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Impact of Capacitive Coupling Element Design on Antenna Bandwidth

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***Abstract*—A coupling element is typically used to excite one of more characteristic modes of a structure to form some desired radiation properties. In particular, non-resonant coupling elements (CEs) are attractive, since it is electrically small and can be more conveniently integrated into the structure, such as the chassis of a mobile terminal. In this case the chassis is the primary radiator of the mobile terminal. However, there is still limited knowledge on how to design and optimize coupling elements. In this paper, we examine how the dimensions of a single capacitive coupling element (CCE) influence the potential bandwidth of exciting the fundamental dipole mode of a rectangular terminal chassis. The parametric study shows that the CCE must not be too small electrically, for the sake of bandwidth. However, the bandwidth saturates when the size of the CCE is increased beyond a certain threshold. Therefore, this study provides some useful insights and guidelines for CCE design.**

***Index Terms*—characteristic modes, impedance bandwidth, terminal antennas coupling elements.**

I. Introduction

Over the past decade, the Theory of Characteristic Modes (TCM) has emerged from relative obscurity into a popular research topic [1]. In particular, the significant volume of research efforts in the past few years has resulted in many interesting new results relating to both theoretical and application aspects of TCM [1]. The growing interest from the industry in using TCM to solve real engineering problems can be seen in the growing number of commercial full-wave electromagnetic software that have made the effort to incorporate characteristic mode (CM) features, including Altair FEKO, CST and WIPL-D.

Despite the recent progress in extending TCM research, there are still many open questions. One important open question is the influence of coupling element (CE) design on impedance bandwidth. Although there have been previous studies relating to this topic, the focus has been on the notion that non-resonant CEs are attractive from a practical standpoint due to their smaller electrical size, as compared to self-resonant CEs or self-resonant antennas that do not rely on other structures to radiate.

For example, the first detailed study on non-resonant CEs [2] utilized an equivalent circuit approach to conclude that both the position and the volume of a non-resonant CE on a terminal chassis are crucial for achieving good impedance bandwidth at the lower band of 900 MHz. A follow-up study [3] attempts to optimally utilize the volume of two non-resonant CEs (one on-ground and one off-ground) for coupling to the chassis at the low band by appropriate choices of the location and shape of the coupling. However, these earlier studies make use of relatively large CEs that span the entire width of the chassis. A more recent study presents results relating to the influence of the height h and width (or off-ground clearance) d of a more compact off-ground non-resonant CE of dimensions $16 \times d \times h$ mm^3 [4]. However, the focus is to achieve the minimum h for a given bandwidth requirement at the low band, allowing for multi-resonance matching and larger return loss. As expected, the minimum required h decreases with a larger d, a larger chassis, a higher order matching, or a higher return loss.

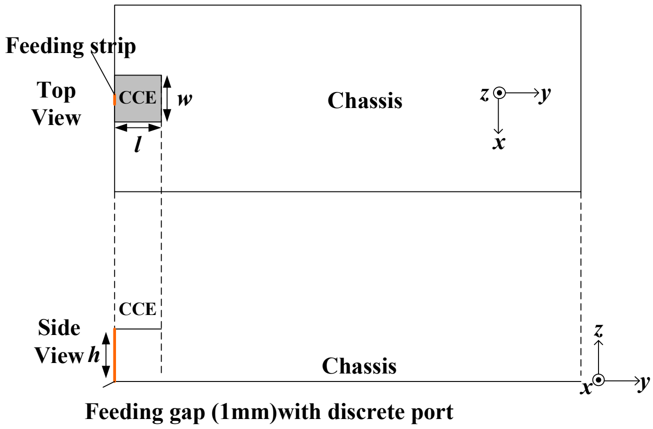

Fig. 1. Layout of the CCE on the 100 mm × 40 mm chassis.

In this work, the bandwidth performance of a simple on-ground CCE design is investigated based on a parametric study. The concept of bandwidth potential [3] is used to calculate the impedance bandwidth achievable with two matching components. The purpose is to gain insight into the behavior of the bandwidth for a more comprehensive set of CCE design parameters than what is available in the literature. The results and observations provide some useful guidelines to practitioners on the efficient use of CCEs for antenna design, especially for the basic CCE design used in this paper, to meet a given bandwidth requirement.

