# Compact Highly Integrated Planar Duplex-Antenna for Wireless Communications

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***Abstract*—Compact highly integrated multi-function RF front ends are critical for future wireless communication systems. In this paper, a novel concept of integrating the duplexer and the antenna is proposed and a proof-of-concept design is presented. First, a duplexer composed of split-ring resonators (SRR) and stub-loaded resonators (SLR) is designed. The SLR is used to transmit and receive the signals with different frequencies from two groups of split-ring resonators. To verify the concept, the duplexer is designed to operate in 2.48-2.63 GHz for transmitting and 2.8-2.9 GHz for receiving with a guard band of 170 MHz. It is shown that the duplexer designed is able to achieve a TX/RX isolation over 30 dB. Then, a novel dual band patch antenna is proposed for the first time by feeding the patch with a hairpin resonator through a slot in the ground plane. The hairpin resonator and the patch have the same resonant frequency and the two operating bands can be controlled by tuning the size of the slot, namely the coupling strength between them. The dual-band antenna operates in the same radiating mode and polarization at both frequency bands, which is always required in civil wireless communications. By using a co-design approach, a highly integrated duplex-antenna is designed. The duplexer and patch are designed in a planar stacked structure, sharing the same ground plane in the middle layer, which results in a compact size and potentially low cost. The duplex-antenna designed is shown to be able to work in 2.52-2.65 GHz (5%) for transmitting and 2.82-2.94 GHz (4.2 %) for receiving with TX/RX isolation over 32 dB at both bands. Simulated results agree well with the measured results, showing good performance in impedance matching, isolation and radiation patterns.**

***Index Terms*—Duplexer, duplex-antenna, integrated design, dual band, filtering, split-ring resonator, stub loaded resonator.**

## I. Introduction

WIRELESS communication systems, especially mobile communication, have experienced rapid development during the recent decades. In the traditional base-station communications, the uplink and downlink channels use two separated frequency bands with a guard band between them. A duplexer is used for the transmitter and receiver to share the same antenna, as shown in Fig. 1(a). The duplexer is required to have a high isolation between the transmitting port and receiving port so as to reduce the channel interference and protect the receiver module [1] [2].

Several technologies have been used to design a duplexer with improved performance. In [3], high temperature superconducting duplexer is designed for the base-station application. The isolation between the transmitter port and receiver port is greater than 35 dB. In [4], two balun diplexers based on stub-loaded resonators (SLR) are demonstrated, which achieved a common mode rejection better than 38 dB. An integrated compact duplexer is developed by using vertical stacked 3-D low loss cavity bandpass filters with a Tx-to-Rx channel isolation better than 35 dB [5]. Also, several planar duplexers with compact sizes are proposed using higher order modes of the resonators [6], or dual-mode resonators [7] [8].

In the applications for mobile communication, a broadband antenna or multiple antennas are always adopted to cover the uplink band, downlink band and the guard band between them. In [9], two PIFA with tunable capacitor loaded are designed to operate at transmitting and receiving channel, respectively. The advantage of this design is that the duplexer, which is used to isolate the transmitting and receiving channels, can be removed. However, this design requires much more space for placing the antenna. Besides, the isolation between the transmitting and receiving channel is poor, because the limitation of the spacing between the two antennas. To provide a better performance for the multiple transceivers, the use of a broadband or multi-band antenna is always a better option. Furthermore, to improve the robust of the base-station communications, two orthogonal polarizations are used for uplink and downlink communications simultaneously, which requires the two operating modes (two bands) to have the same polarization in the same antenna.

Highly integrated RF modules with multiple functions and compact size are increasingly important for modern wireless communication applications due to the requirements for reduction of the size, mass and cost of the system. The integrated design of passive components such as filters, power dividers, duplexers and antennas in the RF front-end has attracted great research interests in the past several years. The filtering antenna has been studied for its compact size, enhanced bandwidth, higher frequency selectivity, harmonic suppression and flatter antenna gain [10]-[13]. In [14], an integrated antenna-triplexer based on multi-mode excitation is presented. However, the three bands in the design were greatly

Manuscript submitted on Mar. 8, 2015; This work is supported by the project 'DIFFERENT' funded by EC FP7 (grant number: 6069923).

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frequency separated and the polarizations of the three ports are different. In addition, the design is lack of sufficient studies about the applications with closely located frequency bands and the isolation realization between them.

