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Radiation Characteristics of Antenna Structures in Clamshell-Type Phones in Wide Frequency Range

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Abstract—In this paper, the radiation and resonance characteristics of open and closed position clamshell-type phone structures are studied at wide frequency range (from 0.6 GHz to 3 GHz) with help of coupling elements. In the closed position of the phone, the $\lambda/2$ resonance of the chassis located close to the operating band of E-GSM900 system shows to be problematic due to low bandwidth potential and a radiation efficiency minimum. To improve the closed position performance of the antenna structure, a novel frequency tunable matching circuitry is proposed and studied with simulations. The results of this paper provide useful and novel information for the designers of antennas for clamshell-type phones. The findings of this paper can be also applied with traditional self-resonant antennas.

Keywords — Clamshell phone, coupling element, antenna, frequency tunable, matching circuitry, resonant wavemode

I. INTRODUCTION

In recent years, clamshell (or folder-type) phones have taken an increasing market share. The development towards handsets with changing mechanics has set new challenges for antenna engineers. Close to the first order resonant frequency of a monoblock-type chassis, and at frequencies below it, the wavemode of the chassis typically works as the main radiator of the phone [1]. When the electrical characteristics of the chassis are changed, e.g. by tuning the length of the chassis, also the properties of the antenna structure of the terminal become thus affected. Obviously, the issue is closely related to the performance of antenna structures in clamshell-type phones. The antenna structure of a clamshell phone should provide good impedance matching and radiation efficiency in both the open and closed positions of the phone. This can be expected to be challenging to achieve with passive antenna structures, as the resonance characteristics of the chassis can differ significantly between the different mechanical usage positions

of the phone. A good understanding of the radiation and resonance characteristics of the chassis with changing mechanics can be thus considered as an important prerequisite for an antenna designer. Moreover, it is useful to know, how the impedance matching and relative bandwidth of the antenna structure of a clamshell phone are affected by opening or closing the phone.

Earlier work on antenna structures for clamshell-type phones includes e.g. [2-5]. Typically, only the open position performance of the phone has been considered. Furthermore, proper attention has usually not been given for understanding the radiation and resonance behavior of the chassis in the different mechanical usage positions of the phone. In [6], these issues were for the first time studied thoroughly with help of coupling elements [1,7]. In [8], the theory of characteristic modes [9] was used to study the resonant wavemodes on the chassis of a clamshell phone.

This paper reports the main findings of [6], together with some new results. The radiation and resonance characteristics of open and closed position clamshell-type phone structures are studied at wide frequency range (from 0.6 GHz to 3 GHz) with simulations and measurement of a prototype. A simple coupling element is used to excite the wavemodes of the chassis. To overcome the inherently narrow bandwidth potential of a closed clamshell phone, a novel frequency tunable matching circuitry is additionally studied with simulations. The paper is organized as follows: Section two presents the geometry of the studied prototype clamshell phone model. This is followed by presentation of the simulation and measurement results obtained with the prototype. In the fourth section, simulation results obtained with the frequency tunable matching circuitry are presented and discussed. Finally, conclusions are given.

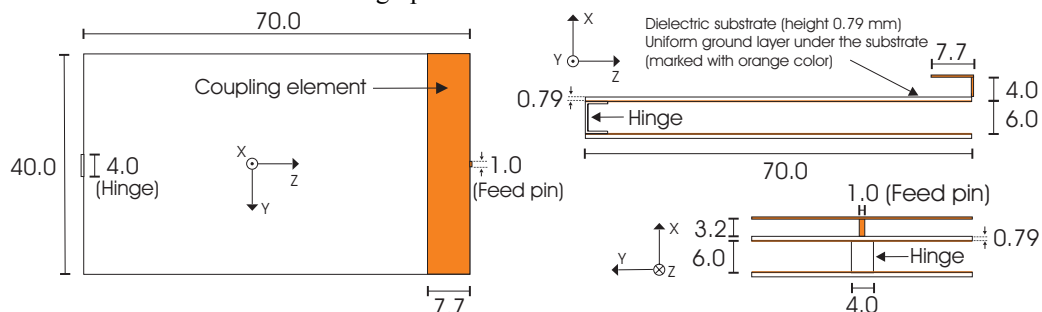


Figure 1. Geometry of the closed position of the prototype antenna structure. All dimensions are given in millimeters.

