Large-Signal Analysis and Characterization of a RF SOI-Based Tunable Notch Antenna for LTE in TV White Space Frequency Spectrum

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Abstract. In this paper, a compact frequency-agile notch antenna for LTE low-band using TV white space frequencies is designed and fabricated. The antenna aperture tuning is provided by a SOI CMOS tunable capacitor. The tunable capacitor RF non linearity analysis was studied and measured. The simulated and experimental performances are presented and demonstrate antenna tuning operation from 800 MHz down to 500 MHz. High linearity is validated with measured ACLR levels lower than −30 dBc up to 22 dBm input power in the considered frequency range.

Keywords: Tunable notch antenna · TV white space · Tunable capacitor · LTE · Linearity

1 Introduction

Due to the rapid demand for data over cellular networks, it has became difficult to cover all the traffic with current frequency bands. Thus, more frequency will be required to attend the increasing demand. However, it is becoming more and more challenging to allocate parts of spectrum for the data demand since most of the frequency bands which are suitable to mobile communications, are already assigned to the existing wireless systems.

The concept of Cognitive Radio (CR) proposed by [1] presents a solution to lower the usage of these widely used bands. The CR principles enable the unlicensed users to dynamically locate the unused spectrum segments and to communicate via these unused spectrum segments. CR used with TV White Space (TVWS) is one of solutions to excel spectrum resources shortage. TVWS are frequencies available for unlicensed use at locations where the spectrum is not being used by licensed services, such as television broadcasting. This spectrum is located from 470 MHz to 790 MHz in Europe [2].

The antennas usually used for this band are geometrically large to cover the entire frequency band. Several wideband antennas have been proposed in these bands [3]. In [4], an asymmetric fork-like printed monopole antenna is presented for DVB-T application, which achieves a −10 dB bandwidth of 451–912 MHz but with a size of

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247×35 mm^2. In [5], an UHF wideband printed monopole antenna has been introduced with dimension of 120×240 mm^2. This antenna achieves a gain higher than −6 dBi and an efficiency better than 14 % over the bandwidth 470–862 GHz. Reconfigurable antennas, which are much more compact and have a low profile structures, are the most compelling for TVWS where instantaneous bandwidth is only a narrow part of the overall band.

Therefore, in this paper a tunable miniaturized notch antenna working in the TVWS bands is designed using a tunable capacitor. Since transmit RF circuits generally operate at high power level, linearity is a critical parameter to prevent distortions or inter-channel interferences. As a result some typical reconfigurable RF component as varactor cannot be implemented. A large signal analysis and characterization of the tunable antenna has been performed by realizing adjacent channel leakage Ratio (ACLR) measurements on the antenna prototype using a LTE signal.

In this paper, a frequency-agile notch antenna using a SOI CMOS tunable capacitor and addressing TVWS from 510 MHz to 900 MHz has been studied, implemented and measured. First, TC tunable capacitor specifications are provided. Second, design, analysis and antenna measurements (impedance and efficiency) are presented. Finally, the linearity analysis is discussed.

2 Tunable Capacitor

The Tunable Capacitor (TC) used in this study is a SOI CMOS integrated circuit based on a network of binary-weighted switched capacitors. Floating body FET transistors are used as low-loss switches to select the appropriate capacitance value. Multiple FET transistors are stacked in series in order to prevent breakdown in OFF-state by providing voltage division of the high-power RF signal [6].

The 5-bit tunable capacitor has been modeled and designed under ADS simulation tool. The capacitance is digitally controlled through a SPI interface and it can be tuned from 1.3 pF to 7.1 pF at 1 GHz, Fig. 1.

