This article has been accepted for publication in IEEE Letters on Electromagnetic Compatibility Practice and Applications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/LEMCPA.2026.3674766

IEEE EMC Society | Letters on Electromagnetic Practice and Applications

Do-It-Yourself Sheet-Metal Open TEM Cell

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***Abstract*—This paper presents an improved open transverse electromagnetic (TEM) cell for pre-compliance testing. The design shows a 300 mm septum height and works over CISPR Bands C and D (from 30 MHz to 1 GHz). The improvement lies in its do-it-yourself construction, enabling in-house manufacturing using laser-cut, bendable sheet metals with rectangular slots removed to ease bending. The resulting structure is cost-effective and mechanically robust. 3D-printed supports extending only between the septum and the upper conductor improve the accessibility to the test volume. The design is tested experimentally (minimum return loss of 11.5 dB), and its reproducibility is validated over four independently assembled samples.**

***Index Terms*—Do it yourself, Electromagnetic compatibility, Manufacturing, TEM cell**

I. INTRODUCTION

Transverse electromagnetic (TEM) cells [1] are well-known tools for conducting radiated emission and immunity tests in electromagnetic compatibility (EMC) [2]. Beyond EMC testing, they have been effectively applied in dielectric characterization [3], [4] and field exposure of biological cells [5], [6]. Initially, TEM cells were closed, but later open designs based on striplines were introduced for easier access to the uniform test volume (UTV) [7]. Open TEM cells, though influenced by the surroundings [8], are increasingly used in pre-compliance testing as cost-effective, straightforward EMC testing tools [9], especially across small companies that cannot afford the high costs of repeated EMC tests in accredited laboratories.

To foster the use of TEM cells, we propose a cost-effective do-it-yourself (DIY) TEM cell to be assembled in-house from laser-cut sheet metal. The structure of such TEM cells relies on bent sheet metal that are stiffened by introducing folds and have bending aids manufactured into them. This allows for in-house assembly that requires minimal tooling and yields reproducible results. Based on the TEM cell design in [7] with the septum profile shaped as in [10], this paper proposes a DIY version of the same design – the reference design is called *original design* hereinafter.

Low-cost DIY TEM cell designs are not new in literature. For example, [11] describes a TEM cell using an FR4 substrate with copper layers on both sides; [12] proposes a basic DIY version; and [13] presents a lightweight, low-cost 3D-printed design. However, these

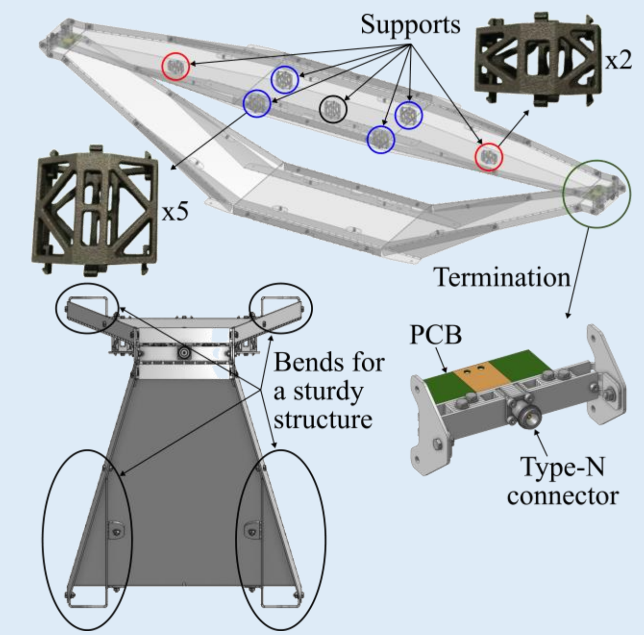

Fig. 1. Visual summary. Views of TEM cell model: transparent isometric view (top) and from one port (bottom left). The supports are of two types: five parts for the left one (blue and black circles) and two parts for the right one (red circles).

implementations suffer from limited performance, assessed in terms of frequency range, minimum return loss (RL) and septum height. In [11], [12], the minimum return loss is below 8 dB, and the septum height 90 mm. In [13], the septum height is even less (50 mm).