In this paper, a planar highly integrated design of duplex-antenna is presented for the first time for the potential applications of mobile base station communications. To achieve this goal, a duplexer and a dual-band patch antenna are designed simultaneously. The duplexer is designed based on the single mode split-ring resonator (SRR) and dual modes stub-loaded resonator (SLR). The two sets of SRR operate at uplink and downlink frequencies and the SLR is used to converge the two channels and connect to the antenna. To realize the transmitting and receiving in one antenna simultaneously, a novel dual-band patch antenna with same polarization is also designed. The antenna is composed of a patch and a hairpin resonator with the same resonant frequency. The dual band is achieved by separating the two resonant modes of the resonator-patch system through mutual coupling between the hairpin resonator and patch. Finally, the duplex-antenna is achieved by combining the duplexer and dual band antenna and removing the ports and 50 Ω interfaces between them. The simulated and measured results agree well, demonstrating that this highly integrated compact duplex-antenna has good performance and is suitable for the potential applications of wireless communications.

This paper is organized as follows. Section II, describes the integrated device structure and the design method. Section III presents a planar duplexer based on the SRR and SLR. Section IV presents a novel integrated dual band patch antenna with consistent polarization. Section V integrates the duplexer and dual band antenna to a duplex-antenna. Section VI presents the measured results followed by conclusion in Section VII.

## II. SYSTEM DESCRIPTION AND DESIGN METHOD

Fig. 1(a) shows the block diagrams of the conventional front-end module of a traditional wireless communication system. The system is composed of receive port, transmit port, duplexer and a antenna. Due to the receiver and transmitter modules works simultaneously in a system, duplexer is a necessary component to isolate the transmitting channel from the receiving channel for reducing the interference and protect the receiver from the high-power transmitting signals. Usually, a single broadband antenna is demanded to cover the uplink and downlink frequency band. Sometimes, multi-band antenna or multiple antennas are also used for transmitting/receiving. The antenna and the duplexer are designed separately and connected through 50 Ω interfaces, which lead to a large footprint of the cascade duplexer and antenna.

To reduce the volume of the RF front-end and meet the requirements for low cost and multifunction in the modern applications, an integrated front-end module is proposed in this paper, as shown in Fig. 1 (b). In this module, duplexer and antenna are integrated into a single module called "duplex-antenna", which combines the functions of a duplexer, filters and an antenna. As a result, the volume and cost could be

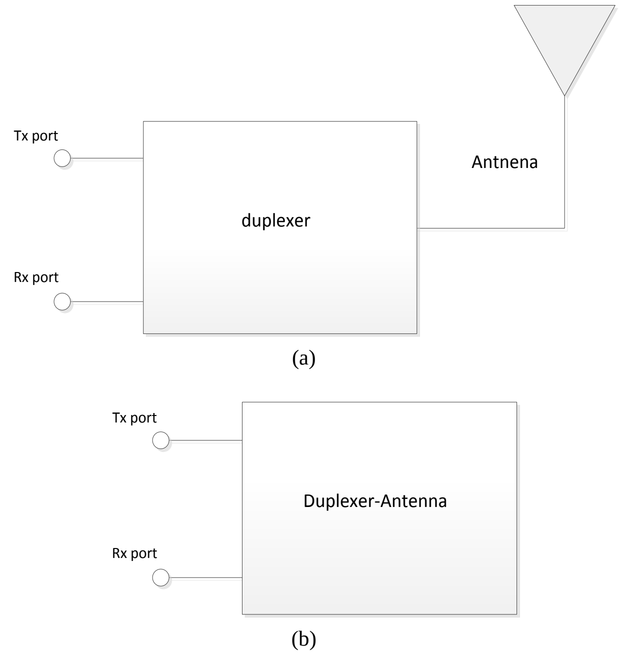



Fig. 1 The block diagrams of a RF front end: (a) Traditional, (b) With an integrated duplex-antenna

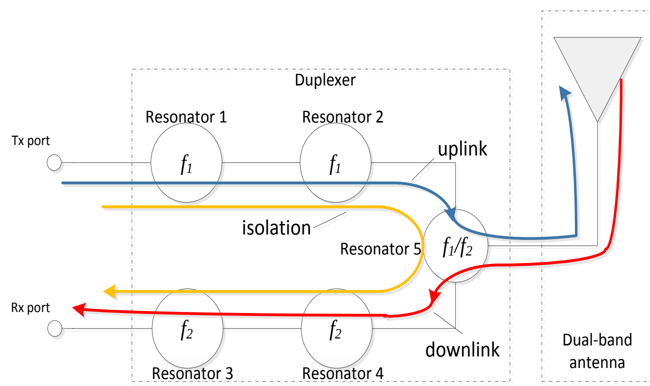



Fig. 2 The block diagram and realization of the integrated duplex-antenna through coupled resonators without transmission-line interfaces

reduced greatly. The duplex-antenna has two ports, one for transmitting and the other for receiving.