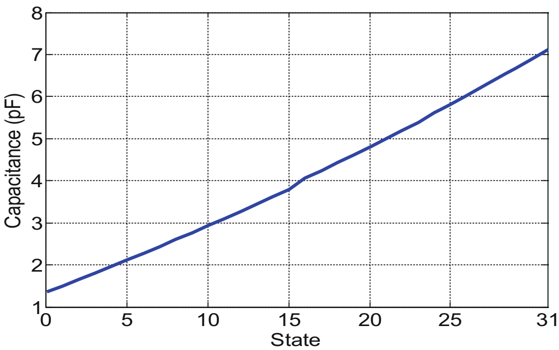


Fig. 1. Simulated capacitance (@1 GHz) vs TC state in shunt configuration

One of the most commonly emphasized electrical specifications for the tunable component is the Quality Factor (Q), which is determined by the resistive (dissipative) losses of the component. Tuning states versus obtained capacitance quality factor at 1 GHz is given in Fig. 2. It can be observed that a minimum quality factor of 40 is achieved for the highest TC state, whereas a maximum Q of 103 is obtained for the lowest state. This, demonstrate that the equivalent series resistance (ESR) is inversely proportional to the tuning state.

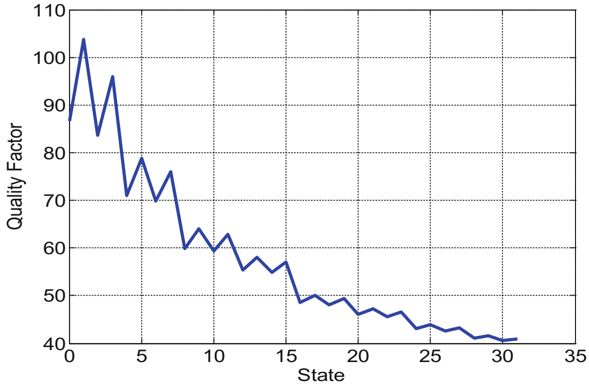


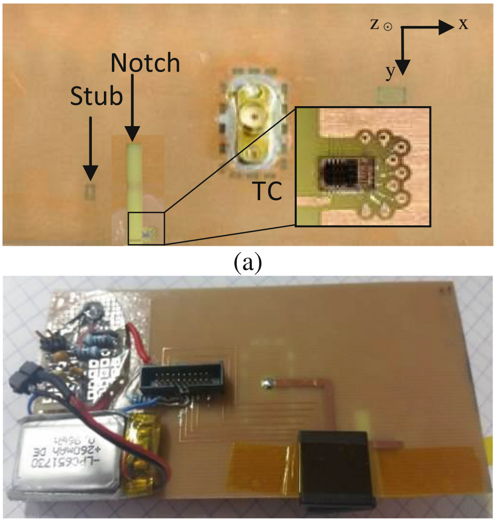
Fig. 2. Simulated quality factor (@1 GHz) vs TC state in shunt configuration

3 Frequency-Reconfigurable Antenna

3.1 Antenna Design

The proposed antenna is a notch antenna designed on FR4 substrate (εr = 4.3, tg δ = 0.025) with a thickness of 0.8 mm. The slot size is 18 mm by 3 mm (which correspond to λ/32.6 by λ/196.7 at 510 MHz) etched on a ground plane size of 103 mm by 50 mm (λ/5.7 * λ/11.8 at 510 MHz), typical smartphone size [7]. Microstrip feeding line and control lines for the SOI tunable capacitor are located on the bottom layer. An open stub is set at the end of the microstrip line to match the antenna impedance (Fig. 3a). Orthogonal orientation and central positioning of the coaxial connector on the PCB helps to minimize interactions with measurement cable and disturbance of the radiated EM field as the surface currents are mainly located at the edges of the PCB, which contribute to the radiation. A small circuit powered by a miniature battery is used to maintain the tunable capacitor value during the anechoic chamber characterization (Fig. 3b). The tunable capacitor is positioned at the open end of the notch, where high electric fields are concentrated, to allow the antenna tuning at TVWS bands.

The input impedance is shown in Fig. 4. Good agreement is observed between simulated and measured results. The unloaded antenna resonance frequency is 2.3 GHz which does not correspond to $\lambda_g/4$ due to the capacitive effect of the TC footprint at the open end of the slot.