In contrast, the DIY TEM cell design presented in this work shows a septum height of 300 mm while achieving a minimum RL greater than 10 dB across CISPR Bands C and D (30 MHz to 1 GHz). Moreover, the reproducibility of results under handcrafted assembly is validated through four independently built samples.

II. MATERIALS AND METHODS

In the original design, expensive PTFE supports are used. To get rid of them and pursue a cost-effective DIY design, the mechanical

Take-Home Messages:

- A foldable sheet-metal design enables a do-it-yourself open asymmetric TEM cell suitable for pre-compliance testing and flat-packed shipment.
- The DIY design performs well as earlier TEM cells while being more compact, easier to assemble, and cost-efficient.
- The results prove to be reproducible over four samples, without the need for adjustments based on measurements.
- Supports only extend between upper conductor and septum, making the test-volume below the septum more accessible.
- The design leverages newly accessible production methods, i.e., on-demand 3D printing and low-volume laser cutting.

Manuscript received xxx; revised yyy; accepted zzz. Date of publication zyzy; date of current version xz. *(Corresponding author: Giacomo Giannetti.)*

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structure in Fig. 1 is developed. The structure is composed of sheet metal which is laser-cut and bent with bending pliers. Rectangular slots are introduced in the outer conductors to ease bending by reducing the resistance moment and precisely localizing the bending line.

To have a sturdy and self-supporting design, the sides of the outer conductors are bent away from the inner part of the TEM cell (Fig. 1). The septum is connected to the upper conductor by 3D-printed, snap-fit supports, positioned as shown in Fig. 1. As the supports only extend between the upper conductor and the septum, this design makes the test-volume below the septum more accessible.

The supports are realized with the Hewlett-Packard (HP) Multi Jet Fusion printer, and the material is PA12 (polyamide) from HP. The parts were black dip-coated after printing. The material has been characterized using a cavity method [14] at 1 GHz. The cavity described in [15], [16] is used, with capacitive prove [17], [18] and coaxial resonators removed. The retrieved permittivity and loss tangent are 2.73 and 0.0125, respectively.

The effort required to bend the sheet metal depends on the bending torque. Referring to Fig. 2, the torque per unit length required to bend a sheet metal along the bending line is [19]

$$T = n\sigma \frac{H^2}{4} \frac{1}{1 + R/B} \tag{1}$$

where $\sigma = 80$ MPa is the flow stress of aluminum (grade EN AW-5754), $H = 2$ mm is the sheet metal thickness, $n = 1.6$ is a correction coefficient for the hardening of the material, R is the slot length, and B is the metal length. The slot width is 1 mm (Fig. 2) and does not play a role in (1). The torque per unit length (1) versus the slot-to-bridge ratio R/B is shown in Fig. 3.

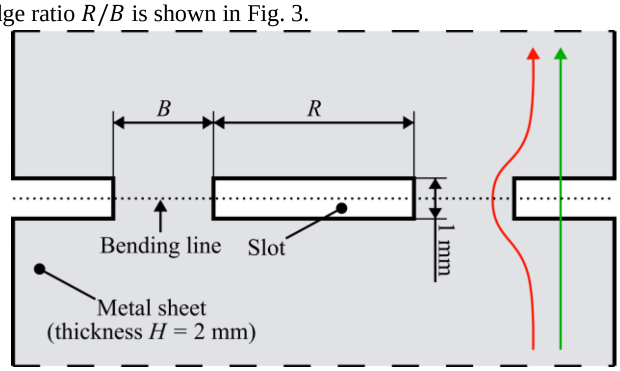

Fig. 2. Slots and indicative current density lines: straight path without slots (green line) and bent path with slots (red line).