An unique feature of this design is that the duplexer antenna is formed exclusively of coupled resonators without the use of separate modules of duplexers and antennas together with the inter-connection cables and matching networks between them. This effectively provides a multi-pole filtering network with all the resonators and the resonant radiation element contributing to the bandwidth and frequency selectivity.

In order to realize the duplex-antenna, a design method based on resonators and dual band antenna is proposed, as described in Fig. 2. The duplexing function is realized by adopting two sets of single mode resonators as channel filters and a dual-mode resonator at the junction between the channel filters and the antenna. The first set of resonators (namely resonator 1, 2) resonate at a frequency of $f_1$, whereas the second set (namely resonator 3, 4) with the resonant frequency of $f_2$. The junction resonator exhibits dual modes at $f_1$ and $f_2$. The isolation between the transmit port and receive port is determined by the path of resonators as shown in Fig. 2. The isolation can be further

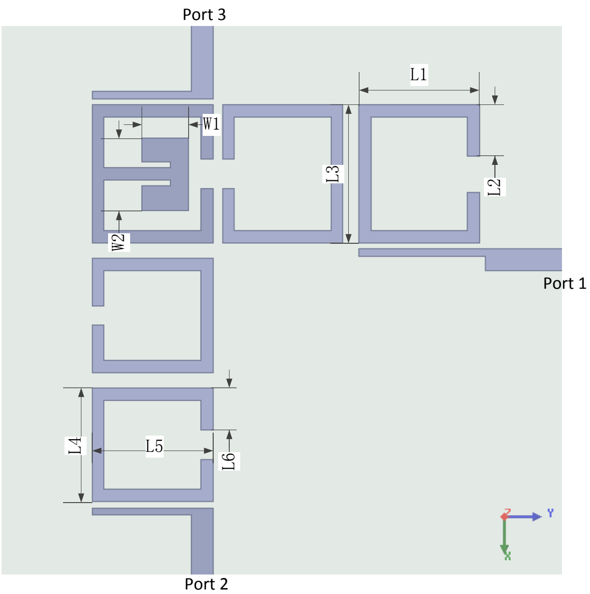



Fig. 3 The configuration of the all-resonator based duplexer with a dual-band SLR resonant junction

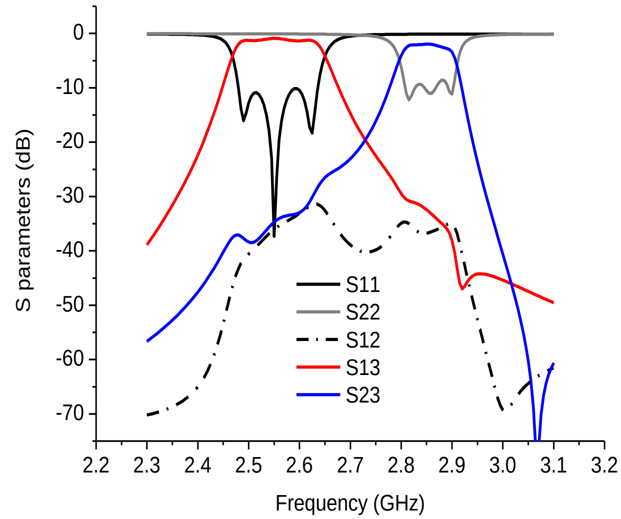



Fig. 4 The simulated S parameters of the duplexer

TABLE I

PARAMETERS OF THE ANTENNA PROPOSED: (MM)

| L1 | L2 | L3 | L4 | L5 | L6 | L7 | L8 |
|---|---|---|---|---|---|---|---|
| 10 | 3.5 | 11.4 | 9.4 | 10 | 3 | 10 | 8.4 |
| W1 | W2 | Patch_L | S_L | S_W | H1 | H2 | |
| 4 | 6 | 26.6 | 13.5 | 1 | 0.813 | 2.34 | |

improved when more resonators are used in the uplink and downlink routes. There are other ways to improve the isolation such as introducing transmission zeros, which will be investigated in the future work.

## III. PLANAR DUPLEXER DESIGN

Fig. 3 shows the configuration of the proposed duplexer, which is composed of two groups of split ring resonators and a T-shaped-stub loaded resonator. The T-shaped stub is used for reducing the length of the stub. The two split ring resonators adjacent to the port 1 resonate at the lower frequency $f_1$, whereas the two split ring resonators adjacent to the port 2 resonate at the higher frequency $f_2$. The split ring resonator is a half wavelength resonator, whereas the resonant frequencies of the T-shaped stub loaded resonator can be analyzed using odd- and even-mode method [15]. The SLR offers more degrees of freedom in tuning its two resonant frequencies so as to match with the two groups of split ring resonators as well as with port 3. The duplexer is printed on the Rogers 4003 substrate with dielectric loss tangent of 0.0027. All the designs and simulations process in this work were performed using HFSS 15.