(a)

(b)

Fig. 3. Antenna structure (a) top view (b) bottom view

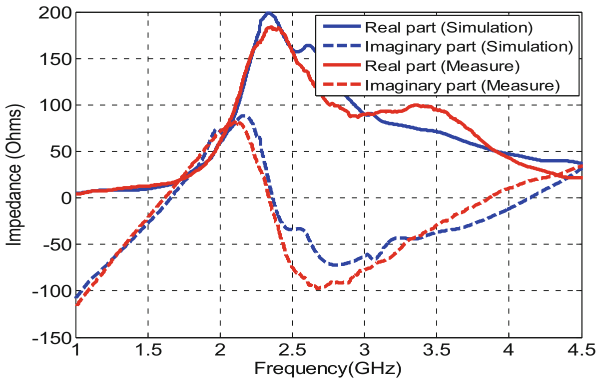


Fig. 4. Comparison of input impedance for the unloaded antenna

3.2 Antenna Tuning

The tunable capacitor has been modeled under ADS and each state is imported into the EM simulator. Figure 5 gives a comparison between simulation and measurement of the antenna response for a fixed capacitor connected at the end of the stub ($C_{stub} = 1$ pF) and different settings of the tunable capacitor. Simulated resonance frequency can be tuned from 550 MHz up to 960 MHz. The achievable bandwidth at −6 dB reflection coefficient ranges from 12 MHz to 70 MHz (Fig. 6) when operating frequency increases. The measured frequency response of the notch antenna for the different tunable capacitor settings ranges between 510 MHz and 900 MHz. The difference between simulations and measurements can be explained by some inaccuracies in the TC model.

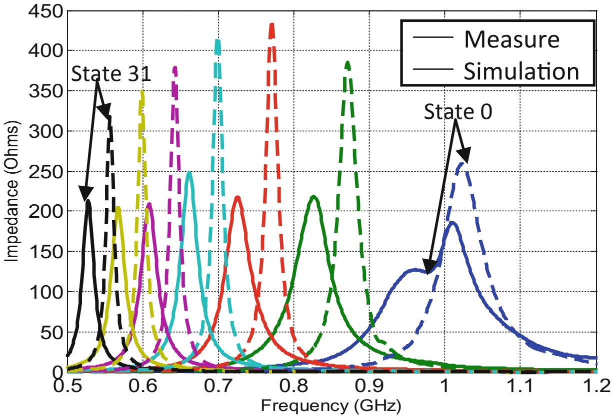


Fig. 5. Comparison of simulated and measured antenna input impedance (real part)

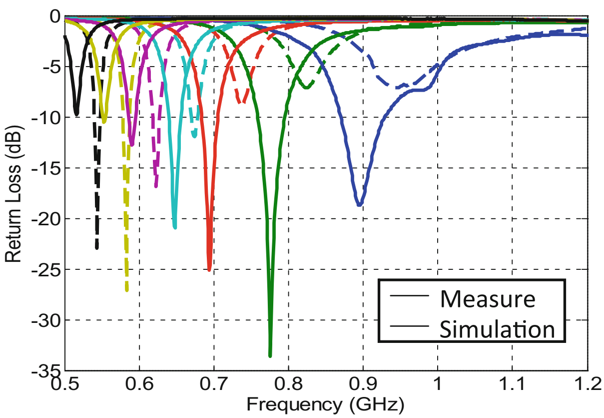


Fig. 6. Comparison of simulated and measured antenna response

To address TVWS, a limited set of capacitor states (from 5 to 31) will be considered. Frequencies from 470 MHz to 510 MHz are not addressed with actual devise. It is so easily to cover them, just to use another tunable capacitor with a higher tuning ratio or to connect a fixed capacitor in parallel configuration. The time estimating to finish transition between states has been measured to about 5 μs. Details will be published in other works.

The measured antenna radiation patterns including the co polarization and the cross polarization in both (xz) and (xy) planes at 510 MHz and 770 MHz are presented in Fig. 7. The gain was measured in the CEA-Leti anechoic chamber. It is important to note that radiation measurements are carried on without any metallic coaxial cable nor