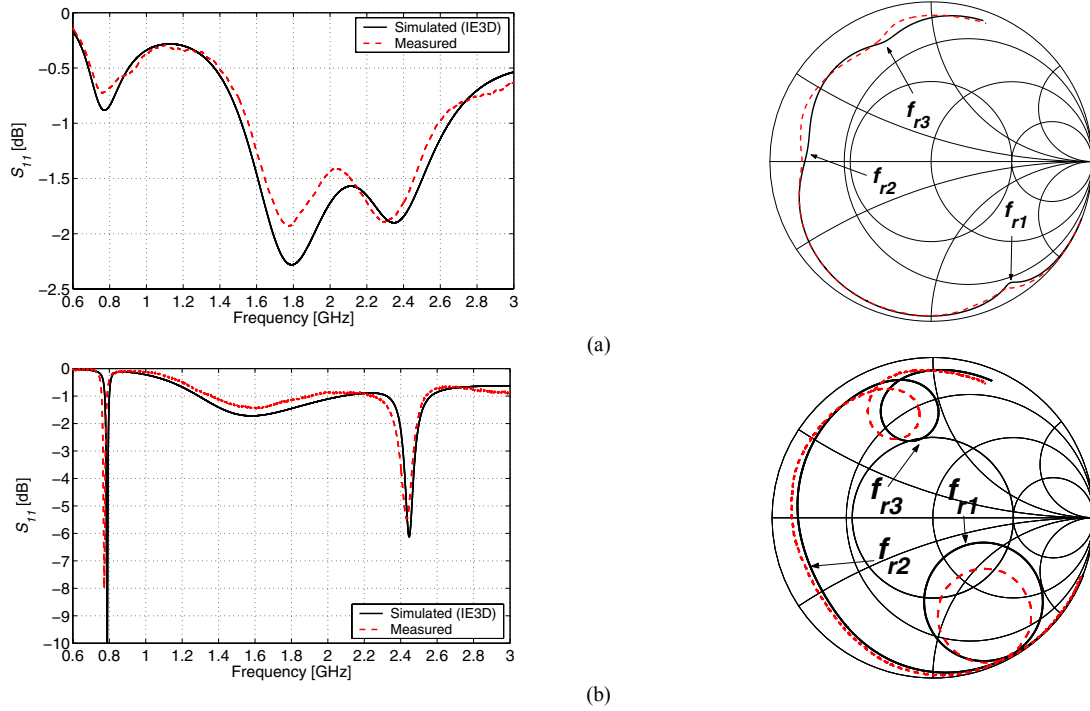


Figure 2. Simulated (solid line, IE3D) and measured (red dashed line) frequency responses of the reflection coefficients for the (a) open and (b) closed positions of the clamshell phone. The $\lambda/2$, λ , and $3\lambda/2$ resonances of the chassis are marked on the Smith charts with f_{r1} , f_{r2} , and f_{r3} , respectively.

II. PROTOTYPE ANTENNA STRUCTURE

The idea of coupling elements [1,7] can be successfully used as an indirect method in studying of the resonant wavemodes of the chassis of a mobile terminal. As coupling elements are usually very simple and do not include any matching arrangement, the underlying characteristics of the chassis wavemodes are clearly visible in the input impedance of the coupling element. Similar study would be difficult to carry out with complex self-resonant antenna elements with integrated matching. Another approach for the problem would be to apply the theory of characteristic modes [9], as in [8].