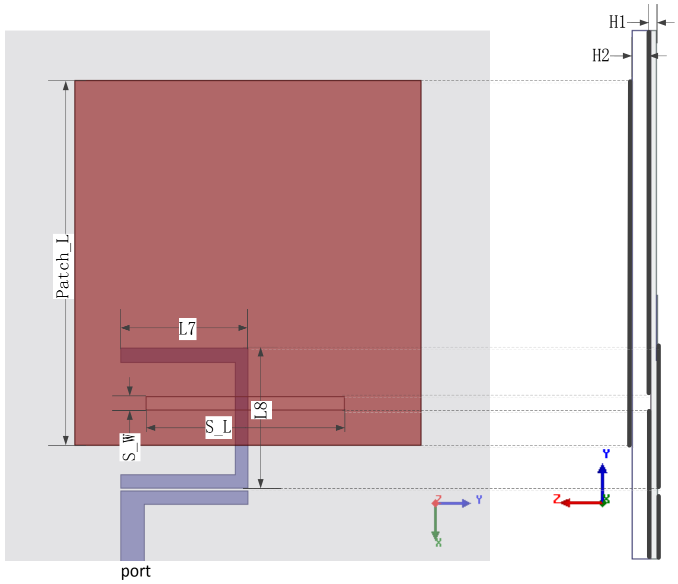
Since the duplexer is an intermediate design towards the duplex-antenna, it was not fully optimized. Fig.4 show the simulated S-parameters of the duplexer. It is observed that the duplexer has a passband of 2.48-2.63 GHz from port 1 to port 3 and a passband of 2.8-2.9 GHz from port 2 to port 3. The inserted loss in the passband is about 2 dB, which is mainly caused by the impedance matching performance. The isolations between the port 1 and port 2 in the two bands are over 32 dB and 35 dB, respectively. The geometry parameters of the duplexer is listed in Table I.

## IV. DUAL BAND PATCH ANTENNA DESIGN

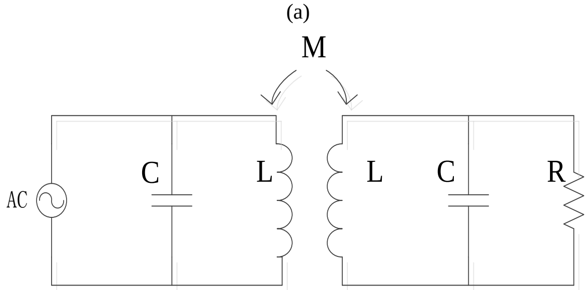
In order to realize a duplex-antenna, a broadband or a multiband antenna is usually required to match with the duplexer. Dual band or multiband antennas are usually designed by utilizing the multiple-patch or splitting slits in the patch [16]-[19]. However, the radiating direction and polarization purity in these designs cannot be guaranteed. In this paper, we propose a novel method to design a closely adjacent dual band patch antenna with the consistent polarization and radiating direction. Fig. 5 (a) shows the configuration of the dual band patch antenna. The patch is printed on the top layer of the upper board. A hairpin resonator and the feeding line are printed on the bottom layer of the lower board. The patch and the resonator share the same ground plane in the middle layer, which makes the design more compact and easy for integration.

The patch and the hairpin are synchronously tuned and coupled with each other through a slot in the ground plane. To better illustrate the realization of dual-band characteristics, the schematic diagram of hairpin-patch antenna sub-system is presented in Fig. 5 (b). In this schematic, the hairpin resonator is equaled as a lumped shunt *LC* resonator, while the patch is equaled as a lumped shunt *RLC* resonator and *R* represents the radiating impedance of the patch. In order to realize the dual band characteristics, the two resonators should be tuned to the same resonant frequency. In this sense, the hairpin-patch effectively form a second order resonant circuit, which generates two resonant frequencies.