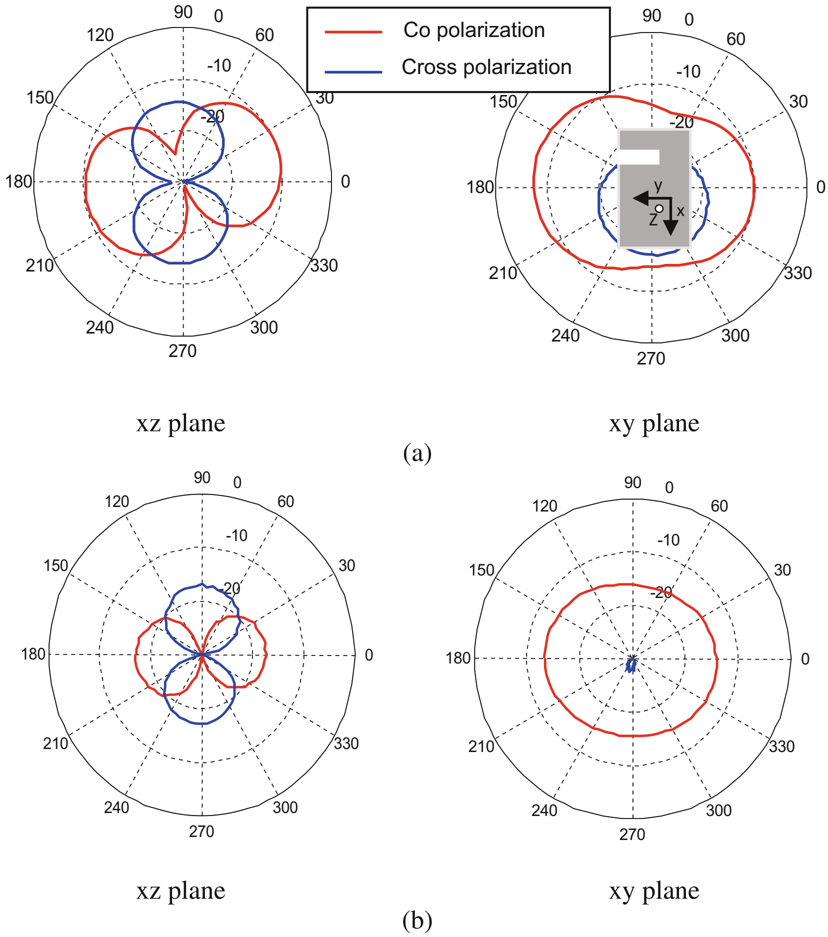


Fig. 7. Measured radiation pattern (realized gain) of the antenna at (a) 770 MHz and (b) 510 MHz (Color figure online)

control interface not to perturb the antenna radiation and consequently the efficiency estimation. The gain decreases as expected when the antenna is tuned to lower frequencies, at 770 MHz the notch length is λ/21 and at 510 MHz the notch is λ/33. In fact, as the antenna is tuned away from its natural resonance, higher currents run on the miniaturized surface and the series resistance (ESR) of the tuning component causes higher insertion losses. The ohmic losses in the TC ESR which are proportional to the square of these high currents, increase and cause higher efficiency degradation. Thus, it is a trade-off between antenna size, radiation performances and ESR. This ESR value results of both the IC design and the IC technology.

As a result of the reduction in realized gain, a total efficiency degradation is observed (−10 dB at 770 MHz). In order to demonstrate losses introduced by the ESR, an ideal TC (ESR = 0 Ω) was simulated and results indicate that for state 5 the antenna resonance frequency is 770 MHz and the corresponding total efficiency is −2.5 dB and for state 31, the total efficiency is −5.8 dB. Equally at low frequency, the antenna is miniaturized and consequently, bandwidth and efficiency decrease as predicted by the fundamental limits of electrically small antennas [8], these are the losses of the finite conductivity. The TC ESR decreases the efficiency with a shift of 7.5 dB for state 5. In next works, methods to reduce ESR and improve the antenna efficiency will be addressed.

4 Analysis and Characterization of Tunable Antenna Linearity

One critical specification for digital communication systems is the Adjacent Channel Leakage Ratio (ACLR) corresponding to signal distortion leaking in neighboring channels. Leakage power influences the system capacity as it interferes with the reception in adjacent channels. Therefore it must be rigorously controlled to guarantee correct communication for all subscribers in a network. ACLR is the ratio of the power in the adjacent channels to the power in the transmit channel. ACLR limits are given in the standard for the whole system, however up to now there are no specific constraints for the antenna.

