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On the Currents Magnitude of a Tunable Planar-Inverted-F Antenna for Low-Band Frequencies

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Abstract—Tunable antennas are a promising way to overcome bandwidth limitations for the new communication standards. Nevertheless they become very lossy at low frequencies. This paper presents an investigation on the currents running through the source, the short and the capacitor of a tunable Planar Inverted F Antenna (PIFA) for hand-held devices. Simulations suggest that the losses due to the currents running through the external tuning component depend on its location and value. Therefore it should be placed the furthest away from the location of the source and the short in a PIFA design and have small capacitances.

Keywords—tunable antenna; PIFA; losses; capacitor; currents.

I. INTRODUCTION

For the next Long Term Evolution (LTE) standard, the mobile terminals will need to operate in frequency bands between 700 MHz and 2.6 GHz. One of the challenges for antenna designers is to be able to cover the whole frequency spectrum. Wide-band and multi-band antennas have been one way to cover different standards. Hexa-band antennas [1] - [3] with small size can cover many bands; but they are often designed for frequencies above 1.5 GHz and the next 4th Generation (4G) communication standards requires to cover 21 bands, starting at 700 MHz. Such bandwidth for wide-band antennas type would require a space that is not available in the small handsets since size and bandwidth are inversely related [4] - [6]. Moreover a strong trend in the mobile communication technology is to decrease even more the size of the handsets. Those two tendencies obviously oppose each other and the consequence on antenna design is significant. In this respect tunable antennas are investigated. Tunable antennas in comparison with multi-band antennas have the advantage to be more compact and therefore occupy less volume in the mobile terminal [7] - [11]. They can also be narrow-band since they only need to cover one channel instead of a full band. Channels in LTE are between 1.4 MHz and 20 MHz [12]. This narrow-band advantage of tunable antennas allows for designs with a high Quality factor (Q). The antenna Q is widely investigated, mainly for the calculation of its low bound which determines the bandwidth potential of a design [13].

This study presents a PIFA which is a widely used design in mobile phone industry because of its integrated and low

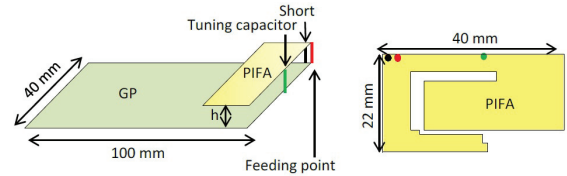


Fig. 1. Geometry of the radiating structure.

profile design, low fabrication cost and good performance. The proposed PIFA is tuned with an additional capacitor placed between the antenna plate and the Ground Plane (GP) plate. The investigation focuses on a cause of the degradation of the antenna total efficiency at the low frequencies (800 MHz band). The paper is structured in five sections. The investigated antenna design is introduced in Section II. Successively Section III describes the applied tuning techniques. This is followed in Section IV by measurement results and finally conclusions are disclosed in Section V.

II. ANTENNA DESIGN

The investigation on the currents running through a tunable lumped component are done on a PIFA whose dimensions are shown in Fig. 1. The tuning component is a lossless capacitor. Its position and value will vary throughout the analysis.

A. Phone Form Factor

The investigation is made at frequencies in the 800 MHz band for a small phone form factor in order to choose a tough design. On the one hand the Ground Plane (GP) dimensions are 100×40 mm² and its resonance frequency is therefore around 1.1 GHz, whereas on the other hand the investigated frequencies are 300 MHz lower. Therefore resonances with large bandwidths and good radiation properties are harder to achieve. When the two resonances (GP and PIFA) are close the Quality factor (Q) of the overall structure is rather low and the bandwidth wide; coupling with the GP enhances the radiation and lowers the Q of the resulting structure. The Q of the proposed antenna is affected by the tuning which is presented in the following sections as well.