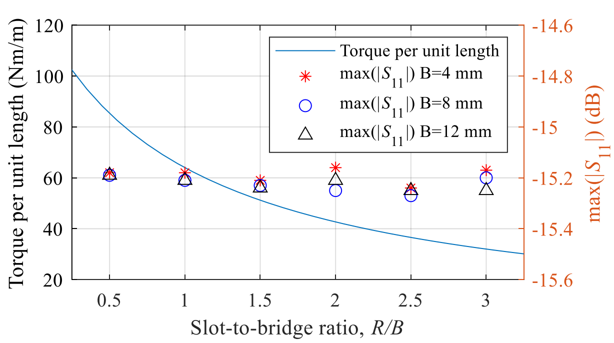

Fig. 3. Torque per unit length and maximum $|S_{11}|$ versus the slot-to-bridge ratio.

The slots are orthogonal to the desired current paths (green arrow in Fig. 2), forcing the current lines to curve around the slots, as shown in Fig. 2. To evaluate the impact of slots on the TEM cell's performance, simulations varied both slot length and slot-to-bridge ratio. Since the mechanical CAD model (Fig. 1) is characterized by too many features, leading to an excessive number of degrees of freedom for the simulation to run, a simplified simulation model had to be simulated (Fig. 4 (a)). This is as the model in [10], but with the slots for bending and the PTFE pillars removed. The model is simplified by omitting the septum supports, screw holes in both the outer conductors and the septum, and the bends on the lateral sides. For the numerical values of the geometrical parameters, the reader is referred to [10]. All simulations presented in this paper were performed using the frequency-domain solver in Ansys Electronics Desktop.

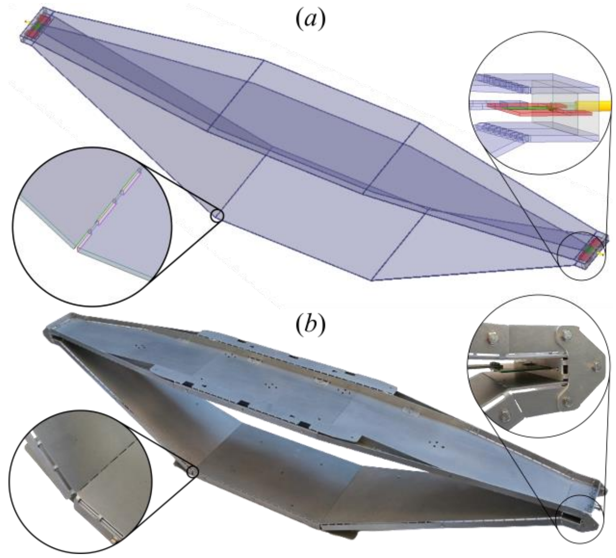

Fig. 4. DIY TEM cell: (a) simulated model and (b) realized sample #3.

Simulated results in Fig. 3 show that for $B \in [4, 8, 12]$ mm and $R/B \in [0.5, 1, 1.5, 2, 2.5, 3]$ the maximum $|S_{11}|$ is not affected. The reason for this is that the slot length R is much shorter than the shortest used wavelength, i.e., 300 mm (maximum value considered for R is 36 mm). We then set $B = 4$ mm, and $R = 10.5$ mm in the central stripline and R = 10 mm at the terminations. In such a way, $R/B \approx 2.5$ and the torque per unit length reduces to less than 40 Nm/m, a value which requires simple tools and which is then DIY-friendly.

III. Results and Discussion

Fig. 4(b) shows the realized TEM cell, which weights 8.8 kg and measures 1854 mm × 403 mm × 304 mm. The cost is around 433 € and comprises 330 € for the laser-cut sheet aluminum, 48 € for the 3D-printed supports, 40 € for the PCBs and 15 € for the screws. Based on the authors' experience, the assembly time is between 4 and 8 hours, depending on the manual ability of the assembler(s). The tools needed are bending pliers, wrenches, and deburring tool. The bending of an outer conductor is shown in Fig. 5.

