IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received October 21, 2019, accepted November 4, 2019, date of current version November 27, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2954164

A Wideband Equivalent Circuit for Stripline-Fed Cavity-Backed Slot Radiating Elements

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This work was supported in part by the Spanish Ministerio de Educación, Cultura y Deporte (Programa para la Formación del Profesorado Universitario) under Grant FPU15/06457, and in part by the Spanish Ministerio de Ciencia, Innovación y Universidades (Programa Estatal de I+D+i Orientada a los Retos de la Sociedad) under Grant RTI2018-097098-J-I00.

ABSTRACT An equivalent circuit for stripline-fed cavity-backed slot radiating elements is proposed. The proposed equivalent circuit consist of a transmission line model for the slot mode, a slot end-effect which includes the radiation, and a strip-slot transition model. The equivalent circuit is validated using both simulated and measurement results and good agreement is found over a bandwidth of 5 GHz in the 3.5 GHz band. Compared with other equivalent circuits from the literature, the proposed model is capable of providing physical insight and accurate results in a wide frequency band with the advantage of simplicity, a small number of elements and a clear behavior of its parameters.

INDEX TERMS Cavity-backed slot, equivalent circuit, stripline, transmission line, wideband.

I. INTRODUCTION

In the last decades, the use of compact and high-performance wireless devices have spread significantly, and they are becoming essential in our everyday life. This has increased the need for wideband, low-profile, low-cost and low-loss antennas with suitable radiation characteristics. Slot-like antennas have been widely used, as they meet the aforementioned requirements and, thus, they have been extensively studied and analyzed in the past [1]–[4]. In order to help with the design and understanding of this radiating element, several Transmission-Line-based (TL-based) equivalent circuits for single-layer radiating slots have been proposed in the literature [5]–[8]. Very recently, an improved circuit model was introduced in [9], which provides both physical insight and accurate results. However, these radiating elements have bilateral radiation which limits the applicability of these elements in directive arrays. To solve this problem, traditionally, a shallow cavity is placed behind the slot, forming a Cavity-Backed Slot (CBS).

Recently, CBS antennas have increased in popularity, due to their unidirectional radiation pattern and the easy manufacturing of the cavity using SIW-like technology [10]–[12]. CBS radiating elements were extensively studied in the past. In [13], the admittance of a CBS antenna was analytically derived. This admittance was mathematically related to the one from a single-layer slot in [14]. Furthermore, a more general and accurate approach was presented in [15]. These studies, however, computed the input parameters of the structure, without providing a simple, understandable model for the CBS. Very recently, the TL modeling of a CBS antenna was tackled for the first time [16], but the proposed circuit lacked of enough parameters to provide accurate results.

Strip-feeding is a common way to excite a CBS radiating element [17]–[23]. This type of feeding requires a more complex analysis than the previous case, but it was nonetheless performed in [24]–[26]. Again, these analyses did not find a model which provided physical insight about the structure. The modeling of strip-fed CBS radiating elements was first tackled in [27]. This model included the effect of the slot as a parallel RLC circuit which does not help with the understanding of its behavior and is narrowband. Besides, it includes the effect of the rectangular cavity as TE_{10} modes propagating in waveguides which are coupled to the rest of the circuit by transformers. This added unnecessary complexity to the model. A magnetic-coupling equivalent circuit was proposed in [28], [29]. The slot is modelled as a lossy transmission line which accounts for all the radiation of the structure, neglecting the radiation of the slot end-effect and the dielectric and conductor losses. Furthermore, the previously proposed

The associate editor coordinating the review of this manuscript and approving it for publication was Andrei Muller.

equivalent circuit is not truly wideband because the effect of the cut-off frequency of the CBS mode is not considered.

The CBS mode was acknowledged for the first time in [30]. This mode has cut-off frequency, which is highly dependent on the width of the slot and the transverse dimensions of the cavity. This leaky mode is now used as the radiating mechanism in current leaky-wave antennas [31], [32].