The layout of the closed position of the studied clamshell phone is presented in Fig. 1. Open position of the phone can be obtained by rotating the base part of the chassis on the same plane with the flip part of the chassis. The chassis of the phone consists of two ground planes of the same size (70 mm x 40 mm), which are connected to each other with a 4 mm narrow hinge. The metallic surface of a dielectric substrate RT Duroid 5870 ($\sigma = 5.75 \cdot 10^7$ S/m, $\tan \delta = 0.0012$, $\epsilon_r = 2.33$, $h = 0.79$ mm) is used to form chassis for the clamshell phone. A low-volume (1.2 cm³) coupling element is placed on top of one end of the chassis. Both the coupling element and the hinge are constructed of a 0.2 mm thick sheet of tin bronze ($\sigma = 0.8 \cdot 10^7$ S/m). One should note that the dimensions and the location of the coupling element have not been optimized for the needs of any wireless communication system

III. SIMULATION AND MEASUREMENT RESULTS

Fig. 2 presents the simulated (IE3D) and measured frequency responses of reflection coefficients for the open and closed

positions of the clamshell phone. According to Fig. 2, the simulated and measured reflection coefficients agree very well. The resonant frequencies of the chassis can be easily distinguished from the reflection coefficient curves. In the closed position, for example, the $\lambda/2$ and $3\lambda/2$ resonances of the chassis are seen on the Smith chart as clear resonance circles. Table I summarizes the resonant frequencies of the chassis.

The next step was to study the effect of the resonant wavemodes of the chassis on the bandwidth potential of the clamshell phone. Bandwidth potential as a function of frequency was calculated computationally as the 6 dB relative bandwidth obtained when the input impedance of the coupling element was critically matched to 50 Ω at each simulation frequency by a lossless two-component matching circuitry (see [7]). Results for the open and closed positions of the clamshell phone with three different hinge-widths are presented in Fig. 3. As can be seen from Fig. 3 (a), the relative bandwidth curves obtained with the open clamshell phone have local maxima at the $\lambda/2$, λ , and $3\lambda/2$ resonances of the chassis. The first order resonant frequency of the chassis is unfortunately slightly too low for the GSM850 and E-GSM900 systems. Decreasing of the width of the hinge shifts the first and third maxima to lower frequencies, while the second maximum remains almost unchanged. This behavior is expected, as narrowing of the hinge makes the chassis electrically longer. The second peak is not affected because at the full-wave resonance (λ) of the chassis, current minimum is located at the hinge.

TABLE I. SIMULATED (IE3D) $\lambda/2$ (f_{r1}), λ (f_{r2}), AND $3\lambda/2$ (f_{r3}) RESONANT FREQUENCIES OF THE CHASSIS OF THE PROTOTYPE ANTENNA

	f_{r1} [GHz]	f_{r2} [GHz]	f_{r3} [GHz]
Clamshell open	0.77	1.79	2.35
Clamshell closed	0.79	1.58	2.45

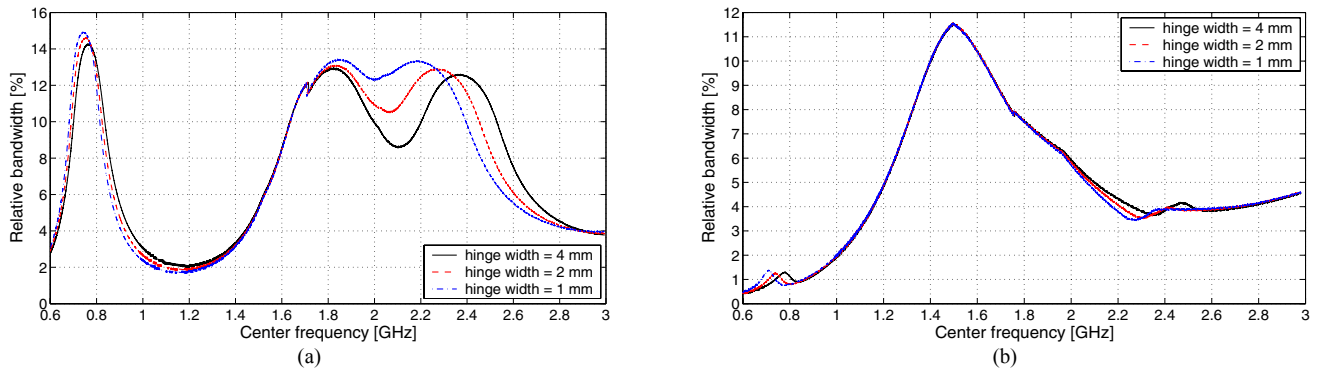


Figure 3. Bandwidth potentials obtained in the (a) open and (b) closed positions of the clamshell phone. Results are shown for three different hinge widths.