Fig. 6 shows the simulated imaginary part and real part of




(a)




(b)

Fig. 5 The dual band patch antenna: (a) configuration, (b) schematic diagram of hairpin-patch sub-system

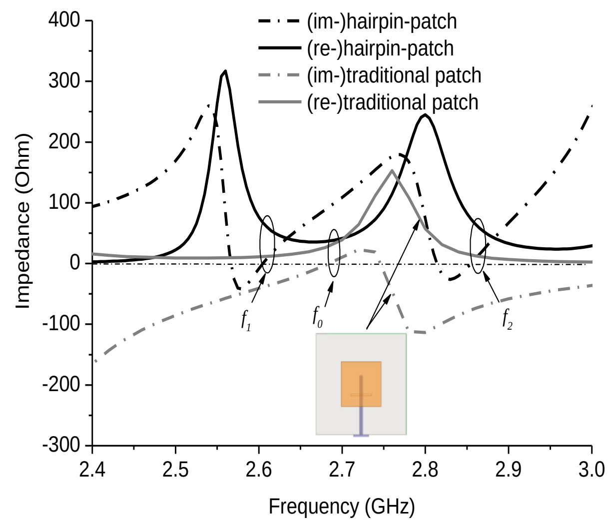



Fig. 6 The simulated input impedance of the hairpin-patch antenna and the traditional patch

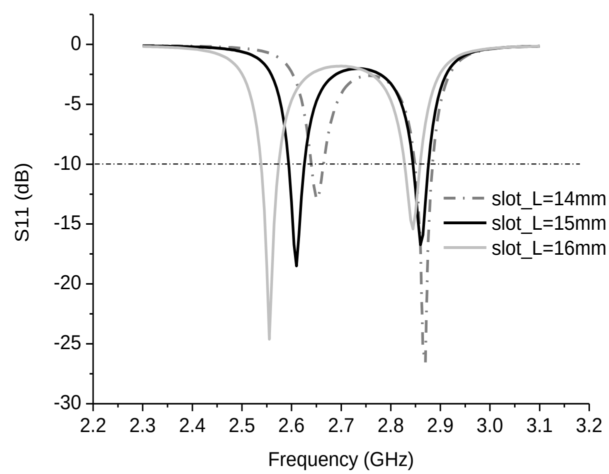
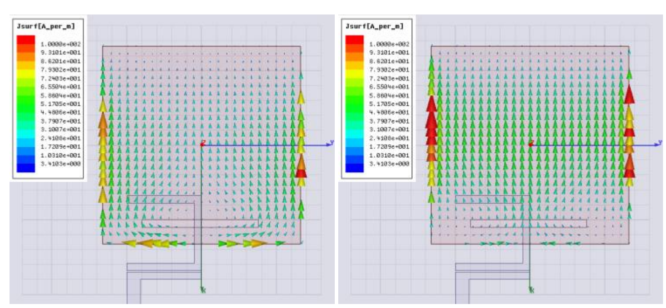



Fig. 7 The variation of simulated $S_{11}$ with different lengths of the slot



(a) (b)

Fig. 8 The simulated current distribution: (a) 2.6 GHz, (b) 2.84 GHz

input impedance of the dual band hairpin-patch antenna and a traditional patch antenna. It is observed from gray curves that the traditional patch has only one resonant frequency $f_0$ at around 2.7 GHz. However, when the patch is fed by a hairpin resonator, two resonant frequencies $f_1$ and $f_2$ are generated at 2.6 and 2.84 GHz, respectively (dark curves). As a result, dual band characteristics of the antenna can be achieved. Compared with the traditional patch, one more operating band can be produced without changing the antenna architecture.

Due to the middle part (maximum magnetic field) of the hairpin resonator is used for coupling in this design, the magnetic coupling way is in dominant [20]. When the hairpin resonator and patch over-coupled by increasing the dimension of the slot, the two resonant modes will separate accordingly. Fig. 7 shows the simulated $S_{11}$ vary with different lengths of the coupling slot. It is observed that the spacing between the two resonant frequencies increases when the length of the slot increases from 14 mm to 16 mm. It is also noticed but not shown here that the width of the slot has a similarly effect as the length. A wider slot will increase the separation between the two resonant frequencies.

The current distributions of the dual band patch antenna at 2.6 and 2.84 GHz are displayed in Fig. 8. It is observed that the patch operates in the base radiating mode at two resonant frequencies. The current is distributed along X-axis with the maximum current at the middle part of the patch. The current distribution determines that the antenna has a similar radiation and same polarization characteristics when operates in uplink and downlink bands.