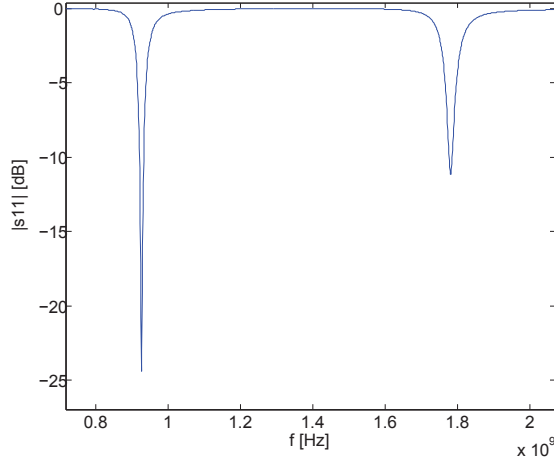


Fig. 2. $|S_{11}|$ of the investigated PIFA design.

B. Radiating Element

The proposed PIFA is a dual band element which resonates at 918 MHz and at 1.8 GHz, without tuning capacitor. The thickness (h) is set to 2 mm which results in a slim and narrow-band design. It exhibits then a Q of 57 at 918 MHz and a bandwidth (BW) of 20 MHz at -6 dB, as shown in Fig. 2.

III. TUNING SIMULATIONS

The location of the tuning capacitor on the PIFA design is fundamental for the tuning range. That is to say, at a given location increasing the capacitor value will decrease the resonance frequency of the resulting structure. Additionally different locations of the same capacitor will also tune the resonance frequency. The above-described results suggest that different combinations of capacitance and location can lead to the same resonance frequency. This has a strong consequence on the tuning range and the tuner range : on the tuning range since if large steps are allowed very low frequencies can be achieved and therefore the tuning range is wide whereas if fine tuning is required a position closer to the source is needed and the tuning to a very low frequency requires a very high capacitance. The tuner range is also affected by it since the fine tuning depends on the lowest capacitance achievable by it, and this determines then the position of the tuning capacitor on the PIFA design. Moreover it has consequences on the efficiency of the system : to better understand this mechanism an investigation of the currents running through the source, the short and the capacitor has been performed.

A. Q value

The investigation of the antenna Q at the resonance frequency (f_r) is relevant to the study because of its strong relation with the fields and therefore with the currents in the antenna structure. At resonance the input impedance is purely real and the Q is defined as :

$$Q_{fr} = \frac{2\omega_r W}{P} [13],$$

TABLE I
Q VALUES FOR A CAPACITOR 17 MM AWAY FROM THE SOURCE

	f_r [MHz]	C [pF]	Q
Stage 1	875	0.82	87
Stage 2	867	1	87
Stage 3	830	1.7	138
Stage 4	811	2.07	162

where W is the time-average energy stored and P is the dissipated power. In this paper the antenna Q refers to the matched VSWR Q and it relates to the Matched Bandwidth (MBW) as follows :

$$Q_{fr} = \frac{2\sqrt{\beta}}{MBW_{fr}}, \text{ with } \sqrt{\beta} = \frac{VSWR - 1}{2\sqrt{VSWR}} [13],$$

where the characteristic impedance of the antenna is perfectly matched to the 50 Ω antenna's feed point resistance at the tuned frequency. When the antenna element is tuned further away from the GP resonance frequency, towards lower frequencies, over-coupling happens between the GP and the PIFA. This phenomenon leads to an increase of the Q .

B. Fixed Capacitor Location

Four frequencies are chosen in the 800 MHz band as an example. Tuning is first achieved with 4 different capacitance values up to 2 pF. The capacitor is arbitrarily placed in a middle position at a distance of 17 mm from the source location. Results are presented in TABLE I where it is also shown the Q of the resulting antenna for the four stages of tuning. Lowering the antenna resonance frequency by 60 MHz with a 2.07 pF capacitor results in an increase for the Q of 180 %.

Fig. 3 shows the magnitude of the currents running through the main connections between the PIFA and the GP for the above-mentioned 4 stages of tuning. The source, the short and the capacitor experience different current magnitudes as the resonance frequency is tuned and the Q increased. The magnitudes are normalized to 1 W input power in order to be comparable to each other and to nowadays components. As the capacitance of the tuning element increases the currents running through the source slightly decrease, but the ones through the short increase and the ones delivered to the capacitor significantly increase. The percentages of increase of the magnitudes of the currents are shown in TABLE II and calculated with respect to the stage 1 of tuning. The currents running through the capacitor are increased by 220 % between the first and the last tuning stages. A capacitor has an Equivalent Series Resistance (ESR) which produces losses proportional to the square of the currents : $P_L = I^2 \times \text{ESR}$. This relationship dictates the importance of the currents delivered to the capacitor. They are source of total efficiency degradation and should be minimized.