In the closed position of the clamshell phone, the relative bandwidth curves (Fig. 3 (b)) behave similarly as in the open position; local bandwidth maxima are found at the resonant frequencies of the chassis, and the first and third maxima are shifted downwards when the hinge is made narrower. However, bandwidth potentials at the $\lambda/2$ and $3\lambda/2$ resonances of the chassis are clearly lower than in the open position. This can be explained by examining voltages in the base and flip parts of the chassis. At the $\lambda/2$ and $3\lambda/2$ resonances, voltages in the base and flip parts are opposite in sign. Electric fields are thus concentrated between the base and flip parts, which leads to non-radiating-type differential mode currents. At the full-wave resonance of the chassis, voltages in the base and flip parts are of the same sign, which leads to well-radiating common mode currents. The above-discussed findings of [6] and this paper are fully supported by the results of [8].

To further validate the above discussion, radiation efficiencies of the antenna structure without matching circuitry were simulated with IE3D. Results with three different hinge widths are presented in Fig. 4. In the open position, radiation efficiencies are generally very high. Local efficiency maxima can be found at the $\lambda/2$, λ , and $3\lambda/2$ resonances of the chassis. A local efficiency minimum can be additionally found at the “anti-resonance” of the chassis at 1.2 GHz. Decreasing of the width of the hinge moves the first and third maxima to lower frequencies. In the closed position, radiation efficiencies are otherwise very high, but a significant drop is seen at the $\lambda/2$ resonance of the chassis. As expected, the non-radiating resonance moves downwards as the hinge is made narrower.

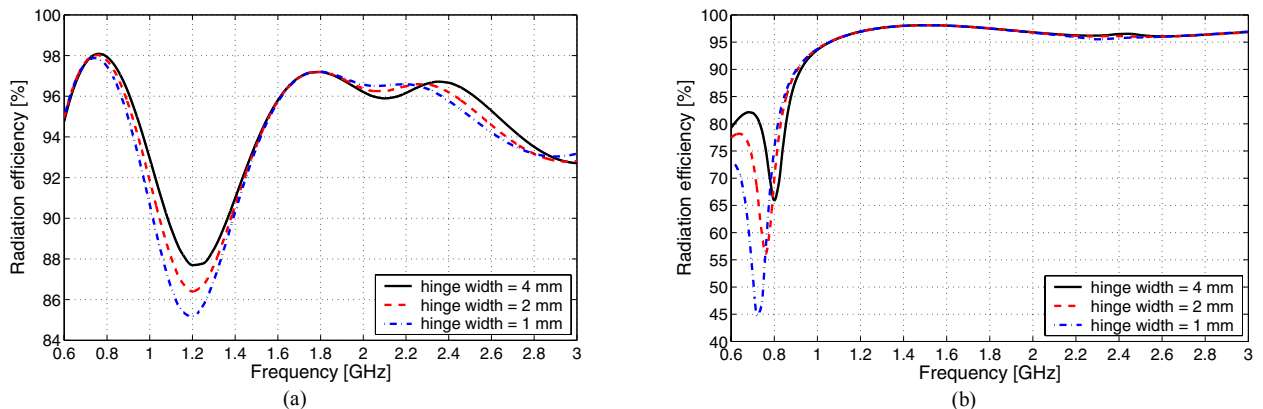


Figure 4. Simulated (IE3D) radiation efficiencies of the (a) open (b) closed clamshell phone model. Results are shown for three different hinge widths.