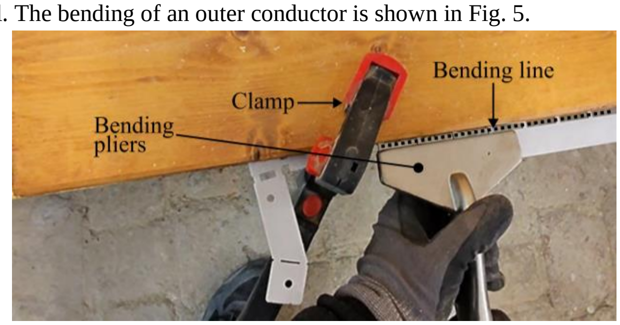

Fig. 5. Bending of an outer conductor using bending pliers.

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To validate the design, four samples were built. Samples #1 to #3 were assembled by the authors, while sample #4 was assembled by a mechanical technician without specialized RF training. The technician completed the assembly independently, without guidance from the authors. As shown next, the performance of sample #4 is consistent with that of the other samples. Sample #1 is used as the reference throughout the experimental analysis.

The DIY TEM cell response is shown in Fig. 6 and compared with the results from [10] and the commercial TEM cell TBTC2 from TekBox [20] (septum height 100 mm, length 636 mm, width 300 mm, height 205 mm). Here and in the following, the comparison is performed based on scattering parameters magnitude, i.e., $|S_{11}|$ and $|S_{21}|$, and time domain reflectometry (TDR) impedance. A more in-depth analysis in terms of field homogeneity [2] is omitted as the original design already satisfies the field requirements [7], and the lack of the PTFE supports is expected to be beneficial on the field homogeneity since the propagating waves encounter less obstacles, as the results of the TDR impedance will show.

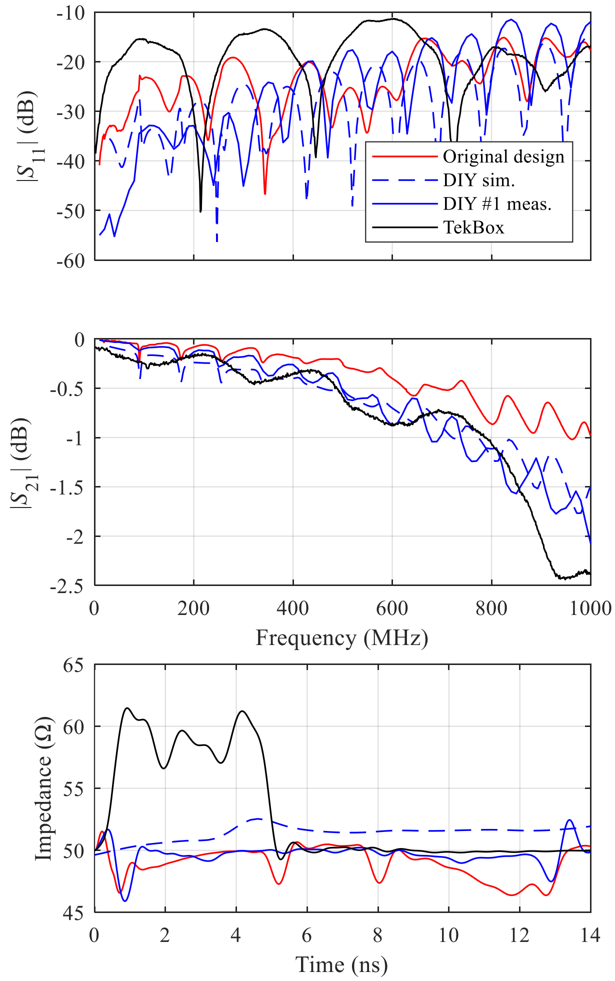

Fig. 6. Comparison for TEM cell in [10], DIY simulations, DIY #1 measurements, and commercial TEM cell: (a) $|S_{11}|$; (b) $|S_{21}|$; (c) TDR impedance.