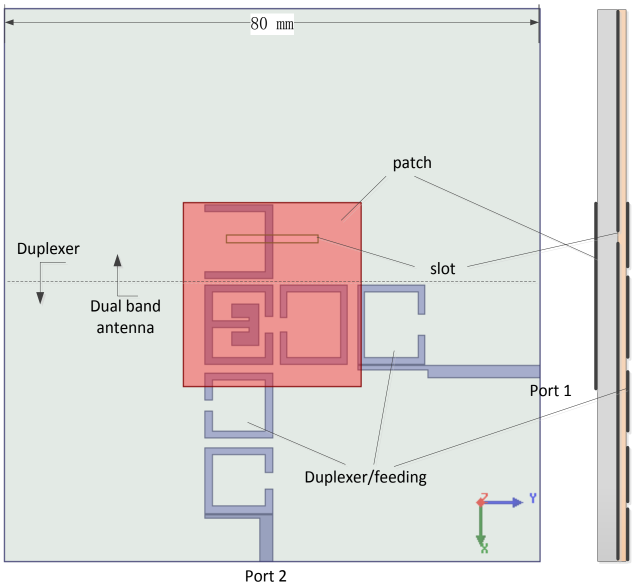
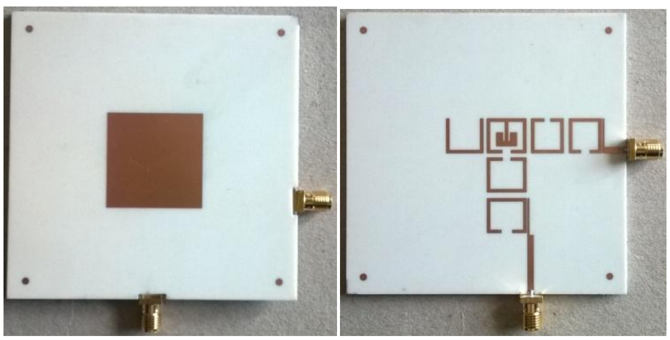



Fig. 9 The configuration of the integrated duplex-antenna



(a) (b)

Fig. 10 The prototype of the integrated duplex-antenna: (a) top layer, (b) bottom layer