IV. FREQUENCY TUNABLE MATCHING CIRCUITRY

Based on the previous section, the main challenge in antenna design for clamshell phones seems to be the closed position of the phone. With the studied clamshell phone, bandwidth potential in the closed position at 900 MHz was only some 1.2 %, which is clearly too low for the GSM850 and E-GSM900 systems. The non-radiating resonance of the chassis located close to the lower GSM bands further complicates antenna design. The resonance could be moved downwards by tuning the hinge of the phone, but this would severely decrease bandwidth potential at the GSM850 and E-GSM900 system bands in the open position of the phone. In addition, problems might arise from detuning of impedance matching when a clamshell phone is opened or closed.

In this section, the challenges described above are addressed with a novel frequency tunable matching circuitry connected to the feed of the studied antenna structure. The aim has been to improve the closed-position performance of the antenna structure at the problematic E-GSM900 band (880 MHz – 960 MHz). This paper presents a first, simulation-level study of the results. The layout of the matching circuitry designed to produce a dual-resonant impedance matching for the studied antenna structure is shown in Fig. 5. In simulations, the lumped elements of the matching circuitry were modeled with the S-parameters of Murata’s LWQ18A-series inductors and ATC’s (American Technical Ceramics) 600S-series capacitors. The switches were modeled with the S-parameters of NEC’s μ PG2012TK SPDT switch.

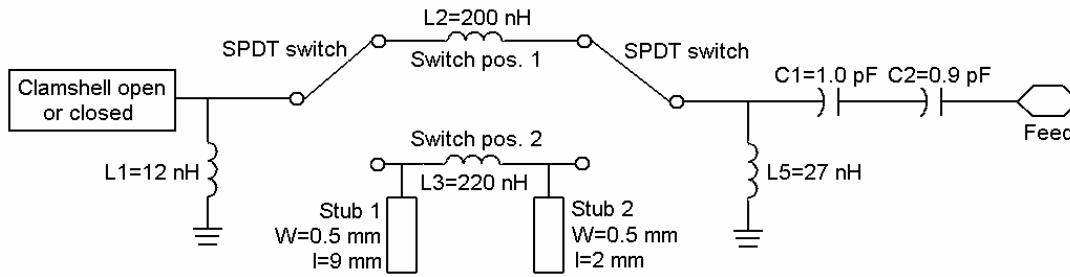


Figure 5. The topology of the frequency tunable matching circuitry. The block on the left represents the open or closed clamshell phone seen from the feed pin of the coupling element. Stub 1 and Stub 2 represent open-circuited microstrip lines on RT-Duroid 5870 (W = width, l = length, $\epsilon_r = 2.33$, $h = 0.8$ mm, $\delta = 0.0012$).

In a coarse level, the operating principle of the matching circuitry in switch pos. 1 is as follows: Inductors $L1$ and $L2$ are first used to tune the antenna structure to a single resonance. The dual-resonant response is obtained by moving the single-resonant loop to the center of the Smith chart using $L5$, $C1$, and $C2$. In the matching circuitry, inductor $L1$ controls the resonant frequency of the antenna structure while $L2$ controls the size of the resonance loop on Smith chart. Frequency tuning can be thus obtained by tuning the first matching component, which in our case has been accomplished with the SPDT switch and Stub 1. Stub 1 could be alternatively implemented as a parallel shorted inductor. When the resonant frequency of the antenna structure is tuned, both the size and location of the dual-resonant impedance loop on the Smith-chart become detuned. The detuning can be compensated by tuning the second component of the matching circuitry ($L3$), and by adding another stub (Stub 2) before the second matching switch. Impedance matching with the frequency tunable matching circuitry was

optimized for the closed position of the phone according to 6 dB return loss criterion.