In this communication, a wideband equivalent circuit is proposed for stripline-fed CBS radiating elements which are excited in the center of the slot. In order to provide both physical insight and accurate results along a wide frequency band, the slot behavior is modelled by a CBS-mode TL element. To the authors' knowledge, it is the first time that this sort of TL is used to propose the equivalent circuit of a finite-slot. To complete the equivalent circuit, the well-known model of the slot end-effect and the strip-slot transition is included. The main radiation effect of the structure is modelled by the end-effect resistance of the slot, placed at the end of the TL. A novel capacitive effect is also added to the strip-slot transition which considers the shift of the resonance frequency of the slot when the distance between the strip and the slot is changed. A simple dependence with this distance of the element values of the transition is also found. All parameters of the equivalent circuit are extracted from the electromagnetic simulation of the structure. The working bandwidth of the model is limited by other resonant modes which have not been taken into account, like cavity-resonant modes. Furthermore, the fact that the structure is fed exactly in the middle can cancel some of these significant resonant modes. In any case, the proposed model is very useful for the design of series-fed arrays (like leaky-wave antennas) using CBSs in which the prior knowledge of the radiating element behavior is a powerful tool to avoid the heavy computation of the whole array simulation.

The problem of finding an equivalent circuit for the stripline-fed CBS is tackled by modeling three different parts of the structure in order. The first one is the characterization of the mode propagating along a CBS-line segment, which is shown in Section II. The second consists in adding to the proposed TL the well-known end-effect of the slot, which is done in Section III. The third part adds the effect of feeding the slot by a stripline, described in Section IV. Once the three effects are added to the equivalent circuit, it is applied to a more realistic case with measurements in Section V. Conclusions are given in Section VI.

II. CHARACTERIZATION OF A CBS-LINE SECTION

To find an equivalent circuit for a section of the CBS-line, the parameters, γ_{CBS} and Z_0, of this TL will be found. These parameters will only depend on the dimensions of the transverse section of the structure shown in Fig. 1 and the medium inside the cavity. A CBS-line section has been simulated using the commercial software HFSS. To properly excite the slot mode without exciting the rectangular-waveguide modes, the line has been fed using two lumped ports, placed between the edges of the slot in each end of the line. The dimensions

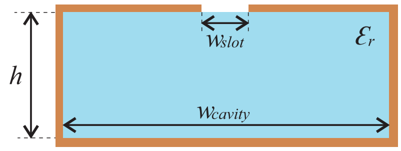


FIGURE 1. Transverse section of the CBS.

of the transverse section of the simulated structure are as follows: $h = 10$ mm, $w_{cavity} = 20$ mm and $w_{slot} = 1$ mm. The length of the line is $l = 80$ mm. The dielectric inside the cavity is considered lossless, with dielectric constant $\varepsilon_r = 2.2$ and zero-thickness PEC is used for the conductor parts. From the S-parameters of the simulated segment, the image parameters can be obtained using, as shown in [33],

$$\gamma_{im} = \cosh^{-1}\left(\frac{1 - S_{11}^2 + S_{21}^2}{2S_{21}}\right) \tag{1}$$

$$Z_{im} = Z_{0,ref}\sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}}, \tag{2}$$

where $Z_{0,ref}$ is the reference impedance used to obtain the S-parameters. Then, from the definition of the image parameters, $Z_0 = Z_{im}$ and $\gamma_{CBS} = \gamma_{im}/l$. Fig. 2 shows the γ_{CBS} and the Z_0 of the simulated structure. Ripples appear at frequencies around 2.3, 3.4 and 4.6 GHz (shadowed regions). At these frequencies, the length of the line is a multiple of half-wavelength ($\beta l = k\pi$) so the line gives little information about itself. It is believed that these resonances make the simulation results extremely sensitive to the parasitic effects introduced by the lumped ports and the end-effect of the line. This problem can be mitigated by simulating lines with different lengths and neglecting the results near the resonances. Simulating shorter lines is not recommended since the higher-order modes produced by the lumped-port excitation must attenuate enough to obtain accurate results. Given the shape of the γ_{CBS} and the Z_0 of the simulated results, the CBS-mode seems to correspond to a lossy mode with cutoff frequency.