4.1 ACLR Measurement Setup

ACLR measurements are made using a spectrum analyzer and the required test signals are built using a signal generator. In the following setup, a Vector Signal Generator with an internal baseband generator is connected to the antenna in transmission to allow generation of a LTE signal and the received signal from the measurement (Horn) antenna is connected to a Spectrum Analyzer (Fig. 8). For LTE, depending on the considered signal bandwidth, the adjacent channels are located at ± 1.4 MHz, ± 3 MHz, ± 5 MHz, ± 10 MHz, ± 15 MHz and ± 20 MHz offsets [9].

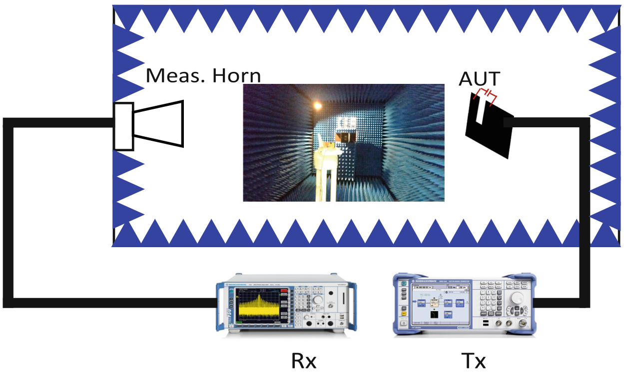


Fig. 8. Measurement setup around the anechoic chamber

4.2 ACLR Measurement Results

Figure 9 shows the measured ACLR characteristic of the tunable antenna for TC state 5 and a 16 QAM LTE 10 MHz uplink signal at 770 MHz for different antenna input power (Pin) ranging from 5 dBm to 23 dBm. Dotted line corresponds to the noise floor. The tunable antenna respects the standard ACLR specification of −30 dBc up to 22 dBm input power at 770 MHz.

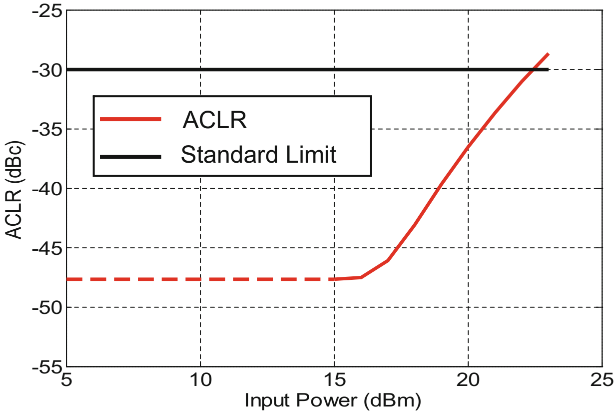


Fig. 9. Measured ACLR versus input power with a LTE 16 QAM 10 MHz signal at 770 MHz (Color figure online)

ACLR was measured for different TC states and frequencies using an LTE 16 QAM 10 MHz uplink signal.

Table 1 summarizes the linearity performance of the tunable antenna.

Table 1. Measured power at the input of the tunable antenna for ACLR = −30 dBc

State	State 5	State 10	State 15	State 31
Frequency	770 MHz	685 MHz	630 MHz	510 MHz
Pin (ACLR = −30 dBc)	22 dBm	22 dBm	23 dBm	22 dBm

The tunable antenna respect the standard specification up to 22 dBm input power which corresponds to the LTE UE transmit power as specified in 3GPP TS36.101 (UE core specification) [9].

5 Conclusion

In this paper, a miniature tunable notch antenna is proposed to address LTE low bands in TVWS spectrum. The notch antenna incorporates a SOI CMOS tunable capacitor at its open-end to operate in the different communication bands ranging from 510 MHz to 900 MHz. Measured results demonstrate trade-off between compact size, limited instantaneous operating bandwidth and efficiency. The RF linearity characterization of the tunable antenna has been performed through ACLR measurements on the antenna prototype and obtained results demonstrate that the proposed tunable antenna respects the standard specifications. Due to the dynamic frequency allocation within TVWS, fast transition times between frequency bands are expected to satisfy high quality communications. At last notice the proposed antenna solution is not restricted to LTE but is also compatible with other waveforms.

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