For reference, a passive dual-resonant matching circuitry was designed for the antenna structure. The topology of the matching circuitry was the same as in [10,11], i.e. it composes of in total five lumped and distributed elements. The lumped elements were characterized in the simulations with S-parameters as described earlier in this section. The dual-resonant frequency response obtained with the reference matching circuitry was optimized in such a way that the minimum return loss at the frequency band of E-GSM900 system became as high as possible. Impedance matching was optimized for the closed position of the phone. The frequency responses of reflection coefficients obtained with the frequency tunable and reference matching circuitries are shown in Fig. 6. Results are shown for both the closed and open positions of the phone.

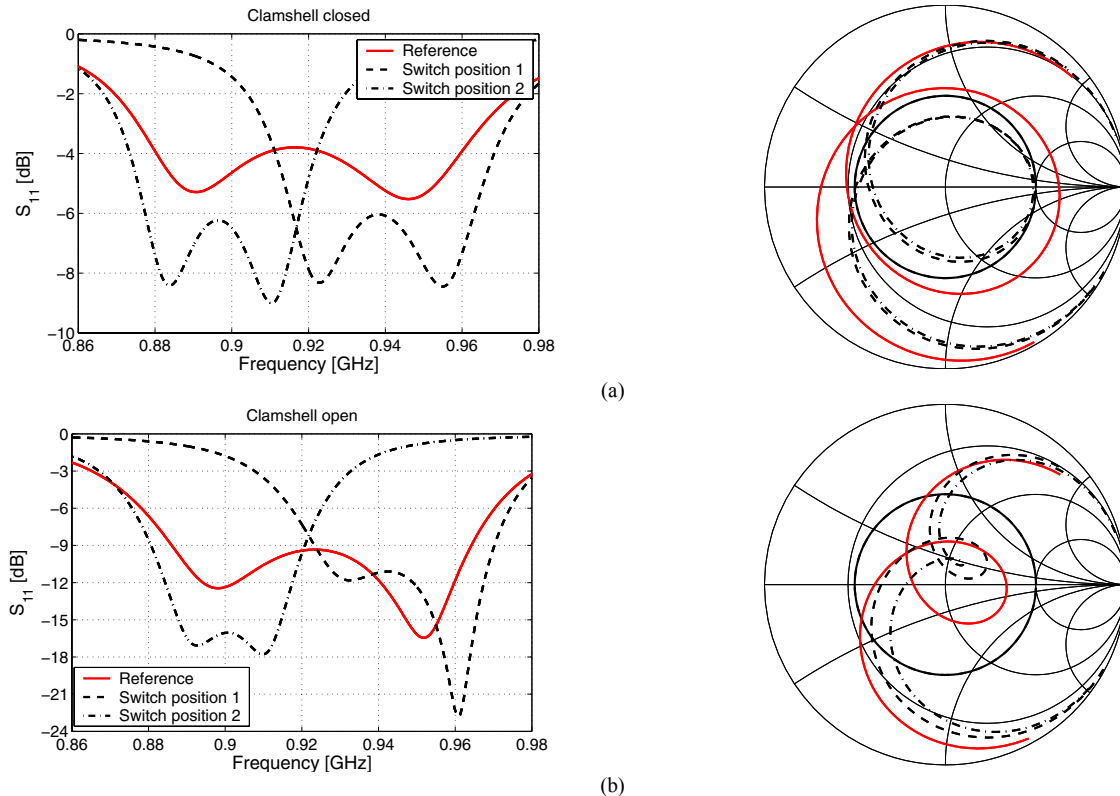


Figure 6. Comparison of the frequency responses of the reflection coefficients obtained with the frequency tunable matching circuitry (dashed and dash-dotted black lines) and reference matching circuitry (solid red lines) connected to the (a) closed and (b) open clamshell phone model. The solid circles in the centers of the Smith charts represent 6 dB return loss.