As in slotlines, the propagation mode in a CBS is almost Transverse Electric (TE) in nature [34]. However, in the case of CBS-lines, there is a low-frequency cutoff, because it is a single-conductor structure. As shown in the simulated results, even in presence of PEC and lossless dielectrics only, there are losses due to the radiation of the structure. For these reasons, in order to model the TL parameters of the structure, a lossy TE-mode will be considered. The propagation constant and the characteristic impedance of a TE-mode in a lossy medium enclosed by PEC, as shown in [35], are given by

$$\gamma_{CBS} = j\frac{2\pi f\sqrt{\varepsilon_r' - j\varepsilon_r''}}{c}\sqrt{1 - \left(\frac{f_c}{f}\right)^2 \frac{\varepsilon_r'}{\varepsilon_r' - j\varepsilon_r''}} \tag{3}$$

$$Z_0 = \frac{Z_m}{\sqrt{\varepsilon_r' - j\varepsilon_r''}\sqrt{1 - \left(\frac{f_c}{f}\right)^2 \frac{\varepsilon_r'}{\varepsilon_r' - j\varepsilon_r''}}}, \tag{4}$$

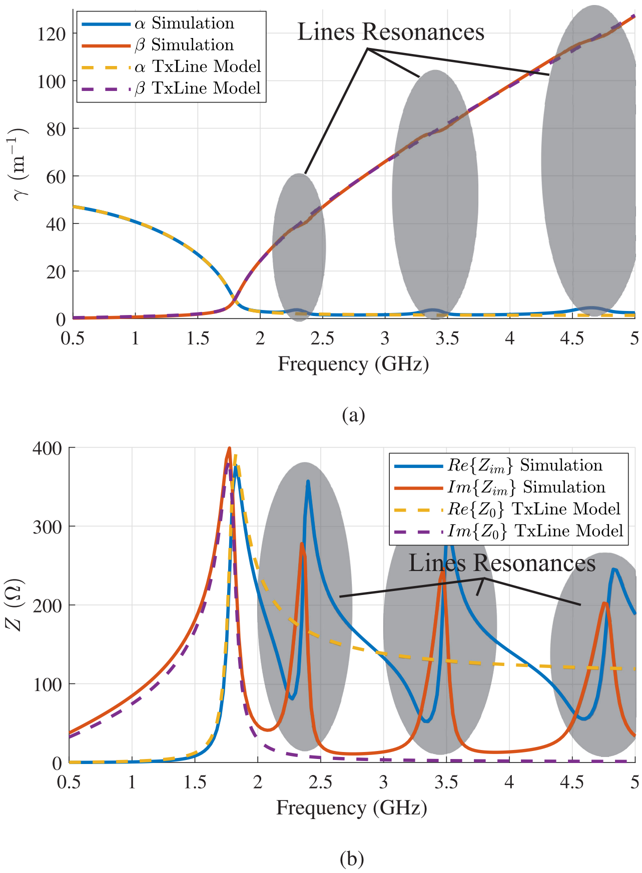


FIGURE 2. **Comparison between image parameters of a simulated CBS section and the TL equivalent circuit. Simulated results in the shadowed region are inaccurate due to resonances in the simulated line. (a) Propagation constant. (b) Characteristic impedance.**

where f_c is the cutoff frequency of the mode, c the speed of light in vacuum and the electric permittivity of the medium, ε_r, is split into its real and imaginary parts as follows:

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r''. \tag{5}$$

The value of the impedance Z_m depends on the impedance of free space, the geometry of the section of the structure, the ε_r of the material inside the cavity, and the voltage definition (the possible definitions can be checked in [36]). Even though these expressions are only valid for closed structures, they show great concordance with the simulated results of the CBS-line from Fig. 2(a). Thus, the proposed equivalent circuit of the slot section is a TL whose propagation constant, γ_{CBS}, and characteristic impedance, Z_0, are defined, respectively, by (3) and (4).