Simulations for the DIY TEM cell indicate improved $|S_{11}|$ compared to [10], but measurements show a minor decrease in the RL. The lowest RL across samples is 11.5 dB, compared to 15.2 dB for [10]. The gap between simulations and measurements may be due to unmodeled realization details. However, both simulated and measured results for the DIY TEM cell exhibit more regular resonances than [10], due to fewer discontinuities. The DIY TEM cell offers superior RL over the commercial TekBox TEM cell up to 650 MHz.

Fig. 6(b) reveals that The DIY TEM cell exhibits higher insertion loss (IL) than the original design, likely due to manufacturing details. The commercial TEM cell performs similarly to the DIY version up to 850 MHz but worsens thereafter. IL shows good simulation–measurement agreement for the DIY cell, unlike RL.

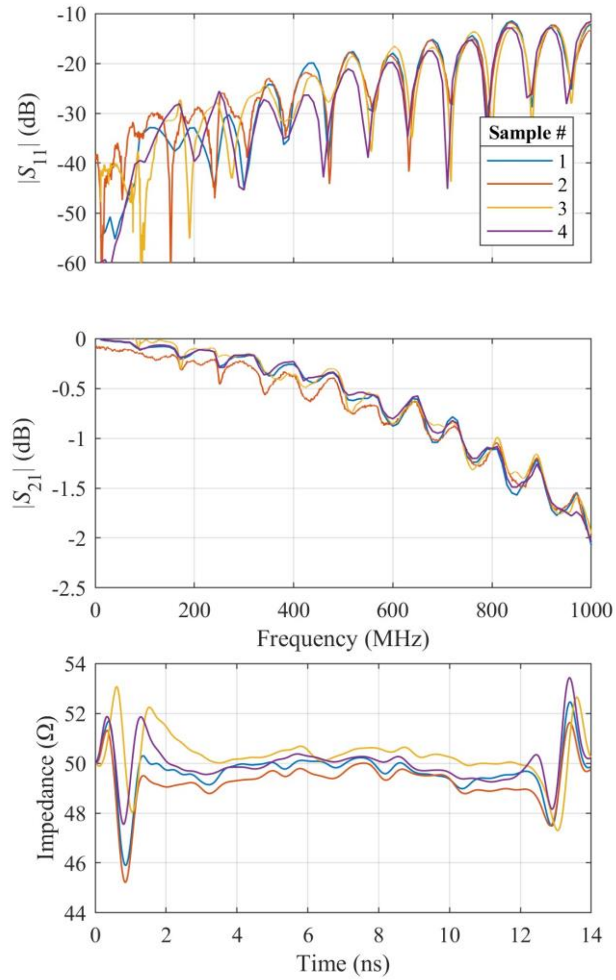

Fig. 7. Comparison over samples: (a) $|S_{11}|$; (b) $|S_{21}|$; (c) TDR impedance.

Regarding TDR impedance, the commercial cell is shorter and deviates more from the ideal 50 Ω. The length of the DIY TEM cell corresponds to a round-trip delay of 12.4 ns in free space. Both the TEM cell in [10] and the DIY versions are near 50 Ω, with the TDR impedance remaining flat in the center. The terminations pose significant design challenges, exhibiting deviations near the ports around 1 ns and 13 ns. Notably, the original design with PTFE pillars shows two valleys at about 5 ns and 8 ns, unlike the DIY cell where such oscillations are not evident due to the shorter supports. The simulated TDR impedance has slight oscillations and is nearly flat beyond 6 ns.

For DIY design reproducibility, four realized samples are compared in Fig. 7. There is only a slight difference between the curves, thus proving the reproducibility of the design. Interestingly, the curves for the TEM cell assembled by a non-RF expert technician are not distinguishable from the others. Consequently, this design is suitable for distributed flat packages and can be assembled on-site yielding consistent results. This is possible since critical dimensions are determined by brackets that are fastened into place, while bending aids designed directly into the sheet metal precisely locate the folds.