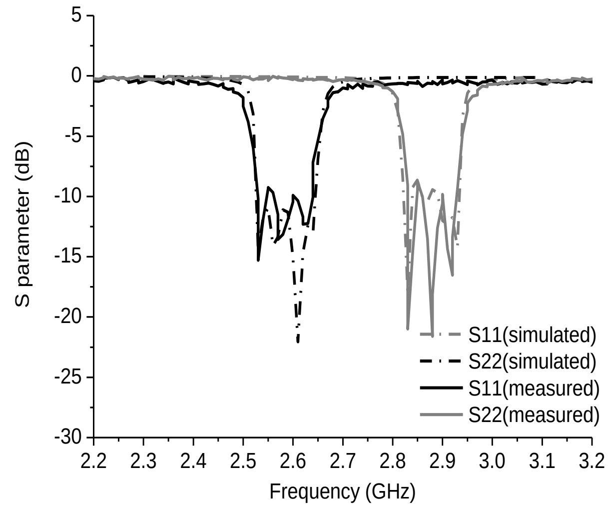



Fig. 11 The simulated and measured reflection coefficient of the duplex-antenna

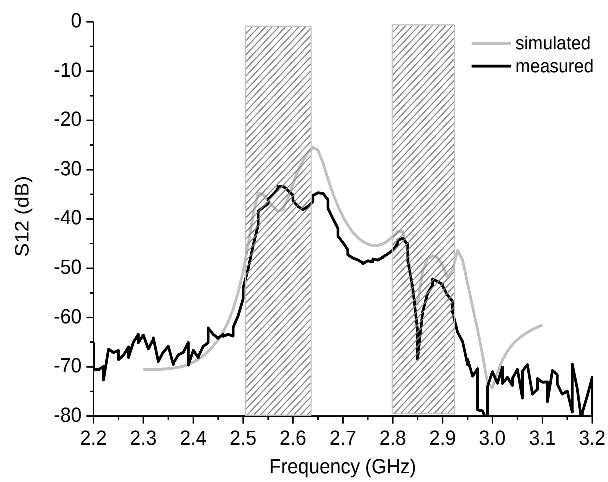



Fig. 12 The simulated and measured $S_{12}$ of the duplex-antenna

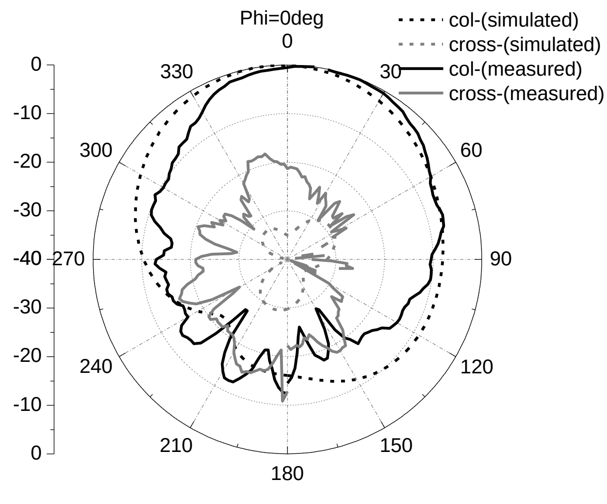
## V. INTEGRATED DUPLEX-ANTENNA DESIGN

Fig. 9 shows the configuration of the duplex-antenna proposed. It is an integration through electromagnetically coupling between the duplexer and the dual band patch antenna. The input ports of the antenna and the duplexer, the transmission lines as well as the matching circuit between them are removed, which result in a compact size. The whole duplex-antenna is composed of a network of seven coupled resonators including the resonant patch antenna and the dual mode SLR. This forms an eight-pole filtering network. In each channel, multiple poles can be realized, which is confirmed by the simulation and measurement results in Fig. 11.

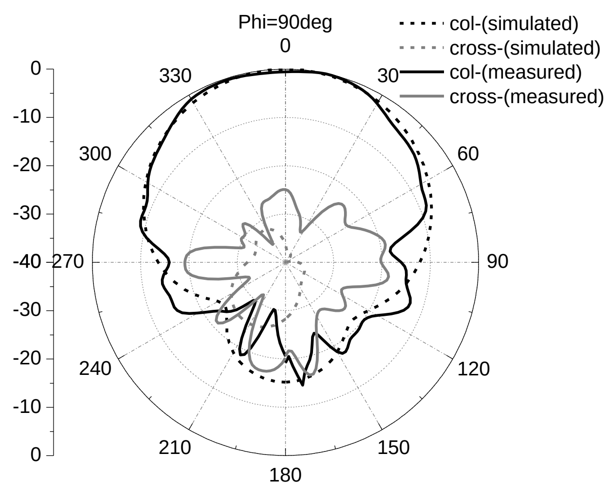
In this integrated design, the stub-loaded resonator plays a very important role. It not only combines the transmitting and receiving channels together, but also couples to the hairpin-patch antenna. We choose the uplink and downlink frequencies of 2.5 and 2.86 GHz as a demonstrator for potential wireless communication applications. It should be noted that the operating frequencies can be tuned according to the requirements of applications. Fig. 10 shows the photograph of the top and bottom layer of the integrated duplex-antenna.

## VI. RESULTS AND DISCUSSION

The simulated and the measured S parameters are displayed in Fig. 11. It is observed that measured results agree well with the simulated ones, showing a uplink operating band from 2.52 to 2.65 GHz (FBW =5%) and a downlink band from 2.8 to 2.92 GHz (FBW=4.2%), respectively. It is also observed that there are multiple reflection zeros in the both of the two bands, which are introduced by the third-order resonators and the patch antenna. Compared with the two bands of the antenna in Fig. 7, the bandwidths are greatly improved from about 1.2% to over 4%. The improvement in bandwidth is also attributed to the integrated design of the antenna and the duplexer. The difference between the simulated and measured results is attributed to the fabrication and measurement error. Furthermore, the duplex-antenna exhibits a good filtering performance with a rapid transit from out-of-band to in-band

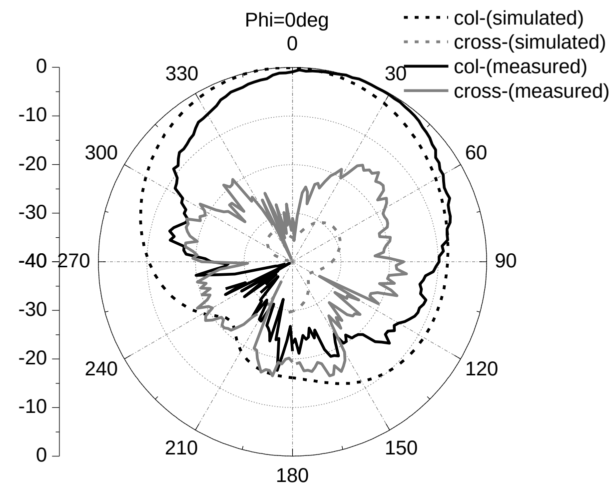



(a)

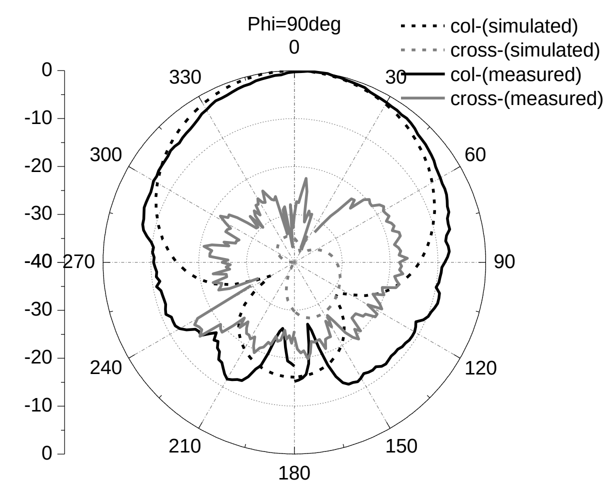



(b)