Using the previous simulation results, it is possible to find the values of the TL parameters. The cutoff frequency, f_c, in the cases of lossy modes, is defined as the frequency when $\alpha(f_c) = \beta(f_c)$, where α is the attenuation constant and β the phase constant [35]. Thus, it can be extracted directly from simulated results. After f_c is found, ε_r' can be adjusted so both the β obtained from simulation and the equivalent circuit have the same asymptotic behavior for higher frequencies. The value of ε_r'' can be chosen to be frequency-dependent or constant, depending on its suitability modeling the loss phenomenon. In this case, the only considered losses are due to radiation and it has been found, heuristically, that these losses can be associated with a constant conductivity:

$$\varepsilon_r'' = \frac{\sigma}{2\pi f \varepsilon_0}, \tag{6}$$

where ε_0 is the electric permittivity in vacuum, and σ is an equivalent conductivity. The value of σ can be found so that the attenuation constant, α, of the simulation and the equivalent circuit, have the same level under the cutoff frequency. Lastly, the value of Z_m from (4) is obtained so $|Z_0| = |Z_{im}|$ at f_c.

Using the aforementioned procedure, the parameters of the model have been obtained: $f_c = 1.795$ GHz, $\varepsilon_r' = 1.7$, $\sigma = 0.009$ S/m and $Z_m = 148\ \Omega$. As expected, the value of ε_r' is very close to the $\varepsilon_{r_{eff}}$ of a slotline, which would be 1.6. As also shown in Fig. 2, the agreement between the simulation and the equivalent circuit is very good near the cutoff frequency and below. As expected, the inaccuracies of the simulated γ_{CBS} and Z_{im} around the resonance frequencies of the line make difficult to verify the model with the simulation at those frequencies. It can be seen, however, that the asymptotic behavior is similar.

III. END-EFFECT OF THE SLOT

Once the slot segment has been modeled, an equivalent circuit for the short-circuit termination must be found. The short-end discontinuity of a slotline was studied in [37], and the proposed equivalent circuit was an inductor and a frequency-dependent resistance connected in series. The inductive effect makes the slotline appear electrically longer than it really is, while the resistance represents the effect of the radiation in the discontinuity. In the case of a CBS, the discontinuity has similar characteristics to the slotline and, thus, the same equivalent circuit is used here.

Up to this point, the proposed equivalent circuit of the CBS, assuming center-feeding, would be the parallel combination of two TLs ended in the series combination of R_{end} and L_{end}. The length of the TLs would be half the length of the slot, $l_{slot}/2$, and their propagation constant and characteristic impedance would be those from (3) and (4):

$$Z_{in} = \frac{1}{2} Z_0 \frac{R_{end} + j2\pi f L_{end} + Z_0 \tanh(\gamma_{CBS} l_{slot}/2)}{Z_0 + (R_{end} + j2\pi f L_{end}) \tanh(\gamma_{CBS} l_{slot}/2)}. \tag{7}$$

The values of this Z_{in} cannot be accurately computed using lumped ports in HFSS, as the length of a standard slot is too short and higher-order mode effects appear. It could be possible to compute it in the case of very long slots, but the value of R_{end} and L_{end} would not be the same as the ones of a standard-length slot. For this reason, the values of the end-effect parameters, R_{end} and L_{end}, will be extracted from the simulation results of stripline-fed CBS, in Section IV, using a wave port.