C. Fixed Capacitance

The capacitor is now placed at different positions along the edge of the PIFA. Its value is kept constant and it is arbitrarily

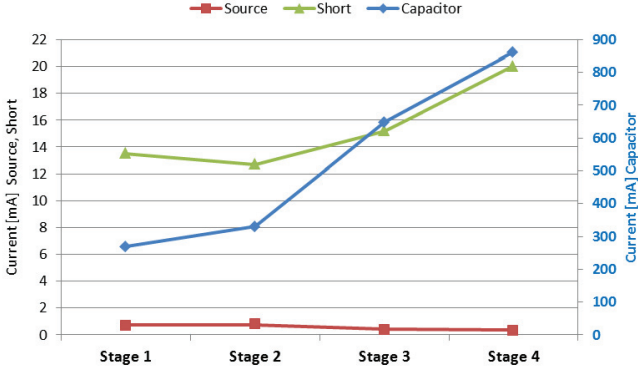


Fig. 3. Currents through the capacitor, the source and the short of a PIFA when it is tuned towards lower resonance frequencies with a capacitor placed at 17 mm from the source. Normalized to 1 W input power.

TABLE II
INCREASE IN THE CURRENTS FOR A CAPACITOR 17 MM AWAY FROM THE SOURCE

	ΔI_C [%]	ΔI_S [%]	ΔI_{Sh} [%]
Stage 1	0	0	0
Stage 2	22	1.8	-6
Stage 3	140	-42	12
Stage 4	220	-53	48

chosen to be equal to 1 pF. The same resonance frequencies than in Section III-B can be obtained. Changing only the component position along the edge of the PIFA and not its capacitance allows for the same tuning range. The Q of the antenna is calculated for the 4 stages of tuning. The TABLE III shows the distances to the source (D_S) where the capacitor is placed and summarizes the Q values of the resulting structure at the resonance. As previously the Q of the overall antenna increases when the resonance frequency is tuned towards lower frequencies. However it increases in a slower manner, for the whole tuning range the Q has only been increased by 150 % instead of 180 % previously. This tendency is reflected in the currents magnitudes shown in Fig. 4 - normalized to 1 W input power. The increase of the currents is less dramatic than in the previous case. The currents through the capacitor and the short are increased by 87 % and 48 % respectively, as summarized in TABLE IV. In these tuning configurations the losses due to the ESR will be smaller than in Section III-B.

Of course a mechanical tuning with only one capacitor would be very difficult to implement, space consuming and not robust. But the point of this study is to show that the choice of the location of the tuning component will have an impact on the losses of the antenna over the tuning range and it should be made after a parametric investigation from an efficiency point of view. It is inferred from the simulations that some locations and capacitance values will lead to great losses in the total efficiency (η_T) because of the high currents running through the capacitance. Then, the further from the source location, the lower the capacitance needed to achieve low frequencies

TABLE III
Q VALUES FOR A 1 pF CAPACITOR

	f_r [MHz]	D_S [mm]	Q
Stage 1	875	15	87
Stage 2	867	17	87
Stage 3	830	25	138
Stage 4	811	33	135

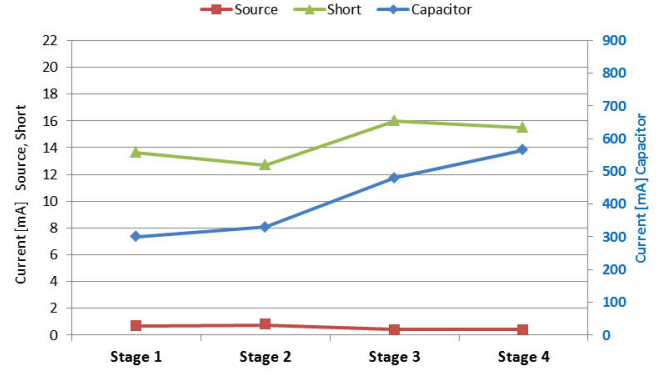


Fig. 4. Currents through the capacitor, the source and the short of a PIFA when it is tuned towards lower resonance frequencies with a 1 pF capacitor placed at different locations. Normalized to 1 W input power.