II. Simulation Setup

A. CCE and Chassis Structure

As shown in Fig. 1, the CCE is an infinitely thin plate of dimensions l mm × w mm. Its outer edge is aligned to the middle of the smaller edge of an infinitely thin, rectangular chassis of dimensions 100 mm × 40 mm. The chassis is chosen to be of the same size as that used in [2] and [3]. It is fed at the center of the outer CCE edge using a vertical strip

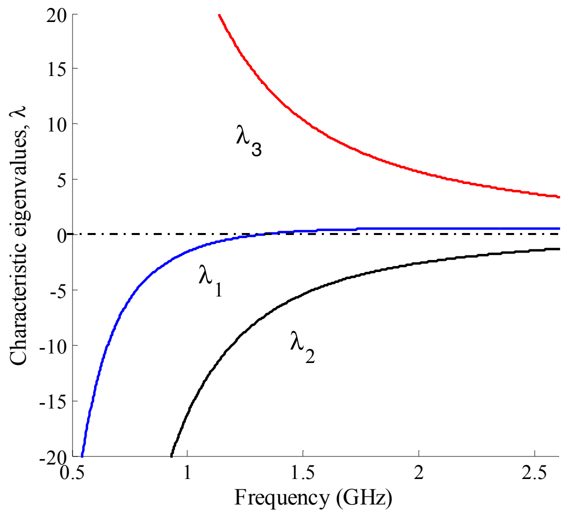

Fig. 2. Characteristic eigenvalues over frequency for the 100 mm × 40 mm chassis.

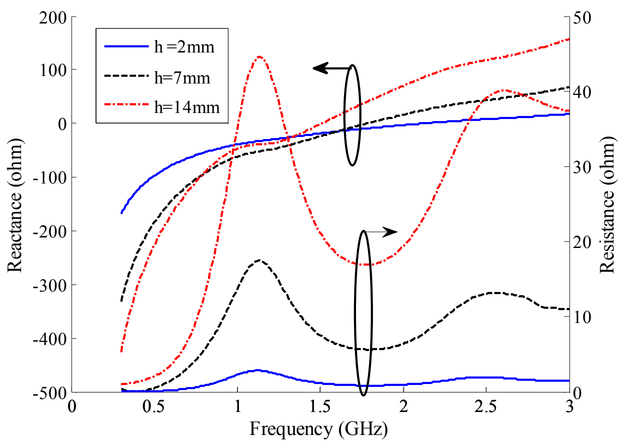

Fig. 3. CCE feed impedance over frequency for different CCE heights.

of 1 mm in width. The entire structure is a perfect electric conductor (PEC). To start with, the CMs of the plain 100 mm × 40 mm chassis (with no CCE) were calculated using the CM-solver of CST Microwave Studio 2017 [5], and the characteristic eigenvalues are shown in Fig. 2. It is observed that the first mode or fundamental dipole mode (i.e. half-wave dipole along y-axis) resonates at around 1.26 GHz. However, when this mode is excited using the CCE in Fig. 1 (with dimensions *l*= 6, *w*= 40 mm, *h*= 2, 7 or 14 mm), the resonant frequency is around 1.1 GHz (see Fig. 3 for the unmatched input impedance). This is because the CCE loads the chassis at one of its shorter edges, which slightly lower the resonant frequency of its dipole mode. This phenomenon is also observed for a self-resonant CE in [6].

B. Bandwidth Potential

The bandwidth potential metric was originally proposed in [3] as a pragmatic way to measure the extent to which the bandwidth of an antenna can be improved by suitable matching components. This metric helps to speed up the antenna design process. It is based on numerically matching the input impedance of an antenna with two-component lossless L-section matching circuits to 50 ohm at a given frequency, for a given return loss level. The maximum bandwidth achieved by any of two-component matching circuits is the bandwidth potential. Bandwidth potential can be calculated using a post-processing template in CST [5]. The matched bandwidth (given as fractional bandwidth) will typically be located asymmetrically around the evaluation frequency. In CST, the user can choose to output only the symmetric bandwidth, which is double the smaller side of the bandwidth range.

III. Simulation Results

The frequency domain solver of CST 2017 is used for the full-wave antenna simulations. To obtain insights into the behavior of the impedance bandwidth for the CCE design parameters of height *h*, width *w* and length *l*, a parametric study was performed. Throughout this study, the feed is kept at the same location at the smaller edge of the chassis, since the shorter edge is where the magnitude of the electric field is maximum for the first mode (i.e., mode to be excited by the CCE) [6].

For the parametric study, one CCE parameter was varied in turn while the other two parameters were fixed. The fixed parameter values were: *h* = 10 mm, *w* = 40 mm and *l* = 6 mm. These values were chosen to be large enough so that they do not significantly limit the potential bandwidth of the parameter under test. The bandwidth potential was calculated for 10 dB return loss at the first resonant frequency of the combined structure (i.e., 1.1 GHz). In particular, the symmetric bandwidth option was selected.