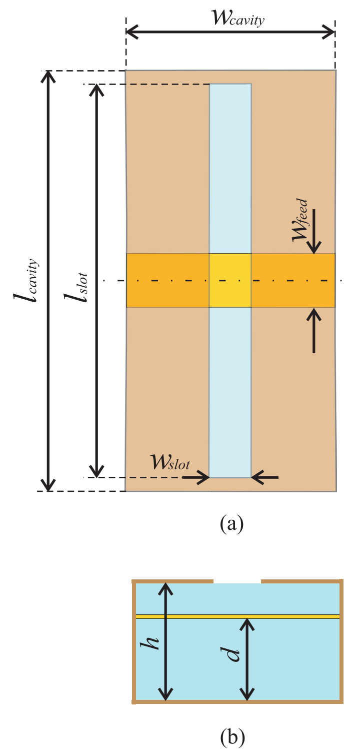


FIGURE 3. **Top and side views of the stripline-fed CBS structure. (a) Top view. (b) Side view.**

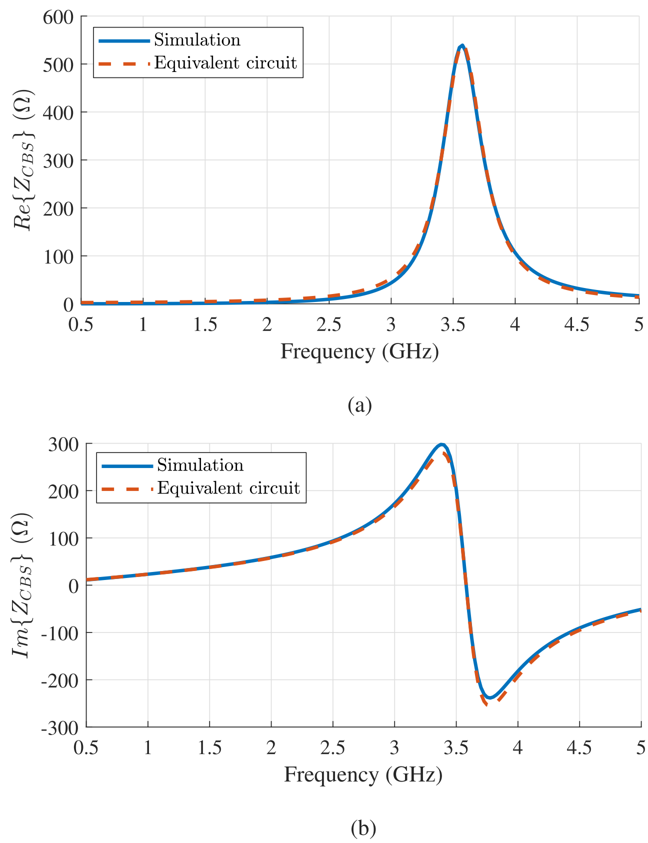


FIGURE 4. **Impedance of the stripline-fed CBS, according to simulation and model when d = 9 mm. (a) Real part. (b) Imaginary part.**

IV. STRIPLINE-FEED EFFECT

In this section, a stripline-fed CBS will be considered. The feeding strip is beneath the slot, at a certain distance from the bottom of the cavity, d, and feeds the slot across its center. Fig. 3 shows the geometry of this structure.

For the third and last part of the model, an equivalent circuit of the transition between the feeding stripline and the CBS is obtained. As found in the literature [34], this transition has been traditionally modeled by an ideal transformer. The turns ratio, n, of this transformer represents the amount of coupling between the stripline and the slot fields. When the distance between the slot and the stripline, $h - d$, is small, both are strongly coupled, and n is higher.

Taking into account the effect of the transformer, the total impedance of the slot, according to the proposed equivalent circuit, is

$$Z_{slot} = \frac{n^2}{2} Z_0 \frac{R_{end} + j2\pi f L_{end} + Z_0 \tanh(\gamma_{CBS} l_{slot}/2)}{Z_0 + (R_{end} + j2\pi f L_{end}) \tanh(\gamma_{CBS} l_{slot}/2)}. \quad (8)$$