TABLE IV
INCREASE IN THE CURRENTS FOR A 1 pF CAPACITOR

	ΔI_C [%]	ΔI_S [%]	ΔI_{Sh} [%]
Stage 1	0	0	0
Stage 2	9	7	-6
Stage 3	60	-38	16
Stage 4	87	-40	14

and therefore the smaller the losses. It can be also noted that the currents running through the short can be high and lead to further losses.

IV. MEASUREMENTS

The previous sections showed that the location and the value of an ideal capacitor influence the magnitude of the currents delivered to it. This has an impact on the losses of the antenna since the ESR dissipates a power proportional to the square of the currents running through it. In this section the radiation efficiency of a mock-up is investigated. In order to have comparable results, the locations and the capacitance values have been chosen with the aim of hitting the same resonance frequencies. In the first case a 1 pF capacitor is placed at 33 mm from the source, in the second case a 4 pF capacitor is placed at 16 mm. In both cases the resonance frequency is 867 MHz, due to the fabrication process. However it is a proof of principle. The measured η_T of the PIFA are shown in TABLE V. They are computed from the 3-D radiation patterns by using the 3-D pattern integration technique. The two components,

TABLE V
MEASURED EFFICIENCIES AT 867 MHz

Mock-up	Tuning Capacitance	ESR	D _S	η_r
Mock-up 1	1 pF	0.47 Ω	33 mm	-1.6 dB
Mock-up 2	4 pF	0.29 Ω	16 mm	-2.8 dB

having different capacitance, have thus a different ESR. The difference of the measured efficiencies is greater than 1 dB.

V. CONCLUSION

In this paper we have investigated the magnitude of the currents running through the main components of a PIFA when it is tuned towards lower frequencies in two cases. In the first case an usual tuning mechanism is investigated where a tunable capacitor is placed at a fixed position on the PIFA. The capacitance is increased and the resonance frequency is thus decreased. In the second case different positions of the tunable capacitor are investigated. In both cases the chosen resonance frequencies are in the 800 MHz band. They are identical so that comparisons can be made. It is observed that in both cases the magnitude of the currents at the short and at the capacitor increase when the capacitance increases. In the one hand when the capacitor is kept at a fixed position the currents in the short increase 48 % between 875 MHz and 811 MHz. This is for a capacitance of 2 pF, and the currents delivered to the capacitor have increased 220 %. In the other hand when the capacitor is moved along the edge of the PIFA the currents in the short are only increased by 14 % and the currents to the capacitor by 87 % - for a shift between 875 MHz and 811 MHz. Since the power dissipated in the ESR of the capacitor is proportional to the square of the currents delivered to it, the increase of the currents has a large impact on the efficiency of tunable antenna. Moreover the location of the capacitor determines the amount of currents in the short and capacitor. Therefore the location of the tunable component has an influence on the tuning, but more importantly on the efficiency. The simulation results are confirmed by measured results in the same frequency range. They are done on a mock-up of the proposed design with fixed capacitors. They show a difference of 1.2 dB between different set-ups for a fixed resonance frequency. In this paper it is proposed an explanation for the source of loss of tunable antennas in the low band. Based on the obtained information, the currents in the main connections between the GP and the PIFA should be kept low. This is done by placing the capacitor far from the source.

However the distance between the source and the capacitor is not the only parameter that affects the magnitude of the currents running through the short and the capacitor. The capacitance itself has an influence as well. It is inferred that the overall efficiency of the system would be improved if the tuning capacitor is placed in a low currents location (far from the source) and if it is used with small capacitance values.

In a more practical point of view, sensitive points for soldering can be identified : the short and the capacitor. Because of the high currents running at these locations, the soldering with tin might result in even greater losses and its amount should be minimized as much as possible.

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