A. Variation in CCE Height

For the first parametric sweep, the height of the CCE from the surface of the chassis is changed from 2 mm to 30 mm. The unmatched input impedances of the CCE antenna are shown in Fig. 3 for three different heights (*h* = 2, 7 and 14 mm). As can be seen, the radiation resistance increases by increasing the height. Furthermore, the bandwidth potential of the half-wave dipole mode of the chassis increases almost linearly (at 1.1 GHz) with the height of the CCE (see Fig. 4). However, the bandwidth potential saturates after reaching the maximum value of 43% at *h* = 19 mm. Increasing the height further causes the bandwidth to degrade slightly. The bandwidth potential will increase again at even larger *h*, as can be expected from the fundamental limit of an antenna of increasing size. However, this effect is not studied further as terminal antenna design requires a low-profile CCE (commonly, *h* < 10 mm). The linear relationship between bandwidth potential and CCE height confirms the height (or clearance) of an antenna structure being a key factor in determining its bandwidth performance. It can be seen that bandwidth potential approaches zero as the height goes to zero, even if the other CCE parameters are fixed at moderate values of *w* = 40 mm and *l* = 6 mm.

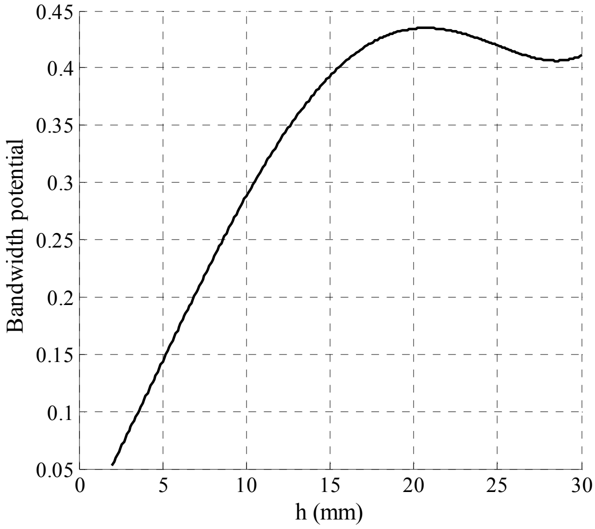

Fig. 4. Bandwidth potential versus CCE height.

B. Variation in CCE Length

For the second parameter sweep, the length of the CCE was changed from 4 mm to 35 mm, with the other two parameters fixed to w = 40 mm and h = 10 mm. The bandwidth potential results are shown in Fig. 5. It can be seen that the bandwidth increases almost linearly. However, even with l = 4 mm, a relatively large bandwidth potential of 23% is already available. In this case, the maximum bandwidth potential of 35% is reached at l = 14 mm, beyond which the bandwidth decreases monotonically.

This observation of deceasing bandwidth can be explained by the electric field generated in the region between the CCE and the chassis starting to become dissimilar to the electric field of the dipole mode, as the length increases beyond 14 mm. Consequently, the CCE's ability to excite the mode decreases, which in turn decreases the bandwidth potential. This situation may be illustrated using the electric field distribution 3 mm above the ground plane for both the dipole mode and the excited CCE with l = 10 mm and 15 mm (see Fig. 6). As can be seen, the field inside the CCE is more similar to the modal field for the case of l = 10 mm (see Fig. 6(b)) than the case of l = 15 mm (see Fig. 6(c)).

C. Variation in CCE Width

Finally, the width of the chassis was changed from 5 mm to 80 mm, keeping the other two parameters as l = 6 and h = 10. As shown in Fig. 7, as the CCE width increases from 5 mm, the bandwidth potential increases almost linearly from a very small bandwidth of 5%, until it saturates at around 50% with w = 70 mm. However, for practical terminal antenna design, the CCE width should not exceed the chassis width. Therefore, like the CCE height, the CCE width is a key parameter for obtaining a larger bandwidth. Therefore, it should be possible to trade the decrease in height by a corresponding increase in width, and vice versa.

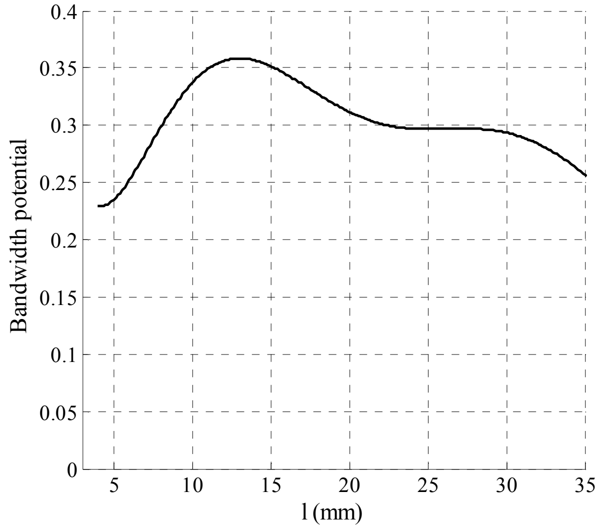

Fig. 5. Bandwidth potential versus CCE length.