First, this impedance was computed using HFSS. In this simulation, however, the feeding striplines were excited by wave ports and the reference planes were placed coincidently at the center of the structure. The width of the stripline was $w_{feed} = 2$ mm, and its distance from the bottom of the cavity is $d = 9$ mm. The total length of the slot is $l_{slot} = 40$ mm and the length of the cavity is $l_{cavity} = 60$ mm. The transverse section of the CBS was not changed from that of Section II. Then, the value of the simulated Z_{slot} is compared with the value of (8), where Z_0 and γ_{CBS} are those extracted in Section II from (3) and (4). Using least-squares fitting, the other parameters, n, R_{end} and L_{end}, are found. The results showed a value for R_{end} of 11.7 Ω, which was considered constant vs. frequency for the sake of simplicity, and a negligible L_{end}, which seem to be reasonable compared with the results of [37]. The value for the turns ratio, n, was found to be 0.96. Fig. 4 shows the comparison between simulation and the equivalent circuit.

As expected, since the slot and strip were close, the obtained value of n was high, close to 1. As the distance between them increases (i.e. as d decreases), the value of n is reduced. However, the resonance frequency of the slot also shifts. This effect is modeled using a capacity, C, placed in parallel with the rest of the circuit and its value is higher as the distance between the strip and slot increases. Fig. 5 shows the proposed equivalent circuit for the complete structure. Fig. 6 shows four additional comparisons, where the distance of the strip from the bottom of the cavity has been gradually reduced. The obtained values of n and C are shown for these and several more cases in Fig. 7. The rest of parameters of the equivalent circuit were not changed. Since the values of n clearly increase linearly with d, the values were curve fitted using $n = 0.106d(\text{mm})$ and plotted altogether in Fig. 7. In the same manner, the values of C were curve fitted using $C(\text{pF}) = 40d(\text{mm})^{-3}$. These results show how simple the

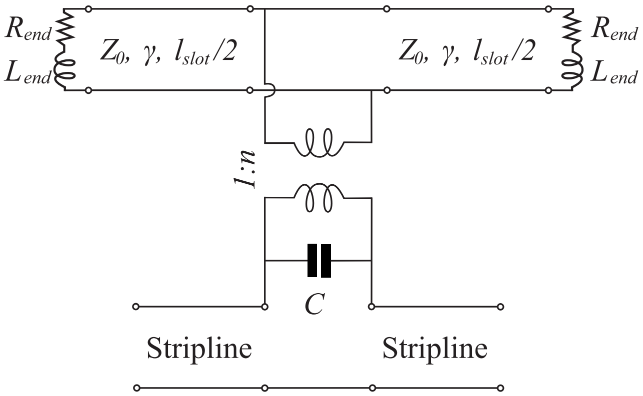


FIGURE 5. Proposed equivalent circuit for the stripline-fed CBS.

