show a good agreement with the corresponding measured results. It should be noted that the measured TDS exhibits about a 0.2 ns longer in time than the simu-

TABLE I. First Pulse Amplitude and Time Delay Spread for Various Notch Filters

Notch Filter		Simulated	Measured	Simulated	Measured
Type	Rejection Level (dB)	First Pulse Amplitude	First Pulse Amplitude	Time Delay Spread (ns)	Time Delay Spread (ns)
1st CRCC	20	0.78	0.74	0.89	1.0
2nd CRCC	29	0.62	0.65	1.5	1.65
2nd DGS	22	0.86	0.85	1.1	1.3
3rd DGS	30	0.72	0.80	0.92	1.1

lated results, which is due to the extra received pulse ringing caused by other sources of hardware distortion that have not been considered in the simulation model, such as the antenna dispersion and the ringing from the 300 ps pulse generator itself. Based on Table I, it is clear that the 3rd order DGS filter provides enough rejection level (30 dB) while maintaining both a relatively large FPA (0.8) and a small TDS (1.1 ns) and could be adapted in our UWB system.

V. CONCLUSION

The LO leakage from the up-converter in the carrier-based UWB localization system could be remedied by using a multistage band-stop filter. Based on our analyses and measurements, it was found out that the filter order number needs to be optimized to satisfy specific pulse amplitude and delay spread requirements while providing sufficient band rejection level. Meanwhile, a narrower rejection bandwidth with the associated higher Q value would lead to the larger FPA and less TDS, thus would benefit the UWB system with minimum pulse dispersion. For example, the fabricated 3rd order DGS filter has provided adequate rejection level while maintaining a relatively large FPA and small TDS, making it the most suitable candidate for filtering the LO leakage in our carrier-based UWB system design.

REFERENCES

1. D. Barras, F. Ellinger, H. Jäckel, and W. Hirt, A robust front-end architecture for low-power UWB radio transceivers, IEEE Trans Microwave Theory Tech 54 (2006), 1713–1723.
2. M. Mahfouz, C. Zhang, B. Merkl, M. Kuhn, and A.E. Fathy, Investigation of high accuracy indoor 3D positioning using UWB technology, IEEE Trans Microwave Theory Technol 56 (2008), 1316–1330.
3. S. Khorram, Programmable mixer for reducing local oscillator feedthrough and radio applications thereof, US Patent 6,970,689, November, 2005.
4. M. Osoba, F. Westall, D. Crawford, J. Irvine, and R. Stewart, Mitigation of LO leakage DC offset in homodyne receiver, The 2nd IEE/EURASIP Conference on DSPenabledRadio, Southampton, UK, 19–20 September, 2005.
5. R.W. Charles, Local oscillator feedthru cancellation circuit, US Patent 5,001,773, March, 1991.
6. Datasheet, HMC553LC3B, available at: http://hittite.com/.
7. R. Minarik, Circuit for canceling local oscillator leakage through mixers, Microwave J 28 (1985), 182–186.
8. K. Chung, J. Kim, and J. Choi, Wideband microstrip-fed monopole antenna having frequency band-notch function, IEEE Microwave Wireless Compon Lett 15 (2005), 766–768.
9. J. Kim, C.S. Cho, and J.W. Lee, 5.2 GHz notched ultra-wideband antenna using slot-type SRR, Electron Lett 42 (2006), 315–316.
10. S. Zhang, G. Huff, and J.T. Bernhard, Antenna efficiency and gain of two new compact microstrip antennas, Proceedings of Antenna Applications Symposium, Allerton Park, Monticello, 2001, pp. 108–116.
11. D.J. Woo, T.K. Lee, J.W. Lee, C.S. Pyo, and W.K. Choi, Novel U-slot and V-slot DGSs for bandstop filter with improved Q factor, IEEE Trans Microwave Theory Tech 54 (2006), 2840–2847.
12. S.-W. Qu, J.-L. Li, and Q. Xue, A band-notched ultra-wideband printed monopole antenna, Antennas Wireless Propag Lett 5 (2006), 495–498.

BIOGRAPHIES

Cemin Zhang received the B.S. and M.S. degrees in electronic engineering from Zhejiang University, China, in 2001 and 2004, respectively, and received the Ph.D. degree in electrical engineering at the University of Tennessee, Knoxville, in 2008. In 2003, he worked as a RF engineer with UTStarcom Co., Hangzhou, China. In early 2004, he worked as a product engineer at Intel Co., Shanghai, China. Since 2008, he joined Hittite Microwave Corporation, Chelmsford, MA, as an MMIC design engineer. He has established a novel unsynchronized UWB system architecture to achieve the real-time mm-range 3D localization accuracy. He has authored/coauthored more than 30 journal/conference papers. Dr. Zhang is a member of Sigma Xi, Phi Kappa Phi, and National Scholars Honor Society. He was the recipient of 2007 URSI Student Fellowship and 2008 UT Chancellor's Citation for Extraordinary Professional Promise. He has served as a reviewer for IET Signal Processing and many international conferences.

Adel Elsherbini received his B.S. and M.S. degrees in electrical engineering from Ain Shams University, Cairo, Egypt, in 2004 and 2008, respectively. He is currently pursuing his Ph.D. degree in applied electromagnetics at the Radiation Laboratory, University of Michigan. His research interests include the design of ultra wideband antennas and subsurface remote sensing. Mr. Elsherbini is a member of Phi Kappa Phi and Tau Beta Pi. In 2008, he received the 2nd prize at the URSI General Assembly student competition and Rakham International Student Fellowship from the University of Michigan.

Aly E. Fathy received the B.S.E.E. degree, the B.S. degree in pure and applied mathematics, and the M.S.E.E. degree from Ain Shams University, Cairo, Egypt, in 1975, 1979, and 1980, respectively, and the Ph.D. degree from the Polytechnic Institute of New York, Brooklyn, in 1984. In February 1985, he joined the RCA Research Laboratory (now Sarnoff Corporation), Princeton, NJ, as a Member of the Technical Staff. In August 2003, he joined the University of Tennessee, Knoxville, as an Associate Professor. He holds 11 U.S. patents. Dr. Fathy is a member of Sigma Xi and Eta Kappa Nu. He was the recipient of five Sarnoff Outstanding Achievement Awards. He is an active member of the IEEE MTT-S International Microwave Symposium Technical Program Committee, the IEEE Antenna and Propagation Symposium, and the IEEE Radio and Wireless Steering Committee. He is the Technical Program Chair of the 2008 IEEE Radio and Wireless Conference.

Mohamed R. Mahfouz (S'98–M'01–SM'06) received the B.S.B.M.E. degree and the M.S.B.M.E. degree from Cairo University, Cairo, Egypt, in 1987 and 1992, respectively. He received the M.S.E.E. degree from the University of Denver, Denver, CO, in 1997 and the Ph.D. degree from the Colorado School of Mines, Golden, CO, in 2002. From 1998 to 2002, he served as Technical Director at the Rocky Mountain Musculoskeletal Research Laboratory in Denver, CO. In 2002, he became both Technical Director for the Center for Musculoskeletal Research and an Associate Professor at the University of Tennessee in Knoxville, TN. His current research interests include medical applications of UWB, biomedical instrumentation, medical imaging, surgical navigation, MEMS bio-sensors, and 3-D bone and tissue reconstruction. He has received numerous NIH and NSF grants and has authored many journal articles, conference papers, and book chapters. Dr. Mahfouz is a senior member of the IEEE.