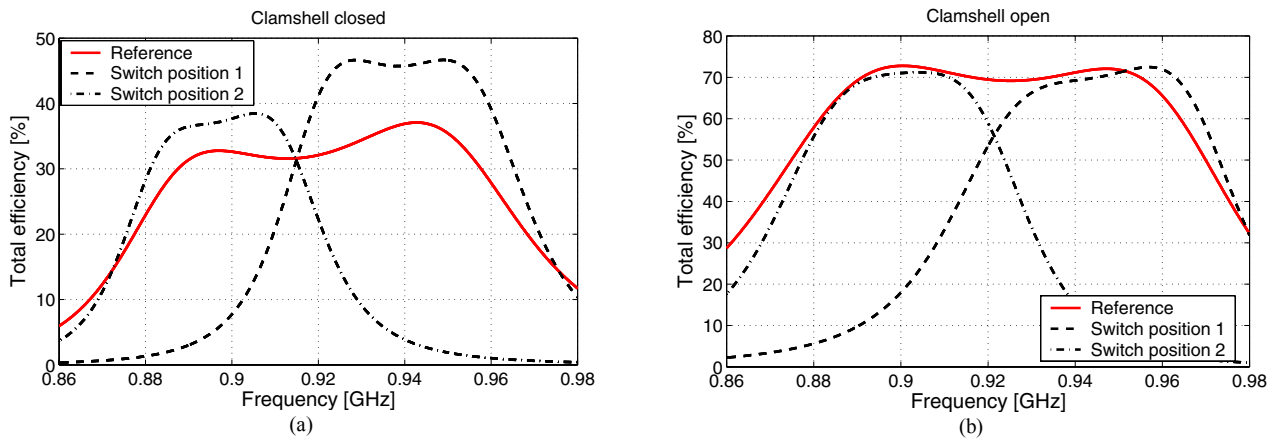


Figure 7. Comparison of the total efficiencies obtained with the frequency tunable matching circuitry (dashed and dash-dotted black lines) and reference matching circuitry (solid red lines) connected to the (a) closed and (b) open clamshell phone model.

According to Fig. 6 (a), the operating band of E-GSM900 system can be covered in the closed position with 6 dB matching by using the frequency tunable matching circuitry. With the passive reference matching circuitry, a minimum return loss of roughly 4 dB has to be accepted with an optimally tuned dual-resonant response. When the phone is opened (see Fig. 6 (b)), the sizes of the dual-resonance circles on the Smith chart decrease notably. For this reason, impedance matching has been in this paper optimized for the closed position of the clamshell phone. Optimization of the impedance matching for the open position would result in a badly deteriorated impedance matching in the closed position, as the dual-resonance circles on the Smith chart would become clearly too overcoupled. As a general notice from Fig. 6 (b), a very good impedance matching over the E-GSM900 band is obtained in the open position with both the frequency tunable and reference matching circuitries. This is due to the high bandwidth potential of the clamshell phone in the open position (see Fig. 3 (a)).

Fig. 7 presents the simulated total efficiencies obtained with the frequency tunable and reference matching circuitries. The results include all dielectric and ohmic losses of the antenna structure (Fig. 1) and the matching circuitry, and the losses caused by imperfect impedance matching. In the closed position, according to Fig. 7 (a), the frequency tunable matching circuitry clearly outperforms the reference matching circuitry. Total efficiencies are generally fairly low, which is due to the very high Q (low bandwidth potential) of the load circuit, i.e. the combination of the coupling element and the chassis. In the open position of the phone, total efficiencies are clearly higher than in the closed position, as expected. The total efficiencies obtained with the frequency tunable and reference matching circuitries are of roughly the same order in the TX (880 MHz – 915 MHz) and RX (925 MHz – 960 MHz) bands of E-GSM900 system. Based on the presented results, the frequency tunable matching circuitry fulfills its goal, i.e. the performance of the antenna structure is clearly improved in the problematic closed position of the phone without sacrificing the open position performance of the phone.

V. CONCLUSIONS

The results of this paper point out the importance of understanding the radiation characteristics of the resonant

wavemodes of the chassis of clamshell-type phones, and provide a good starting point for an antenna designer. To improve the problematic closed position performance of the studied antenna structure, a novel frequency tunable matching circuitry is proposed and thoroughly studied with simulations. The work continues with prototyping and measurement of the frequency tunable matching circuitry.

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