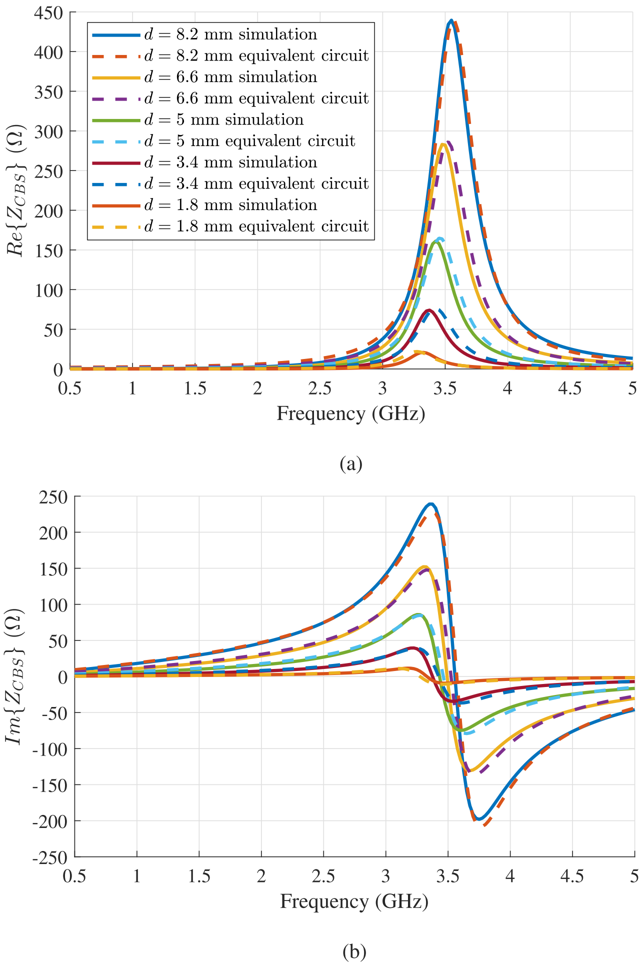


FIGURE 6. Impedance of the stripline-fed CBS, according to simulation and model for different values of *d*. (a) Real part. (b) Imaginary part.

variation of the equivalent circuit parameters with the distance between the slot and the feeding strip is.

V. MEASUREMENT RESULTS

In order to verify the proposed equivalent circuit with experimental results as well, it was applied to a different case with

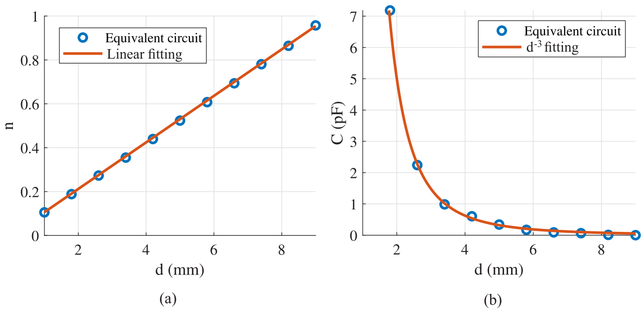


FIGURE 7. Values of the turns ratio and capacitance of the equivalent circuit for different values of *d* and curve fitted using simple equations. (a) Turns ratio *n*. (b) Parallel capacitance *C*.

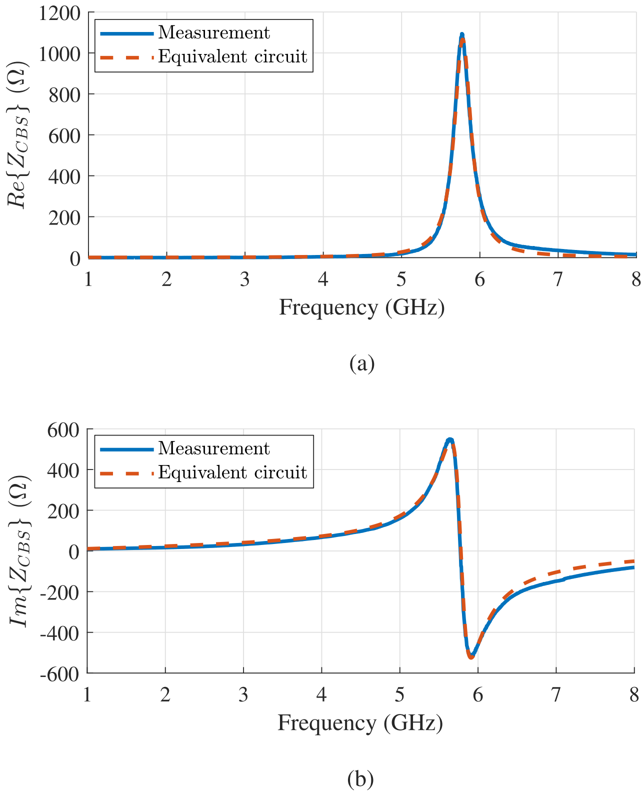
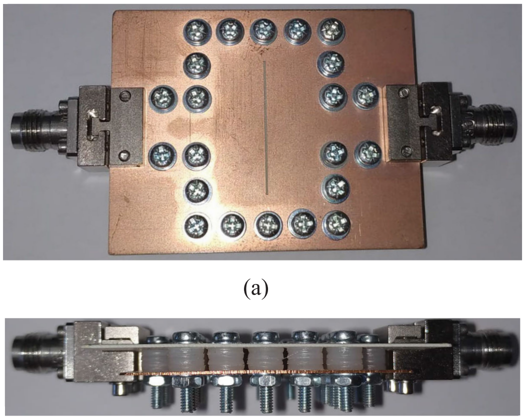