Fig. 13 The normalized radiation patterns at 2.6 GHz when port 1 is excited: (a) φ=0 deg, (b) φ=90 deg




(a)




(b)

Fig. 14 The radiation patterns at 2.84 GHz when port 2 is excited: (a) φ=0 deg, (b) φ=90 deg

and guard band between the two bands.

The simulated and measured inter-channel isolation $S_{12}$ of the duplex-antenna are presented in Fig. 12. The measured results agree well with the simulated one, showing a good isolation of over 32 dB in the uplink frequency band (2.52 to 2.64 GHz) and over 42 dB in the downlink frequency band (2.8 to 2.93 GHz). To further improve the isolation between the two ports, higher order filters or cross coupling could be used in the design.

Fig. 13 shows the normalized simulated and measured radiation patterns in two orthogonal planes at 2.6 GHz when port 1 is excited and the port 2 is terminated with a 50 Ω load. The measured results agree well with the simulated ones. The duplex-antenna exhibits a maximum radiation in the board side direction with a polarization in X-axis direction. The measured results show that the cross polarization discrimination (XPD) is over 20 and 25 dB in the two orthogonal planes, respectively.

Fig. 14 shows the normalized simulated and measured radiation patterns in two orthogonal planes at 2.84 GHz when port 2 is excited. The radiation patterns also exhibit a maximum radiation in positive Z axis direction and the main polarization in X-axis direction. The measured cross polarization discrimination is over 30 dB and 28 dB in φ=0 deg and φ=90 deg planes, respectively.

The simulated and measured antenna gains are shown in Fig. 15. It is observed that the duplex-antenna has a flat antenna gain about 5 dBi from 2.52 to 2.64 GHz (uplink) when port 1 is excited, which sharply decreases to below -20 dBi out of the band. In the band for downlink, the antenna gain is suppressed below -22 dBi. When port 2 is excited (downlink), the antenna has a stable gains about 4.5 dBi from 2.82 to 2.93 GHz. In the band of uplink, the antenna gains is suppressed below -19 dBi. The curves of antenna gain reveal that a very good isolation is achieved between the uplink channel and downlink channels.

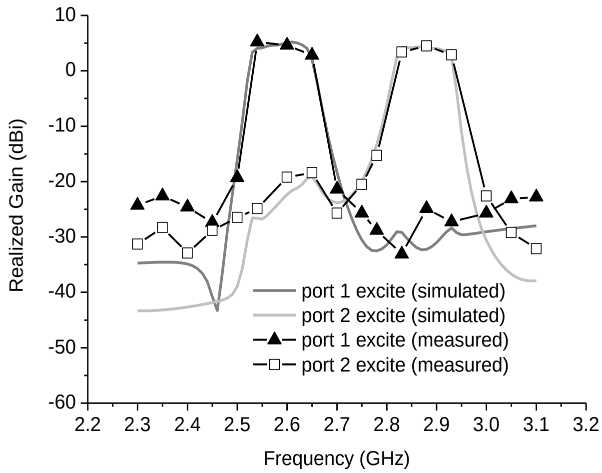



Fig. 15 The simulated and measured antenna gain

## VII. CONCLUSION

A novel concept and design method of integrating the duplexer with dual band antenna is proposed in this paper for the applications of wireless communication. To prove this design concept, a novel planar duplexer based on the single-mode split ring resonators and dual-mode stub loaded resonator is first designed. This is all-resonator based duplexer without any transmission line based signal distribution network. The dual mode SLR has been used as the junction resonator. Next, a novel dual band patch antenna with the same polarizations is presented by electromagnetically coupling the hairpin resonator with the patch antenna. The duplex-antenna is then realized by integrating the duplexer and the dual band antenna again through electromagnetic coupling without resorting to any transmission line interfaces between them. This highly integrated multifunction design renders significant reduction in the volume and the potentially in the cost of the RF front-end. The frequency response, such as bandwidth and frequency selectivity, can be improved. The simulated results agree well with the measured ones, showing a good performance in terms of impedance matching, isolation, radiation patterns, XPD and antenna gains, demonstrating that this design method is suitable for applications of wireless communications.


## ACKNOWLEDGMENT

The work is part of the project "DIFFERENT" funded by EC FP7 (grant number 6069923).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