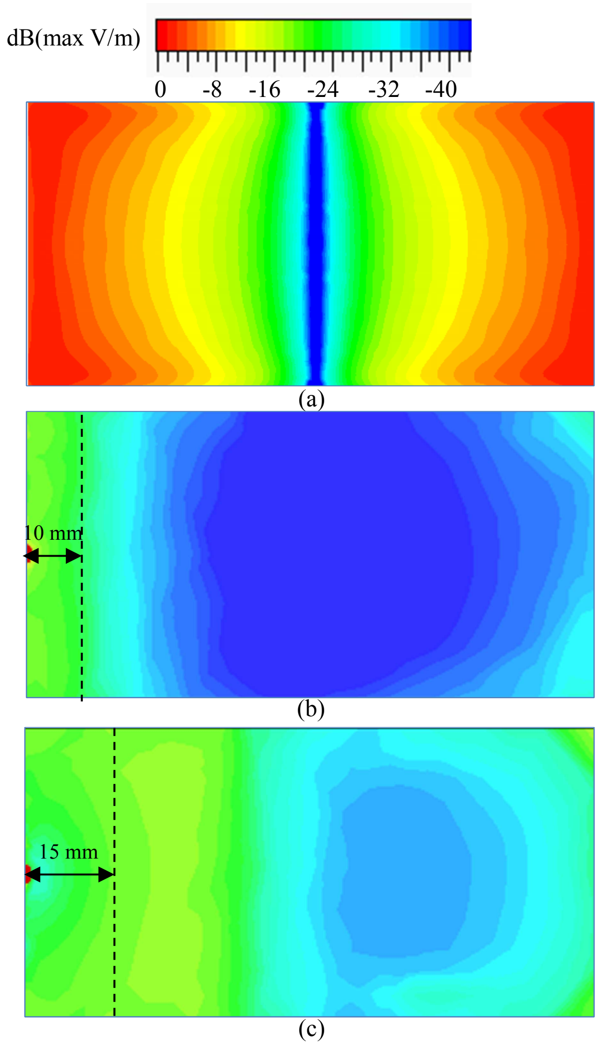

Fig. 6. Magnitude of electric near-field at 1.1 GHz on a 100 mm × 40 mm plane 3 mm above the chassis for (a) a standalone chassis (modal near-filed), a chassis excited by the CCE with (b) l = 10 mm and (c) l = 15 mm.

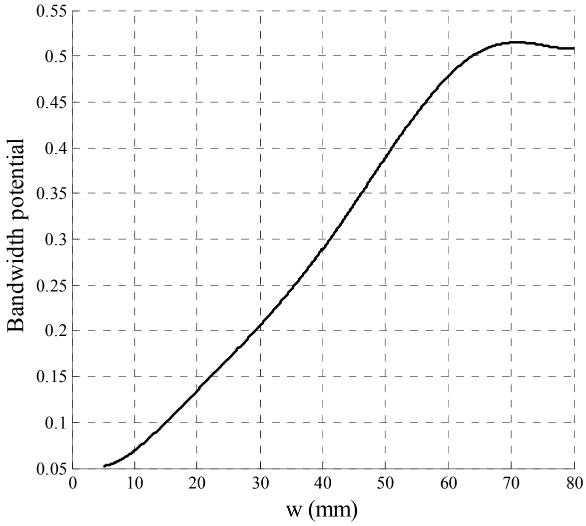

Fig. 7. Bandwidth potential versus CCE width.

IV. CONCLUSIONS

In general, the results in the preceding section show that the bandwidth potential increases in an approximately linear fashion with length, width and height until a certain maximum is reached. However, it should be highlighted that the potential bandwidth approaches zero as the height approaches zero. Likewise, the width is also observed to be an important parameter for bandwidth. Moreover, increasing the width (especially if it goes beyond the chassis width) can also significantly modify the CMs of the chassis. The length seems to be less critical, since the bandwidth potential is over 20% even for very small lengths. However, it is important to ensure that the length is chosen appropriately to avoid it being larger than necessary while providing a smaller bandwidth than what is achievable for a smaller length.

It should be noted that the results obtained in this paper are mainly aimed at the simple CCE design. Further studies are needed to draw more general conclusions on CCE designs as well as the impact of chassis size. Other limitations of the current study include the structure being lossless and that no specific attempt was done to match the CCE design to the near-field behavior of the mode to be excited. Another possible future work is to use an alternative metric of unloaded Q-factor [7] to verify the results and conclusions in this paper. However this method, which involves the calculation of the slope of the input resistance and reactance, is less accurate than the bandwidth potential calculation, especially if the impedance data is noisy or if multiple resonances are present.

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