FIGURE 8. Impedance of the stripline-fed CBS, according to measurement and model. (a) Real part. (b) Imaginary part.

an available prototype, which is shown in Fig. 9. To make the fabrication easier, the measured prototype was fed by an enclosed microstrip and the cavity walls were made using screws. Rogers RO4350B with dielectric constant, ε_r, of 3.66 and thickness of 0.51 mm was used. The width of the microstrip line was 1.1 mm, the width of the cavity was 22.4 mm, its length of 32 mm, and its height of 3.71 mm. The length of the slot was 22 mm and its width of 0.3 mm. The screws had a diameter of 2 mm and were placed with a separation of 5.6 mm between them. A TRL calibration kit was fabricated in the same technology and used to place the reference planes at the center of the structure. More information about this prototype can be found in [38].



(a)

(b)

FIGURE 9. Picture of the available prototype used to experimentally verify the model. (a) Top view. (b) Side view.

Since the TL model proposed in Section II neglected dielectric losses in the line, those have been considered by changing the value of ε_r'', to the following:

$$\varepsilon_r'' = \varepsilon_r' tan\delta, \tag{9}$$

where $tan\delta$ is an equivalent loss tangent that accounts for the losses of the TL, and is, in this case, another parameter of the equivalent circuit. The conductor and radiation losses of the line have not been taken into account in this particular case since dielectric loss is the main loss factor at the frequencies of interest.

Fig. 8 shows the values of the impedance of the CBS structure from the measurement results and using the proposed equivalent circuit. The equivalent circuit parameters are: $f_c = 2.418$ GHz, $\varepsilon_r' = 1.75$, $tan\delta = 0.004$, $Z_m = 132$ Ω, $R_{end} = 4.3$ Ω, $L_{end} = 0$, $n = 0.86$ and $C = 0$. The agreement between measurement and the equivalent circuit is excellent up to 6.5 GHz. Between 6.5 GHz and 8 GHz, a small discrepancy is found. This is caused by the effect of the resonant mode TE_{101} [36] inside the cavity, which was not considered. The resonance frequency of this mode in this case is 7.5 GHz and its effect has been shown in [23], [38].

VI. CONCLUSION

We have introduced a wideband equivalent circuit for stripline-fed CBS radiating elements. The proposed model provides physical insight and accurate results while being simple. The equivalent circuit consists of a lossy TL with cutoff frequency ended in a resistor and inductor connected in series. The frequency dependence of the losses can be chosen depending on the dominant losses (dielectric, conductor or radiation). The TL is connected to the feeding stripline through an ideal transformer and a parallel capacitor and the relation of these parameters with the distance between the stripline and the slot is found. An almost direct extraction of the parameters of the model is also provided. Although the equivalent circuit has only been applied to two particular cases, it is expected that it will behave properly under a wide range of geometric and electric parameter values of the structure. The fact that all the parameters of the model except for the resistance of the end-effect of the slot are constant over the frequency band provides the equivalent circuit with a general character and confirms its validity. By separating each of the effects of the CBS, the equivalent circuit greatly helps with the understanding of its behavior, allowing to discern how each part of the structure affects the response of the circuit. The model can be used as an approximated starting point for wideband stripline-fed CBS antennas or arrays where the CBS is the radiator, like in series-fed arrays or leaky-wave antennas. Besides, the characterization of the slot-mode propagation can be of use in leaky-wave antennas and the proposed transition for the strip-slot could also be of great help in the design of circuits and transitions.

ACKNOWLEDGMENT

The authors would like to thank Prof. J. Esteban, from Universidad Politécnica de Madrid (Spain), for helping with the computation of the propagation constant of the CBS-line.

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