Furthermore, the TEM cell performance is investigated with varying 3D-printed support configurations: (i) all supports in place; (ii) only the outer supports removed (red circles in Fig. 1); (iii) all supports removed except the central one (black circle in Fig. 1).

The results for these three cases are shown in Fig. 8. For $|S_{11}|$, only a small discrepancy between curves appears for frequencies higher than 350 MHz, the differences being more evident for lower frequencies. For $|S_{21}|$, there is almost no change, while larger deviations characterize the TDR impedance. Apparently, removing the supports, the TDR impedance deviates from the desired 50 Ω value. This effect is enhanced for case (iii). The line impedance increases as the distance between the septum and the upper conductor increases without supports, thus lowering the capacitance per unit length. In turn, this leads to an increase of the line impedance, as the capacitance per unit length C is at the denominator in the expression for the line impedance $Z_c = \sqrt{L/C}$, being L the inductance per unit length.

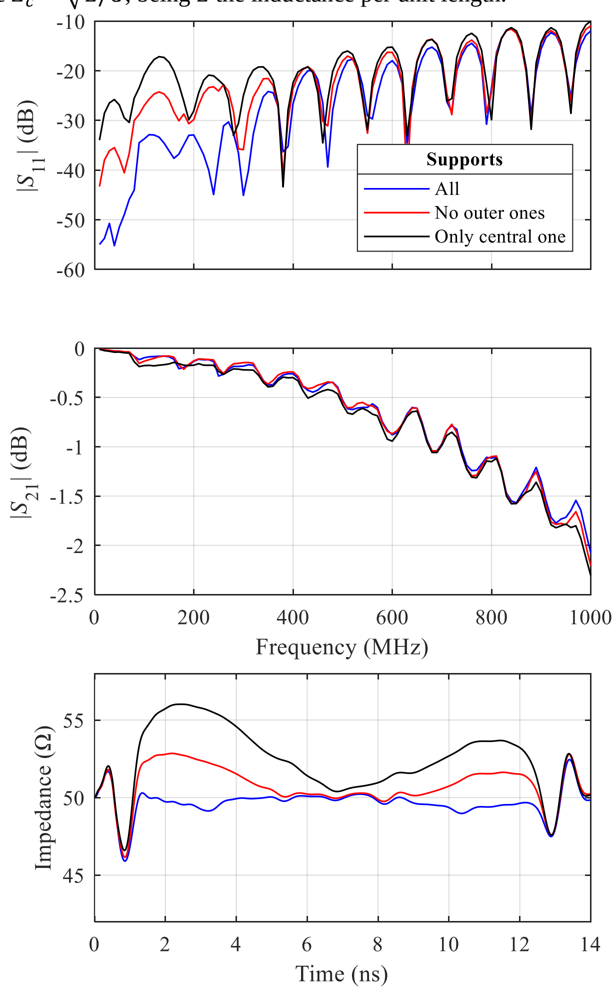

Fig. 8. Comparison considering a different number of supports for sample #1: (a) $|S_{11}|$; (b) $|S_{21}|$; (c) TDR impedance.

IV. Conclusions

The feasibility of a DIY TEM cell with a septum height of 300 mm, operating from 30 MHz to 1 GHz, is demonstrated. Four prototypes were manufactured, showing excellent reproducibility. The DIY design compares well with commercial prototypes, though its performance is slightly worse than the original non-DIY design (lower RL and higher IL). The absence of PTFE pillars results in an almost-flat TDR impedance at the center of the TEM cell. The simplified simulation model agrees well with measurements at low frequencies but is less accurate at high frequencies. A more detailed DIY TEM cell model is necessary for better predictions at higher frequencies. Finally, the removal of supports between the septum and the upper conductor leads to an increase of the TDR impedance and the field homogeneity will be investigated in future work.

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